CENTRAL DELTA WATER AGENCY
235 East Weber Avenue • P.O. Box 1461 • Stockton, CA 95201
Phone 209/465-5883 • Fax 209/465-3956

October 30, 2015

<u>Via Email to BDCP.comments@icfi.com</u>

Re: <u>SUPPLEMENTAL</u> CDWA Comments on the BDCP/California WaterFix Partially Recirculated Draft EIR/Supplemental Draft EIS

These comments supplement other comments being submitted on the above-referenced matter by the Central Delta Water Agency (CDWA).

Attached hereto is a complete copy of the 446 page comments on this matter previously submitted on July 29, 2014 entitled, "<u>SUPPLEMENTAL</u> CDWA Comments on the Draft Bay Delta Conservation Plan and its Draft EIR/EIS and Draft Implementing Agreement."

Those comments are being resubmitted because they are all directly relevant to matters addressed in this Partially Recirculated DEIR/DEIS and identify numerous deficiencies that should have been, but were not, addressed in that recirculated DEIR/DEIS.[1]

To properly correct the deficiencies alleged therein, and in other comments by the CDWA and others, a large amount of "significant new information" within the meaning of CEQA Guidelines section 15088.5, subdivision (a), must necessarily be added to the DEIR/DEIS. Accordingly, the DEIR/EIS will have to be recirculated yet again, and much more comprehensively so, to afford all interested persons and agencies the opportunity to meaningfully review and comment on that new information.

It is truly mind-boggling that anyone, much less our governmental officials who have been entrusted with the responsibility to protect the Delta estuary, could in good faith and with

---

[1] Those comments are being resubmitted, rather than incorporated by reference, because the BDCP did not acknowledge receipt of the email submitting those comments on July 29, 2014 as requested by CDWA. Hence, it is uncertain whether the BDCP properly processed those comments or whether there was a breakdown or other problem with the BDCP's processing of these, and potentially numerous other emailed comments. Such a breakdown or problem would be tremendously prejudicial if it did indeed occur. Attached hereto is a copy of the email submitting those comments and a copy of the "cc" that was successfully received moments after submittal by the CDWA along with screen shots of Microsoft Outlook showing the same. The email to the BDCP did not come back as undeliverable.

any semblance of a straight face come to the conclusion that constructing a massive physical facility, such as the proposed facility, that is physically capable of depriving the Delta estuary more often that not of virtually its entire source of fresh water, and putting that facility into the hands of folks who could not care less about the "unique cultural, recreational, natural resource, and agricultural values of the Delta" estuary, and whose own values, in fact, are directly contrary to those Delta values, will by any stretch of the imagination further the fundamental and mandatory state goal to "protect[] and enhance[]" those Delta values. (Wat. Code, § 85054.)

It is in fact difficult to conceive of a massive physical facility that could do more short and long term harm to the Delta estuary and all but guarantee its ultimate and complete destruction than the instant facility. To successfully kill an estuary, i.e., a very special place where fresh water meets and mixes with the sea, one must seize control of, and substantially restrict or cut off, the fresh water entering into the estuary. To successfully kill the Delta estuary one must seize control of, and substantially restrict or cut off, the fresh water entering into it from its main artery, the Sacramento River. The instant project from the ground up was designed specifically to seize control of the fresh water entering into the Delta from the Sacramento River and to substantially restrict or cut off that flow. The inevitable, and for many, intended, result will be the destruction of the Delta estuary by converting it into a salty, inland sea. Destroying one area of the state, especially an area of such immense local, state and national importance as the Delta estuary, to benefit another area of the state is unacceptable public policy. No local, state or national governmental official should advocate for the creation of a project that will set the stage for, much less one that is arguably specifically designed to bring about, the destruction of the Delta estuary for the benefit of those who would obtain more water for their unsatiable needs if that estuary were destroyed.

It is respectfully requested and urged that the project be entirely rejected. We as a state are obligated to fulfill the state policy "to reduce reliance on the Delta." (Wat. Code, § 85021.) Entirely rejecting this ill-conceived project that is precisely and unashamedly designed to increase, rather that reduce, that reliance, and using the billions of dollars that would otherwise be wasted on this misdirected project to help "each region that depends on water from the Delta watershed [to] improve its regional self-reliance for water through investment in water use efficiency, water recycling, advanced water technologies, local and regional water supply projects, and improved regional coordination of local and regional water supply efforts," is not only the right thing to do, it is our duty under the law. (Wat. Code, § 85021.)

We in the Delta are counting on our governmental officials that are in charge of overseeing and reviewing this project to protect us and the Delta. It is respectfully requested and urged that those officials use their leadership and common sense to reject this project and help guide the state towards increased regional self-reliance and less dependence on the overly-taxed and beleaguered Delta. The robbing Peter to pay Paul approach to water policy that is epitomized by, and at the foundation of, this project must end, and end now with the wholesale rejection of this project. The movement towards regional self-reliance for those that are currently over-reliant upon the Delta's scare water supplies is inevitable. The question presented is whether to vigorously embark upon that movement now, before the Delta estuary is destroyed, or to construct this project, wait for the Delta estuary to be destroyed, and then embark upon that movement. The choice is obvious to anyone who even remotely cares about the Delta estuary and its innumerable and irreplaceable values.

Thank you for considering these comments and concerns.

Respectfully submitted,

Dante J. Nomellini, Jr.
Attorney for the CDWA

Enclosures

Dante Nomellini, Jr.

From:	Dante Nomellini, Jr. <dantejr@pacbell.net>
Sent:	Tuesday, July 29, 2014 11:43 PM
To:	'BDCP.comments@noaa.gov'
Cc:	Dante Nomellini, Jr. (dantejr@pacbell.net)
Subject:	CDWA SUPPLEMENTAL Comments on Draft BDCP Plan and EIR_EIS
Attachments:	CDWA SUPPLEMENTAL Comments on Draft BDCP Plan and EIR_EIS.pdf

Attached hereto please find the following document:

"CDWA SUPPLEMENTAL Comments on Draft BDCP Plan and EIR_EIS" (approx. 12 MB)

Please reply to this email acknowledging receipt of that document.

Thank you,
Dan Jr.
Attorney for the Central Delta Water Agency

Dante J. Nomellini, Jr. ("Dan Jr.")
Attorney at Law
Nomellini, Grilli & McDaniel
Professional Law Corporations
235 East Weber Avenue
Stockton, CA 95202
Mailing address:
P.O. Box 1461
Stockton, CA 95201-1461
Telephone: (209) 465-5883
Facsimile: (209) 465-3956
Email: dantejr@pacbell.net

This is a copy of the received "cc" email to Dante Nomellini, Jr.

Dante Nomellini, Jr.

From:	Dante Nomellini, Jr. <dantejr@pacbell.net>
Sent:	Tuesday, July 29, 2014 11:43 PM
To:	BDCP.comments@noaa.gov
Cc:	Dante Nomellini, Jr.
Subject:	CDWA SUPPLEMENTAL Comments on Draft BDCP Plan and EIR_EIS
Attachments:	CDWA SUPPLEMENTAL Comments on Draft BDCP Plan and EIR_EIS.pdf

Attached hereto please find the following document:

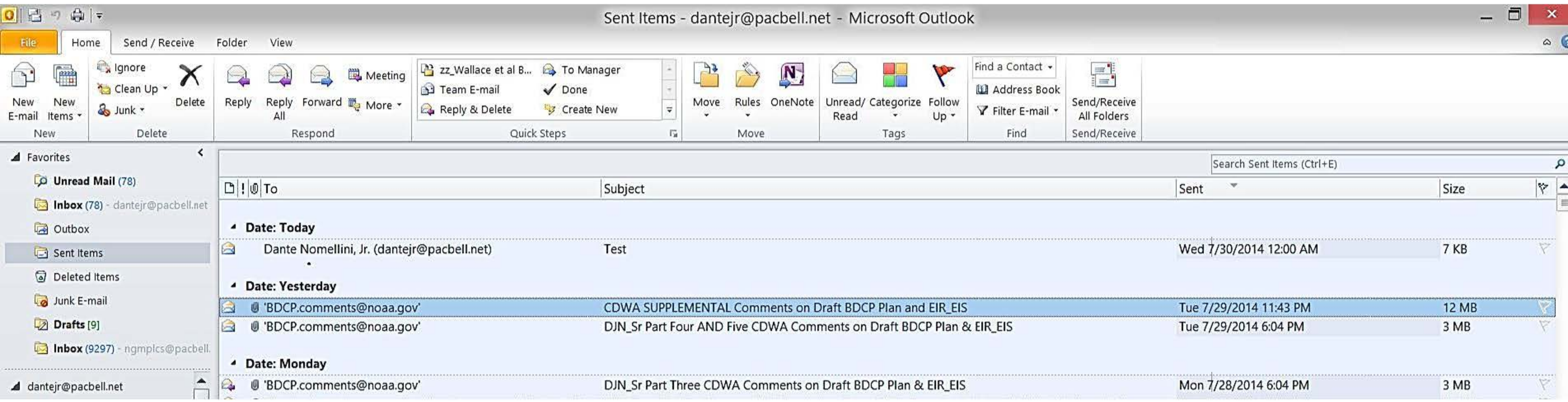
"CDWA SUPPLEMENTAL Comments on Draft BDCP Plan and EIR_EIS" (approx. 12 MB)

Please reply to this email acknowledging receipt of that document.

Thank you,
Dan Jr.
Attorney for the Central Delta Water Agency

Dante J. Nomellini, Jr. ("Dan Jr.")
Attorney at Law
Nomellini, Grilli & McDaniel
Professional Law Corporations
235 East Weber Avenue
Stockton, CA 95202
Mailing address:
P.O. Box 1461
Stockton, CA 95201-1461
Telephone: (209) 465-5883
Facsimile: (209) 465-3956
Email: dantejr@pacbell.net

RECIRC2819.


Sent Items - dantejr@pacbell.net - Microsoft Outlook
File
Home
Send / Receive
Folder
View
New E-mail
New Items
New
Ignore
Clean Up
Junk
Delete
Delete
Reply
Reply All
Forward
Meeting
More
Respond
zz_Wallace et al B...
Team E-mail
Reply & Delete
To Manager
Done
Create New
Quick Steps
Move
Rules
OneNote
Move
Unread/ Read
Categorize
Follow Up
Tags
Find a Contact
Address Book
Filter E-mail
Find
Send/Receive All Folders
Send/Receive
Favorites
Unread Mail (78)
Inbox (78) - dantejr@pacbell.net
Outbox
Sent Items
Deleted Items
Junk E-mail
Drafts [9]
Inbox (9297) - ngmplcs@pacbell.
dantejr@pacbell.net
Search Sent Items (Ctrl+E)
To
Subject
Sent
Size
Date: Today
Dante Nomellini, Jr. (dantejr@pacbell.net)
Test
Wed 7/30/2014 12:00 AM
7 KB
Date: Yesterday
'BDCP.comments@noaa.gov'
CDWA SUPPLEMENTAL Comments on Draft BDCP Plan and EIR_EIS
Tue 7/29/2014 11:43 PM
12 MB
'BDCP.comments@noaa.gov'
DJN_Sr Part Four AND Five CDWA Comments on Draft BDCP Plan & EIR_EIS
Tue 7/29/2014 6:04 PM
3 MB
Date: Monday
'BDCP.comments@noaa.gov'
DJN_Sr Part Three CDWA Comments on Draft BDCP Plan & EIR_EIS
Mon 7/28/2014 6:04 PM
3 MB

RECIRC2819.

Inbox - dantejr@pacbell.net - Microsoft Outlook

File | Home | Send / Receive | Folder | View

New E-mail | New Items | Ignore | Clean Up | Junk | Delete | Reply | Reply All | Forward | Meeting | More | zz_Wallace et al B... | Team E-mail | Reply & Delete | To Manager | Done | Create New | Move | Rules | OneNote | Unread/ Read | Categorize | Follow Up | Find a Contact | Address Book | Filter E-mail | Send/Receive All Folders

New | Delete | Respond | Quick Steps | Move | Tags | Find | Send/Receive

Favorites
- Unread Mail (78)
- Inbox (78)
- Outbox
- Sent Items
- Deleted Items
- Junk E-mail
- Drafts [9]
- Inbox (9297)

dantejr@pacbell.net
- Inbox (78)
- Drafts [9]
- Sent Items
- Deleted Items
- Junk E-mail
- Outbox
- RSS Feeds

Search Inbox (Ctrl+E)

From	Subject	Received	Size
Date: Today			
Dante Nomellini, Jr.	Test	Wed 7/30/2014 12:00 AM	17 KB
Date: Yesterday			
Dante Nomellini, Jr.	CDWA SUPPLEMENTAL Comments on Draft BDCP Plan and EIR_EIS	Tue 7/29/2014 11:47 PM	12 MB
xeroxngm@gmail.com	Scanned from a Xerox multifunction device	Tue 7/29/2014 11:37 PM	196 KB
bdcp comments - NOAA Service Account	Comment on the Draft BDCP and Draft EIR/EIS Re: DJN_Sr Part Four AND Five CDWA Comments on Draft B...	Tue 7/29/2014 6:06 PM	13 KB
Supervisor Mary Nejedly Piepho	**Supervisor Mary Piepho - Important Roadway Closure Notice**	**Tue 7/29/2014 5:35 PM**	**39 KB**
Supervisor Mary Nejedly Piepho	**Supervisor Mary Piepho - Human Case of the West Nile Virus in Contra Costa County**	**Tue 7/29/2014 5:35 PM**	**43 KB**
Nomellini, Grilli & McDaniel PLCs		Tue 7/29/2014 4:53 PM	3 MB
lyris@swrcb18.waterboards.ca.gov	**Notice of Advisory Committee Consensus Comments to the Agricultural Expert Panel**	**Tue 7/29/2014 4:06 PM**	**79 KB**
Bay Delta Conservation Plan	Comment Period on Draft BDCP and Associated Draft EIR/EIS Closes Today	Tue 7/29/2014 2:14 PM	72 KB
lyris@swrcb18.waterboards.ca.gov	**Agenda for Central Valley Regional Water Board Meeting, August 7-8, 2014**	**Tue 7/29/2014 11:03 AM**	**25 KB**
Cenergy Power	**Cenergy Alert: NEMA Program Goes Live in SCE and SDG&E Territory**	**Tue 7/29/2014 10:18 AM**	**52 KB**
BDCPcomments	Read: DJN_Sr Part Three CDWA Comments on Draft BDCP Plan & EIR_EIS	Tue 7/29/2014 9:14 AM	16 KB
DWR Water News Editors	**DWR California Water News - July 29, 2014**	**Tue 7/29/2014 8:38 AM**	**156 KB**
Date: Monday			

DIRECTORS
George Biagi, Jr.
Rudy Mussi
Edward Zuckerman

COUNSEL
Dante John Nomellini
Dante John Nomellini, Jr.

CENTRAL DELTA WATER AGENCY
235 East Weber Avenue • P.O. Box 1461 • Stockton, CA 95201
Phone 209/465-5883 • Fax 209/465-3956

July 29, 2014

Via Email to BDCP.comments@noaa.gov

Re: SUPPLEMENTAL CDWA Comments on the Draft Bay Delta Conservation Plan and its Draft EIR/EIS and Draft Implementing Agreement.

Dear Mr. Wulff:

These comments supplement other comments being submitted on the above-referenced matters by the Central Delta Water Agency (CDWA).

Having finally had the opportunity to flip through at least some of the overwhelming documentation in support of this project, my fears were one-hundred percent validated. There are no ifs, ands or buts about it: **THIS PROJECT WILL DESTROY THE DELTA**. It is truly shocking how anti-preservation-of-the-Delta this project is across the board.

Virtually everything I was able to flip through had major problems in terms of compliance with CEQA and NEPA as well as numerous other laws.

It is extremely disconcerting that the powers that be have already been convinced politically or otherwise that an isolated facility, and the so-called Preferred Alternative for that matter, is a done deal. It strikes me as pure insanity that, in light of the dire state of the Delta ecosystem, state and federal fish and wildlife agencies, in particular, could even remotely consider issuing any semblance of a fifty-year assurance to the Projects that if the Projects do x, y and z, then they will be essentially be completely off the hook for any water commitments or other measures needed in the future to protect fish and wildlife resources within the Delta Watershed. That is especially insane when x, y and z are nothing but an experiment and one that the instant EIR/EIS confirms will destroy the Delta in the process.

There is so much legally and practically wrong the BDCP Plan and its Draft EIR/EIS and Implementing Agreement, that it has been quite frustrating to try to review the documents and comment on them. I will defer to the many others who have embraced this monstrosity in greater detail and will unfortunately only be able to comment on a handful out of what I estimate to be on the order of hundreds of fundamental legal and other flaws.

I highly doubt anyone with any meaningful say on the approval of this project is going to read these comments, but if by chance any such person should, for the sake of the Delta which this project purports to protect, and from someone who was raised in the Delta and genuinely cares about its well-being, I respectfully request and urge that you **PLEASE DO NOT APPROVE THIS PROJECT.** This is clearly not the solution to address the so-called co-equal goals. Not even close.

1. The Preferred Project is Contrary to the Delta Reform Act of 2009.

a. The Preferred Project Fails to Achieve the Co-Equal Goals in a Manner that Protects and Enhances Delta Values.

Speaking of those so-called co-equal goals, from reviewing the various documents associated with the project, it is crystal clear that the proponents of this project did not advance past the first sentence in Water Code section 85054. Section 85054 provides in full as follows:

> "Coequal goals" means the two goals of providing a more reliable water supply for California and protecting, restoring, and enhancing the Delta ecosystem. The coequal goals shall be achieved in a manner that protects and enhances the unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place.

(Emphasis added.) It is simply not possible for one to read through, even the "mere" (132 page) executive summary, for the BDCP Draft EIR/EIS ("DEIR/EIS") and walk away thinking this project in any manner "protects," much less "enhances," the "unique cultural, recreational, natural resource, and agricultural values of the Delta as an evolving place." Simply look at the summary of the countless significant and unavoidable impacts to those values. What kind of twisted interpretation can be given to the phrase "as an evolving place" to justify the undisputed destruction of those values rather than their protection, much less, enhancement?

The Projects' conveyance facilities can be improved in numerous ways (e.g., by constructing the state of the art fish screens on the existing South Delta export facilities that were required by the CALFED ROD to be operational by 2006) that do not involve the mass destruction and impairment of those values.

And to confirm the fact that the BDCP Proponents are indeed entirely overlooking the second sentence in section 85054, all one has to do is review the stated project objectives which say absolutely nothing about protecting, much less enhancing, those values, either as an evolving place or otherwise. Instead, the objectives only mention more reliable water supplies and the Delta ecosystem, i.e., the first sentence (except, of course, they change the phrase "more reliable water supply for California" to "more reliable water supply for exporters").

///

///

b. The Preferred Project Substantially Increases Reliance on the Delta Rather than Reduce that Reliance.

Another provision of the Delta Reform Act of 2009 that apparently none of the BDCP Proponents have yet had the opportunity to review is the following:

> The policy of the State of California is to reduce reliance on the Delta in meeting California's future water supply needs through a statewide strategy of investing in improved regional supplies, conservation, and water use efficiency.

(Wat. Code, § 85021, emphasis added.)

It defies logic and common sense how anyone could examine the BDCP from up-close or even far away and somehow conclude that the 50 or 60 or more billion dollar BDCP is indeed a project that is in furtherance of reducing the BDCP Proponents' reliance on the Delta for meeting their water supply needs. This project is obviously in furtherance of doing the complete opposite of reducing that reliance.

For starters, the entire concept of improving the reliability of Delta water supplies is at odds with the policy of reducing reliance on the Delta because the more reliable that Delta water supply is for exporters, the more it can and will be relied upon by those exports. But the BDCP, however, goes considerably beyond that and unashamedly (and quite frankly, unbelievably) goes so far as to make the following objective one of the project's express objectives:

> Restore and protect the ability of the SWP and CVP to deliver up to full contract amounts, when hydrologic conditions result in the availability of sufficient water, consistent with the requirements of state and federal law and the terms and conditions of water delivery contracts and other existing applicable agreements.

(DEIR/EIS, p. ES-8, emphasis added.) How in the world will "restoring" and "protecting" the ability of the Projects "to deliver up to full contract amounts," i.e., something the projects have NEVER been able to do, in any manner, even remotely, reduce the Projects' reliance on the Delta to meet their future water supply needs? The answer is obviously that it will not. Instead, the entire purpose of this objective is undeniably to substantially increase the Projects' reliance on the Delta to meet their future water supply needs, which should make this project dead on arrival if the persons in charge of enforcing the reduced reliance policy choose to duly enforce that policy.

While it is true that any improved reliability of Delta water supplies for exporters will, by definition or otherwise, arguably increase the exporters' reliance on those supplies, what is being proposed by the BDCP Proponents and what is set forth in the above-referenced project objective is simply off the charts and manifestly unacceptable and contrary to that reduced reliance policy.

c. The Preferred Project Substantially Impairs, Rather than Improves Water Quality Within the Delta.

Yet another significant policy which is likewise entirely being overlooked by the BDCP Proponents is the policy set forth in Water Code section 85020 which provides:

> The policy of the State of California is to achieve the following objectives that the Legislature declares are inherent in the coequal goals for management of the Delta: . . . (e) Improve water quality to protect human health and the environment consistent with achieving water quality objectives in the Delta.

(Emphasis added.) It is nothing short of appalling how the DEIR/EIS has handled the BDCP's impacts to surface and groundwater quality within the Delta. In direct contravention of the above policy, rather than improve that water quality, the DEIR/EIS concludes that both surface and groundwater quality will be "significantly" and "unavoidably" adversely impacted. (See e.g., DEIR/EIS, p. ES-63.)

2. The Preferred Project is Contrary to Numerous Other Laws and Policies.

The Delta Reform Act of 2009 is, of course, not the only source of legislative policies and declarations imposing restrictions on the design of the BDCP. A few of those other sources will be briefly discussed below.

a. Delta Protection Act of 1992.

> "The Legislature finds and declares that the Sacramento-San Joaquin Delta is a natural resource of statewide, national, and international significance, containing irreplaceable resources, and it is the policy of the state to recognize, preserve, and protect those resources of the delta for the use and enjoyment of current and future generations." (Pub. Resources Code, § 29701, emphasis added.)

> "The Legislature further finds and declares that the basic goals of the state for the delta are the following: (b) Protect, maintain, and, where possible, enhance and restore the overall quality of the delta environment, including, but not limited to, agriculture, wildlife habitat, and recreational activities." (Pub. Resources Code, § 29702, emphasis added.)

> "The Legislature further finds and declares as follows:
>
> (a) The delta is an agricultural region of great value to the state and nation and the retention and continued cultivation and production of fertile peatlands and prime soils are of significant value.

(b) The agricultural land of the delta, while adding greatly to the economy of the state, also provides a significant value as open space and habitat for water fowl using the Pacific Flyway, as well as other wildlife, and the continued dedication and retention of that delta land in agricultural production contributes to the preservation and enhancement of open space and habitat values.

(c) Agricultural lands located within the primary zone should be protected from the intrusion of nonagricultural uses." (Pub. Resources Code, § 29703, emphasis added.)

Suffice it to say that it is undisputed that the proposed BDCP will permanently destroy, not "[p]rotect, maintain, and, where possible, enhance," tens of thousands of acres of agricultural land within the Delta, much of which in the primary zone, and, as with Delta surface water quality and ground water quality, the DEIR/EIS concludes that agricultural land as well as recreational opportunities will be "significantly" and "unavoidably" adversely impacted. (See e.g., DEIR/EIS, p. ES-111 & ES-112.)

Moreover, how causing significant and unavoidable adverse impacts to surface and ground water quality and to agriculture and recreational activities in the Delta could be fairly said to be consistent with the basic goals of the state to "[p]rotect, maintain, and, where possible, enhance and restore the overall quality of the delta environment, including, but not limited to, agriculture, wildlife habitat, and recreational activities," is simply mind-boggling. (Pub. Resources Code, § 29702, emphasis added.) Clearly, causing such impacts is by no means consistent with that goal.

b. **Water Code Section 12980 et seq.**

"The Legislature finds and declares that the delta is endowed with many invaluable and unique resources and that these resources are of major statewide significance." (Wat. Code, § 12981, subd. (a), emphasis added.)

"The Legislature further finds and declares that the delta's uniqueness is particularly characterized by its hundreds of miles of meandering waterways and the many islands adjacent thereto; that, in order to preserve the delta's invaluable resources, which include highly productive agriculture, recreational assets, fisheries, and wildlife environment, the physical characteristics of the delta should be preserved essentially in their present form; . . ." (Wat. Code, § 12981, subd. (b), emphasis added.)

Neither the construction of a huge isolated facility through the Delta nor any of the related intakes, forebays, vertical shafts, etc., nor the diversion of fresh water inflows into such an isolated facility, come anywhere remotely close to "preserv[ing]" "the physical characteristics of the delta . . . in their present form; . . . ." (*Ibid.*) Such construction and operation constitute an obvious and destructive alteration of the present physical characteristics of the Delta in direct contravention of the Legislature's findings and declarations in section 12981.

c. **Delta Protection Act of 1959.**

> "The Legislature finds that the maintenance of an adequate water supply in the Delta sufficient to maintain and expand agriculture, industry, urban, and recreational development in the Delta area as set forth in Section 12220, Chapter 2, of this part, and to provide a **common source** of fresh water for export to areas of water deficiency is necessary to the peace, health, safety and welfare of the people of the State . . . ." (Wat. Code, § 12201, emphasis added.)

If water is exported at the northernmost tip of the Delta via an isolated facility as proposed by the BDCP, then such water is plainly not providing a "common source of fresh water for export," instead, it is providing an isolated source of fresh water for export which is entirely devoid of common benefits to essentially the entirety of the Delta and, hence, which is squarely contrary to section 12201 and "to the peace, health, safety and welfare of the people of the State."

Moreover, Water Code section 12205 provides:

> "It is the policy of the State that the operation and management of releases from storage into the Sacramento-San Joaquin Delta of water for use outside the area in which such water originates shall be integrated to the maximum extent possible in order to permit the fulfillment of the objectives of this part." (Emphasis added.)

Since, as just noted, one of the "objectives of this part" is to "provide a common source of fresh water for export" (Wat. Code, § 12201, emphasis added), the Projects have a duty to integrate their releases from storage into the Delta "to the maximum extent possible" to provide that "common" source. Diverting any amount of such releases into an isolated canal, which by definition is entirely devoid of the required commonality of benefits, is obviously not providing the "common" source of fresh water to the maximum extent possible. Rather, it would be blatantly disregarding that mandate.

Water Code sections 12203 and 12204, respectively, provide:

> "It is hereby declared to be the policy of the State that no person, corporation or public or private agency or the State or the United States should divert water from the channels of the Sacramento-San Joaquin Delta to which the users within said Delta are entitled."

> "In determining the availability of water for export from the Sacramento-San Joaquin Delta no water shall be exported which is necessary to meet the requirements of Sections 12202 and 12203 of this chapter."

Even assuming that the "common pool" mandate could somehow be circumvented, before one drop of water is placed into an isolated facility, there needs to be a comprehensive analysis regarding how many drops of water, and at what times of year, and during what hydrological and ecological situations, etc., can such drops of water be legally deemed to be surplus to what "users within [the] Delta are entitled" (Wat. Code, § 12203) and surplus to what is "necessary to meet the requirements of Sections 12202 and 12203 of this chapter." (Wat. Code, § 12204.) Until that comprehensive analysis is duly undertaken (which thus far it has not), a discussion, much less the development and threatened approval of a plan, to improve the Projects' conveyance facilities in the Delta is entirely premature and misplaced.

d. **Watershed Protection Act.**

Water Code section 11460 provides:

> "In the construction and operation by the department [i.e., the SWP and CVP] of any project under the provisions of this part a watershed or area wherein water originates, or an area immediately adjacent thereto which can conveniently be supplied with water therefrom, <u>shall not be deprived by the department directly or indirectly of the prior right to all of the water reasonably required to adequately supply the beneficial needs of the watershed, area, or any of the inhabitants or property owners therein</u>." (Emphasis added.)

In light of the conceded significant and unavoidable adverse impacts to the water quality in the Delta that will result from implementation of the BDCP, and the resulting significant and unavoidable detriment to humans and environmental resources that utilize and depend upon that water quality, the implementation of the BDCP would squarely violate this fundamental duty that the Projects' specifically avoid any such detriment from their operations.

The BDCP as proposed simply makes a mockery of this and essentially every other law intended to protect the Delta and its water supply and quality, and all of its "natural [and "irreplaceable"] resource[s] of statewide, national, and international significance . . . ." (Pub. Resources Code, § 29701, emphasis added.)

It is nothing short of amazing and deeply disconcerting that there could be so much momentum, even by those who could care less about the Delta, to implement a project, such as the BDCP, that is so completely at odds with so many legislative declarations and policies. This is truly a sad state of affairs.

3. The Preferred Project if Contrary to the CALFED Record of Decision.

As if being squarely contrary to nearly every legislative declaration and policy intended to protect the Delta from something like the BDCP was not enough, the BDCP is also squarely contrary to the CALFED Record of Decision's thirty (30) year plan, which to remind anyone who may have forgotten, was adopted on August 28, 2000 and, hence, has about another 15 years before it expires.

According to the CALFED ROD, "Carrying out [its] mission, achieving the objectives, and adhering to the solution principles will ensure that CALFED fulfills its commitment to continuous improvement in all of the four problem areas." (DEIR/EIS, App. 3A, attmt. 1, p. 8.)

With regard to the CALFED ROD's objectives, those objectives are the following:

> CALFED developed the following objectives for a solution:
> - Provide good water quality for all beneficial uses.
> - Improve and increase aquatic and terrestrial habitats and improve ecological functions in the Bay-Delta to support sustainable populations of diverse and valuable plant and animal species.
> - Reduce the mismatch between Bay-Delta water supplies and current and projected beneficial uses dependent on the Bay-Delta system.
> - Reduce the risk to land use and associated economic activities, water supply, infrastructure and the ecosystem from catastrophic breaching of Delta levees.

(DEIR/EIS, App. 3A, attmt. 1, p. 9.)

While I will let others address the BDCP's significant and unacceptable negative impacts on aquatic and terrestrial habitats, suffice it to say that, as discussed above, the BDCP not only fails to meet all of those objectives, but, instead, it actually impairs several, if not all, of those objectives. As discussed above, the BDCP results in significant and unavoidable adverse impacts to surface and groundwater quality within the Delta and, hence, entirely defeats the first objective. That impairment also defeats the third objective by directly limiting the beneficial water supply available to in-Delta diverters, not to mention to the in-Delta environmental resources. As discussed further below, the decade-plus construction of the BDCP has the clear potential to <u>increase</u> rather than "[r]educe the risk to land use and associated economic activities, water supply, infrastructure and the ecosystem from catastrophic breaching of Delta levees."

Hence, rather than be in furtherance of the CALFED ROD's solution and its four basic objectives, the BDCP directly impairs the fulfilment of that solution and objectives.

However, what takes the cake, is the CALFED ROD's requirement that "any CALFED solution <u>must satisfy</u> the following [six] solution principles:

> - <u>Reduce Conflicts in the System</u>. Solutions will reduce major conflicts among beneficial uses of water.
> - <u>Be Equitable</u>. Solutions will focus on solving problems in all problem areas. Improvements for some problems will not be made without corresponding improvements for other problems.
> - <u>Be Affordable</u>. Solutions will be implementable and maintainable within the foreseeable resources of the Program and stakeholders.

– Be Durable. Solutions will have political and economic staying power and will sustain the resources they were designed to protect and enhance.
– Be Implementable. Solutions will have broad public acceptance and legal feasibility, and will be timely and relatively simple to implement compared with other alternatives.
– Have No Significant Redirected Impacts. Solutions will not solve problems in the Bay-Delta system by redirecting significant negative impacts, when viewed in their entirety, within the Bay-Delta or to other regions of California.

(DEIR/EIS, App. 3A, attmt. 1, p. 9.)

Is there really any need at this point to say anything further? Could anyone that has spent any fair amount of time learning about the BDCP and reviewing the DEIR/EIS claim with a straight face that the BDCP satisfies any of those solution principles, much less all of them?

Needless to say it should appear manifestly clear to such persons that:

(1) The BDCP by no means "reduces conflicts in the system," instead it creates the mother of all conflicts in the system.

(2) The BDCP is by no means "equitable" since it is unashamedly focused on Project exporters and (ostensibly at least) the Delta ecosystem, and intends to significantly destroy Delta values and resources in its wake.

(3) The BDCP is by no means "affordable." To this day the BDCP Proponents still refuse to pay all of the costs associated with the project presumably because it would not be affordable for them to do so.

(4) The BDCP is by no means "durable," since its too expensive, it will not produce any where near the water the BDCP Proponents are banking on, and the vast majority of experts agree it will result in the ultimate destruction of the resources it is purportedly designed to protect and enhance, namely fish and wildlife.

(5) The BDCP is by no means "implementable." It is laughable and sad at the same time to suggest that the BDCP has "broad public acceptance" and "legal feasibility." It patently has neither. And with regard to whether it "will be timely and relatively simple to implement compared with other alternatives," if this is not the most convoluted and time-consuming project to implement in the western hemisphere if not the world, then it is unquestionably a runner up..

(6) And last, but certainly not least, it would literally be difficult to design a project that had more "significant redirected impacts" than the BDCP. The sheer number of significant and unavoidable adverse impacts to the Delta amply tells the story.

> The BDCP's redirection of significant impacts is egregious, blatant and entirely unacceptable and unfair.

If being squarely contrary to the Delta Reform Act of 2009, the Delta Protection Acts of 1959 and 1992, Water Code sections 12980 et seq., and the Watershed Protection Act are not enough reason to abandon the BDCP and go back to the drawing board, then its respectfully requested and urged that the powers that be revisit and considered the foregoing CALFED ROD mission statement, objectives and solution principles, which the powers that be themselves came up with and approved, and reject the BDCP in its present form and work towards crafting a true solution that myself, the Central Delta Water Agency and everyone else could get behind and support.

Substantially improving the levee system throughout the entire Delta would be a wonderful place to start along with installing the state of the art fish screens at the existing South Delta facilities which, of course, were supposed to be implemented within the first seven years of the CALFED ROD program and which are now approximately eight years past due.

4. The DEIR/EIS Fails to Properly Address the Impacts from the Substantial Erosion of the "Common Pool" That Would Result From the Construction of an Isolated Facility.

One of the most significant negative effects, if not <u>the</u> most significant negative effect, from the BDCP on the short and long term viability of the Delta and its water supply, water quality, ecosystem and all of its "natural [and "irreplaceable"] resource[s] of statewide, national, and international significance . . ." is the BDCP's substantial and unlawful impairment of the "common pool" requirement mandated by the Delta Protection Act of 1959 via the BDCP's construction of an isolated facility.

The Delta Protection Act of 1959's mandate that exports from the Delta be taken from the "common pool" within the Delta, and not from the uppermost northern tip of the Delta as proposed by the BDCP, has ensured that the state and federal government, as well as the millions of people who receive Delta export water and the owners and operators of hundreds of thousands of acres of farmland that utilize such water, have a direct stake in ensuring that the Delta water quality remains fresh. Under the common pool requirement, what is good for the goose is good for the gander.

It does not take a masters degree in water-related political science to realize that the substantial, if not entire, removal from that much voting and political power in the state (and, in the end, essentially greed) of the fundamental vested interest in preserving the water quality within the Delta as a whole would be at the top of the list of the most foolish things a person could advocate if a person was truly interested in preserving the short and long term viability and, hence, water quality of the Delta estuary.

At the end of the day, what is really keeping the Delta fresh and from turning into an inland sea as a result of corruption and greed is the fact that the Projects themselves want the Delta to be fresh because they currently export water from what is essentially the bottom of the Delta.

The DEIR/EIS must discuss and acknowledge the direct and indirect impacts from approximately 2/3rds of the state losing its direct beneficial interest in the water quality in the Delta. That discussion must include a thorough discussion and analysis of the environmental impacts with and without an isolated facility during a drought emergency where the Governor (and even the President) can simply, with the stoke of a pen, wipe out any and all laws and protections with respect to protecting water quality in the Delta.[1] In that event, the DEIR/EIS must thoroughly examine, and compare and contrast, how Delta water quality, and all of its natural values and resources that depend on that quality, will fare with and without an isolated facility. The same type of analysis must also be performed with respect to the so-called apocolaptic levee failure scenario.

Mitigation measures as well must be thoroughly discussed and ultimately adopted to mitigate the impacts that would result with an isolated facility during such emergency events.

Moreover, the DEIR/EIS must thoroughly explain what it would take for the Projects to export 15,000 cfs (or more) through the so-called 9,000 cfs isolated facility. In particular, how many pumps and what other modifications would need to be made, and how much would it cost, to divert substantially beyond 9,000 and, hence, effectively eliminate the common pool once and for all and, hence, send the final death blow to the Delta.

The ommission of all of the foregoing information constitutes a fatal flaw of the DEIR/EIS because, among other reasons, it "subverts the purposes of CEQA [by] omit[ting] material necessary to informed decisionmaking and informed public participation." (Lighthouse Field Beach Rescue v. City of Santa Cruz (2005) 131 Cal.App.4th 1170, 1202.)

///

///

---

[1] See for example, Government Code section 8571:

"During a state of war emergency or a state of emergency the Governor may suspend any regulatory statute, or statute prescribing the procedure for conduct of state business, or the orders, rules, or regulations of any state agency, including subdivision (d) of Section 1253 of the Unemployment Insurance Code, where the Governor determines and declares that strict compliance with any statute, order, rule, or regulation would in any way prevent, hinder, or delay the mitigation of the effects of the emergency."

5. The DEIR/EIS Fails to Properly Address the Impacts to Levee Integrity from the Construction of the BDCP.

As CEQA Guidelines section 15064 explains:

> (d) In evaluating the significance of the environmental effect of a project, the lead agency shall consider direct physical changes in the environment which may be caused by the project and reasonably foreseeable indirect physical changes in the environment which may be caused by the project. (1) A direct physical change in the environment is a physical change in the environment which is caused by and immediately related to the project. . . . (2) An indirect physical change in the environment is a physical change in the environment which is not immediately related to the project, but which is caused indirectly by the project.

As Guidelines section 15126.2, subdivision (a), further provides:

> Direct and indirect significant effects of the project on the environment shall be clearly identified and described, giving due consideration to both the short-term and long-term effects.

As Guidelines section 15151 provides:

> An EIR should be prepared with a sufficient degree of analysis to provide decisionmakers with information which enables them to make a decision which intelligently takes account of environmental consequences. An evaluation of the environmental effects of a proposed project need not be exhaustive, but the sufficiency of an EIR is to be reviewed in the light of what is reasonably feasible. . . . The courts have looked not for perfection but for adequacy, completeness, and a good faith effort at full disclosure.

While it is indisputable that a levee failure anywhere within the vicinity of the proposed new conveyance facilities would rank among the highest of impacts on the significance scale and would be devastating to both the environment as well as to humans (not to mention to the construction of those facilities), in the tens of thousands of pages comprising the DEIR/EIS there appears to be only the tiniest of references to the potential for the construction of the new conveyance facilities to undermine the integrity of the numerous levees that such construction will directly and indirectly impact.

Two of the many potentially significant impacts on levee integrity which have thus far not been adequately investigated, discussed or analyzed, much less mitigated, include: (1) the tunnel boring machines' potential impacts on levee integrity; and (2) the impacts on levee integrity from the extensive dewatering of groundwater to facility the construction of the conveyance facilities.

a. The DEIR/EIS Fails to Properly Address the Tunnel Boring Machines' Potential Impacts on Levee Integrity.

While the DEIR/EIS appears to at least acknowledge that the tunnel boring machines (TBMs) have the potential to cause subsidence of the ground surface,[2] the DEIR/EIS does not give any meaningful attention to the potential for the TBMs to impair the integrity of the numerous levees they will cross under (not once but twice where there are parallel tunnels) via TBM induced subsidence, settlement, vibration or otherwise.

While the DEIR/EIS states that "[b]ased on the preliminary data regarding Delta ground conditions, it is assumed that an earth pressure balancing TBM will be used for all tunneling" (DEIR/EIS, p. 3B-7), is it well-established that:

> The development of very large settlement (>150 mm) in a localized area, or sinkholes, over EPB driven tunnels is much more common than is generally recognized. Shirlaw and Boone (2005) record 57 cases in 77 km of urban tunnelling in Canada and Singapore. The overall frequency was greater than one per 1.4 km of EPB driven tunnel.

(See the enclosed excerpt [Enclosure No. 1] from "Controlling the risk of sinkholes over EPB driven tunnels–a client perspective," p. 1 [i.e., p. 439], the full version of which can be found via this link:
http://books.google.com/books?id=0P19OPlcHyoC&pg=PA439&lpg=PA439&dq=controlling+the+risk+of+sinkholes+over+EPB+driven+tunnels+-+a+client+perspective&source=bl&ots=3nlGEeP-FI&sig=nn2-XsMghDx3QwkiEYRTHx2k0s4&hl=en&sa=X&ei=QdrXU-aMOKbt8QHLzYGIAQ&ved=0CCQQ6AEwAg#v=onepage&q=controlling%20the%20risk%20of%20sinkholes%20over%20EPB%20driven%20tunnels%20-%20a%20client%20perspective&f=false)

Not only is settlement common from Earth Pressure Balancing TBMs (as well as other types of TBMs), but the unique soil characteristics in the Delta and the fragility of the levees that overly those soils make the risks of the TBMs' impairment of the integrity of those levees, and potential to cause their overtopping or failure, all the more significant. DWR's engineers, themselves, plainly acknowledge the following:

> [The] [d]epth and diameter of soft ground tunnels [as proposed by the

[2] "Localized settlement could occur during construction of BDCP water conveyance facilities. In particular, settlement above tunnels could occur in response to removal of earth materials at the tunnel face, convergence of voids created around the tunnel excavation, and stress redistribution around the excavated tunnel. The magnitude and extent of ground settlement depends on the excavated diameter of the tunnel, the amount of ground cover above the tunnel, excavation methods, workmanship, details of tunnel construction, and the geotechnical properties of the ground." (DEIR/EIS, p. 3B-7.)

BDCP] are pushing the state of the art for tunneling projects in North America.

(See the enclosed excerpt [Enclosure No. 2] from DWR's report entitled, "Delta Habitat Conservation and Conveyance Program: "The Pipleline/Tunnel Option," p. 3 [i.e., p. 367], the full version of which can be found via this link: http://books.google.com/books?id=Lpbe_nnYPqwC&pg=PA357&lpg=PA357&dq=Delta+Habitat+Conservation+and+Conveyance+Program:+%E2%80%9CThe+Pipeline/Tunnel+Option&source=bl&ots=Y64LSS5_Cu&sig=0NrSAnAUlx1niZxxz8FtJ-nzaIE&hl=en&sa=X&ei=N9bXU9iLFIGP8gGBoIF4&ved=0CDIQ6AEwAw#v=onepage&q=Delta%20Habitat%20Conservation%20and%20Conveyance%20Program%3A%20%E2%80%9CThe%20Pipeline%2FTunnel%20Option&f=false.)

The fact that the BDCP tunnels will be "pushing the state of the art" is all the more reason why the public and decision makers must be presented with an "adequa[te], complete[], and . . . good faith effort at full disclosure" of the TMBs' potential impacts on levee integrity. (Guidelines, § 15151.)

Included in that full disclosure there must be a thorough discussion and analysis of the recent partial levee failure cause by a TBM crossing under a levee in Newark, California in connection with the San Francisco Public Utilities Commission's "Bay Division Pipeline Reliability Upgrade Project." Enclosed herewith as Enclosure No. 3 is a photo of that failure extracted from Westlands Water District's November 20, 2013 power point presentation entitled, "District Workshop, Bay Delta Conservation Plan & Delta Habitat Conservation & Conveyance Program."

Pursuant to the Environmental Impact Report for that San Francisco pipeline, "[t]he diameter of the tunnel bore [was] approximately 16 feet" and "the depth of the tunnel would be between approximately 70 and 103 feet below mean sea level." (See pages 3-57 & 3-17, respectively, from the SFPUC's "Bay Division Pipeline Reliability Upgrade Project," Final EIR, Volume 1, excerpts of which are enclosed herewith as Enclosure No. 4.)

In contrast to the 16-foot diameter bores for the San Francisco pipeline, the BDCP intends to have not one, but two, 40-foot inside-diameter bores crossing under numerous levees. The depth of those borings will be similar to the San Francisco borings: "The tunnel invert elevation is preliminarily assumed to be at 100 feet below mean sea level (msl), primarily to avoid peat deposits." (DEIR/EIS, p. 3-93.)

The fact that despite all of the presumed careful planning, mitigation measures and precautions undertaken by San Francisco, the 16 foot diameter boring approximately 100 feet below mean sea level in Newark, California nevertheless caused a substantial partial levee failure, significantly bolsters the need for the DEIR/EIS to recognize the potential significance of such a failure from the considerably larger borings that are "pushing the state of the art" and crossing under numerous levees, the failure of which, would have widespread significant adverse environmental and human consequences.

The fact that the DEIR/EIS does not even consider such failures to be "potentially significant impacts" warranting a formal CEQA and NEPA mitigation measure discussion and analysis is in-and-of-itself alarming and unsupportable. As with numerous other impacts, the DEIR/EIS attempts to avoid a formal discussion of mitigation measures for such impacts by declaring them to not be potentially significant, and hence not worthy of such a discussion, on account of the so-called "environmental commitments" that will allegedly be implemented by the BDCP Proponents and, hence, allegedly reduce the significant of the impacts.

Regardless of the terminology the DEIR/EIS uses, i.e., "mitigation measures" or "environmental commitments," the DEIR/EIS has committed a threshold failure to provide the requisite "facts and analysis, [and] not just the agency's bare conclusions or opinions," and the requisite "detail sufficient to enable those who did not participate in its preparation to understand and to consider meaningfully" the TBMs' potential impacts on levee integrity and whether the proposed "environmental commitments" are sufficient to lessen those risks to a level of insignificance. (Laurel Heights Improvement Assn. v. Regents of Univ. of California (1988) 47 Cal. 3d 376, 404-05.) Thus far, the DEIR/EIS is required to, but has not come close to, "demonstrat[ing] to an apprehensive citizenry that the [lead] agenc[ies have], in fact, analyzed and considered the [TBMs' impacts on levee integrity, much less duly mitigated them]." (CEQA Guidelines, § 15003.)

i. The DEIR/EIS Improperly Defers the Formulation and Adoption of Mitigation Measures to Address the Tunnel Boring Machines' Potential Impacts on Levee Integrity.

With regard to mitigating the TBMs' impacts on levee integrity to a level of insignificance, as with numerous other impacts from the BDCP, the DEIR/EIS simply kicks that can down the road and essentially tells the public to trust them and to have faith that the BDCP Proponents will duly investigate and mitigate those impacts at some point down the road. While CEQA authorizes the deferral of the formulation of mitigation measures in special circumstances, none of those circumstances are applicable.

As CEQA Guidelines section 15126.4 explains:

> (a)(1) An EIR shall describe feasible measures which could minimize significant adverse impacts . . . . (B) . . . Formulation of mitigation measures should not be deferred until some future time. However, measures may specify performance standards which would mitigate the significant effect of the project and which may be accomplished in more than one specified way.

As the court explains in POET, LLC v. California Air Res. Bd. (2013) 218 Cal.App.4th 681, at page 735, "There is not a single, all-encompassing statement of the judge-made exception to the general rule prohibiting the deferral of the formulation of mitigation measures." Nevertheless the courts have identified the various criteria that need to be satisfied before such deferral can lawfully take place.

(1) A Complete Analysis of the Significance of the Environmental Impacts Has Not Yet Been Undertaken.

The first criteria is that the lead agency "undertook a complete analysis of the significance of the environmental impact . . . ." (POET, p. 737.) As discussed at length above, the lead agency has come nowhere near rendering the threshold "complete analysis" of the significance of the TBMs' potential impacts on levee integrity. As discussed above, there is essentially no analysis.

(2) Mitigation Is Not Known to Be Feasible.

The second criteria is that "mitigation is known to be feasible" for the particular impact. (POET, p. 736.) Unfortunately, as discussed above, settlement is known to be quite common for TBMs and despite reasonable and prudent efforts to avoid it, it still happens. Moreover, the instant issue is not merely whether the ground will settle. Instead, the issue is whether the ground will settle, shake or otherwise be altered in a manner that causes a partial or complete levee failure (or any other significant impairment of the levee's integrity).

Thus, while a particular level of ground settlement may not adversely affect a seismic-retrofitted concrete building, such settlement made be enough to partially or entirely undermine a non-seismic-retrofitted dirt levee, built upon loosely consolidated soils that are highly saturated and under extreme stress from a high water, high rain and/or high wind event, not to mention one that may also be suffering from rodent holes or other cavities that impair the structural integrity of the levee. In such circumstances, ground settlement or vibrations that would not be expected to topple a "normal building" may very well be sufficient to topple or significantly impair a typical Delta levee in normal or high stress conditions.

If there is evidence confirming that it is well-established that there are indeed feasible mitigation measures that can be adopted to ensure that there will be no significant impairment to any of numerous levees the TBMs will be crossing under regardless of whether those levees are undergoing high stress conditions or have pre-existing structural deficiencies, etc., then the DEIR/EIS has done a woefully inadequate job of providing facts and analysis to confirm the existence of such feasible mitigation measures. The available evidence along with the recent Newark, California partial levee failure confirm that the risk of significant impairment of levees from TBM machines is something, that at the end of the day, cannot be feasibly or otherwise mitigated to a level of insignificance.

(3) Practical Considerations Do Not Prohibit the Formulation and Adoption of Mitigation Measures within the Context of the DEIR/EIS.

The third criteria that must be satisfied in order to lawfully defer the formulation of mitigation measures is that "practical considerations prohibit devising such measures early in the planning process (e.g., at the general plan amendment or rezone stage) . . . ." (POET, p. 736.)

Assuming there are feasible mitigation measures to reduce the TBMs' impacts on levee integrity to less than significant (which, again, it appears there are not), the DEIR/EIS fails to explain why such measures cannot be formulated prior to the approval of the construction of the conveyance facilities. If, for example, the lead agency believes it needs additional geotechnical studies in order to gather data necessary to meaningfully formulate those measures, then, instead of simply approving the construction of the conveyance facilities in advance of those studies, the lead agencies must perform those studies prior to approving that construction.

There are least two methods that the lead agency can address the fact that it allegedly needs additional geotechnical studies in order to meaningfully formulate mitigation measures to address levee impacts. The first is to simply conduct those studies prior to approving the construction of the project. To the extent the lead agency needs to exercise eminent domain to acquire access to conduct those studies, then the lead agency should pursue such eminent domain. One of the lead agencies, i.e., DWR, did in fact pursue eminent domain, however, it dismissed its eminent domain actions and, instead, chose the more convenient route of simply approving the construction without those studies.

The second method is to refrain from trying to approve the new conveyance facilities at a "project level" and, instead, treat the conveyance facilities like all of the other 21 "conservation measures" and address them at this stage at a "programmatic level." The fact that the lead agency allegedly needs to conduct extensive geotechnical studies that will reveal not only the specific design of the conveyance facilities (which, as of the date of the release of the DEIR/EIS were at an approximately ten percent [10%] level of design),[3] but more importantly, will reveal the potentially significant impacts from that design and facilitate the formulation of mitigation measures necessary to address those impacts, means that the conveyance facilities are not ready for a "project level" environmental review and, hence, not ready for approval.

There is simply no practical reason why the lead agencies cannot refrain from approving the construction of the new conveyance facilities until they first develop sufficient information to design and identify, and especially mitigate, the potentially significant impacts from that design and properly describe, discuss and analyze that design and those impacts and mitigation measures within the context of the CEQA and NEPA process. Hence, the "practical considerations" criteria to justify deferring mitigation measures until after approval of conveyance facilities cannot be satisfied.

(4) A List of Potential Mitigation Measures Has Not Been Set Forth in the DEIR/EIS.

The fourth criteria that must be satisfied in order to lawfully defer the formulation of

---

[3] See page 2 of Enclosure No. 3 which is a slide extracted from Westlands Water District's November 20, 2013 power point presentation entitled, "District Workshop, Bay Delta Conservation Plan & Delta Habitat Conservation & Conveyance Program."

mitigation measures is that the agency must set forth “a list of the mitigation measures to be considered, analyzed and possibly incorporated in the mitigation plan.” (POET, p. 737.) Again, as discussed above, this assumes that feasible mitigation measures to reduce the TBMs’ impacts on levee integrity to less than significant are “known” to exist, which is an unwarranted assumption. In any event, the DEIR/EIS fails to set forth such a list and instead leaves it a mystery as to what those mitigation measures might entail.

The only semblance of such a list is seemingly set forth on page 3B-7 which states:

> [S]hould geotechnical reports indicate that settlement is likely in certain areas, pre-excavation grouting will be performed ahead of the TBM to fill voids and stabilize ground prior to mining. Utilization of an Earth Pressure Balanced TBM with advanced features and a comprehensive grouting program, as required, will control and avoid ground settlement due to tunnel construction. Further protection methods and associated monitoring programs would be evaluated during design and implemented during construction if required. A settlement monitoring program will be implemented on sensitive features—including levees, structures, facilities, pipelines, and utilities—as required, to ensure that tunneling-induced settlement is controlled within acceptable limits.

This so-called list is fraught with inadequacies. While the DEIR/EIS does indeed list “pre-excavation grouting” and the use of an “Earth Pressure Balanced TBM,” with regard to the latter it is anyone’s guess what those “advanced features” are and what precisely that “comprehensive grouting program” entails. But worse is the acknowledgment that additional mitigation measures might still be required yet there is no description of those measures. Instead, the DEIR/EIS only vaguely makes reference to “[f]uther protection methods and associated monitoring programs” without providing any specification of what those methods and programs entail. Moreover, while the DEIR/EIS also mentions a “settlement monitoring program,” there is, once again, no description of what that would entail.

And getting back to second criteria set forth above, that “mitigation [must be] known to be feasible,” because there is there no discussion (much less facts and analysis to support a determination) of how much settlement or vibration or other interference under any particular levee that the TBMs will cross would be deemed to be “within acceptable limits,” there is no discussion, nor facts and analysis, to support that the settlement monitoring program, nor any of the other referenced mitigation measures, will be capable of feasibly rendering the TBMs impacts on levee integrity to less than significant.

Hence the DEIR/EIR not only fails to properly describe mitigation measures that, if adopted, would render the TBMs’ impacts on levee integrity less than significant, but the DEIR/EIS also omits the essential threshold discussion and demonstration that such measure are indeed capable of feasibly and sufficiently rendering those impacts less than significant. This latter omission is the result of DEIR/EIS failing to articulate what amount of settlement, vibration or other interference is “within acceptable limits.” Any formulation of mitigation measures, either deferred formulation or otherwise, will be ineffective without such articulation.

(5) The Lead Agencies Have Not Made a Commitment to Formulate and Adopt Mitigation Measures in the Future.

The fifth criteria necessary to defer the formulation of alternatives is that "the agency committed itself to formulating the mitigation measures in the future." (POET, p. 736.) Even this seemingly simple criteria is not satisfied. As noted above, the "[u]tilization of an Earth Pressure Balanced TBM with advanced features and a comprehensive grouting program," will only be used "as required." Utilizing it "as required," means it might or might not be required. The same is true with the "[f]urther protection methods and associated monitoring programs," and "a settlement monitoring program." Those will likewise be implemented "as required."

The critical questions are under what circumstances will these mitigation measures be required and under what circumstances will they not? As discussed immediately above, the answers of course depends on what amount of settlement, vibration or other interference is caused by the TBMs crossing under a levee is "within acceptable limits" (taking into consideration any and all of the non-TBM stresses that any particular levee may be facing at the time of such crossing, e.g., high water, high wind waves, high saturation from rainfall, heavy loads from flood control vehicles or levee repair, squirrel holes or beaver holes, etc.).

Hence, the commitment to adopt mitigation measures "as required" when there is no specification of under what circumstances they will be required is simply no commitment at all.

(6) The Lead Agencies Have Not Set Forth and Adopted Specific Performance Criteria for Evaluating the Efficacy of the Mitigation Measures.

The sixth criteria necessary to defer the formulation of alternatives is that "the agency [must] commit itself to specific performance criteria for evaluating the efficacy of the measures implemented." (POET, p. 738.) "Specific performance criteria" are "objective performance criteria for measuring whether the stated [mitigation] goal will be achieved." (POET, p. 740.) In this case, the lead agencies have rendered it impossible for them to set forth objective performance criteria for measuring whether "the stated [mitigation] goal will be achieved" because the lead agencies have not properly stated such a goal. Instead, as just discussed, the only semblance of a goal stated in the DEIR/EIS is the goal to avoid settlement that exceeds "acceptable limits."

Because there is no specification whatsoever regarding what constitutes "acceptable limits" in terms of the degree of settlement, vibration or any other TBM related interference that the lead agencies believe would be sufficient to render such interference less than significant to the integrity of any particular levee undergoing any particular non-TBM related stress, there is no way to meaningfully set forth objective performance criteria to measure whether any of the DEIR/EIS's proposed mitigation measures, e.g., pre-excavation grouting, will achieve that unspecified "within acceptable limits" goal.

Accordingly, for these reasons, the lead agencies' failure to meet this criteria as well as all other criteria necessary to authorize the deferral of the formulation and adoption of mitigation measures to address the TBMs' impacts on levee integrity renders such deferral wholly unwarranted and contrary to law.

b. The DEIR/EIS Fails to Properly Address the Impacts to Levee Integrity from the Extensive Dewatering Operations.

In addition to the TBMs' potential impacts on levee integrity, one of the other potentially significant impacts on levee integrity from the construction of the conveyance facilities that has likewise not been adequately investigated, discussed or analyzed, much less mitigated, is the impacts on levee integrity from the extensive dewatering of groundwater that is required to enable the construction of the various conveyance facilities.

As the DEIR/EIS explains:

> Construction of the conveyance facilities would require dewatering operations. The dewatering wells would be generally 75 to 300 feet deep, placed every 50 to 75 feet apart along the construction 20 perimeter as needed, and each would pump 30–100 gpm. Dewatering for the tunnel shaft constitutes the deeper dewatering (300 feet deep) while the shallow (75 feet deep) dewatering is reserved for open trench construction; no dewatering is required along the tunnel alignment; and the 50–75 feet dewatering wells frequency distance applies to the pipelines, intakes, widened levees, the perimeter of the forebay embankments, the perimeter of excavation for the pumping plants, and the perimeter of tunnel shafts. Dewatering would occur 24 hours per day and 7 days per week and would be initiated 1 to 4 weeks prior to excavation. Dewatering would continue until excavation is completed and the construction site is protected from higher groundwater levels. Dewatering requirements of features along this alignment are assumed to range from approximately 240 to 10,500 gpm (California Department of Water Resources 2010b).

(DEIR/EIS, p. 7-46.)

Upon review of the DEIR/EIS there does not appear to be any discussion or analysis of the potential impacts that such extensive, and unprecedented, dewatering operations may have on the integrity of the surrounding levees. At a minimum, such dewatering would be expected to substantially alter, i.e., increase, the hydraulic gradient between the surface waters in the rivers and other nearby watercourses and the hydraulically connected groundwaters that are being substantially dewatered, i.e., lowered.

It is common knowledge that one of the major threats to levee integrity is the flow, or "seepage," of surface waters through and under the levee as a result of those surface waters being higher in elevation than the lands and groundwater tables on the landside of those levees. As explained on page 14 of "Analytical Study on Flood Induced Seepage Under River Levees" (a copy of which is enclosed herewith as Enclosure No. 5):

> Whenever a levee is subjected to a differential hydrostatic head of water as a result of river stages higher than the surrounding land, seepage enters the pervious substratum through the bed of the river and riverside borrow pits or the riverside top stratum or both, and creates an artesian head and hydraulic gradient in the sand stratum under the levee. This gradient causes a flow of seepage beneath the levee and the development of excess pressures landward thereof. If the hydrostatic pressure in the pervious substratum landward of the levee becomes greater than the submerged weight of the top stratum, the excess pressure will cause heaving of the top blanket, or will cause it to rupture at one or more weak spots with a resulting concentration of seepage flow in the form of sand boils.
>
> In nature, seepage usually concentrates along the landside toe of the levee, at thin or weak spots in the top stratum, and adjacent to clay-filled swales or channels. Where seepage is concentrated to the extent that turbulent flow is created, the flow will cause erosion in the top stratum and development of a channel down into the underlying silts and fine sands, which frequently exist immediately beneath the top stratum. As the channel increases in size or length, or both, a progressively greater concentration of seepage flows into it with a consequent greater tendency for erosion to progress beneath the levee.
>
> The amount of seepage and uplift hydrostatic pressure that may develop landward of a levee is related to the river stage, location of seepage entrance, thickness and perviousness of the substratum and of the landside top stratum, <u>underground storage</u>, and geological features. Other factors contributing to the activity of the sand boils caused by seepage and hydrostatic pressure are the degree of seepage concentration and <u>the velocity of flow emerging from the boils</u>."

(Emphasis added.)

See also, the Corps' publication entitled, "Performance of Levee Underseepage Controls; A Critical Review," enclosed herewith as Enclosure No. 6, which discusses the problems with "preferential" pathways through the soil which are often referred to as "defects" or "discontinuities" in the soil profile. (See e.g., ["There is considerable evidence that boil occurrence is often related to concentration of seepage at discontinuities and defects in the top [soil] blanket" [*id.*, p. 14]; and "[soil] permeability [is] controlled by defects in the top [soil] blanket (cracks, root holes, fenceposts, etc.) rather than properties of intact soil" [*id.*, p. 5].)

With regard to the groundwater table elevation's affect on seepage, as DWR itself has previously observed in the context of an examination of RD 501:

> The RD 501 drainage system artificially lowers groundwater levels (typically 2-3 feet below ground surface). The artificial lowering of groundwater levels further increases the seepage pressure from Miner Slough toward Ryer Island.
>
> The artificial lowering of groundwater levels increases the hydraulic gradient from Miner Slough toward Ryer Island.

(See "Site Characterization and Groundwater Monitoring Data Analysis Summary Prospect Island Tidal Habitat Restoration Project Solano County, California," pp. iii & 7, respectively, emphasis added, located at http://www.water.ca.gov/environmentalservices/docs/frpa/Prospect_Island_Ryer_Island_Data_Analysis_Summary_Memo_Report_Final_ReaderView_6_19_14.pdf ; an excerpt of which is enclosed herewith as Enclosure No. 7).

Moreover, as other researchers have further observed:

> [C]hanges in the groundwater table level could lead to alterations in the structure of a levee, which in extreme cases – alongside other modifications due to such external events as atmospheric precipitation, changing water levels in rivers and water reservoirs protected by flood embankments, might cause levee failure or damage.

(See "Modelling Events Occurring in the Core of a Flood Bank and Initiated by Changes in the Groundwater Level, Including the Effect of Seepage," p. 1 [i.e., p. 144], located at http://www.uwm.edu.pl/wnt/technicalsc/tech_14_2/B02.PDF an excerpt of which is enclosed herewith as Enclosure No. 8)

Most of the new conveyance facilities that will require extensive dewatering are either immediately adjacent to levees or very close to them. Such dewatering has the clear potential to significantly increase the hydraulic gradient from the surface waters to those groundwaters, and as a result, increase the seepage pressure through and under those levees to the potential detriment of those levees.

As noted above, CEQA Guidelines section 15064 provides:

> (d) In evaluating the significance of the environmental effect of a project, the lead agency shall consider direct physical changes in the environment which may be caused by the project and reasonably foreseeable indirect physical changes in the environment which may be caused by the project. (1) A direct physical change in the environment is a physical change in the environment which is caused by and immediately related to the project.

As Guidelines section 15126.2, subdivision (a), further provides:

> Direct and indirect significant effects of the project on the environment shall be clearly identified and described, giving due consideration to both the short-term and long-term effects.

As Guidelines section 15151 provides:

> An EIR should be prepared with a sufficient degree of analysis to provide decisionmakers with information which enables them to make a decision which intelligently takes account of environmental consequences. An evaluation of the environmental effects of a proposed project need not be exhaustive, but the sufficiency of an EIR is to be reviewed in the light of what is reasonably feasible. . . . The courts have looked not for perfection but for adequacy, completeness, and a good faith effort at full disclosure.

The dewatering operations' potential impacts on levee integrity from increases in the hydraulic gradient and, hence, increases in seepage pressure on, through or under the various levees in the vicinity of those operations constitute "direct physical change[s] in the environment" that the lead agencies have a duty to duly consider. (Guidelines, § 15064.)

In light of the obvious devastation that would ensue if a levee were to fail, the lead agencies must thoroughly investigate this issue and provide the requisite facts and analysis necessary to "demonstrate to an apprehensive citizenry that [they have], in fact, analyzed and considered the [dewatering operations' impacts on levee integrity, as well as duly mitigated any such impacts]." (CEQA Guidelines, § 15003.) Thus far, there appears to be no semblance of any such investigation or demonstration.[4]

6. The DEIR/EIS Improperly Defers the Formulation and Adoption of Mitigation Measures to Address Agricultural Impacts.

As discussed above, one of the criteria that must be satisfied in order to lawfully defer the formulation of mitigation measures is that "practical considerations prohibit devising such measures early in the planning process (e.g., at the general plan amendment or rezone stage) . . . ." (POET, p. 736.) The DEIR/EIS makes no demonstration whatsoever why the development of an Agricultural Lands Stewardship Plan (ALSP) (i.e., mitigation measure "AG-1"), which the lead agencies find is necessary to mitigate the impacts on agricultural resources, cannot be prepared for CM1 prior to the approval of CM1. In fact, the DEIR/EIS requires that "[f]or each

[4] Note that while the foregoing comments focus on the TBMs' and the dewatering operations' potential impacts to levee integrity, the DEIR/EIS likewise lacks a meaningful consideration of the potential impacts to levee integrity from all of the other aspects of the construction and implementation of CM1 through CM22.

conservation measure or site-specific project activity other than Conservation Measure 1 that would cause such effects, a draft ALSP shall be included with any publicly circulated environmental document for the proposed conservation measure or project activity in order to obtain public input." (DEIR/EIS, p. 14-112.) The fact that a ALSP not only can be feasibly prepared in advance of the adoption of all of the other conservation measures, but in fact is required to be so prepared, confirms that there is indeed no valid reason why a draft ALSP cannot also be developed prior to the approval of CM1 and included as part of the instant DEIR/EIS.

With regard to the criteria that "the agency committed itself to formulating the mitigation measures in the future" (POET, p. 736), mitigation measures AG-1a and AG-1c, for example, which are components of the overall mitigation measure AG-1, only need to be formulated, and ultimately adopted, "if [the BDCP proponents determine that] the measures are applicable and feasible" and "necessary and feasible," respectively. (DEIR/EIS, pp. 14-112 & 14-117, emphasis added.) Thus, the commitment is merely a commitment to consider such formulation and adoption, not to ultimately undertake such formulation and adoption.

With regard to the criteria that "the agency [must] commit itself to specific performance criteria for evaluating the efficacy of the measures implemented," (POET, p. 738), there is no semblance of any such performance criteria for mitigation measure AG-1. This mitigation measure is as open ended as it gets and not only lacks an identified mitigation goal, which is a prerequisite to the establishment of meaningful performance criteria, but, as result, entirely lacks any such criteria. The specification of the degree of mitigation the lead agencies believe is feasible and must be obtained for impacts to agricultural resources, and the specification of the objective performance criteria necessary to measure whether that degree of mitigation will be achieved by the proposed mitigation measures, are specifications that CEQA (and NEPA) require the lead agency to make before they can lawfully defer the ultimate formulation and adoption of mitigation measures until some time after they approve the project. Having failed to make either of those specifications, as well as meet the other criteria for deferral, this deferral constitutes yet another highly unwarranted and unlawful deferral.

7. **The DEIR/EIS Fundamentally Mishandles the Impacts to Water Quality and Improperly Defers the Formulation and Adoption of Mitigation Measures to Address those Impacts.**

With regard to the projects' impacts on water quality, not only is there a manifest unlawful deferral of the formulation and adoption of mitigation measures to address those impacts, but even worse, there is a manifestly unwarranted assumption that under the preferred alternative, for example, there may not be any feasible way to avoid violations of various water quality standards.

For example, with regard to the SWRCB's Bay-Delta Water Quality Control Plan (WQCP) chloride standards, the DEIR/EIS states:

> It is currently unknown whether the effects of increased chloride levels . . . associated with CM1 operations (and hydrodynamic effects of tidal restoration under CM4), can be mitigated through modifications to initial operations. [¶] Following commencement of initial operations of CM1, the BDCP proponents will conduct additional evaluations described herein, and develop additional modeling (as necessary), to define the extent to which modified operations could reduce or eliminate the additional exceedances of the 250 mg/L Bay-Delta WQCP objective for chloride currently modeled to occur under Alternative 4.

(DEIR/EIS, pp. 8-429 & 8-430.) The DEIR/EIS makes similar findings with respect to the Bay-Delta WQCP EC standards (see pp. 8-441 & 8-442.)

As the DEIR/EIS's preparers well know, the SWRCB's Decision 1641 currently imposes the burden on the SWP and CVP, as conditions to their water right permits that allow them to divert and store water from the Delta Watershed, to at all times meet and maintain the Bay-Delta WQCP chloride and EC standards. Hence, compliance with those standards is not optional under any BDCP alternative, including the preferred alternative.

Elsewhere in the DEIR/EIS, the DEIR/EIS appears to fully recognize the SWP and CVP's mandatory obligation to meet the Bay-Delta WQCP standards under all BDCP alternatives and provides assurance that full compliance with those standards is indeed built into the modeling. For example, as the DEIR/EIS explains with respect to the modeled EC standard violations under the various BDCP alternatives:

> Water quality modeling using CALSIM II and DSM2 for BDCP alternatives adjusts SWP and CVP operations to fully comply with D-1641 standards. . . . [However] DSM2 results may show an exceedance of D-1641 standards when, in these cases, this is a modeling anomaly and not reflective of an actual violation.
>
> It should be noted that many of the modeling results showing exceedance of D-1641 standards reported in Appendix 8H are the result of this mismatch in modeling time-step, known shortcomings in the ANN model to mirror DSM2 modeled flow-salinity interaction, and/or CALSIM II model's limited ability to simulate real-time operational adjustments to avoid exceedance of the standards in shorter time-steps.

(DEIR/EIS, p. 8H-1, emphasis added.) The DEIR/EIS goes on to state:

> DWR and USBR have every intention of operating SWP and CVP facilities by fine tuning reservoir storage and exports in real time to meet D-1641 standards, and any changes to D-1641 as adopted by the SWRCB. Actual operations are continuously adjusted to respond to reservoir storages, river flows, exports, in-Delta demands, tides, and other factors to insure compliance to regulatory

requirements to the extent possible.

(DEIR/EIS, p. 8H-1.)

Accordingly, it is highly inappropriate for the DEIR/EIS to conclude that "[i]t is currently unknown whether the effects of increased chloride levels [and EC]" from any of the BDCP alternatives "can be mitigated through modifications to initial operations." Not only has the modeling assumed full compliance with the chloride and EC standards, but, regardless of the modeling, in the real world, the SWP and CVP will have to modify their operations to meet those standards, otherwise they will be in breach of their water right permit conditions and will have to cease all diversions of water to and from storage within the Delta Watershed until those standards are duly met.

Thus, notwithstanding the fact that the alternatives are modeled to fully comply with the chloride and EC standards, to the extent that modeling reveals exceedances of those standards that are not modeling "anomalies" or other glitches, but, instead, for whatever odd reason that modeling reveals anticipated real-world exceedances, then the DEIR/EIS must thoroughly investigate and analyze what SWP and CVP operations (i.e., storage operations, exports operations, water purchase/transfer operations, etc.) can be adjusted to avoid those exceedances to ensure the SWP and CVP are in compliance with their permit conditions.

What the DEIR/EIS cannot lawfully do, is what it does in fact do, i.e., merely kick this can down the road and, after the particular alternative has already been approved, merely let the SWP and CVP look into which exceedances are modeling oddities and which ones are real, and let the SWP and CVP decide what modifications to their operations if any they think can "feasibly" avoid those exceedances.

i. The DEIR/EIS Improperly Defers the Formulation and Adoption of Mitigation Measures to Address Water Quality Impacts.

The instant matter is a particularly egregious mishandling of the lead agencies' CEQA and NEPA responsibilities that goes well beyond the unlawful deferral of the formulation and adoption of mitigation measures. In an event, it can be readily seen that such mishandling fails to meet all of the criteria necessary to tolerate such deferral.

With regard to the first criteria that the lead agency must have "undert[aken] a complete analysis of the significance of the environmental impact . . . ." (POET, p. 737), as discussed above, the lead agencies have thus far made no attempt to identify which of the exceedances were due to modeling anomalies and which were not, and made no attempt to identify or analyze the cause of the non-modeling exceedances which is a threshold determination necessary to the meaningfully formulation of mitigation measures, even if the ultimate formulation and adoption is deferred.

With regard to the second criteria that "mitigation is known to be feasible" (POET, p.

736), while compliance with mandatory water quality standards should certainly be feasible, the lead agencies nevertheless inappropriately conclude that "[i]t is currently unknown" whether compliance with the standards is feasible. (See DEIR/EIS, pp. 8-429 & 8-430, and 8-441 & 8-442.) Hence, according to the lead agencies, this criteria for deferral is not satisfied.

With regard to the third criteria that "practical considerations prohibit devising such measures early in the planning process . . . " (POET, p. 736), there is simply no practical or other reason why the various "additional evaluations . . . and . . . additional modeling" that the lead agencies direct the BDCP Proponents to perform "to define the extent to which modified operations could reduce or eliminate the additional exceedances of the [chloride and EC standards]" (see e.g., DEIR/EIS, pp. 8-429 & 8-430) cannot be performed by the lead agencies themselves within the context of the instant DEIR/EIS, rather than at some point in the future entirely outside of the CEQA and NEPA processes. Performing those type of evaluations and modeling within the context of CEQA and NEPA public and agency review processes is one of the fundamental, if not the fundamental, purposes of those processes.[5]

With regard to the forth criteria that the lead agencies must set forth "a list of the mitigation measures to be considered, analyzed and possibly incorporated in the mitigation plan" (POET, p. 737), while the lead agencies do list some actions that could be taken, the lead agencies ultimately leave it up to the BDCP Proponents to "identify" and "develop" the mitigation measures and the BDCP Proponents are allowed to entirely ignore all of the lead agencies' suggested measures, as well as any they identify and develop on their own, to the extent they determine they are not "feasible." (See e.g., DEIR/EIS, pp. 8-429 & 8-430, and 8-441 & 8-442.) Hence, in the end, the mandatory list of feasible mitigation measures from which the BDCP Proponents can ultimately select which ones to implement is non-existent.

With regard to the fifth criteria that "the agency committed itself to formulating the mitigation measures in the future" (POET, p. 736), once again, because the BDCP Proponents have the power to do nothing if they conclude there are no feasible mitigation measures, the lead agencies cannot be said to have made any commitment to formulate, or adopt, any mitigation measures in the future. Instead, it is clearly anticipated that there will be no such formulation or adoption.

Finally, with regard to the sixth criteria that "the agency [must] commit itself to specific performance criteria for evaluating the efficacy of the measures implemented" (POET, p. 738),

---

[5] "The Legislature finds and declares that it is the policy of the state that public agencies should not approve projects as proposed if there are feasible alternatives or feasible mitigation measures available which would substantially lessen the significant environmental effects of such projects, and that the procedures required by this division are intended to assist public agencies in systematically identifying both the significant effects of proposed projects and the feasible alternatives or feasible mitigation measures which will avoid or substantially lessen such significant effects." (Pub. Resources Code, § 21002.)

because the BDCP Proponents do not have to adopt any mitigation measures if they determine that none of the mitigation measures the lead agencies have suggested or any others than they can think of are feasible, the lead agencies' duty to commit themselves to specific performance criteria to evaluate the effectiveness of those measures has been completely undermined. In any event, assuming for the sake of argument that the BDCP Proponents were indeed required to adopt one or more mitigation measures (and could not avoid such adoption on the grounds that those measures are not feasible), the lead agencies fail to establish a meaningful goal in terms of chloride and EC impacts which would render ineffective any performance criteria (even if the lead agencies adopted such criteria which they do not) that would be established to ensure that goal is duly met.

For example, with regard to chloride, the so-called "goals" are non-specific and far too general to meaningfully evaluate compliance with those goals. The various chloride mitigation goals, for each of the three sub-parts to Mitigation Measure WQ-7, appear to be the following: (1) to "reduce or eliminate the additional exceedances of the 250 mg/L Bay-Delta WQCP objective for chloride currently modeled to occur under Alternative 4"; (2) to "either avoid, minimize, or offset for reduced seasonal availability of water that meets applicable water quality objectives and that results in levels of degradation that do not substantially increase the risk of adversely affecting the municipal and industrial beneficial use"; and (3) to "avoid or minimize the chloride level increases in the marsh, with the goal of maintaining chloride at levels that would not further impair fish and wildlife beneficial uses in Suisun Marsh." (DEIR/EIS, p. 8-430 & 8-431.)[6]

General terms like "reduce" and "minimize" fail to set forth a meaningful goal. The key question is how much reduction or minimization must be achieved? Without such a specification, the range of allowable reduction or minimization can run the gamut from extremely insignificant to extremely significant, and anything in between. In any event, regardless of the defective goals, the lead agencies fail to adopt "objective performance criteria for measuring whether [those goals] will be achieved." (POET, p. 740.) Once again, no mitigation measures need to be adopted if the BDCP Proponents determine none of the mitigation measures are feasible, but even if one or more measures were required to be adopted, the lead agencies have failed to set forth any objective performance criteria to enable the lead agencies, as well as the public, to measure the actual, real world success of those measures in achieving, even the highly nebulous goals. Put simply, by what mechanism or protocol will anyone know if those goals are being met?

Because the lead agencies cannot satisfy any of the criteria necessary to defer the formulation and adoption of mitigation measures to address chloride and EC impacts, and

---

[6] The goals with regard to EC impacts are substantially similar and equally non-specific: "The goal of specific actions would be to reduce/avoid additional exceedances of Delta EC objectives and reduce long-term average concentration increases to levels that would not adversely affect beneficial uses within the Delta and Suisun 30 Marsh." (DEIR/EIS, p. 8-441.)

because all of those criteria must be satisfied to tolerate such deferral, as with the other attempted deferral of mitigation measures for this project, this deferral is highly egregious and contrary to law.[7]

8. The DEIR/EIS Improperly Omits Site-Specific Details and Analysis of the Extensive Geotechnical (and Environmental) Studies that Will be Required to Construct the Project.

According to the DEIR/EIS:

> Detailed subsurface investigations will be performed at the locations of the water conveyance alignment and facility locations and at material borrow areas. . . . The work to be performed will include a subsurface investigation program to provide the information required to support the design and construction of the BDCP water conveyance facilities. . . . The geotechnical investigation will also include a small scale environmental screening to assess the presence or absence of dissolved gases that will help guide the tunnel ventilation design and disposal considerations for excavated materials and tunnel cuttings. . . .

(DEIR/EIS, p. 3B-6.)

> Site-specific geotechnical studies are expected to include the following, as appropriate [:] . . . . Drilling and sampling of soil borings, cone penetration, and other in-situ tests, slug tests, aquifer/pumping tests, and test pits to evaluate the subsurface conditions. Installing wells and monitoring groundwater elevations for use in liquefaction evaluation and dewatering requirements.

(DEIR/EIS, p. 3B-7.)

The DEIR/EIS acknowledges the following at page 31-17:

> Activities implemented as part of geotechnical studies would have the potential to result in significant environmental impacts due to the inadvertent release of hazardous materials, impacts to groundwater quality, ground disturbance, and noise.

Notwithstanding the acknowledgment of the potential to result in significant environmental impacts, the DEIR/EIS improperly fails to specify and disclose the locations where these studies will take place. According to the DEIR/EIS:

---

[7] Note that while the foregoing comments focus on chloride and EC impacts, the same wrongful deferral of the formulation and adoption of mitigation measures likewise applies to the DEIR/EIS's mishandling of bromide impacts (as well as other impacts).

> The locations of borings and other test locations will be based on a review of available geologic data to identify data gaps in the conveyance alignment and on the locations of critical facilities such as hydraulic structures and tunnels. The spacing of the borings and test locations likely will average about 1,000 feet along proposed canal and tunnel alignments and approximately 100 to 200 feet at intakes, pumping plants, forebays, siphons, and other hydraulic structures.

At this stage of the game, i.e., after years and millions of dollars have been invested in the pursuit of this project, and at the so-called "project level" review of the BDCP, it is neither acceptable, nor reasonable, for the anticipated and foreseeable locations, as well as quantity, of such borings and other test locations to remain a mystery and be kept hidden from the public, as well as the decision makers. Surely a "review of available geologic data to identify data gaps" has already been done, and to the extent it has not, it should have been done prior to release of the DEIR/EIS.[8]

As CEQA Guidelines section 15146 explains:

> The degree of specificity required in an EIR will correspond to the degree of specificity involved in the underlying activity which is described in the EIR. (a) An EIR on a construction project will necessarily be more detailed in the specific effects of the project than will be an EIR on the adoption of a local general plan or comprehensive zoning ordinance because the effects of the construction can be predicted with greater accuracy.

According to the lead agencies, the DEIR/EIS <u>is</u> "[a]n EIR on a construction project," and, hence, matters such as the locations and quantity of geotechnical (and any other) tests necessary to design and construct the project are critical matters that must be included in the DEIR/EIS. (See e.g., Guidelines, § 15161 ["The EIR shall examine all phases of the project including planning, construction, and operation"].)[9]

---

[8] Note that elsewhere in the DEIR/EIS, it is acknowledged that such review has indeed already taken place. See for example, DEIR/EIS page 9-45: "The available data within the Plan Area, as presented in the CERs and the Geotechnical Data Reports . . . <u>were compiled and reviewed</u>. Available soil boring logs, subsurface cross sections, soil stratigraphy, and groundwater data from the CER were used. Geology and soil maps (from the U.S. Geological Survey and Natural Resources Conservation Service) for the Plan Area were also used, with particular focus on areas where soft, loose, and compressible soils are present." (Emphasis added.)

[9] See also, <u>Orinda Assn v. Board of Supervisors</u> (1986) 182 Cal.App.3d 1145, at page 1171: "A public agency is not permitted to subdivide a single project into smaller individual sub-projects in order to avoid the responsibility of considering the environmental impact of the project as a whole."

As the California Supreme Court explains in Laurel Heights Improvement Assn. v. Regents of Univ. of California (1988) 47 Cal. 3d 376, at pages 404-05:

> "To facilitate CEQA's informational role, the EIR must contain facts and analysis, not just the agency's bare conclusions or opinions." [Citations.] An EIR must include detail sufficient to enable those who did not participate in its preparation to understand and to consider meaningfully the issues raised by the proposed project.

An identification of the locations and quantity, not to mention a detailed description, of the various drillings, cone penetration tests, other in-situ tests, slug tests, aquifer/pumping tests, test pits and groundwater monitoring wells is imperative "to enable those who did not participate in [the DEIR/EIS's] preparation to understand and to consider meaningfully the issues raised by" those activities. (Ibid.) The nature, extent and significance of the potential environmental impacts from those activities will directly depend on the site-specific circumstances occurring at any particular location. Those circumstances include the presence of above or below ground public or private utilities; fish and wildlife habitat; archaeological or cultural resources; levees or other reclamation works; irrigation or drainage canals; domestic or commercial wells; residences; farming and other operations taking place on the lands; etc. In essence, those site-specific circumstances include all the matters that make up the "natural and man-made conditions" existing at the particular site, i.e., the matters that make up the "environment" at those sites:

> "Environment" means the physical conditions which exist within the area which will be affected by a proposed project including land, air, water, minerals, flora, fauna, ambient noise, and objects of historic or aesthetic significance. The area involved shall be the area in which significant effects would occur either directly or indirectly as a result of the project. The "environment" includes both natural and man-made conditions.

(CEQA Guidelines, § 15360.)

The location where proposed activities take place, as well as the nature and extent of such activities, is obviously essential to a meaningful CEQA and NEPA analysis. For a so-called "project level" EIR/EIS which is intended to be sufficient to authorize the construction of the Preferred Alternative, the lack of specification of the location, nature and extent of the extensive geotechnical studies necessary to construct this massive project, not to mention the lack of investigation and analysis of the site-specific impacts from such studies, constitutes a prejudicial abuse of the lead agencies' discretion. The lack of such specification, investigation and analysis "'subverts the purposes of CEQA [because] it omits material necessary to informed decisionmaking and informed public participation.' [Citation.]" (Lighthouse Field Beach

Rescue v. City of Santa Cruz (2005) 131 Cal.App.4th 1170, 1202.)

Not only is a meaningful determination of the nature and extent of the potential site-specific impacts from such studies substantially thwarted, but so is the lead agencies' duty to set forth and evaluate, and the public's opportunity to review and comment on, the feasible mitigation measures and alternatives to avoid or lessen any such impacts. At a minimum, the DEIR/EIS must be redrafted and recirculated to correct this fundamental omission.[10] [11]

9. Other Significant Deficiencies in the DEIR/EIS.

a. **The BDCP's "Build it First, Then Figure out How to Operate it" Approach is Highly Inappropriate.**

The BDCP's "let's just go ahead and build the tunnels, then at some point after they are built, we'll sort out how we will operate them and so inform the public and the regulators" approach is as inappropriate as it is offensive. Such an approach is the antithesis of CEQA and NEPA. It should be clear to anyone that reviews the DEIR/EIS that the BDCP is no where near ready to be approved, either at a "project" or "programmatic" level.

Needless to say, pursuant to principles of common sense and good faith and fair dealing, not to mention CEQA and NEPA, as well as HCP and NCCP and numerous other principles, the BDCP Proponents must obviously first figure how they plan to operate the new facilities, as well as all other components of the BDCP, before they authorize the construction and implementation of those facilities and components. Within the context of CEQA and NEPA, to do otherwise turns the CEQA and NEPA processes on their heads. As the California Supreme Court explains:

> A fundamental purpose of an EIR is to provide decision makers with information they can use in deciding *whether* to approve a proposed project, not to inform them of the environmental effects of projects that they have already approved. If post-approval environmental review were allowed, EIR's would likely become nothing more than *post hoc* rationalizations to support action

---

[10] As an example of some of the potentially significant impacts from the geotechnical studies, please see the enclosed "Statement of Christopher H. Neudeck, R.C.E." enclosed herewith as Enclosure No. 9.

[11] The BDCP Proponents also presumably intend on conducting extensive "environmental studies" in furtherance of the planning, construction and implementation of the BDCP. For the same reasons discussed above with respect to the geotechnical studies, those environmental studies must likewise be thoroughly and specifically described and addressed within the context of the instant DEIR/EIS. As a example of what those environmental studies entail, please see the enclosed pleadings in DWR's "Petition for Order Permitting Entry and Investigation of Real Property" in DWR v. RD 548 enclosed herewith as Enclosure No. 10.

already taken. We have expressly condemned this use of EIR's. [Citation]."

(Laurel Heights Improvement Assn. v. Regents of University of California (1988) 47 Cal.3d 376, 394).

b. The DEIR/EIS's Proposed Analysis of CM1 at a "Project Level" and the Rest of the "Conservation" Measures at a "Programmatic Level" is Also Highly Inappropriate.

In light of the fact that, as discussed above, it is clear that the DEIR/EIS lacks sufficient detail to properly analyze even the construction of the new conveyance facilities at a "project level," much less the operation of those facilities,[12] it is somewhat comforting that the DEIR/EIS at least acknowledges that the other 21 "conservation" measures are no where close to being developed at the "project level." The fundamental problem, however, is that the construction and operation of the BDCP is inextricably tied to the implementation of other 21 conservation measures.[13]

Accordingly, it is highly inappropriate to separate the conveyance facilities from all of those other measures and approve the construction and operation of those facilities prior to the approval and authorization of those other measures because, among other reasons, (1) those other measures cannot be lawfully approved without undergoing a project level CEQA and NEPA analysis; and (2) until that project level review takes place, no one, including, the BDCP Proponents knows with any degree of certainty the ultimate natural and extent of any of those approvals. The entire purpose of the CEQA and NEPA processes is to force the consideration of the environmental impacts from whatever activity is being approved so that measures can be taken, including approving alternatives to the proposed project including the "no project" alternative, in order to avoid or reduce those impacts.

Hence, when you have a project such as the BDCP where the implementation of one of the so-called conservation measures (CM1) is inextricably tied to the implementation of several other conservation measures it is simply inappropriate and unlawful to approve one without the other, and approving one without the other is precisely what is being proposed in the DEIR/EIS.

---

[12] For example, as noted above, at the time of the release of the DEIR/EIS the conveyance facilities were at an approximately ten percent (10%) level of design). (See page 2 of Enclosure No. 3.)

[13] See for example, the DEIR/EIS at page ES-18: "The 22 BDCP conservation measures [not just one of those 22] comprise the specific actions to be taken to meet the biological the goals and objectives. Most of the conservation measures address several goals and objectives, and most objectives will be met through a combination of conservation measures. Actions implemented as part of the conservation measures will meet the requirements of the ESA and the NCCPA." (Emphasis added.)

c. The DEIR/EIS's Alternative Analysis is Grossly Deficient.

i. Lack of a Range of Potentially Feasible Alternatives.

Guidelines section 15126.6, subdivision (a), provides that "[a]n EIR *shall* describe a range of reasonable alternatives to the project, or to the location of the project, *which would feasibly attain* most of the basic objectives of the project." (Emphasis added.) Because all of the alternatives in the DEIR/EIS that contain an isolated facility and/or one or more conservation measures that are contrary to one or more laws, including the laws discussed at the beginning of these comments, those alternatives are not feasible. Hence, the DEIR/EIS's mandatory range of potentially feasible alternatives is fatally deficient.

ii. Lack of Meaningful Comparisons Between the Alternatives.

While the more comprehensive the alternative analysis the better, the DEIR/EIS must ultimately ensure that the alternative analysis is meaningful. Unfortunately, as will be readily apparent to anyone who examines that analysis, it is nearly impossible to meaningfully compare the alternatives with each other becomes when it comes to making those comparisons there are so many variables that change that is nearly impossible to get a meaningful understanding of the core differences among the alternatives. For example, some alternative have the head of old river barrier in place and some do not; sometimes the Sacramento River inflow was assumed to be upstream of the proposed north Delta intakes for modeling purposes and sometimes it was not. It is in actuality an utter mess that fails to satisfy the fundamental purposes behind CEQA and NEPA's mandatory requirement to perform a thorough alternative analysis.

iii. Lack of a Range of Reasonable Alternatives.

Apart from the lack of an adequate number of "potential feasible" alternatives discussed above, the DEIR/EIS's range of alternatives also suffers from a gross lack of a "reasonable" range. Despite Water Code section 85320, subdivision (a)(2)(B)'s requirement that the DEIR/EIS's reasonable range of alternatives include "through-Delta" alternatives as well as "isolated conveyance alternatives," out of the twelve alternatives in the DEIR/EIS only one of them is a "through-Delta" alternative. That selection of alternatives not only confirms that the decision makers have already made up their mind that the adopted alternative will indeed have an isolated facility, but that grossly unbalanced selection is contrary to section 85320 as well as to general reasonableness.

In its comments on the Notices of Preparation for this project, the CDWA requested that the following alternatives concepts be consider either as stand alone alternatives or components of various alternatives. The CDWA hereby renews that request. Without a substantial expansion and modification to the DEIR/EIS's existing range of alternatives, that range is fatally deficient.

Alternatives which comply with the statutory "common pool" mandate and, thus, do not have any form of an isolated facility, dual or otherwise.

An alternative of "regional self-sufficiency" where Peter (human and environmental water users within the Delta watershed) are not robbed to pay Paul (i.e., export contractors). Instead, every feasible effort is made to the maximum extent possible to develop new non-Delta watershed water and/or make better use of existing non-Delta watershed water to meet the needs of export contractors. The intended result being, that such export contractors can ultimately wean themselves off Delta watershed water, substantially or entirely, such that the Delta watershed water can be used to meet the needs within that watershed.

Ultimately there should be several alternatives which contemplate a *reduction* in exports from the Delta over historical levels.

With regard to the feared apocalyptic collapse of numerous Delta levees from an earthquake. Numerous alternatives should be considered to address such a collapse. To the extent the desire is to avoid the disruption of export deliveries the DEIR/EIS should first thoroughly explain as precisely as possible what the water quality will likely be under existing conditions should the Projects desire to continue exporting water during such a apocalyptic failure. Then the DEIR/EIS should clearly explain how long that water quality will likely remain in that state assuming the recently adopted emergency preparedness plans are in place, etc. to close those levee breaches. The DEIR/EIS should then thoroughly explain whether the Projects can still divert and utilize water of that level of quality for agricultural beneficial uses, urban, etc. in either blended form with water stored in San Luis or blended with other water supplies. Assuming the water cannot be used in its current "degraded" state, the DEIR/EIS should explain what facilities could be constructed to desalinize that water, or better allow for the blending of that water will other higher quality supplies, etc., and the costs of the construction and operation of such facilities.

In the event, the Projects simply cannot feasibly use the water in the Delta after an apocalyptic levee failure and/or cannot get by with other supplies while the levees breaks are being repaired, then the fortification of various master levee scenarios should be considered to minimize the intrusion of bay waters in the event of such failures much like what is already being implemented at the present time. So called "polders" should also be considered whereby areas are protected by master levees such that not all levees need to be substantially upgraded. Rather, only "master" levees need to be so upgraded which would serve to protect the polders or various sections of land within the Delta.

Tidal gate structures should also be evaluated to help repel bay salinity in the event of such a massive failure.

The forgoing measures to protect against an apocalyptic levee failure could also serve the additional benefit of protecting the Delta from reasonably anticipated sea level rise.

In addition, with regard to the apocalyptic earthquake, the DEIR/EIS's analysis should thoroughly examine the likelihood of such a magnitude earthquake near all of the Project's major export facilities, not the least of which is the export pumping facilities themselves as well as the California Aqueduct and Delta-Mendota canals which essentially track major fault lines. Alternatives to protect against damage and disruption of export supplies resulting from such earthquakes should be thoroughly evaluated.

With regard to protecting fishery resources within the Delta, actual, state of the art, fish screens on all Project export facilities should be evaluated to enable water that is truly surplus from the needs of the Delta, assuming there is any such water, to be exported with minimal impacts to fish. If an actual, state of the art fish screen is included for an isolated facility in any alternative which includes such an isolated facility, then such a screen must naturally also be included in all the alternatives that do not involve an isolated facility and should be installed on all exiting Project export facilities.

> An alternative should be considered that includes substantially increased Delta outflows. Such an alternative could draw sensitive fishery species away from the existing export facilities, thereby increasing the "reliability" of such exports, and also enable the restoration of the Suisun Marsh which could provide tremendous benefits to numerous fishery species.

The DEIR/EIS should include an extensive discussion of desalinization options in order to promote regional self-sufficiency. Such a discussion would be in furtherance of Water Code section 12946 which provides:

> It is hereby declared that the people of the state have a primary interest in the development of economical saline water conversion processes which could eliminate the necessity for additional facilities to transport water over long distances, or supplement the services to be provided by such facilities, and provide a direct and easily managed water supply to assist in meeting the future water requirements of the state.

Opportunities for environmentally friendly desalinization of ocean waters as well as brackish ground waters (as well as the saltier Delta waters which presumably will result from a massive levee failure) should be thoroughly examined.

To the extent the objectives of the BDCP are ultimately to "provid[e] for the conservation of covered species and their habitats, address[] the requirements of the federal and State endangered species laws, and improv[e] water supply reliability" (NOP, p. 4), it is easy to see that weaning the export contractors off the Delta watershed such that exports from the Delta could be ultimately substantially reduced would seemingly satisfy those objectives better than any other alternative. Accordingly, as stated above, multiple alternative scenarios which seek to accomplish such weaning should be thoroughly considered.

d. The DEIR/EIS's Scope of its Impact Analysis is Unlawfully Truncated.

As CEQA Guidelines section 15064 explains:

> (d) In evaluating the significance of the environmental effect of a project, the lead agency shall consider direct physical changes in the environment which may be caused by the project and reasonably foreseeable indirect physical changes in the environment which may be caused by the project. (1) A direct physical change in the environment is a physical change in the environment which is caused by and immediately related to the project. . . . (2) An indirect physical change in the environment is a physical change in the environment which is not immediately related to the project, but which is caused indirectly by the project.

As Guidelines section 15126.2, subdivision (a), further provides:

> Direct and indirect significant effects of the project on the environment shall be clearly identified and described, giving due consideration to both the short-term and long-term effects.

The DEIR/EIS fundamentally fails to comply with these guidelines by unlawfully limiting the scope of its analysis. Critical examples of such limitation is the exclusion of an analysis of the direct and indirect impacts of the project on areas to the west of Suisun Marsh, including the San Francisco Bay and the Ocean, and in all of the upstream areas whose water resources, via water transfers, exchanges or otherwise, are among the sources of water that will be utilized in the implementation of the BDCP. This is yet another egregious violation of CEQA and NEPA that must be duly corrected.

In a similar vein, because the DEIR/EIS anticipates substantial increases in exports of water from the Delta pursuant to various alternatives, the DEIR/EIS must, but thus far has not, identify the likely sources of that exported water and thoroughly examine the full range of potentially significant direct and indirect impacts from the export of such water, including impacts in the source areas and in the areas where the water is ultimately used and everywhere in between, including, as well, matters such as the potential adverse return flow impacts from the use of such water to the San Joaquin River or other waterways.

e. The DEIR/EIS Suffers from a Widespread Unlawful Deferral of Mitigation Measures and a Failure to Establish the Funding and Enforceability of those Measures.

The DEIR/EIS relies on the expansive deferral of mitigation measure nearly across the board. Those deferrals all suffer from one or more violations of the criteria, discussed at length above, that must be met to properly effectuate such a deferral. Due to time constraints these comments were only able to focus on a handful of those unwarranted deferrals.

Moreover, Guidelines section 15126.4, subdivision (a)(2), provides that "[m]itigation measures must be fully enforceable through permit conditions, agreements, or other legally-binding instruments."

Because adequate funding for the project, much less any of the mitigation measures, has not by any means been secured, the DEIR/EIR also suffers from a widespread failure to discuss the "enforceability" of any of those mitigation measures which, includes as a primarily component of that enforceability, the ability of the project proponents to fully fund those measures. As it stands the DEIR/EIR has proposed or deferred countless mitigation measure with essentially zero guarantee that they will be fully funded or otherwise enforceable.

On the matter of funding, the construction of an isolated facility, of course, relies on no less than twenty-one other "conservation" measures for its authorization. Those other "conservation measures" likewise suffer from a manifest lack of assurance of adequate funding ensure that they to are "fully enforceable" and will actually take place. This is a particularly egregious deficiency that is fatal to not only CEQA and NEPA but also to the other state and federal governmental approvals that must be obtained for this project.

f. The DEIR/EIS Fails to Properly Address and Mitigate the Growth Inducing Effects of the BDCP.

As the DEIR/EIS explains:

> With respect to the indirect growth inducement associated with water delivery, implementation of Alternatives 1A, 1B, 1C, 2A, 2B, 2C, 3, 5 and (for select hydrologic regions) Alternative 9 would increase M&I deliveries to SWP contractors. While an adequate water supply is not an impetus to growth, it is a primary public service needed to support growth. [¶] Growth is projected to occur in the hydrologic regions, and the above alternatives would remove a potential constraint to that growth: lack of adequate, reliable, water supplies. The analysis estimates potential increases in population based on increases in average annual M&I deliveries. This analysis makes several conservative assumptions, including the assumption that any increases in M&I deliveries would support population increases (rather than be used for other purposes).

(DEIR/EIS, p. 30-125.)

As noted above, as part of the Delta Reform Act of 2009, the legislation has declared that "[t]he policy of the State of California is to reduce reliance on the Delta in meeting California's future water supply needs through a statewide strategy of investing in improved regional supplies, conservation, and water use efficiency." (Wat. Code, § 85021, emphasis added.)

Accordingly, it would be directly contrary to that policy for the BDCP to induce growth on account of any additional water supplies the BDCP would provide. Hence, to avoid such inducement (and any increased reliance on the Delta as a result of the BDCP for that matter), the DEIR/EIS must describe potential measures that could be taken to prevent such inducement and reliance and the BDCP Proponents must ultimately adopt such measures to ensure no such inducement or reliance occurs. Potential measures could include express restrictions on the use of the water set forth in the BDCP Plan itself and/or in the Projects' water supply contracts, or otherwise.

It is entirely beside the point that, as the DEIR/EIS contends, "[n]either DWR or Reclamation nor the contractors are land use planning agencies and, consequently, do not have the authority to approve or deny urban development within the study area or to impose mitigation for the environmental 3 consequences of such development." (DEIR/EIS, p. 30-114.) Even if that overstatement was 100% true, which it is not, both DWR and Reclamation, as well as their respective contractors, can fully control the ultimate use and distribution of the water they obtain from the BDCP and, hence, can most certainly take action to successful prevent growth inducement resulting from the use of that water as well as the full range of potentially significant impacts resulting therefrom.

g. The DEIR/EIS Fails to Adequately Address the Tunnels' and Other Facilities' Performance in Earthquakes.

While one of the motivations of the project is seemingly on account of the belief that the new conveyance facilities are more earthquake resistant than the existing through delta conveyance facilities, the DEIR/EIS does an inadequate job of providing facts and analysis to support an assessment of how the tunnels and shafts and other new conveyance facilities will actually fare in such events. Instead, the DEIR/EIS essentially says, trust us, we will design them properly and comply with all various building codes and standards, etc., however, without specifying and assisting the reader (and decision maker) with identifying the particular codes and standards that will be directly applicable to the construction of 40-foot-inside-diameter "soft ground tunnels [that] are pushing the state of the art for tunneling projects in North America." (See Enclosure No. 2)

h. The DEIR/EIS Fails to Properly Address the State and Federal Anti-degradation Laws.

The Federal Environmental Protection Agency ("EPA") requires all states to adopt an "antidegradation policy" similar to the State Water Resources Control Board's ("SWRCB") Resolution 68-16. (40 C.F.R. 131.12.) Resolution 68-16 is further intended to, and does, implement Water Code section 13000 which requires the SWRCB to regulate all "activities and factors which may affect the quality of the waters of the state" such that they "attain the highest water quality which is reasonable."

The State Water Resources Control Board's ("SWRCB") "Resolution 68-16 [commonly referred to as the SWRCB's "Anti-Degradation Policy"] provides in pertinent part:

> "Whenever the existing quality of water is better than the quality established in policies as of the date on which such policies become effective, such existing high quality will be maintained until it has been demonstrated to the State that any change will be consistent with maximum benefit to the people of the State, will not unreasonably affect present and anticipated beneficial use of such water and will not result in water quality less than that prescribed in the policies."

The DEIR/EIS fails to adequately discuss, address and implement these Anti-Degradation Policies in general, and in the context of its discussion and formulation of mitigation measures and alternatives.

i. The DEIR/EIS Fails to Properly Include the Installation of State of the Art Fish Screens on the Projects' Current Export Facilities as a Proposed Mitigation Measure and/or Component of the Alternatives.

It is nothing short of mind-boggling that the BDCP, which will purportedly rely so heavily on the existing South Delta export facilities (on the order of 50% of the time), is not proposing, or even offering as a potential mitigation measure, the installation of state of the art fish screens at those existing facilities, i.e., the fish screens that the CALFED ROD required to be installed and operational by 2006. Such screens should unquestionably be a part of all alternatives that intend on using such facilities to pump any amount of water "through the Delta."

What is equally mind numbing is how the BDCP Proponents can with a straight face, and presumably without any shame, propose and seek the installation of fish screens on other diversions within the Delta which pale in size to the Projects' South Delta facilities pursuant to the BDCP's Conservation Measure 21. Needles to say, some truly misdirected planning is at play.

j. It Remains to be Seen Whether CEQA's Mandated Notice Procedures Have Been Properly Complied With.

Public Resources Code section 21092.3 provides: "The notices required pursuant to Sections 21080.4 [notice of preparation of an EIR] and 21092 [notice of draft EIR] for an environmental impact report shall be posted in the office of the county clerk of each county in which the project will be located and shall remain posted for a period of 30 days."

Because environmental impacts from the instant project will occur throughout a substantial portion of the state (if not the entire state), such notices must be posted in nearly every county of the state. Without having access to information attesting to the postings of such notices, CDWA hereby alleges that the lead agencies have failed to properly and timely file those notices in all of the respective counties as required by section 21092.3.

With regard to the notice of the DEIR/EIS, that notice must also be posted via one of the three methods in Public Resources Code section 21092, subdivision (b): (1) "Publication . . . in a newspaper of general circulation in the area affected by the proposed project"; (2) "Posting of notice . . . on- and off-site in the area where the project is to be located"; or (3) via "Direct mailing to the owners and occupants of contiguous property . . . ." CDWA once again lacks access to information to verify the lead agencies' compliance with one of these methods and, accordingly, hereby alleges the lead agencies' have failed to properly and timely provide notice of their DEIR/EIS pursuant to section 21092.

Because "substantial rather than complete compliance with CEQA-mandated notice procedures [is] an abuse of discretion requiring vacating of the administrative decision," the failure to properly comply with the foregoing and any other CEQA-mandated notice procedures would be a fatal error that must be corrected. (*Gilroy Citizens for Responsible Planning v. City of Gilroy* (2006) 140 Cal.App.4th 911, 922-923.)

k. The DEIR/EIS Must be Recirculated after its Considerable Deficiencies are Corrected.

Guidelines section 15088.5, subdivision (a), explains:

> A lead agency is required to recirculate an EIR when significant new information is added to the EIR after public notice is given of the availability of the draft EIR for public review under Section 15087 but before certification. As used in this section, the term "information" can include changes in the project or environmental setting as well as additional data or other information. New information added to an EIR is not "significant" unless the EIR is changed in a way that deprives the public of a meaningful opportunity to comment upon a substantial adverse environmental effect of the project or a feasible way to mitigate or avoid such an effect (including a feasible project alternative) that the project's proponents have declined to implement.

To properly correct the DEIR/EIS's deficiencies alleged herein, and in other comments by the CDWA and others, a large amount of "significant new information" within the meaning of section 15088.5, subdivision (a), must necessarily be added to the DEIR. Accordingly, the DEIR/EIS will have to be recirculated to afford all interested persons and agencies the opportunity to meaningfully review and comment on that new information.

///

///

Thank you for considering these comments and concerns.

Very truly yours,

Dante John Nomellini, Jr.
Attorney for the CDWA

Enclosures Nos. 1 through 10.

Enclosure No. 1

Geotechnical Aspects of Underground Construction in Soft Ground – Bakker et al (eds)
© 2006 Taylor & Francis Group, London, ISBN 0 415 39124 5

Controlling the risk of sinkholes over EPB driven tunnels – a client perspective

J.N. Shirlaw
Golder Associates, Singapore

S.J. Boone
Golder Associates, Mississauga, Canada

N.B. Sugden
Land Transport Authority, Singapore

A. Peach
Terratec, Australia

ABSTRACT: The occurrence of occasional sinkholes or very large settlements over EPB driven tunnels has been documented on a number of projects. Primary responsibility for avoiding sinkholes must lie with the tunnelling contractor, and the shield manufacturer. Almost all of the documented cases can be ascribed directly to failures in the planning, procedures, operation and maintenance of the machine, or to the design of the machine. However, the client has a major stake in controlling this risk. Sinkholes in urban areas are likely to lead to damage to roads and utilities, may damage buildings, and pose a risk to the public. It is current experience that simply appointing an experienced tunnelling contractor and requiring experienced operators are inadequate to control the risk of sinkholes occurring. A client can help to control the risk by providing sufficient site investigation, developing specifications that set minimum standards, and appointing experienced site supervision teams.

1 INTRODUCTION

The development of very large settlement (>150 mm) in a localized area, or sinkholes, over EPB driven tunnels is much more common than is generally recognized. Shirlaw and Boone (2005) record 57 cases in 77 km of urban tunnelling in Canada and Singapore. The overall frequency was greater than one per 1.4 km of EPB driven tunnel. Cases in many other countries are recorded in other published papers (Shirlaw et al 2003) although, generally, the records are not in sufficient detail to allow the frequency of the incidents to be assessed. It is also unlikely that all of such incidents have been recorded in the public domain, as many owners and contractors are concerned about the adverse publicity involved.

The potential for localised, large, settlements and sinkholes poses a particular problem for the client. Traditionally, tunnelling contracts have been let on a performance basis. The specialist tunnelling contractor assesses the ground conditions, specifies and sources the appropriate tunnelling machinery and develops the tunnelling procedures. Financially, the contractor is rewarded for tunnelling rapidly with the lowest cost machinery that can achieve the required production. With traditional, open face shields the effect of a major ground loss on the contractor was severe, with the shield buried and/or flooded, requiring a major and costly effort to recover the tunnel and resume tunnelling. In contrast, overexcavation during EPB tunnelling often has little adverse effect on tunnelling progress. The direct impact on the contractor is therefore generally minimal. However, for the client, the adverse effects of large settlements or sinkholes are potentially very serious. Much urban tunnelling takes place below roads and, increasingly, beneath buildings. Any major loss of ground therefore poses an unacceptable risk to the general public. Even incidents that do not endanger life or property may cause major concern among the general public, and could result in major delays to the project.

The client's interests are such that it is essential that active measures are taken to ensure that the contractor minimises the risk of large settlements or sinkholes developing over the tunnel. The past cases of large

Enclosure No. 2

DELTA HABITAT CONSERVATION AND CONVEYANCE PROGRAM: "THE PIPELINE/TUNNEL OPTION"

Rich Sanchez ■ State of California, Department of Water Resources

Teresa Engstrom ■ State of California, Department of Water Resources

Mike Cherry ■ DHCCP Program

Carlos Jaramillo ■ URS Corporation

Galen Samuelson Klein ■ URS Corporation

ABSTRACT

The Delta Habitat Conservation and Conveyance Program (DHCCP) "Pipeline/Tunnel Option" is one of the conveyance concepts by the Department of Water Resources (DWR) that is being considered in the environmental review of the Bay Delta Conservation Plan. This conveyance would bring water from the Sacramento and San Joaquin Rivers to the State and Federal pumping plants in the south Delta. The proposed project alignment is 43 miles long and would convey a maximum of 15,000 cfs. The project includes intakes, pumping stations, forebays, sedimentation basins and tunnels. The main tunnels are 37 miles of twin 33-foot ID and are anticipated to be constructed in variable soils at depths below 120 feet. This paper describes the DHCCP "Pipeline/Tunnel Option."

INTRODUCTION

The Delta Habitat Conservation and Conveyance Program (DHCCP) has developed various concepts to convey water from the Sacramento River in the north around the Delta to the existing export pumping plants in the south part of the Delta through an isolated conveyance facility. This effort supports the Bay-Delta Conservation Plan (BDCP) which proposes to revise the current means of conveyance which is solely through the existing Delta channels. Conceptual engineering has been performed to support the environmental impact report (EIR) and environmental impact statement (EIS) process.

The DHCCP is a Department of Water Resources program. The proposed conveyance would become an integral part of the State Water Project and the federal Central Valley Project by providing water directly to the export pumping plants for each of these projects.

The project is currently in conceptual engineering. The system includes: intake facilities with fish screens, sedimentation basins, pumping plants, pipelines, conveyance tunnels, two forebays and control gates. Preliminary engineering is scheduled to begin in 2011. Figure 1 shows the current alignment for the isolated conveyance facility pipeline/tunnel option. Figure 2 is a schematic of the system.

If the construction of precast concrete segments were removed from the construction contracts this would affect contract size and schedule. The current recommendations for contract packaging are to:

- Focus on one bore of the tunnel first and aggressively bid the second bore as the market conditions allow.
- Break each bore into six contracts.
- Consider taking the segments out of the tunneling contracts.
- Stagger award of construction contracts by 3 months.

CONSTRUCTION SCHEDULE

The goal of the program is to construct the project as rapidly as is feasible. There have been many different opinions within the construction industry about the amount of work that can realistically expected to be performed at once. The construction schedule for the tunnels will depend on the contract packaging, TBM availability, contractor availability, the ability of the contracting community to respond to the needs of the Program, and other factors. The original schedule assumed that 12 TBMs were used, one for each tunnel section and both bores were constructed at the same time. This would allow completion within 60 months (5 years). This schedule was not adopted because it was thought to be too much work at one time for the construction industry to absorb.

A revised schedule was prepared which assumed two tunnel bores, six contracts per bore and 1 contract being awarded every three months. This schedule would allow completion within 8 years. This is the currently recommended schedule for the program.

If the construction industry is not able to respond to all $6 billion worth of tunneling work at once, the program could delay construction of the second bore until the first bore has been mostly completed. This would allow the market to "recover" before bidding the second tunnel contracts. This schedule would allow completion within 12.3 years.

CONSTRUCTABILITY

Due to the large scale of the project, the depth of the tunnels and shafts, and the variability of the soils that will necessarily be encountered during construction of 37 miles of twin tunnel, there are constructability concerns and issues that will need to be understood and addressed during preliminary and final engineering for the project. The following issues and concerns will need to be considered in order to proceed with the project and manage the risk associated with tunnel and shaft construction. A detailed and comprehensive risk analysis will need to be performed for the project. Some of the constructability issues and project challenges are:

- Funding during this recessionary time of unbalanced budgets.
- High groundwater levels across the entire project.
- Permits required for discharge of any water produced and collected as part of the tunnel or shaft construction.
- Presence of soft soils along the tunnel alignment.
- Tunnels at depth of 120 feet or more.
- Likely potentially gassy or gassy tunnel gas classification.
- Variability of geology across project.
- Difficulty obtaining access and permission to drill geotechnical borings.
- Shaft construction in soft soils requiring ground treatment.
- Contract interface issues.

- Large size of tunneling contracts.
- Environmental impacts.
- Energy costs and power access. A very large electrical load will be required for construction of the project.
- Construction areas need to be protected from floods. Breach of levees along the alignment needs to be considered.
- Some work areas are water accessible only.
- Depth and diameter of soft ground tunnels are pushing the state of the art for tunneling projects in North America.
- Spoil disposal.

RECOMMENDATIONS FOR PRELIMINARY ENGINEERING

The work that has been performed on the project to date has led the team to identify areas that would need further study. When the tunnel conveyance project moves into the next phase of work, the following issues will be of critical importance to the design:

- Performing more detailed alignment studies.
- Developing and adopting leakage criteria.
- Reviewing tunnel loading cases.
- Determining preferred method for resisting internal pressures on precast segments.
- Study of the gasket capabilities.
- Performing more detailed seismic evaluations and refining the liquefaction analysis.
- Refining the shaft loading.

FUTURE OF DELTA HABITAT CONSERVATION AND CONVEYANCE PROGRAM

Currently (January 2011), the preliminary engineering of the project is on hold to allow the environmental work to catch up. The Environmental Impact Report is anticipated to have a record of decision in 2011. The preliminary engineering for the tunnels is anticipated to start in 2011. The schedule for preliminary engineering assumes 18 months. The schedule for final design assumes 12 months. Based upon these assumptions the first construction contract would be scheduled to be bid in 2014. Based on this, water could begin to be delivered by 2022.

BIBLIOGRAPHY

Delta Habitat Conservation and Conveyance Program Team,"Conceptual Engineering Report All Tunnel Option, Delta Habitat Conservation and Conveyance Program (DHCCP)," prepared for Department of Water Resources, Division of Engineering, March 10, 2010.

Delta Habitat Conservation and Conveyance Program Team, "Draft Report of the Analysis and Optimization of the Pipeline/Tunnel Option, Delta Habitat Conservation and Conveyance Program (DHCCP), prepared for Department of Water Resources, Division of Engineering, December, 2010.

Enclosure No. 3

District Workshop

Bay Delta Conservation Plan

&

Delta Habitat Conservation & Conveyance Program

2013 Nov 20

3d. Risks Affecting Assumptions:

Construction & Operating Costs:

- Future Scope Changes or 'refinements' (currently at ~ 10% design)
- Geotechnical conditions encountered vs. assumed
- Cost of schedule delays. Disruptions occurring both internally & externally as well as near-term vs. during construction
- Cost of risk & its allocation
- Role of Reclamation – How does BDCP benefit CVP contractors (including refuges and exchange contractors)?
- Continued Participation: Impact if a water agency 'opts out'

Blue font denotes risks that affect both cost allocation and water supplies to CVP south of Delta water service contractors

3d. Risks Affecting Assumptions:

Illustration: Partial levee failure as TBM passed underneath

Project: SFPUC's Bay-Division Tunnel,
Levee at Cargill Salt Pond
Newark CA

Date: 2012 Aug (Dutra)

~ 100 ft. = Depth to Tunnel

Enclosure No. 4

RECIRC2819.

SAN FRANCISCO
PUBLIC UTILITIES COMMISSION

Bay Division Pipeline Reliability Upgrade Project

Alameda and San Mateo Counties, California

SCH# 2006062002

FINAL

ENVIRONMENTAL IMPACT REPORT

Volume 1 of 3

Changes from the Draft EIR text are indicated by a dot (●) in the left margin.

Prepared for
The San Francisco Planning Department
Major Environmental Analysis Division

July 2009

Draft EIR Publication Date: December 23, 2008
Draft EIR Public Hearing Date (Fremont, CA): January 14, 2009
Draft EIR Public Hearing Date (Menlo Park, CA): January 20, 2009
Draft EIR Public Hearing Date (Redwood City, CA): January 21, 2009
Draft EIR Public Hearing Date (San Francisco, CA): January 22, 2009
Draft EIR Public Comment Period: December 23, 2008 – February 5, 2009
Certification Hearing Date: July 9, 2009

industrial business parks and open-space land uses near San Francisco Bay. The site of the Newark Valve Lot and the proposed Bay Tunnel shaft is located in an industrial area of Newark, just west of Willow Street. The residences closest to the Newark Valve Lot are approximately 2,000 feet away.

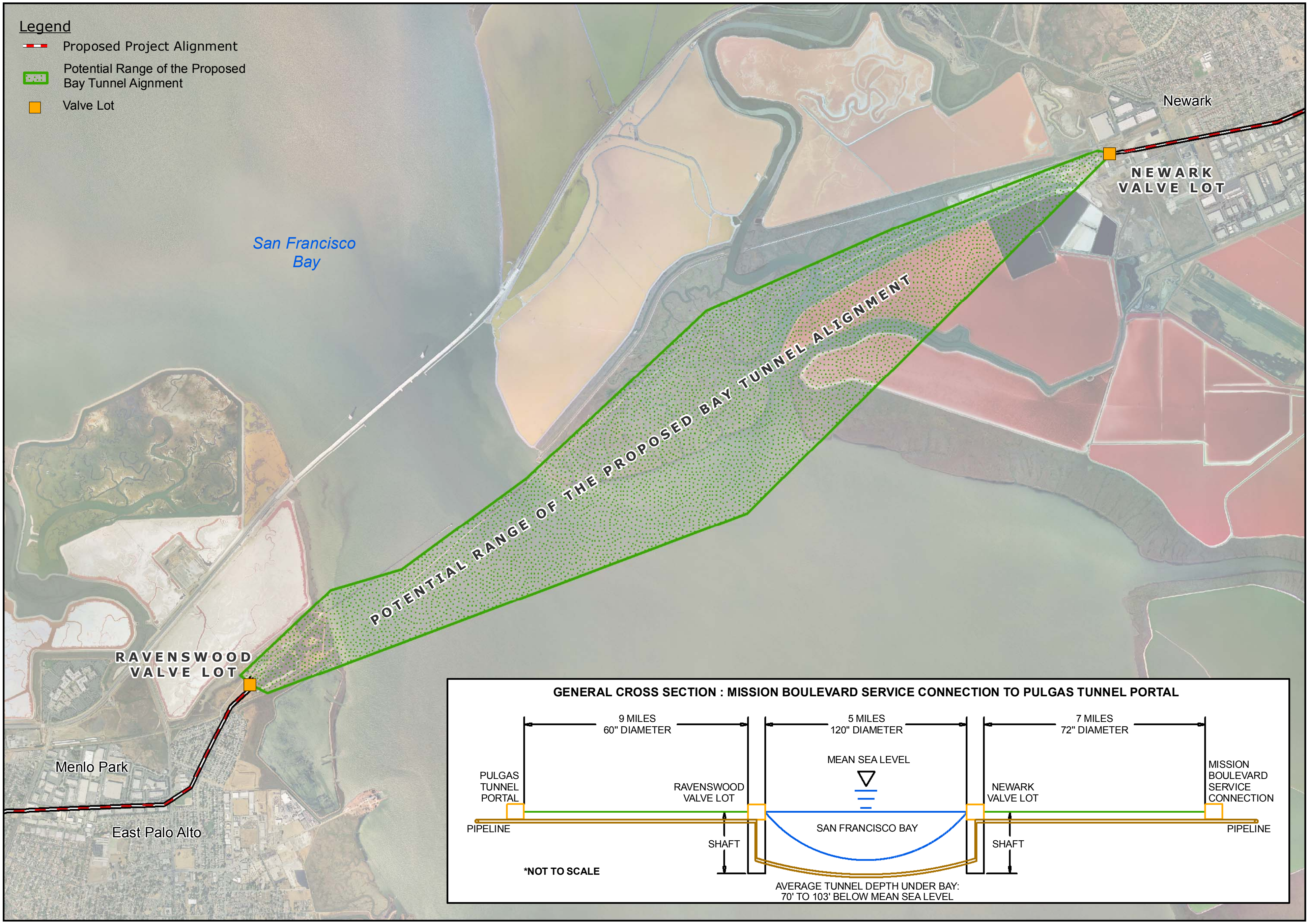
Near Locust Street in Newark, parts of the ROW are being used to store equipment from adjacent industrial activities. To provide owners of industrial parcels sufficient time to locate alternative storage sites, the SFPUC would give them early notice regarding the removal of these materials. The ROW also traverses the parking lots of shopping centers, including Mowry East Shopping Center off Farwell Drive in Fremont. The pipeline alignment would avoid the vaults associated with BDPL Nos. 1 and 2 near Boone Drive in Fremont and near Moores Avenue in Newark.

Reach 5-4: Bay Tunnel

Reach 5-4 consists of the proposed Bay Tunnel, which measures approximately five miles in length. The ends of the tunnel (i.e., the tunnel shafts) would be located at the Newark Valve Lot in Newark on the eastern side of the Bay and at the Ravenswood Valve Lot in Menlo Park on the west side of the Bay. Just east of the Newark Valve Lot, the tunnel would be constructed approximately 60 feet beneath sewage force mains owned by the Union Sanitary District. Figure 3-3 depicts the area within which the tunnel alignment corridor would be located. On the eastern side of the Bay, the tunnel would cross under the Caltrain railroad tracks along two locations on the alignment. It would cross under the Don Edwards San Francisco Bay National Wildlife Refuge and, depending on the final alignment, could cross under Newark Slough. The depth of the tunnel would be between approximately 70 and 103 feet below mean sea level. A tunnel-boring machine (TBM) launched from the Ravenswood shaft site would be used to construct the tunnel. Upon completion of boring, the TBM would be removed through the retrieval shaft at the Newark shaft site (see Section 3.9, Shaft and Tunnel Construction, below).

Reach 5-5: Ravenswood Valve Lot to Redwood City Valve Lot

Reach 5-5 would be 4.9 miles long, extending from the proposed Bay Tunnel shaft at the Ravenswood Valve Lot in Menlo Park to the Redwood City Valve Lot. Land uses adjacent to the Ravenswood Valve Lot include wildlife habitat, utility corridors, and residential areas of East Palo Alto approximately 900 feet to the west. As they progress westward, the BDPL ROW and proposed alignment extend into East Palo Alto at the SamTrans crossing, proceeding south-southwest. The SamTrans line has been deactivated, and therefore the project is proposing to open-cut this crossing. Adjacent land uses are low-density, single-family homes, multifamily dwelling units, and commercial establishments along University Avenue. The BDPL ROW and proposed alignment traverse University Village, a neighborhood consisting primarily of single-family residences in north-central East Palo Alto, and crosses the grounds of the Costaño Elementary School on Fordham Street near



Source: San Francisco Public Utilities Commission, 2005

Figure 3-3
Potential Tunnel Alignment Corridor and Bay Cross-Section

3.9 Shaft and Tunnel Construction

3.9.1 Shaft Construction

The Bay Tunnel would be constructed between two shafts, one at the Ravenswood Valve Lot in Menlo Park and the other at the Newark Valve Lot in Newark. The tunnel boring machine (TBM) would be launched from the Ravenswood tunnel shaft site. The tunnel grade would be nearly flat with a minimum slope designed to drain to the Ravenswood shaft. The pipeline within the Bay Tunnel would be a welded-steel or concrete pipe with an inside diameter of 108 to 120 inches. At the completion of tunneling, the TBM would be recovered from the Newark shaft on the east side of the Bay.

Shaft construction would require approximately eight months. The launching shaft would be approximately 55 to 65 feet in diameter, and the retrieval shaft approximately 25 to 38 feet in diameter. The Newark shaft would be located near the valve house at the Newark Valve Lot (see Figure 3-4). The Ravenswood shaft would be located northeast of the valve house at the Ravenswood Valve Lot (see Figure 3-5). The tunnel shafts would have depths of up to approximately 135 feet.

Because the tunnel shafts would be constructed in soft ground conditions and below the groundwater table, they would be constructed within a watertight lining system to reduce the amount of water entering the work shaft. This could include a slurry panel wall, a caisson,[12] or a secant pile wall method. Slurry panel walls are composed of reinforced concrete panels constructed within a slurry-filled trench. A series of straight panels or linear segments form the circular shaft. After the trench is excavated and the reinforcement is installed, the concrete is poured and placed from bottom to top. Secant pile walls are similarly constructed as a series of overlapping concrete-filled drilled piers, installed around the perimeter of the shaft. These methods would also prevent contaminated groundwater from flowing between aquifers during shaft construction.

Soils within the shaft walls would be removed using a crane with a clam-shell bucket. These saturated soils from below the water table would be placed in trucks to be hauled off-site. After soil excavation, the remaining water would be pumped out and treated in accordance with the project's NPDES dewatering permit.

The construction contractor would also discharge excess water during shaft excavation and tunneling. During shaft construction, temporary groundwater infiltration would be a maximum of 10 gallons per minute (gpm) (Jacobs 2007b). Areas with higher infiltration rates would be repaired. Groundwater infiltration through the shaft invert would be

12 A caisson would be constructed by building successive ring sections of the shaft and excavating the material below, allowing the caisson to sink downward using its own weight.

controlled with reinforced concrete tremie[13] slabs to prevent excessive inflows and maintain stability of the shaft invert.

Groundwater inflow could also occur when the TBM is breaking out of the Ravenswood Shaft or breaking into the Newark Shaft, particularly if the seals between the shaft and TBM are compromised. To reduce the volume of groundwater inflows during break-in and break-out, the construction contractor would treat the soils around the shaft/tunnel intersection with jet grouting, reducing its permeability. In addition, the contractor would attach a ring seal to the shaft wall to further reduce the chance of temporary large groundwater inflows.

During break-in and break-out, groundwater inflow could temporarily be as high as 2,000 gpm for up to 48 hours or until grouting cuts off the inflow (Jacobs 2007b). Because the Newark Tunnel Shaft would be proximal to existing contaminated groundwater plumes, the shaft would be filled with water and partially backfilled with soil to equalize pressures during break-in of the TBM and to reduce inflows. Because the Ravenswood Tunnel Shaft would be the launching shaft, temporary backfilling/watering will not be an option; a temporary water treatment facility would be sized to handle the maximum inflow rate during break-out of the shaft.

Through its construction contract specifications, the SFPUC would require that its contractor limit groundwater inflows during tunnel excavation to 4 gpm per 1,000 feet of tunnel, and 0.05 gpm for any four-foot length of tunnel, with a maximum of up to 105 gpm for the entire tunnel (Jacobs 2007b). To minimize tunnel inflow, the TBM would be designed to operate at high hydrostatic pressures. In addition, the contractor would replace gaskets and grout cracks as needed.

The construction contractor would construct the shafts using power generated onsite. The portable temporary generators would be powered by diesel fuel or propane, as discussed below.

3.9.2 Tunnel Excavation

The Bay Tunnel portion of the Project would be excavated by a shielded TBM, which would likely utilize pressure-face methods. Three types of TBMs are commonly used:

- Earth pressure balance machine (EPBM);
- Bentonite slurry face TBM; and
- A hybrid of the above two types, known as the Mixshield™ (developed by Wyass & Frytag with Herrenknecht AG), that can be used in either slurry or earth pressure balance mode.

[13] An apparatus for depositing and consolidating concrete under water, essentially a tube of wood or sheet

The soft ground tunnel could be constructed by either an EPBM or by a slurry machine with ground support provided by a segmental lining of precast concrete that is bolted and gasketed in place. Ground conditions, primarily stiff clay with lenses of dense sand, favor the use of an EPBM, which can, using foam or other additives, condition the soil, reduce material friction, and thereby improve its fluidity.

Based on geotechnical investigations, weathered Franciscan Complex bedrock is expected approximately 1,000 feet west of the Newark Valve Lot. This bedrock, which may be several hundred feet in length, consists of primarily basalt, sandstone and shale with some minor chert and serpentinite (URS 2008). The TBM can tunnel through relatively hard substrate such as this highly weathered bedrock if equipped with the appropriate disc cutters and excavation tools.

Figure 3-10 shows soils produced by a typical EPBM tunneling operation. Figure 3-11 illustrates a typical conveyor belt configuration to transport soils out of the tunnel following excavation. Conditioning increases material volume, most of which is associated with the air in the foam; however, as the foam breaks down and the free water bleeds out of the muck, the soil returns to a more natural state. Stiff clay or silty clay requires minimal conditioning, mainly the addition of water and foam to prevent sticking. Sand typically requires foam and other additives if the material lacks fine particles.

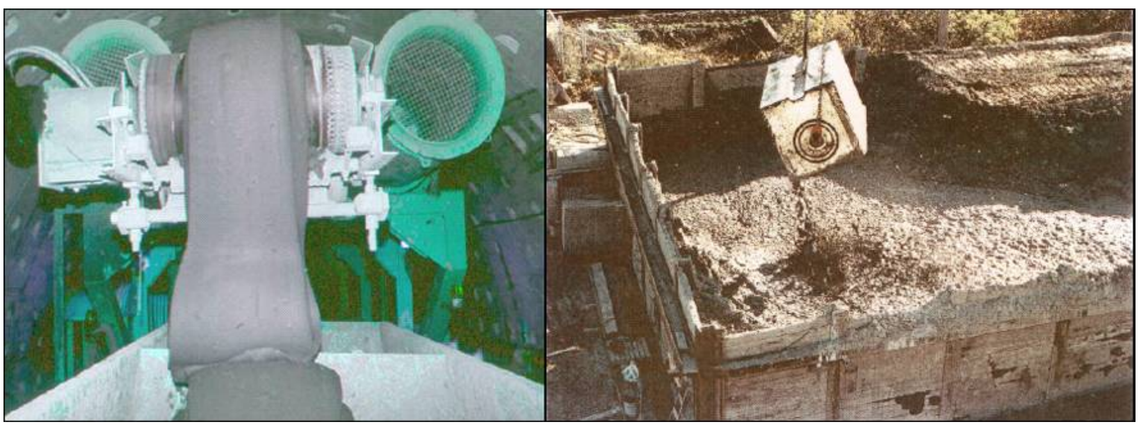


Figure 3-10 EPBM Muck Consistency at TBM (left) and at Surface (right)

metal with a hopper-like top.

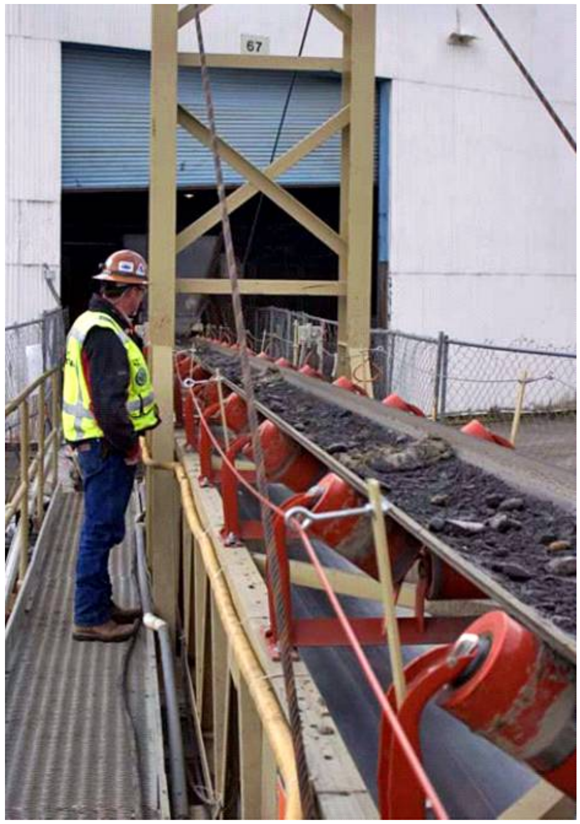


Figure 3-11 Typical Conveyor Transport of Excavated Soils

Slurry machines use bentonite clay to produce the slurry needed to form a stable tunnel face and to transport muck. Most of the bentonite in the slurry would be reused; however, a small residue would remain on the processed muck. Before the slurry is reused in the tunnel, it would be processed to remove tunnel muck. This operation would continue 24-hours per day and would be housed in a sound-insulated building to limit the noise generated by the screens, cyclones, and pumps. The total area required for the slurry treatment plant building and slurry storage tanks would be approximately 0.5 acre.

The tunnel diameter must provide sufficient space for ventilation, spoils removal, liner segment transport, worker access, and ancillary equipment. Ventilation requirements result in a three- to five-foot-diameter air pipe within the tunnel to enable tunneling the entire 5-mile alignment without intermediate shafts. The diameter of the tunnel bore would be approximately 16 feet, allowing for a one-foot-thick initial tunnel liner. SFPUC would monitor accessible ground areas above the excavation for subsidence or settlement. If settlement is detected, work would stop and ground improvement methods (such as injecting grout) would be employed in the tunnel as necessary. An estimate of the amount of excavated material or spoils is provided in Section 3.17.2, Generation of Bay Tunnel Spoils.

Tunnel construction involves repeated cycles of excavation and lining. The excavation portion of the cycle involves mining ahead one ring width with the TBM (approximately three to four feet). After excavation, the tunnel liner or completed segment ring (typically composed of six pieces) would be built within the tail shield of the TBM. During the next excavation cycle, the precast lining is pushed out of the tail of the TBM, and the gap outside the lining is completely grouted to fill the void and ensure good contact between the lining and the surrounding ground. A typical excavation cycle takes 40 to 60 minutes.

After the tunnel is completed, steel pipe or reinforced-cylinder concrete pipe would be installed in the tunnel. Typically, 20- to 40-foot-long sections of pipe are lowered into the shaft and transported into the tunnel, where they are either welded together or locked into place and then welded. After the installation is completed, the pipeline is grouted in place with concrete. Final grouting, lining, and welding would require up to 20 months. During excavation and before the final pipe is installed, groundwater inflows into the tunnel would be limited to about four gpm per 1,000 linear feet of the tunnel (Caulfield 2007). Total combined inflow from the shafts and tunnel before final lining would be about 125 gpm (Caulfield 2007).

3.10 Construction Access Roadways

The existing ROW would be used to provide access for construction equipment and vehicles. An approximately 18-foot-wide permanent access roadway could be required at the Newark Valve Lot and tunnel shaft area. The road would be located at the eastern end of the tunnel shaft site and the entrance to the staging and stockpiling area and would extend east to Willow Street. The driveway would be a mat of crushed aggregate (rock) used to control erosion where the heaviest construction would occur and to provide easy access to the tunnel shaft. This roadway would allow two-way truck traffic in the event of an emergency. The Newark Valve Lot access road would be constructed to be permanent. An alternate construction route could also be through the FMC Corporation property to the south, connecting with Enterprise Drive.

The access road at the Ravenswood Valve Lot and tunnel shaft, which currently connects with University Avenue in East Palo Alto, would be widened from approximately 18 feet to approximately 20 feet and if necessary, repaved. Wider turnout areas would be constructed for larger trucks. Two new paved parking areas would also be added to the Ravenswood Valve Lot site. Improvements to the access road at the Pulgas Tunnel Portal site would include repairing the fencing, repaving, adding a pullout area, and trimming tree branches.

Any improvements at the intersection of existing (or new temporary) access roads with public roadways would meet the appropriate intersection design standards of the applicable local jurisdiction. Truck acceleration and deceleration lanes would be provided, as appropriate, to facilitate truck access into and out of the staging areas and to minimize conflicts between construction vehicles and adjacent traffic flow.

Enclosure No. 5

ANALYTICAL STUDY ON FLOOD INDUCED SEEPAGE UNDER RIVER LEVEES

A Dissertation

Submitted to Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The Department of Civil and Environmental Engineering

by
Senda Ozkan
B.S., Middle East Technical University, 1992
M.S., Louisiana State University, 1996
May 2003

ACKNOWLEDGMENTS

I am very thankful to my main advisor, Dr. Dean Adrian. He always showed his full trust, encouragement and support to my efforts. With his vast guidance, I have experienced the joy of applied mathematics in my research. My appreciation also extends to my dissertation committee, Dr. Vijay Singh, Dr. Roger Seals, Dr. Mehmet Tumay and Dr. Nan Walker for their valuable guidance.

I would like to thank the U.S. Army Corps of Engineers (USACE) for funding this project through contract DACW39-99-C-0028, and Mr. George Sills, USACE Vicksburg District, who first suggested this research idea. I thank the support and understanding of my friends, co-workers, and my managers at Gulf Engineers and Consultants (GEC), Inc. I also thank Mr. William Luellen for his editorial reviews.

I want to acknowledge Ms. Joan Adrian for her continuous support to my family. The Adrians became my second parents in the U.S.

My special thanks go to my spouse, Ahmet who has supported me through all of my graduate studies. He has encouraged me and tried to make contributions at every step of my research. I also owe a lot to my parents and brothers for their inspiration and encouragement. And my very special thanks go to my little boy, Toros. I wouldn't finish this research without his love, joy and cheers.

TABLE OF CONTENTS

ABSTRACT

A common and potentially dangerous phenomenon associated with flooding is seepage under levees and the formation of sand boils. Seepage flow due to hydrostatic head gradients of floods may cause deformation of pervious layers leading to heave, piping and sand boils. Underseepage may also cause irreversible changes in the characteristics of the porous medium. A series of independent flood events may have cumulative effects on pervious layers causing sand boils to grow. Current underseepage analyses for levees are based on steady-state flow. Transient seepage flow due to rapid changes in river head may contribute to cumulative effects and cause critical hydraulic head development under levees and subsequent sand boil formation.

This research examined transient effects on hydraulic head development under levees during a flood event. While the research is focused on levees, this study is applicable to any hydraulic structures (e.g., flood walls, dams, and retaining structures) subject to underseepage. An analytical model was developed for one-dimensional transient flow in a confined aquifer under a levee in response to river stage fluctuations. This analytical model was revised by considering leakage out of confined aquifers to simulate the occurrence of sand boils on the landside of levees. Transient flow nets were also constructed using complex variables. The performance of these analytical models was evaluated by comparing with the limited field studies, current U.S. Army Corps of Engineers underseepage analysis methodology for levees, and a finite element program. The effects of possible cumulative deformations on development of exit hydraulic gradients were also evaluated and discussed.

Transient flow models performed reasonably well compared with the limited field studies, the Army Corps seepage analysis method and SEEP2D finite element program.

Cumulative analysis of underseepage by the transient flow model simulating sand boil formations showed significant increases in exit hydraulic gradients in response to possible cumulative changes in aquifer characteristics.

CHAPTER 1 INTRODUCTION

Underseepage of water through soil below levees during times of flood is a natural phenomenon. Seepage becomes a matter of concern for the safety of a levee when piping occurs and sand boils form. Turnbull and Mansur (1961) summarized the flood induced seepage problem under levees based on their experience with the U.S. Army Corps of Engineers (USACE). If the hydrostatic pressure force in the pervious substratum landward of the levee becomes greater than the submerged weight of the overlying strata, the excess pressure may cause heaving of the upper soil layers and rupture at weak spots with a resulting concentration of seepage flow. Flow from these weakened locations may increase to form sand boils. In addition, the concentrated seepage flow may erode fine soil particles, and carry these fine particles up to the surface. As the erosion process continues, a pipe or open channel may form through the top stratum. The pipe-shaped opening through which water and eroded soil discharge is called a sand boil. A sand boil opening bears some resemblance to a soil-walled pipe through the top stratum. The flowing water exiting through a sand boil carries soil particles that have been eroded from along the water’s seepage path up to the soil surface where it may deposit to form a cone around the sand boil. Heave and piping are the main mechanisms involved in creating a pipe that leads to sand boils. Heaving occurs when seepage forces push the substrata upward. Piping is the phenomenon where seeping water progressively erodes and washes away soil particles, leaving large voids in the soil. Removal of soil through sand boils by piping or internal erosion damages levees, their foundations, or both, which may result in settlement and has the potential to cause catastrophic failures of levees. A schematic view of the underseepage problem is shown in Fig. 1.1.

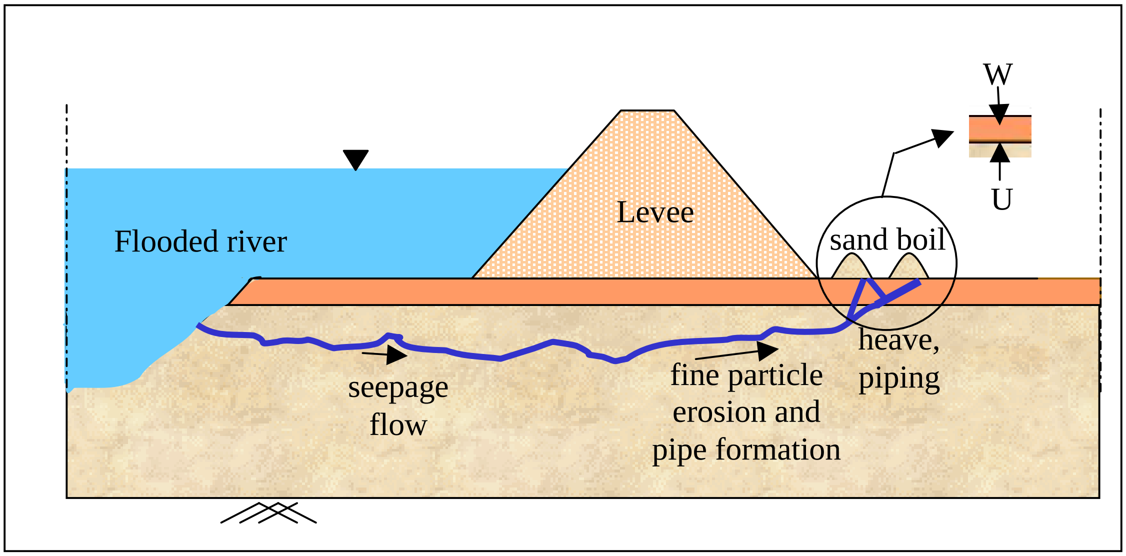


Fig. 1.1 A schematic representation of seepage problem under levees (U: hydrostatic uplift pressures, W: submerged weight of soil).

Although an exit hydraulic gradient of 0.85 on the landside of a levee is commonly considered sufficient to initiate sand boil formation, other field measurements show that sand boils may occur with exit hydraulic gradients in the range of 0.54 -1.02 (Daniel, 1985). A photo of a sand boil in shown Fig. 1.2

While most analyses of underseepage, piping, heaving, and sand boil formation have been based on steady seepage flow, it is unsteady seepage flow that is more common for canal embankments and levees (Peter, 1982). This is because during floods the water level in the river and between the levees changes so quickly that a constant flow regime is unlikely to be established. Instead, rapid changes of water level may cause a head wave moving with varying velocity in the stratified porous medium. Consider that a levee is underlain with a layer of high hydraulic conductivity soil, which extends a distance on the landside of the levee, while a layer of low hydraulic conductivity soil overlies the high conductivity layer on the landside of the levee (Fig. 1.3).

Fig. 1.2 A picture of a sand boil (source: USACE, Vicksburg District).

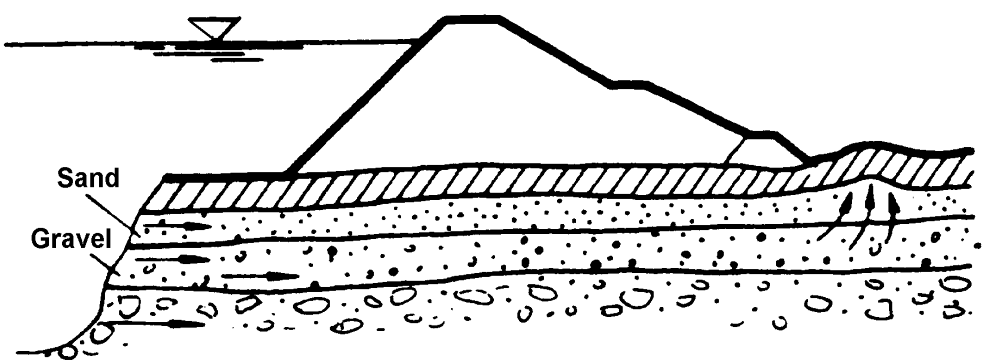


Fig 1.3 A hydraulic structure and seepage forces acting on sand and gravel layer in its subsoil (after Peter, 1982).

When a flood wave occurs in the layer of greater hydraulic conductivity, the head wave reaches farther in a given time than it does in the top layer. As the head wave develops, so do uplift pressures that may induce heave and gradual liquefaction of the overlying layer. Static liquefaction is a soil state at which vertical effective stress on soil becomes zero (Fig. 1.1). A mass of sand in a state of static liquefaction is known as quicksand, which has lost its strength and behaves like viscous liquid (Budhu, 2000).

If the same problem were to be analyzed as a steady state problem, then the upper layer would be assumed to be wet and thus heavier than similar dry material, so the heave would have been less likely to occur. However, steady seepage is frequently assumed in analyses of levees because the computations are simpler and the steady-state seepage parameters are less difficult to determine than the corresponding transient parameters (Peter, 1982). For these reasons, seepage flow based on transient effects due to changes in river head has not been analyzed in as much detail as has steady flow.

At one time, it was thought that sand boils could “heal” or “repair” themselves between flood events (Sills, G., personal communication to CE 7265 class, Fall 1997). After the 1993 floods on the Upper Mississippi River, some engineers with the U.S. Army Corps of Engineers began to question the extent of the inter-flood healing effect and whether there is a cumulative effect caused by sand boils. (Sills, G., personal communication to CE 7265 class, Fall 1997).

A more recent concept is that seepage under levees during a series of independent flood events may cause sand boils to grow as the flood series grows longer. Researchers have not examined the concept that there may be cumulative effects from sand boils, which increase the likelihood of levee failure due to seepage. As a result, the problem of levee failure due to cumulative effects of underseepage is only now being recognized as a problem that may have great urgency for evaluating the danger to lives and property in areas protected by levee systems. Currently, the USACE Engineer Research and Development Center (ERDC) in Vicksburg, Mississippi, is working on research on the cumulative effects of piping under levees (Wolff, 2002). The research unit operates under the Innovative Flood Damage Research Program (IFDR) sponsored by USACE.

1.1 Objectives

The objective of this research was to obtain a better understanding of the sand boil problem. This dissertation explored the following two questions: (1) Is transient flow analysis due to river head fluctuations critical in the development of exit hydraulic gradients and the subsequent sand boil formation? and (2) If sand boils develop more frequently due to cumulative effects associated with repetitive flood events, how can transient flow analysis in conjunction with current underseepage analysis tools respond to this problem? Both questions were addressed by developing transient flow models and comparing them with current underseepage analysis tools. The transient flow models developed in this study are also expected to contribute to the current literature on analytical techniques for seepage problems. The following specific objectives were established for this study:

1. develop an analytical model to describe hydraulic head in response to river head fluctuations in a confined aquifer under a levee,
2. develop an analytical model to describe hydraulic head in response to river head fluctuations under a levee with leakage out of a confined aquifer,
3. construct time-dependent flow nets for underseepage analysis,
4. evaluate the performance of these analytical models by comparing them with other current practice underseepage analysis methods, and
5. evaluate possible cumulative effects in hydraulic head development with new analytical models and other underseepage analysis methods.

1.2 Outline of Dissertation

The dissertation is organized as follows: This chapter gives an introduction to the research, an outline of the problem, the main questions asked, and the specific objectives of the study.

The second chapter gives background information and literature review. It provides detailed information on seepage erosion, previous studies on underseepage of levees conducted by USACE, current underseepage analysis tools, analytical studies on transient flow, and possible cumulative effects due to repetitive flood events.

The third and fourth chapters present transient analytical hydraulic head models; for a confined aquifer in the third chapter and with leakage out of a confined aquifer in the fourth chapter. In both, a solution with Laplace transform method and an approximate solution are presented. The fifth chapter details analytical construction of transient flow nets for infinite-depth aquifers and finite-depth aquifers. The results and a discussion about the transient models and flow nets are given in each chapter.

The sixth chapter provides a performance analysis of the developed models conducted by comparing the results of the analytical models with the USACE levee underseepage method and a finite element program. Results and discussion of this section explore the main question of this study: whether transient effects are critical in development of exit hydraulic gradients, which may trigger sand boil formation.

Cumulative effects due to repetitive flood events are discussed in the seventh chapter and are evaluated by transient flow models, USACE levee underseepage method, and a finite element program. The results and discussion of these evaluations explore the second question of this study: how transient flow analysis and current underseepage analysis tools respond to possible cumulative effects due to repetitive flood events. The conclusions are presented in the eighth chapter.

There are four appendices containing details of mathematical computations and finite element models.

1.3 Scope of Study

This research involved the use of mathematical models, which were supplemented by data from published on-site investigations.

Typical geological features of Mississippi River Valley include a less permeable top stratum and a more pervious substratum. This geological feature may allows us to do confined flow analysis. In the analytical models, linear laws of seepage were studied, where there is a linear relationship between seepage velocity and hydraulic gradient. The pervious substratum typically combines horizontally stratified beds of sand where horizontal conductivity of the main aquifer is so large compared to hydraulic conductivity of the semi-pervious top stratum. Therefore, it is safe to assume that horizontal flow in the pervious substratum is refracted over 90^0 to seep vertically through the semi-confining layer due to hydraulic uplift forces (Hantush and Jacob, 1955). While, all groundwater flow in nature is three-dimensional to a certain extent, symmetry features, i.e. flow to a well, make the problem possible to analyze in two-dimensional form (De Wiest, 1965). The solution may need to be further simplified by reducing the dimensionality of the problem to one due to difficult boundary conditions. Reducing the dimensionality of the problem introduce significant errors and it is up to hydrologists' judgement to estimate the error in engineering practice. In the light of this discussion, certain simplifications were applied in the development of analytical models in this research.

The analytical models for transient flow in a confined aquifer were developed by using the diffusion equation, which was derived under Darcy's law, and the law of conservation of mass. The geologic conditions beneath the levees can be very complex. To simplify the problem the stratum was assumed as saturated, homogenous, and isotropic, and the flow is assumed as one-dimensional. Transient analytical flow models with leakage out of a confined aquifer were presented and a subsurface system with a leaky confined aquifer and a semi-permeable layer on the top of it was considered. The assumptions introduced by Hantush and Jacob (1955) on leaky aquifer systems - that storage in the semi-permeable layer is negligible and the leakage is linearly proportional to the difference in head between two layers - are applicable here.

The methodologies given by Polubarinova-Kochina (1962) were followed for transient analytical flow nets for infinite and finite depth aquifers. The assumptions and the conditions in her solutions were maintained. A downward vertical flow at the riverside of the levee, a horizontal flow under the levee and an upward vertical flow at the landside of levee were assumed. The solution is for homogenous and isotropic soil conditions.

The performance of the analytical models was compared with the other seepage analysis tools. Even though a simple cross-section with typical soil parameters was used, the comparisons may not reflect identical conditions as each method was developed under its own assumptions. The transient flow models and other seepage analysis tools were used to evaluate possible cumulative effects of flood-induced seepage. As explained in the literature survey, there is a distinct lack of published studies on cumulative effects of underseepage problems associated with sand boils. The best evaluation of cumulative effects can be conducted by examining data from long-term site investigations and by conducting laboratory experiments. The evaluation of cumulative effects by empirical, analytical and numerical methods is complicated. The transient analytical models developed in this study attempt to provide a view to the problem of evaluating cumulative effects of sand boils. Further research is needed in this area.

CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

The following items are reviewed in this chapter: seepage erosion mechanisms; levee underseepage and sand boil formation; field observations; soil properties susceptible to piping problem; geology of Lower Mississippi River Valley and its influence on underseepage; previous studies on levee underseepage conducted by USACE; current underseepage analysis methods; analytical studies on transient flow with cyclical boundary conditions; and cumulative effects. A list of symbols is included at the end of the chapter.

2.2 Seepage Erosion

Van Zyl and Harr (1981) classified seepage erosion failures into three modes: heave, piping and internal erosion. Heave is analyzed by comparison of seepage force per unit volume with effective unit weight of selected critical volume of soil. Terzaghi (1929) presented an exit gradient approach to seepage analysis in his classical work on failure of dams by seepage erosion. His theoretical development was based on the summation of the vertical seepage forces exerted by the upward flow of water and the vertical downward weight of the submerged soil. He defined the critical gradient to cause heaving as:

$$i_c = \frac{\gamma_{sub}}{\gamma_w} = \frac{G_s - 1}{1 + e} \tag{2.1}$$

where, γ_{sub} is the submerged unit weight of soil, γ_w is the unit weight of water, G_s is the specific gravity of soil, and e is the void ratio of soil. For typical soils, the critical gradient is approximately 1.0.

Sherard *et al*. (1963) investigated the mechanics of piping in earth and earth-rock dams. As water flows, the pressure head is dissipated in overcoming viscous drag forces, which resist the flow through the small pores. The seeping water also generates erosive forces and tends to drag the soil particles with it as it travels through the pervious layer. If the seepage erosive forces are greater than the erosion resisting forces, the soil particles are washed away and piping starts. If the soil has some cohesion, a small tunnel or pipe can form at the downstream exit face of a seepage path. Once piping starts, the flow in the pipe increases due to the decreased resistance to flow, piping accelerates, and the small tunnel or pipe lengthens. Van Zyl and Harr (1981) stated that the analysis of piping erosion was almost impossible due to control by discontinuities. However, global gradient approaches developed by Bligh (1927) and Lane (1935) are still widely used in the design of dams and weirs. The concept of the length of the path traveled by seeping water led to the development of creep ratios or creep coefficients. Bligh (1927) defined a creep coefficient as:

$$C = \frac{L}{h} \tag{2.2}$$

where L is the length of seepage path measured along the base of weir, and h is the total head loss. Lane (1935) suggested a weighted creep ratio as:

$$C_w = \frac{\frac{L_h}{3} + L_v}{h} \tag{2.3}$$

where, L_h is distance along horizontal contacts (<45^0, measured from the horizontal), L_v is distance along vertical contacts (>45^0) and h is total head loss. Bligh (1927) and Lane (1935) suggested limiting values for creep coefficients obtained by analyzing a large number of structures founded on various soil conditions. Some typical values of weighted creep ratio are: 8.5 to 5.0 for very fine sand to coarse sand, 4.0 to 2.5 for fine gravel to boulders, and 1.8 for hard clay (Lane, 1935).

Internal erosion begins locally by fine particles being moved from the soil matrix into a coarser layer leading to formation of cavities, collapse and failure. The mechanism is an important concern for the analysis of seepage through the hydraulic structures in the event of transfer of particles between zones of earth and rock-fill dams, and in dispersive soils (Sherard *et al*., 1972). While the analysis of internal erosion is generally very difficult, installation of filters designed to proper filter criteria is the common prevention technique (Van Zyl and Harr, 1981).

Casagrande (1937) estimated the exit gradient from flow nets. Khosla *et al.* (1936) and Harr (1962) suggested theoretical methods to determine the exit gradients for confined flow for specific cross-sections. Khilar *et al.* (1985) investigated the potential for clay soils to pipe or plug under induced flow gradients. They presented the following equation as a measure of the critical gradient to cause piping:

$$i_c = \frac{\tau_c}{2.878\gamma_w}\left(\frac{n_0}{k_0}\right)^{1/2} \tag{2.4}$$

where τ_c is the critical tractive shear stress (dynes/cm^2), n_0 is the initial porosity, and k_0 is the initial intrinsic permeability (a typical value is, $k_0 = 10^{-10}$ cm^2). For granular materials, critical tractive shear stress can be estimated from the d_{50} size (Lane, 1935) as τ_c (dynes/cm^2) = 10d_{50} (mm). Aralunandan and Perry (1983) studied the erodibilty of core materials in earth and rock dams. They reported that the erosion resistant soils have a critical tractive shear stress of $\tau_c \geq 9$ dynes/cm^2 based on limited data.

Soil type, rate of head increase and the flow condition are the main dependents for modes of seepage erosion failure (Van Zyl and Harr, 1981). The soil type controls whether heave is followed by a quick condition as in clean sand or whether heave leads to crack formation, concentrated flow and piping. Heave, leading to cracks, concentrated flow and piping, appears to be more common in granular soils with a large percentage of fines.

A rapid increase in head may result in heave of the surface, leading to a quick condition (Van Zyl and Harr, 1981). This could be a typical failure condition on the downstream side of a water retention structure being filled rapidly. A quick condition before heave can also be produced when the head is raised very slowly. Tomlinson and Vaid (2000) presented an experimental study of piping erosion. They tested various artificial granular filter and base soil combinations in a permeameter under variable confining pressures to determine the critical gradient where soil erodes through the filter. They observed that the critical gradient was lower if the head was rapidly increased. Van Zyl and Harr (1981) also pointed out the importance of flow conditions in piping problems. According to the field observations, an unsaturated soil fails at lower gradients than the critical gradient of the soil. The first filling of a reservoir may induce this type of failure.

Sellmeijer and Koenders (1991) stated that empirically, a so-called piping channel or slit develops, extending from the downstream corner of the structure to a length of less than half the bottom length of a dam. They presented a mathematical model for piping. They modeled a prediction of an equilibrium situation in which some materials have washed away from underneath the structure and the channel development has stopped. The result of this study was a mathematical representation of the relation between the pipe length and the difference in water head. Ojha *et al.* (2001) developed a piping model based on Darcy's law. They concluded that the choice of permeability function was critical for the piping model. The permeability functions, which depend only on grain size, have limited value on clarifying piping models while those that include porosity are more useful.

2.3 Development of Underseepage and Sand Boils

Turnbull and Mansur (1961) explained underseepage mechanisms and sand boil formation at Mississippi River levees as a result of the studies and investigations conducted by the Army Corps of Engineers covering a period of 1937 to 1952:

> “Whenever a levee is subjected to a differential hydrostatic head of water as a result of river stages higher than the surrounding land, seepage enters the pervious substratum through the bed of the river and riverside borrow pits or the riverside top stratum or both, and creates an artesian head and hydraulic gradient in the sand stratum under the levee. This gradient causes a flow of seepage beneath the levee and the development of excess pressures landward thereof. If the hydrostatic pressure in the pervious substratum landward of the levee becomes greater than the submerged weight of the top stratum, the excess pressure will cause heaving of the top blanket, or will cause it to rupture at one or more weak spots with a resulting concentration of seepage flow in the form of sand boils.
>
> “In nature, seepage usually concentrates along the landside toe of the levee, at thin or weak spots in the top stratum, and adjacent to clay-filled swales or channels. Where seepage is concentrated to the extent that turbulent flow is created, the flow will cause erosion in the top stratum and development of a channel down into the underlying silts and fine sands, which frequently exist immediately beneath the top stratum. As the channel increases in size or length, or both, a progressively greater concentration of seepage flows into it with a consequent greater tendency for erosion to progress beneath the levee.
>
> “The amount of seepage and uplift hydrostatic pressure that may develop landward of a levee is related to the river stage, location of seepage entrance, thickness and perviousness of the substratum and of the landside top stratum, underground storage, and geological features. Other factors contributing to the activity of the sand boils caused by seepage and hydrostatic pressure are the degree of seepage concentration and the velocity of flow emerging from the boils.”

Turnbull and Mansur (1961) also explained the importance of underground storage on underseepage and excess hydrostatic pressure during relatively low high waters and high waters of short duration. They noted that during a high water, if the ground water table is low, drainage into subsurface storage landward of the levee reduces hydrostatic pressures and seepage rising to the surface. However, if the ground water table is high or the flood is of long duration, this factor has little effect on substratum hydrostatic pressures. In general, piezometric data obtained during the 1950 high water indicated that ground water storage landward of the levees was filled by the time a high flood stage developed.

The critical gradient required to cause sand boils or heaving is estimated by Equation 2.1. Approximate theoretical critical gradients for silty sands and silts is approximately 0.85 and for silty clay and clay is 0.80 (Turnbull and Mansur, 1961). In the field, the critical gradient required to cause sand boils can best be determined by measuring the hydrostatic head beneath the top stratum at the time a sand boil starts. The critical gradient in the field is determined by

$$i_c = \frac{h_x}{z_t} \tag{2.5}$$

where h_x is the head beneath top stratum at distance x landward from landside toe of the levee, and z_t is the thickness of landside top stratum.

2.3.1 Field Observations of Underseepage and Sand Boils

Mansur, *et al.* (2000) reviewed studies carried out since the 1940's on underseepage, piping, and sand boil formation in the Mississippi River Valley. The Mississippi River floods of 1993 produced seepage under some levees which resulted in dramatic levee failures in the Kaskasia Island Levee District in Illinois (Mansur, *et al.*, 2000). A sand boil and subsurface piping caused the Kaskasia Island levee to fail, flooding the entire levee district.

According to witnesses, levee failures due to high water usually starts with sand boil occurrences near the toe of the levee, followed by overtopping. In some cases, the river does not rise above the top of the levee; rather, the levee fails, sinking below the prior river levee elevation. Much sand boil information is derived from observational data based on subjective descriptions by different people and usually does not represent observations made on a continual basis. Mansur *et al*. (2000) gathered sand boil information for seven levee districts after the 1993 high water. Uplift gradients calculated from existing piezometers showed that significant sand boils were observed when uplift gradients were in the range of 0.58 to 0.84.

Mr. Richard Meehan, instructor at Stanford University, California, with USACE background, worked on Feather River hydrographs at levee breaks. Levees near Marysville and Yuba City, California, failed in 1955, 1986, and 1997. The investigators compared the flood hydrographs. The 1955 and 1997 levee failures occurred at just about the time the river stage made its peak. In 1986, floodwaters began to recede, then failure occurred one day after the river stage made its peak. This investigation suggests that the pressures causing failure may lag behind the immediate flood pressures on the levee. For all the failures, the levees were not overtopped but sand boils had been observed at the toe of the levee before failure.

The Mississippi River floods of 1997 resulted in seepage under certain levees in Louisiana, especially those near Angola Prison. The levee at this location developed sand boils, leading to emergency repairs to prevent levee failure.

Li *et al*. (1996) studied widely reported sand boils north of Cairo, Illinois, where 4 m of head existed between the river and the landward ground surface in 1993. The researchers examined sand boils along the Mississippi River levee west of Ware, Illinois. Sand boils were abundant within 5 m of the levee toe, only small pin boils were observed at a distance of 100 m from the levee, and beyond 100 m, there was no significant evidence of surface seepage. Li *et al*. reported the sand boils had dimensions with 0.5 m to 10 m diameter, and they commonly extended 0.3 m above the ground surface. Mansur *et al*. (2000) reported the results of an underseepage and sand boil study after the 1993 high water. The dimensions of many sand boils were up to 30″ in diameter at Prairie DuPont and Ft. Chartres Levee Districts, Illinois. At the other regions of Mississippi River levees, many sand boils of 2″ to 12″ in diameter were observed. Another observation of sand boils was reported by the Corps of Engineers after 1997 high water. A sand boil with a throat of 0.45 m to 0.6 m (1.5 to 2.0 ft) in diameter was observed at about 60 m (200 ft) from the levee at Blue Lake, Arkansas. The uncontrolled flow resembled a large relief well and approximately 23 cu.m (30 cu.yd) of fine to medium sand was deposited.

The U.S. Army Corps of Engineers, New Orleans District Office, conducted a seepage study from Louisiana State University (LSU) to Duncan Point of Pontchartrain Levee District in 1992. This study references data back to a technical manual, TM 3-424 published by USACE in 1956. During the 1937 high water, improperly backfilled seismic shot holes near the LSU campus were attributed as being the cause for sand boils experienced. During the 1950 high water, excess hydrostatic pressures of 12.5 to 15 ft existed along the landside toe of the levee. This hydrostatic pressure corresponds to 75% to 90% of the crest head in the river. Excess heads of 10 to 12 ft were also observed as far as 0.75 mile (1.2 km) landward of the levee. During the 1950 high water, four fairly large sand boils were observed but according to the available records they were not at the same locations as the 1937 boils. During the 1973 high water, sand boils were observed at fairly large distances up to 2.4 km from the levee. In 1975, a sand boil nicknamed “Big Mamou” developed at about 1 mile (1.6 km) from the levee along the banks of Elbow

Bayou due to high water. During the 1983 high water, there was no flow from Big Mamou but a new sand boil developed about 200-ft (61 m) away from it. Again in 1983, a sand boil about 0.5 mile from the levee, which developed at LSU stadium parking lot, was flowing clear.

In 1992, the USACE noted that the studied regions of levees have a relatively thick soil blanket, which is sufficient to withstand high hydrostatic pressures. This fact explains the occurrence of high hydrostatic pressures and sand boils as far as a mile from the levee, where the soil blanket may be thinner. This study concluded that seepage prevention methods, such as seepage berms and relief wells, protect limited areas. Seepage berms may force seepage away from the levees, and relief wells along the landside toe of a levee only create a “dip” in the hydrostatic gradient line.

Recent observations were also conducted at LSU Dairy Farm in July 2002 by Dr. Dean Adrian, Professor, and Senda Ozkan and Curtis Sutherland, graduate students at LSU. A sand boil near a drainage channel was observed about 0.5 mile away from the Mississippi River levee. Apparently, soil under the sand boil was eroded, then discharged into the drainage channel next to the boil. The sand boil turned into a sinkhole (Figure 2.1). The dimensions of the sinkhole were about 4 ft deep, 6 ft wide and 10 ft long. According to the observations, as the water level in the river rose, there was bubbling water at the bottom of the hole, then the accumulated water in the hole drained to the drainage ditch. Later, the sand boil depression was repaired and a relief well was installed (Figure 2.2). It is interesting to note that there is a wastewater lagoon close to the sand boil. However, the water in the sand boil looked fresh and clean, suggesting no flow was leaking from the lagoon into the boil, but instead, water was seeping from the river.

Fig. 2.1 A sand boil turned into a sinkhole at LSU Dairy Farm (July 2002). The sinkhole had been filled before, but reformed after several years.

Fig. 2.2 A relief well was installed into the sinkhole at LSU Dairy Farm (August 2002).

2.3.2 Soil Properties Susceptible to Piping

Peter (1974) examined the conditions associated with piping phenomena in the subsoil, near levees in the Mississippi River region, and in the Danube River region in former Czechoslovakia, Hungary and Yugoslavia. The studies showed that the grain size distribution curves are one of the most appropriate aids for judging the danger of piping problems. From the coefficient of uniformity of the soil, C_u and the coefficient of curvature, C_c, the danger can be determined. The coefficient of uniformity and the coefficient of curvature are defined as:

$$C_u = \frac{d_{60}}{d_{10}} \tag{2.6}$$

$$C_c = \frac{{d_{30}}^2}{d_{10} d_{60}} \tag{2.7}$$

A geological condition favorable for the formation of piping is very permeable sandy gravel which has a substantial amount of fine particles, $d_{10} = 0.25$ mm, the coefficient of uniformity, $C_u > 20$, the coefficient of curvature, $C_c > 3$, and there is a lack of grains of size 0.5 to 2 mm. The pipings in the Danube River levees are connected with geologic conditions similar to those of pipings near the Mississippi River (Peter, 1974).

De Wit *et al.* (1981) conducted laboratory research on piping on a scale model with fine, medium and coarse sand. In general, they observed higher critical exit gradients for the coarser and the denser sand. They also found that when two sands are compared having the same grain size distribution curve, the sand with the higher angle of friction exhibits a higher critical gradient.

A grain-size analysis on one sand boil observed during Mississippi River Flood of 1993 showed that 98% by weight of eroded grains were smaller than 0.125 mm in diameter (Li *et al.*, 1993).

Sherard *et al.* (1972) studied piping in earth dams of dispersive clays. Some natural clay soils disperse in the presence of water and become highly susceptible to erosion and piping. The tendency of dispersive erosion in a given soil depends upon variables, such as mineralogy, chemistry of clay, and the amount of dissolved salts in the soil pore water and eroding water. The susceptibility of a fine grained soil to internal erosion increases with the tendency of its particles to disperse either spontaneously with the presence of water or under the drag force of seepage. Non-cohesive silt, rock flour, and very fine sands also disperse in water and may be highly erosive.

2.4 Geology of the Lower Mississippi River Valley and Its Influence on Underseepage

The U.S. Army Corps of Engineer conducted investigations of the geologic conditions of Lower Mississippi River Valley in 1940's. Geological studies at several sites along the Mississippi River levees showed that there were significant correlations between the distribution of alluvial deposits of sand, silt and clay, and the occurrence of underseepage and sand boils (Turnbull and Mansur, 1961; Kolb, 1973). The Alluvial Valley of Lower Mississippi is about 500 miles long and 50 miles wide on average. The valley begins at the confluence of the Mississippi and Ohio rivers at Cairo, Illinois, and extends to the Gulf of Mexico. The alluvial deposits in the Lower Mississippi River Valley fill a trench ranging in the depth from 100 ft to 400 ft. The alluvial fill was formed about 30,000 years ago, when the glaciers of late Wisconsin stage began to melt, the sea level gradually rose causing the entrenched valley to become filled with sandy gravels, sands, silts and clays that can be grouped as a sand and gravel substratum and a fine-grained top stratum. Turnbull and Mansur (1961) presented an illustration of the entrenched valley and alluvial fill as in Fig. 2.3.

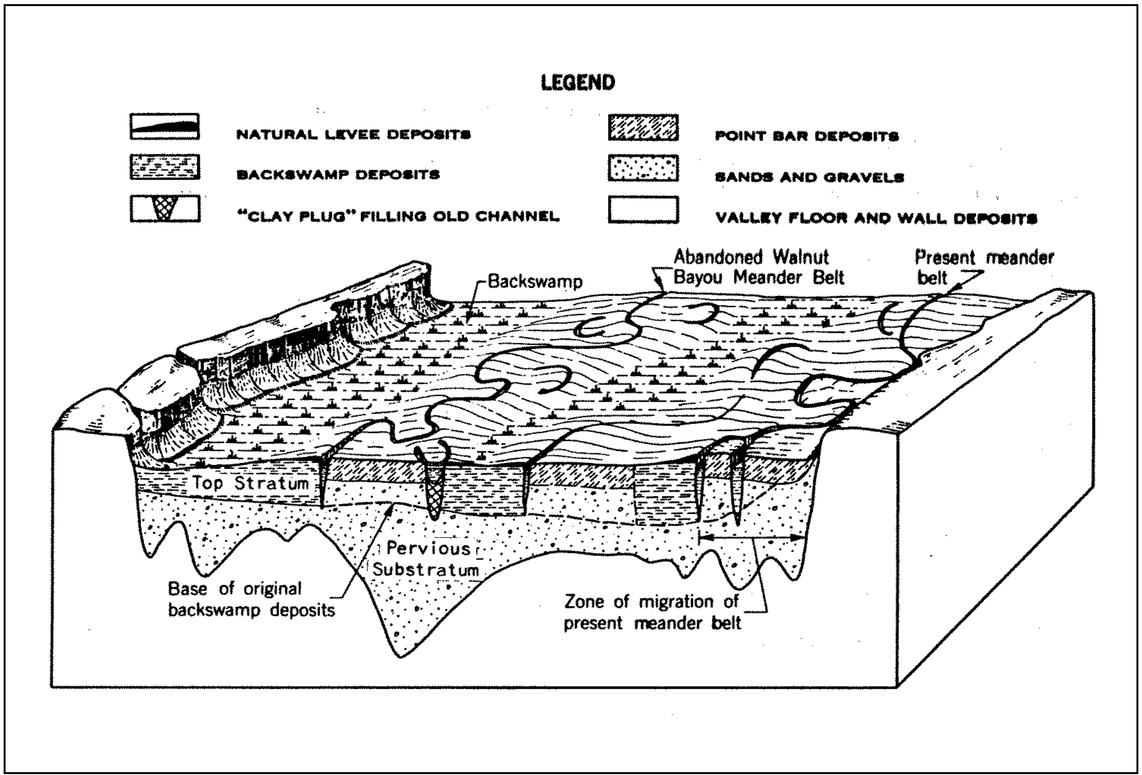


Fig. 2.3 Block diagram of Alluvial Valley of the Lower Mississippi River. The section is at about latitude of Natchez, MS (Turnbull and Mansur, 1961).

The gravel and coarse sand to fine sand substratum has a high seepage carrying capacity. The top of the pervious substratum is considered to be the uppermost portion of the aquifer having a $d_{10} > 0.15$ mm or a hydraulic conductivity of $k > 0.05$ cm/sec. The bottom of the substratum or alluvial valley is taken as the contact between the sand and gravel substratum and the underlying rock. The thickness of sandy alluvium ranges from 75 ft to 150 ft. In design computations, the average hydraulic conductivity of the sandy alluvium was taken as 0.1 cm/sec based on laboratory tests in the 1950's. After relief wells were installed this value was found to be around 0.15 cm/sec (Turnbull and

Mansur, 1961). The top stratum usually consists of several layers of clay, sandy silt and silty sand layers. About 6000 years ago, the sea level reached its present position, rapid filling of the entrenched valley ceased, and the former braided channel was replaced by a meandering stream that deposited sediments including point bar, channel fill, natural levee, and backswamp deposits. The point bar deposits are fine grained deposits with a thickness of 10 ft to 20 ft; the channel fill deposits are relatively impermeable silts and clays with a 55 ft to 125 ft depth; the natural levees are sandy silt and silty clays with a 5 ft to 10 ft depth in the Lower Mississippi Valley. The backswamp deposits are silts and clays with 15 ft to 70 ft depth in southern Louisiana.

Sand boil formation at the landside of a levee is influenced by a number of factors, including: (i) configurations of geological features such as swales and channel fillings and their alignment relative to the levee; (ii) characteristics and thickness of the top stratum; (iii) man made works such as borrow pits, post holes, seismic shot holes, and ditches; (iv) cracks and fissures formed by drying and other natural causes; and (v) organic agencies, such as decay of roots, uprooting of trees, animal burrows, and holes dug by crawfish. In general, the seepage is greatly concentrated along the edges of swales and the landside levee toe (Turnbull and Mansur, 1961; Cunny, 1980).

Kolb (1976) studied underseepage data collected by the USACE Vicksburg District during the 1973 flood along a randomly selected 40-mile stretch of river. He noted that point bar deposits are thin enough and permeable enough to cause underseepage problems. During the 1973 flood, significant underseepage was confined almost entirely to areas where point bar deposits underlie the levee. He presented several alignments of geological features beneath the levees and showed the concentrated sand boils reported at those areas. Figure 2.4 shows how clay channel fillings and swales can cross beneath levees at an acute angle; sand boils tend to form in point bar deposits within the angle between these layers. A borrow pit at the riverside of the levee is important in initiating and increasing underseepage in Fig. 2.4. Expanded section A-A′ shows a semi-pervious natural levee deposit lying between the backswamp clays and the artificial levee where seepage may occur in the extreme landward portions of the natural levee and in old natural levee crevasses backfilled with sand (Kolb, 1976). Borrow pits on the riverside of the levee that have had their impervious top stratum removed may accelerate the problem in this figure. Where swales and channel fill clays cross beneath the levees at approximately right angles (Fig. 2.5), the sand boils are randomly dispersed and not as frequent and severe as when there is an acute angle between the levee and clay bodies. Note also that an oxbow lake partially filling an abandoned channel is an important source for seepage in Fig. 2.5. Kolb (1976) also pointed out a case where drainage ditches penetrating fairly permeable materials on the landside of the levees may cause heavy seepage and sand boil formation (Fig. 2.6).

In the conclusion of his work, Kolb (1976) stated that the disposition of pervious versus impervious floodplain deposits beneath the levee and the angle at which such deposits are crossed by the overlying levees controls the position of sand boils. He also suggested that corrective design of levees should include: (1) a detailed delineation of the surface and subsurface geology; (2) a careful selection of borrow pits to avoid stripping critically thin top-stratum deposits; and (3) the use of riverside or landside berms or blankets, and/or installation of relief wells.

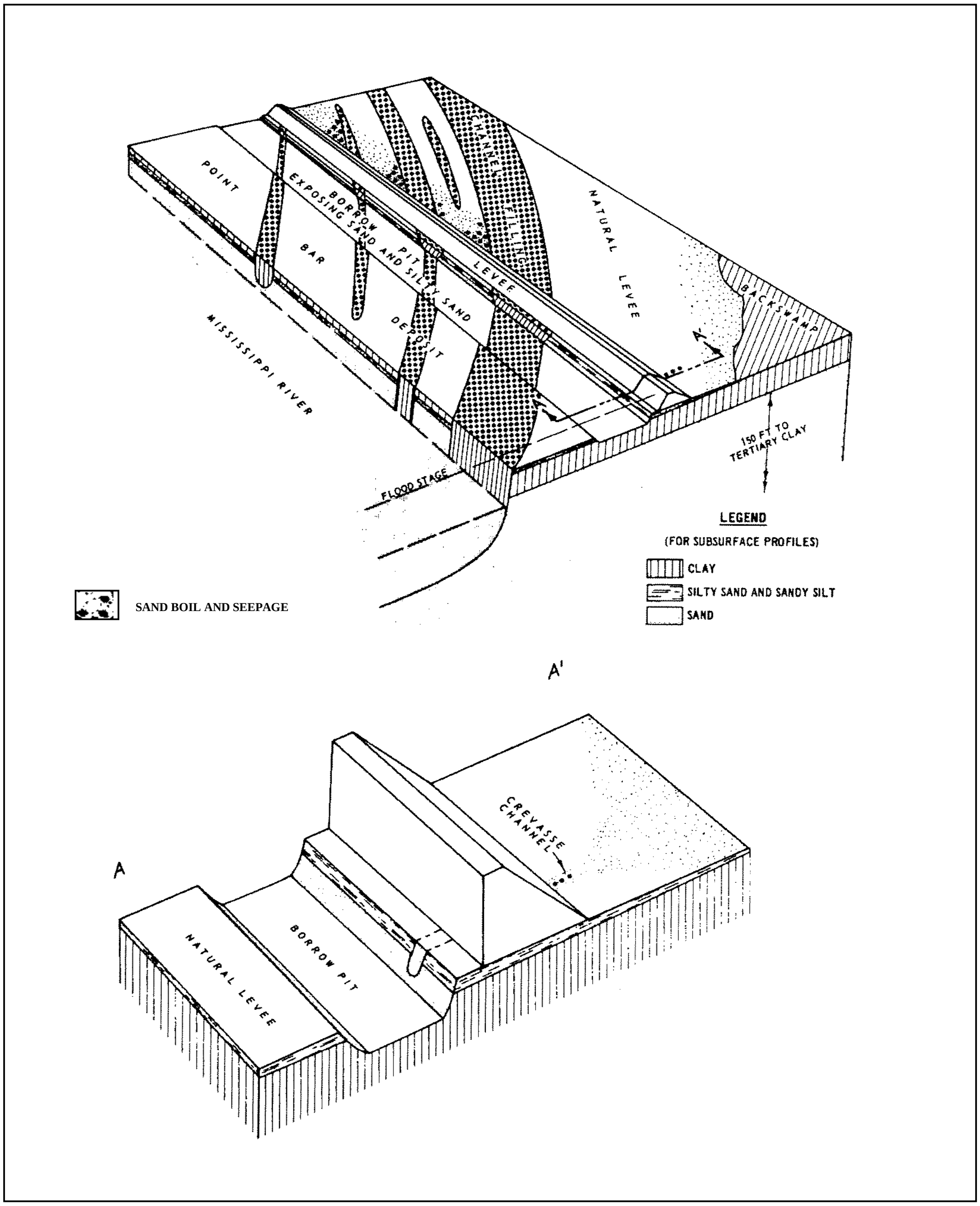


Fig. 2.4 Clay channel fillings and swales crossing beneath levees at an angle (Kolb, 1976).

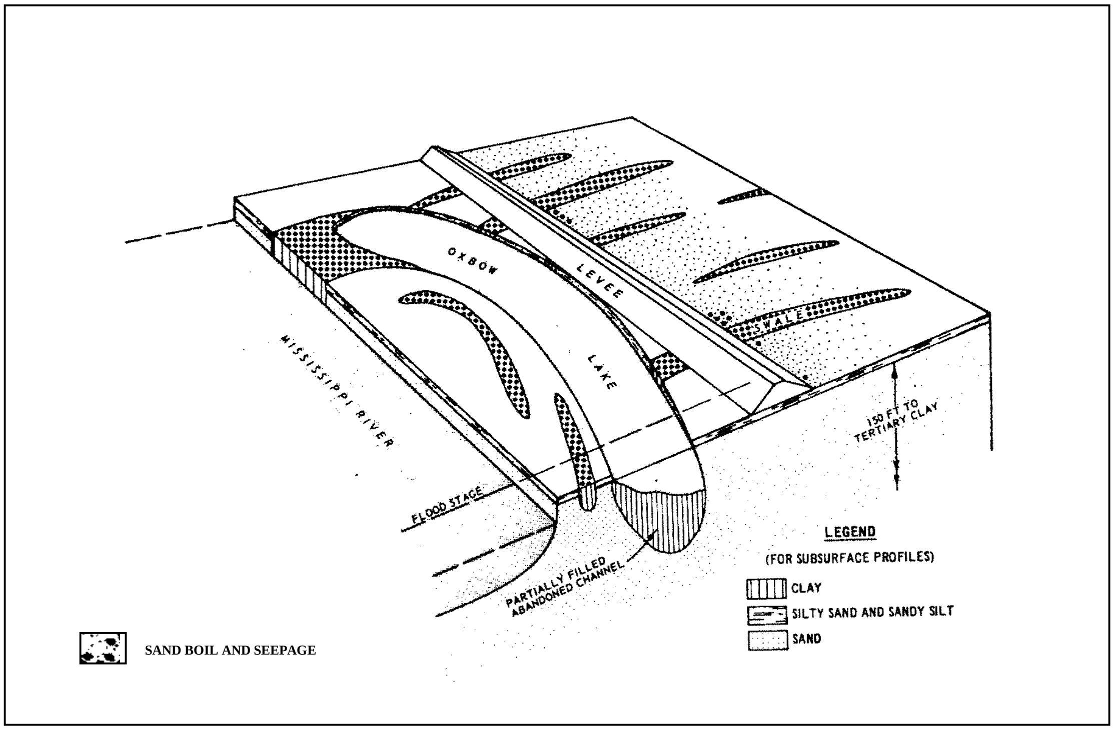


Fig. 2.5 Swales and channel fill clays cross beneath the levees at more or less right angles (Kolb, 1976).

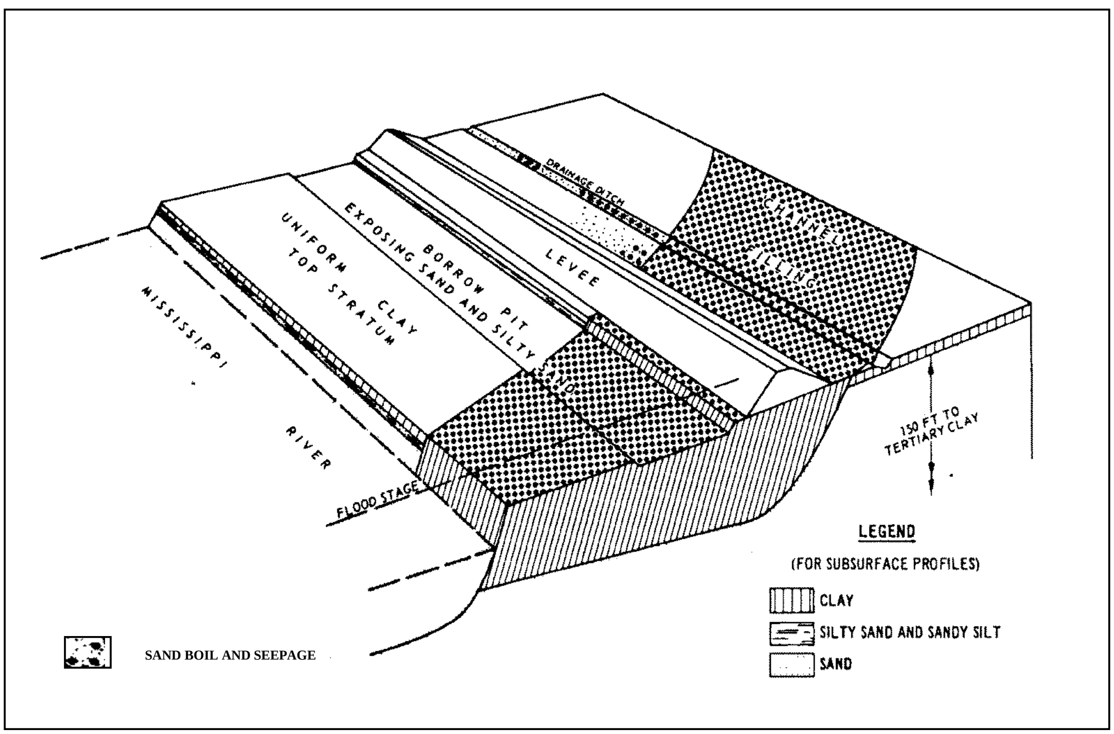


Fig. 2.6 Drainage ditch penetrating fairly permeable materials on the landside of the levee (Kolb, 1976).

2.5 Previous Studies on Levee Underseepage Conducted by USACE

The first investigation of potential levee underseepage was initiated by the USACE Mississippi River Commission in 1937 in response to problems caused by high water conditions. More detailed study was carried out by the USACE Waterways Experiment Station (WES), Vicksburg, MS in the 1940's. Procedures to evaluate the quantity of underseepage, uplift pressures and hydraulic gradients were developed based on closed-form solutions for differential equations of seepage flow presented by Bennett (1946). In 1956, a technical memorandum, TM 3-424 was published by the USACE Waterways Experiment Station documenting the analysis of underseepage and design of control measures for Lower Mississippi Valley levees (Mansur *et al.* 1956). In this document, the top stratum landside of levees is classified into one of three categories: (1) no top stratum; (2) top stratum of insufficient thickness to resist hydrostatic pressures that can develop; and (3) top stratum of sufficient thickness to resist hydrostatic pressures that can develop during the maximum design flood. Kolb (1976) discussed underseepage data collected by USACE Vicksburg District along a randomly selected 40-mile reach of the river during the 1973 flood. He pointed out the most dangerous top stratum category as the second category listed by Mansur *et al*., 1956. In this category, artesian pressures can build up beneath the top stratum landside of the levee to a range of 25% to 75% of the net head on the levee, and may extend significant distances landward of a levee.

Mansur *et al.* (1956) classified seepage as heavy, medium and light. Turnbull and Mansur (1961) presented seepage conditions and upward gradients through the top stratum measured by piezometers during the 1950 high water (Table 2.1). During the high water of 1950, sand boils were observed in a hydraulic gradient range of 0.5 to 0.8. In developing these seepage conditions, sites were eliminated where the top stratum thickness was less than 5 ft or greater than 15 ft (Technical Letter, ETL 1110-2-555, 1997).

Table 2.1 Seepage Conditions and Exit Gradients During the 1950 High Water (Turnbull and Mansur, 1961).

Seepage Condition	Amount of Seepage (Q/H)	Exit Gradient
Light to no seepage	< 5 gal/min/100 ft of levee	0-0.5
Medium seepage	5 - 10 gal/min/100 ft of levee	0.2-0.6
Heavy seepage	> 10 gal/min/100 ft of levee	0.4-0.7

Turnbull and Mansur (1961) summarized the design and analysis procedure of levees presented in TM 3-424. Department of Army published in 1978 (and updated in 2000) an Engineer Manual (EM) 1110-2-1913 “Design and Construction of Levees”. Other than advanced numerical modeling, this Engineer Manual represents the state-of-practice analysis method for evaluating hydraulic gradient due to levee underseepage (Gabr *et al*., 1996).

The Army Corps of Engineers investigated possible remedial measures to underseepage problems, which are discussed below. The most common underseepage control measures include pressure relief wells, landside seepage berms, riverside blankets, drainage blankets or trenches, cutoffs, and sublevees. Muskat (1937) presented a design methodology for relief wells. Middlebrooks and Jervis (1947) revised Muskat’s method to include partial penetration of the relief wells. Barron (1948) presented a design methodology for fully penetrating relief wells. The Department of the Army published Engineer Manual (EM) 1110-2-1905 “Design of Finite Relief Well Systems” in 1963 and EM 1110-2-1914 “Design, Construction, and Maintenance of Relief Wells” in 1992. Mansur *et al*. (1956) stated that pressure relief wells, riverside blankets, and landside seepage berms are generally applicable for Mississippi River levees. Sublevees and drainage blankets or trenches are applicable in certain special situations.

Wolff (1974) and the U.S. Army Engineer District, St. Louis (1976) studied the performance of 200+ mile levee system along the middle Mississippi River from Alton to Gale (Fig. 2.7).

It was reported that the use of the Corps method outlined in Engineer Manual (EM) 1110-2-1913 resulted in a reliable design of levees. It was also concluded that the existing procedure has deficiencies in characterization of a two layer subsurface profile and the inability to model levee bends at corners. Cunny (1980) summarized piezometer data for levees in the Rock Island District, Illinois. Cunny reported that the probability of sand boil occurrence increases with geologic discontinuities. Daniel (1985) reviewed Cunny's report and the other Rock Island data and found that sand boils were observed at gradients ranging from 0.54 to 1.02. A similar statement was also reported earlier in TM 3-424.

Wolff (1987) studied the application of numerical methods to levee underseepage analysis and pointed out the advantages of special purpose computer programs over traditional underseepage analysis and general-purpose numerical analysis programs. Wolff (1989) developed the computer program LEVEEMSU for analysis of levee underseepage. LEVEEMSU was also used to analyze actual data at a number of levee reaches and back-calculate field permeability values. Cunny *et al.* (1989) also developed a computer program, LEVSEEP, to perform regular underseepage analysis outlined in EM 1110-2-1913, TM 3-424, EM 1110-2-1602, as well as to calculate reduced seepage quantities with the choice of control measures including seepage berms, riverside blankets, cutoffs and relief wells. Later, Wolff and Taylor (1991) extended LEVEEMSU to analyze three-layer irregular foundation cases.

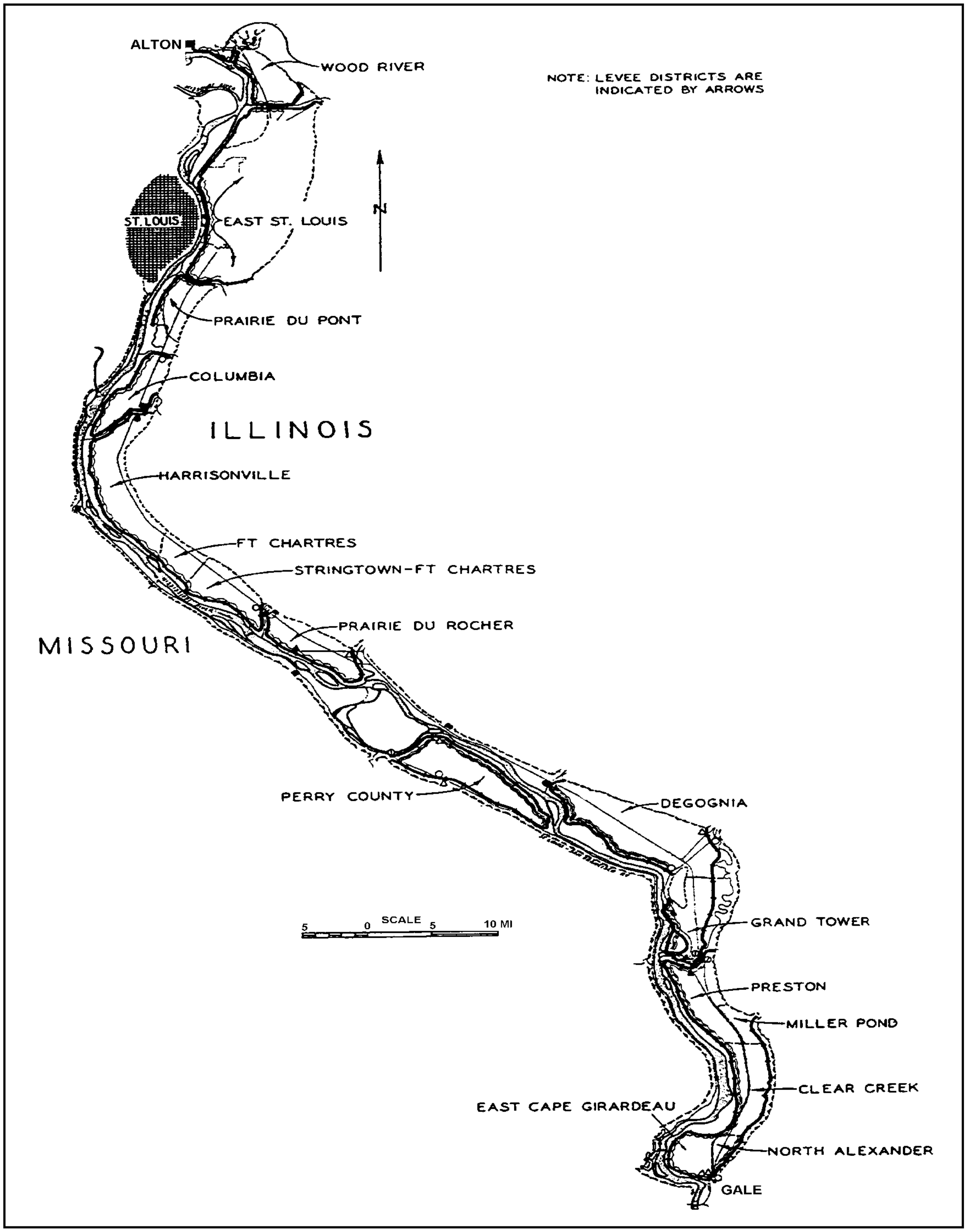


Fig. 2.7 Plan of Levees Along Mississippi River, Alton to Gale, Illinois (after Mansur *et al*., 2000).

2.5 Current Underseepage Analysis Methods

In general, approximate methods of solution to confined flow problems include sketching flow nets, electrical analogs, method of fragments (Harr, 1962), viscous flow models such as Hele-Shaw models, relaxation methods (numerical analysis), and small-scale laboratory models. Advanced numerical modeling and 2-D finite element analysis programs provide sophisticated analysis of seepage flow. Boundary fitted coordinate methods also show promise as a method of analyzing seepage flow problems (Thompson *et al.* 1977; Thompson and Warsi, 1982; Thompson *et al.* 1985, and Hartono, 2002).

The transient effects in seepage have been studied under conditions of partial saturation (EM 1110-2-1901, Seepage Analysis and Control for Dams). The flow in partially or unsaturated soils is considered in a transient state. Therefore, transient effects in seepage are normally studied as the migration of a wetting front into unsaturated soils and variations in hydraulic conductivity according to soil water retention curves. Viscous flow models have been used to study transient flow (EM 1110-2-1901). A viscous flow model was constructed at USACE Waterways Experiment Station (WES) to simulate seepage conditions induced in streambanks by sudden drawdowns of the river level. The results from the model study were compared with field observations, finite difference, and finite element methods (Desai 1970, Desai 1973). Two and three-dimensional finite element seepage computer programs for confined and unconfined flow problems were developed at WES. Steady-state and transient problems can be solved with these computer programs (Tracy 1973a, Tracy 1973b). Transient problems can be treated as a series of steady-state problems. The studies lead by USACE formed a basis for further development of commonly used finite element seepage programs. GMS/SEEP2D is a 2D finite element model that can be used to model steady-state confined, partially confined and unconfined flow. Another finite element seepage analysis program, SEEP/W performs transient seepage analysis considering hydraulic conductivity and water content changes as a function of pore water pressure. Complex geometries, non-homogenous, and anisotropic soil features can be modeled by these finite element models.

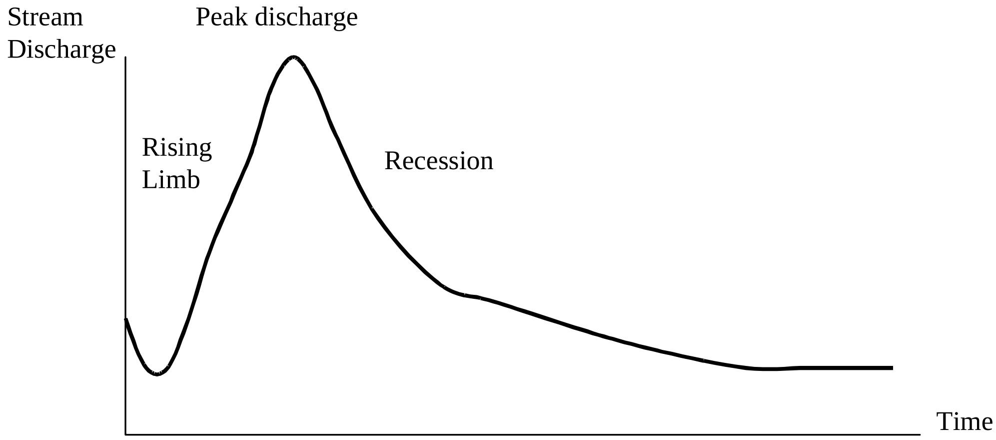
For seepage analysis under levees, U.S. Army Corps of Engineers, Design Guidance on Levees, EM 1110-2-1913, recommends use of numerical analysis models such as LEVSEEP and LEVEEMSU or finite element methods such as CSEEP which include two-layer or three-layer subsurface characterization (ETL 1110-2-555, 1997). The computer program LEVSEEP is based on the modeling of the steady-state flow domain with Bennett's (1946) analytical solutions for underseepage and the method of fragments for cutoff analyses. LEVSEEP provides similar analysis with the hand methods of analysis outlined in EM 1110-2-1913, EM 1110-2-1602, and TM 3-424 (Brizendine *et al*. 1995). LEVEEMSU is based on one-dimensional simplification of the steady-state flow domain using the finite difference method. LEVEEMSU solves Bennett's (1946) differential equation for irregular foundation geometry and non-uniform soil properties.

2.6 Analytical Studies on Transient Flow

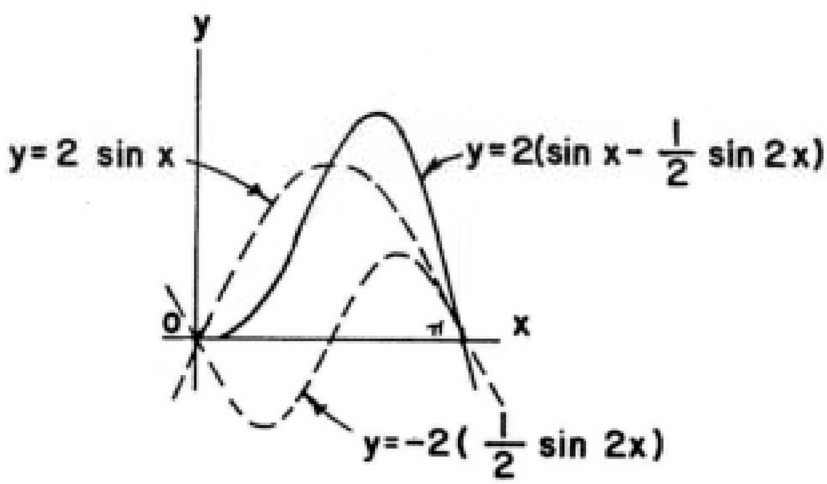
Cyclical boundary conditions represented by sinusoidal head functions represent one type of transient flow. The head profiles are described by the terms steady-state, quasi steady-state and unsteady state. The steady-state case represents the situation where there is no change in head profile with time. If the head profile is not steady-state, the alternative is the unsteady-state case. However, in engineering literature, quasi steady-state is a term used to describe the unsteady-state head profile that is generated with a cyclical boundary condition as time goes to infinity. Quasi steady-state is reached with a cyclical boundary condition when the head profile replicates itself within an acceptable error tolerance with the frequency of cyclical head. Yu *et al.* (1991) used the term "memory time" and "memory length" to describe the time when the quasi steady-state condition exists at a certain location, and the distance from the boundary where the quasi steady-state profile is applicable at a certain time.

Water-level fluctuations in wells can be affected by such natural loading events as earthquakes, ocean and earth tides, changes in river stage, and atmospheric pressure (Domenico and Schwartz, 1998). These fluctuations are evidence that confined aquifers are not rigid bodies but that they respond to small changes in stress by being elastically compressible (Meinzer, 1928 ; Jacob, 1940). There are many examples of the response of water levels to natural events, such as the inland propagation of sinusoidal fluctuations of ground-water levels in response to tidal fluctuations of a simple harmonic motion (Ferris, 1951; Werner and Noren, 1951), and change in head in response to change in river stage (Cooper and Rorabaugh, 1963). These earlier studies of progressive waves in confined and unconfined aquifers caused by cyclical changes in river stage provide insight into solution of one-dimensional diffusion-type equations subject to sinusoidally varying boundary conditions.

A typical hydrograph can be simulated by superposition of a series of sinusoidal fluctuations as shown in Fig. 2.8 (Singh, 1992). Superposition of more than two sinusoidal fluctuations can model more complex hydrograph shapes, and a Fourier series made up of an infinite series of sine and cosine functions can model any smooth function Farlow, 1982).



A Typical Hydrograph (Source: Singh, V. (1992) Elementary Hydrology, Prentice-Hall, Inc.)



(Source: Kirkham D., and Powers W.L. (1972) Advanced Soil Physics, John Wiley and Sons, Inc.)

Fig. 2.8 Simulation of a typical hydrograph with a series of sinusoidal fluctuations.

An idealized flow domain to analyze the transient effects of flood waves on groundwater flow is shown in Fig. 2.9. The aquifer is represented as a semi-infinite, horizontal confined aquifer of uniform thickness bounded on the left by an open boundary. In this case, the open boundary is a river. The water level in the river fluctuates and causes corresponding head fluctuations within the aquifer. From an analysis of aquifer response to the river fluctuations, transmissivity and storage coefficient of the aquifer can be estimated.

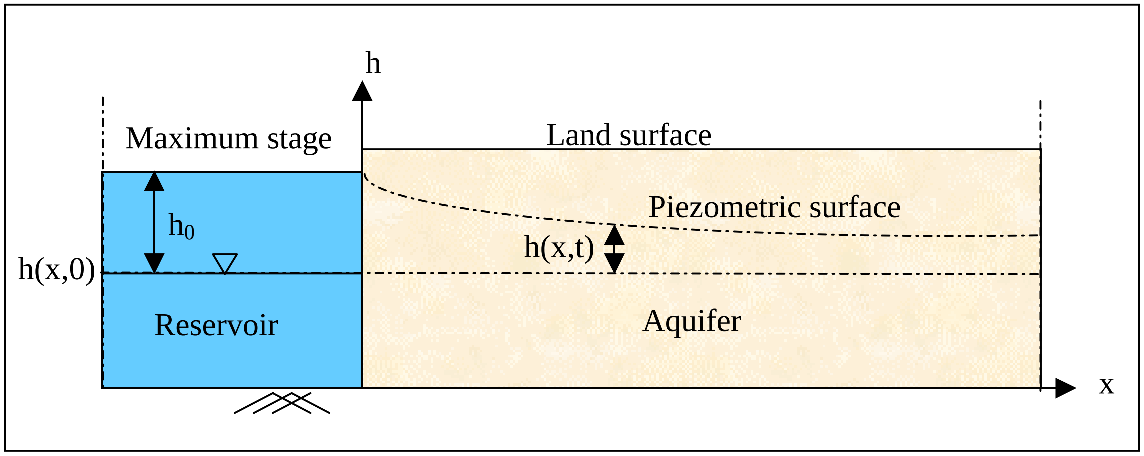


Fig. 2.9 Representation of simplified one-dimensional flow as a function of surface-water stage (source: USACE, EM 1110-2-1421).

One-dimensional flow is described in many textbooks by the equation for linear, non-steady flow in a confined aquifer:

$$\frac{\partial h}{\partial t} = \frac{T}{S}\frac{\partial^2 h}{\partial x^2} \tag{2.8}$$

where h is the rise or fall of hydraulic head in the aquifer, x is the distance from aquifer-river intersection, t is time, T is aquifer transmissivity, and S is aquifer storage coefficient. The solution of Equation 2.8 subject to a fluctuating boundary condition was presented by Ferris 1951; Cooper and Rorabough 1963; Pinder *et al.* 1969; and Hall and Moench 1972. Ferris (1951) observed that wells near bodies of tidal water often show sinusoidal fluctuations of water level in response to periodic changes in water stage. He presented a quasi steady-state solution to the problem. He also presented expressions to determine aquifer diffusivity (T/S) based on the observed values of amplitude, lag, velocity, and wavelength of the sinusoidal changes in groundwater level. If the time lag between surface and groundwater maximum and minimum stages is known then aquifer diffusivity can be estimated by using the following formula (Engineer Manual, EM 1110-2-1421, Equation 6-9)

$$t_{lag} = d\sqrt{\frac{PS}{4\pi T}} \tag{2.9}$$

where t_{lag} is the lag time in occurrence of maximum groundwater stage following the occurrence of a similar surface stage, d is the distance from an observation well to the surface water, and P is the period of uniform tide or stage fluctuations.

Cooper and Rorabough (1963) presented a solution of Equation 2.8 for a single sinusoidal pulse of general form $1\text{-}cos\,\omega t$, where ω is the frequency. Pinder *et al.* (1969) developed solutions to the governing equation using discrete steps approximation to fluctuations in the reservoir boundary. Hall and Moench (1972) applied a convolution equation to find head fluctuations in the aquifer due to an arbitrarily varying flood pulse. They derived equations for the instantaneous unit impulse response function, the unit step response function, and the derivative of unit step response function for finite and semi-finite aquifers, with or without semi-pervious stream banks.

More recently, Moench and Barlow (2000) presented Laplace transform step-response functions for various homogenous confined and leaky aquifer types and for anisotropic, homogenous unconfined aquifers interacting with perennial streams. They inverted the Laplace transform solutions numerically to obtain the real-time step-response functions for use in the convolution integral. Barlow *et al.* (2000) developed two computer programs on the basis of their real-time step-response functions presented in their companion paper of Moench and Barlow (2000). They used computer programs they developed to simulate the responses of hypothetical confined and water-table aquifers to sinusoidal-type flood waves.

As shapes of the stage hydrographs for flood waves vary, a solution of the governing equation with a boundary condition described by a uniform sine wave does not describe the actual domain adequately (Engineer Manual, EM 1110-2-1421). The discrete steps approach is not restricted to fluctuation of sinusoidal or uniform asymmetric curves and allows the use of a stage hydrograph of any shape. An alternative approach for representing the flood wave boundary has been shown in Figure 2.8.

Another application of cyclical boundary conditions in analytical solutions are the studies on tracer transport models in soils and contaminant transport in rivers. Logan *et al.* (1996) studied a one-dimensional model of transport of a chemical tracer in porous media with periodic Dirichlet and periodic flux type boundary conditions. Alshawabkeh and Adrian (1997) studied pollutant transport in a river subject to a sinusoidally varying boundary condition. They applied complex variables and the Laplace transform method to solve for the pollutant concentration distribution. Oppenheimer *et al*. (1999) proved that an unsteady-state solution approaches to the quasi steady-state solution with time. Adrian *et al.* (2001) developed a tracer transport model in a soil column with a periodic loading function, which varies as a sinusoidal curve. They solved the governing equation by applying superposition, Laplace transform and convolution integral, and introduced complex variables to evaluate the convolution integral.

2.8 Cumulative Effects

Cumulative effects of seepage under levees can compromise levee safety. A stratum of sands under seepage flow begins to heave at a particular value of seepage. This heave is related to the size, velocity, and amount of particles that wash away (Peter, 1982). The deformation due to heave may be reversible; however, complete recovery of this expansion is unlikely. When the same stratum of sands is exposed to a subsequent flood, movement of fine particles is expected to be more severe than it was during a previous flood. Besides when piping is localized at the landside levee toe, even if there is no external evidence of a sand boil, there are few if any mechanisms which would bring about healing of a pipe located immediately below a rigid, non-deforming levee. Peter (1982) also noted another serious problem that can contribute to cumulative effects. As the river level drops, the seepage water that had been on the landside may flow back from its former discharging point toward the river leading to backward erosion which may promote development of a pipe on the riverside of the levee. This erosion gradually enlarges and shortens the seepage channel and may cause additional cumulative changes leading to enlargement and lengthening of the internal pipe. Figure 2.10 shows the mechanisms related to the cumulative effects in which backward erosion takes place.

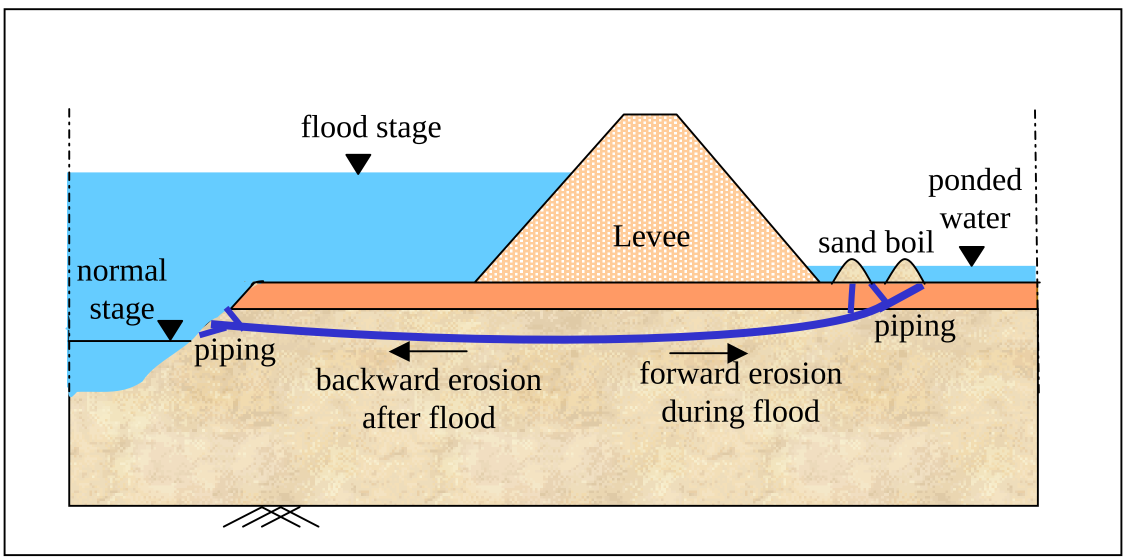


Fig. 2.10 A schematic diagram of underseepage mechanisms that contribute to cumulative effects both during a flood and immediately after a flood.

Although there is no reported study emphasizing the cumulative effects in underseepage problems of levees, Turnbull and Mansur's study in 1961 implies the existence of cumulative effects. During the 1950 high water, upward gradients through the top stratum at some control sites were measured by piezometers. The gradient required to cause sand boils varied considerably at the different sites, possibly because at sites where sand boils had developed previously only fairly low excess heads may have been needed to reactivate these boils in 1950. At sites where no sand boils had occurred in the past, higher gradients may have been required to initiate formation of the boils (Turnbull and Mansur, 1961). They also suggested that pressure relief resulting from the boil might have lowered piezometer readings in the area (Wolff, 2002). Currently, USACE Engineer Research and Development Center (ERDC) in Vicksburg, MS is working on research on cumulative effects of piping under levees as part of the Innovative Flood Damage Research Program (IFDR) sponsored by USACE (Wolff, 2002).

2.9 Summary and Concluding Remarks

In the literature, seepage under levees associated with sand boils has been studied in detail. Qualitative and quantitative models exist to describe the mechanisms of seepage erosion. Geology of Lower Mississippi River Valley has also been well explored. Engineers should consider the complex geology in design of levees and underseepage analysis. As in all civil engineering problems, appropriate assumptions are required to solve confined flow problems. Overall, a variety of tools, design manuals, specifications and guidelines are successfully in use to perform a seepage analysis for levees. However, the literature depicts that transient flow conditions associated with sand boil problems have not been studied in detail in levee underseepage analysis.

As presented in Section 2.6, there are numerous analytical studies on transient flow and a variety of solution methods to the general one-dimensional flow equation (Equation 2.8) subject to fluctuating boundary conditions. However, there is relatively little information on relating these transient flow models to critical hydraulic gradients and sand boil formation. In addition, as noted before, there is almost no information on the cumulative effects of seepage under levees and its relationship to piping.

Overall, the background and literature review presented in this chapter implies that the objectives set in this dissertation are important research topics. Successful completion of the research work would bring a new perspective to the problem.

2.10 List of Symbols and Acronyms

C = creep coefficient (dimensionless)

C_c = coefficient of curvature (dimensionless)

C_u = uniformity coefficient (dimensionless)

C_W = weighted creep ratio (dimensionless)

d = distance (L)

d_{10} = grain diameter corresponding to 10% finer in grain size distribution curve (L)

d_{30} = grain diameter corresponding to 30% finer in grain size distribution curve (L)

d_{50} = grain diameter corresponding to 50% finer in grain size distribution curve (L)

d_{60} = grain diameter corresponding to 60% finer in grain size distribution curve (L)

e = void ratio of soil (dimensionless)

γ_{sub} = submerged unit weight of soil (WL^{-3})

γ_w = unit weight of water (WL^{-3})

G_s = specific gravity of soil (dimensionless)

h = hydraulic head (L)

h = total head loss (L)

h_x = head beneath top stratum at distance x from landside toe of the levee (L)

i_c = critical hydraulic gradient (dimensionless)

k_0 = initial intrinsic permeability (L^2)

L = length of seepage path (L)

L_h = distance along horizontal contacts (L)

L_V = distance along vertical contacts (L)

n_0 = initial porosity of soil (dimensionless)

P = period of uniform fluctuations (T)

S = aquifer storativity (dimensionless)

t = time (T)

t_{lag} = time lag (T)

T = aquifer transmissivity (LT^{-2})

τ_c = critical tractive shear stress ($MT^{-2}L^{-1}$)

x = horizontal coordinate (L)

z_t = thickness of landside top stratum

EM = Engineer Manual

ERDC = Engineer Research and Development Center

ETL = Engineer Technical Letter

GMS = Groundwater Modeling System

IFDR = Innovative Flood Damage Research Program

USACE = United States Army Corps of Engineers

WES = Waterways Experiment Station

TM = Technical Manual

CHAPTER 3 TRANSIENT FLOW MODEL IN A CONFINED AQUIFER

3.1 Introduction

The objective of this chapter was to develop analytical models that describe the hydraulic head in a confined aquifer on the landside of a levee system during the rising limb of a flood wave. One-dimensional linear-laminar saturated flow conditions in a homogenous, isotropic confined aquifer were studied. The top stratum is assumed as impervious. The models used a sinusoidally varying boundary condition to simulate the effects of the rising river stage. In these models, the governing equation is the diffusion equation that was developed under Darcy's law, and the law of conservation of mass (Freeze and Cherry, 1979). Darcy's law is valid as long as the Reynolds number based on grain diameter does not exceed some value between 1 to 10 (Bear, 1972).

Two solutions were presented. Section 3.2 details the development of the transient flow model by the Laplace transform method. Section 3.3 presents an approximate solution to the same problem. The analyses were extended to falling limb of a flood wave due to the fact that some field observations indicated critical situations during falling river stages (Section 2.3.1).

3.2 Analytical Modeling of Transient Hydraulic Head in a Confined Aquifer by Laplace Transform Method

A schematic view of the model is shown in Fig. 3.1. The governing equation for a one-dimensional model of transient seepage through a confined aquifer is known as the diffusion equation (Freeze and Cherry, 1979)

$$\frac{\partial h_1}{\partial t} = \frac{T}{S}\frac{\partial^2 h_1}{\partial x^2} \tag{3.1}$$

where h_1 is the hydraulic head (L), T is the transmissivity (L^2/T), t is time (T), S is the storativity, which is dimensionless and x is the distance from the entrance to the confined aquifer (L). The initial head at time t = 0 is 0, assuming mean low river level is well below the origin which is the most common case. During high water, an initial head of H_0 is developed. During the flood, fluctuation of this head is typical and defined as $H_1 sin(\omega t)$ in the analysis. Another boundary condition is the head h = 0 when x approaches infinity, which represents no influence of head far landward. Therefore, initial and boundary conditions are selected as

$$h_1(x,0) = 0 \tag{3.2}$$

$$h_1(0,t) = H_0 + H_1 \sin(\omega t) \tag{3.3}$$

$$\lim_{x\to\infty} h_1(x,t) \to 0 \tag{3.4}$$

where H_0 is the initial hydraulic head applied to the aquifer, H_1 is the amplitude of the variation from the initial hydraulic head and ω is the frequency of the flood wave. To make the problem realistic H_o and H_1 are positive or zero with the constraint that $H_o \geq H_1$.

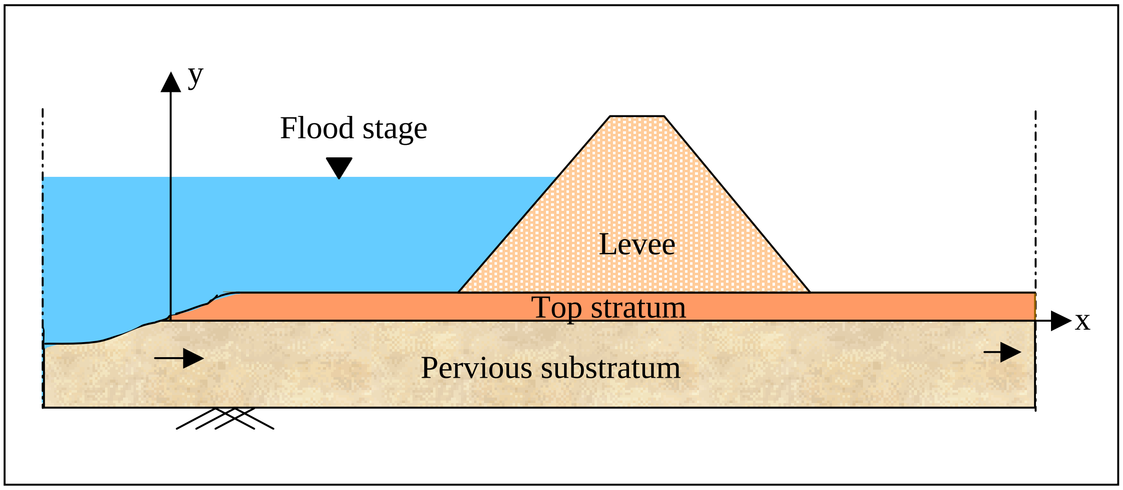


Fig. 3.1 Schematic view of confined flow under a levee.

The approach in setting up the governing equations is similar to the approach followed by Ozisik (1968) and Alshawabkeh and Adrian (1997). We define a new problem with dependent variable $h_2(x, t)$ that is identical to Equations 3.1, 3.2, and 3.4 but the boundary condition is

$$h_2(0,t) = H_0 + H_1 \cos(\omega t) \tag{3.5}$$

Each term in the first problem is multiplied by the complex number *i* and is added to the second problem. Then, a new complex variable is introduced

$$h(x,t) = h_2(x,t) + ih_1(x,t) \tag{3.6}$$

where $h_1(x,t)$, the imaginary part of solution, satisfies the original problem Equations 3.1 to 3.4, and $h_2(x,t)$, the real part of the solution, satisfies the original problem with the boundary condition (Equation 3.3 changed to Equation 3.5).

The governing equation for the complex transient seepage becomes

$$\frac{\partial h}{\partial t} = \frac{T}{S}\frac{\partial^2 h}{\partial x^2} \tag{3.7}$$

$$h(x,0) = 0 \tag{3.8}$$

$$h(0,t) = (1+i)H_0 + H_1 \exp(i\omega t) \tag{3.9}$$

$$\lim_{x\to\infty} h(x,t) \to 0 \tag{3.10}$$

In Equation 3.9, Euler's relationship was used

$$\exp(i\omega t) = \cos(\omega t) + i\sin(\omega t) \tag{3.11}$$

The Laplace transform is applied to Equations 3.7 to 3.10 yielding

$$\frac{d^2\overline{H}}{dx^2} - \frac{pS}{T}\overline{H} = 0 \tag{3.12}$$

$$\overline{H}(0) = \frac{1+i}{p} H_0 + \frac{H_1}{p - i\omega} \tag{3.13}$$

$$\lim_{x \to \infty} \overline{H}(x) \to 0 \tag{3.14}$$

where the term $\overline{H}(x)$ is the Laplace transform of *h(x,t)* and *p* is the parameter in the transform. The solution to the Equation 3.12 subject to Equations 3.13 and 3.14 is

$$\overline{H}(x) = \left(\frac{1+i}{p} H_0 + \frac{H_1}{p - i\omega} \right) \exp\left(-x\sqrt{\frac{pS}{T}} \right) \tag{3.15}$$

The inverse Laplace transforms from Carslaw and Jaeger (1963) applicable to the Equation 3.15 in their original notation are

$$L^{-1}\left\{ \frac{e^{-a\sqrt{p}}}{p} \right\} = erfc\left(\frac{a}{2\sqrt{t}} \right) \tag{3.16}$$

$$L^{-1}\left\{ \frac{e^{-a\sqrt{p}}}{p - \omega} \right\} = \frac{1}{2} e^{\omega t} \left[e^{-a\sqrt{\omega}} erfc\left(\frac{a}{2\sqrt{t}} - \sqrt{\omega t} \right) + e^{a\sqrt{\omega}} erfc\left(\frac{a}{2\sqrt{t}} + \sqrt{\omega t} \right) \right] \tag{3.17}$$

When the inverse transform is applied to the Equation 3.15, the solution becomes

$$\begin{aligned} h(x,t) = (1+i)H_0 erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} \right) + \\ \frac{1}{2} H_1 \exp(i\omega t) \left[\begin{aligned} &\exp\left(-x\sqrt{\frac{iS\omega}{T}} \right) erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{i\omega t} \right) + \\ &\exp\left(x\sqrt{\frac{iS\omega}{T}} \right) erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{i\omega t} \right) \end{aligned} \right] \end{aligned} \tag{3.18}$$

Equation 3.18 should be separated into its real and imaginary parts to be applicable to practical problems. The treatment of the real and imaginary parts of the complex function (Equation 3.18) is the same as the procedure of Fourier as cited by Tikhonov and Samarskii (1963). Separation of the expression

$$E(x,t)=\frac{1}{2}H_1\exp(i\omega t)\left[\begin{array}{l}\exp\left(-x\sqrt{\frac{iS\omega}{T}}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{i\omega t}\right)+\\ \exp\left(x\sqrt{\frac{iS\omega}{T}}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{i\omega t}\right)\end{array}\right] \quad (3.19)$$

from Equation 3.18 into its real and imaginary parts is discussed term by term. By applying Equation 3.11

$$\exp\left(\mp x\sqrt{\frac{iS\omega}{T}}\right)=\exp\left(\mp\sqrt{\frac{Sr}{T}}\cos\frac{\theta}{2}\right)\left\{\cos\left(x\sqrt{\frac{Sr}{T}}\sin\frac{\theta}{2}\right)+i\sin\left(\mp\sqrt{\frac{Sr}{T}}\sin\frac{\theta}{2}\right)\right\} \quad (3.20)$$

where $r=\omega$ and $\theta=\pi/2$.

Next, the complementary error function can be expanded as (Abramowitz and Stegun, 1965)

$$erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{i\omega t}\right)=erfc(R1+iI1) \quad (3.21)$$

$$erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{i\omega t}\right)=erfc(R2+iI2) \quad (3.22)$$

where

$$R1=\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{rt}\cos\frac{\theta}{2} \quad (3.23)$$

$$R2=\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{rt}\cos\frac{\theta}{2} \quad (3.24)$$

$$I1=-\sqrt{rt}\sin\frac{\theta}{2} \quad (3.25)$$

$$I2=\sqrt{rt}\sin\frac{\theta}{2} \quad (3.26)$$

where r and θ were defined in Equation 3.20.

To evaluate the complementary error function of a complex number, the following approximation is used (Abramowitz and Stegun, 1965):

$$erf(R+iI)=F(R,I)+iG(R,I)+\varepsilon(R,I) \tag{3.27}$$

where $erfc(y)=1-erf(y)$, and

$$F(R,I)=erf(R)+\frac{\exp(-R^2)}{2\pi R}\left(1-\cos(2RI)\right)+\frac{2}{\pi}\exp\left(-R^2\right)\sum_{n=1}^{\infty}\frac{\exp\left(-n^2/4\right)}{n^2+4R^2}f_n(R,I) \tag{3.28}$$

$$G(R,I)=\frac{\exp(-R^2)}{2\pi R}\sin(2RI)+\frac{2}{\pi}\exp\left(-R^2\right)\sum_{n=1}^{\infty}\frac{\exp\left(-n^2/4\right)}{n^2+4R^2}g_n(R,I) \tag{3.29}$$

$$f_n(R,I)=2R-2R\cosh(nI)\cos(2RI)+n\sinh(nI)\sin(2RI) \tag{3.30}$$

$$g_n(R,I)=2R\cosh(nI)\sin(2RI)+n\sinh(nI)\cos(2RI) \tag{3.31}$$

and

$$\varepsilon\approx10^{-16}\left|erf(R+iI)\right| \tag{3.32}$$

As $\varepsilon\approx10^{-16}\left|erf(R+iI)\right|$, negligible error is introduced into the calculations when using Equation 3.27. Now Equation 3.12 can be separated into the portion applicable to the sine boundary condition, Equation 3.3 and cosine boundary condition, Equation 3.5. The solution applicable for the sine boundary condition is

$$h_1(x,t)=H_0\,erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}\right)+\mathrm{Im}\{h(x,t)\} \tag{3.33}$$

Equation 3.33 is the solution to the problem introduced in Equations 3.1 through 3.4 where *Im{h(x,t)}* is the imaginary part of *h(x,t)*

$$\operatorname{Im}\{h_1(x,t)\} = \frac{1}{2}H_1\cos(\omega t)\left\{\begin{aligned}&\exp\left(-x\sqrt{\frac{Sr}{T}}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{aligned}&-\cos\left(-x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)G(R1,I1)\\&+\sin\left(-x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R1,I1)\end{aligned}\right]+\\&\exp\left(x\sqrt{\frac{Sr}{T}}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{aligned}&-\cos\left(x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)G(R2,I2)\\&+\sin\left(x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R2,I2)\end{aligned}\right]\end{aligned}\right\}$$

$$+\frac{1}{2}H_1\sin(\omega t)\left\{\begin{aligned}&\exp\left(-x\sqrt{\frac{Sr}{T}}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{aligned}&\cos\left(-x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R1,I1)\\&+\sin\left(-x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)G(R1,I1)\end{aligned}\right]+\\&\exp\left(x\sqrt{\frac{Sr}{T}}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{aligned}&\cos\left(x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R2,I2)\\&+\sin\left(x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)G(R2,I2)\end{aligned}\right]\end{aligned}\right\} \tag{3.34}$$

This solution is applicable to determine time-dependent hydraulic head development beneath the levee as a response to the stage fluctuations observed in the river.

Similarly, the solution to the problem with cosine boundary equations, Equations 3.1, 3.2, 3.4 and 3.6, is

$$h_2(x,t) = H_0\,erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}\right) + \operatorname{Re}\{h(x,t)\} \tag{3.35}$$

where *Re{h(x,t)}* is the real part of *h(x,t)*

$$\mathrm{Re}\{h_2(x,t)\} = \frac{1}{2}H_1\cos(\omega t)\left\{\begin{array}{l} \exp\left(-x\sqrt{\frac{Sr}{T}}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l}\cos\left(-x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)\left(1-F(R1,I1)\right) \\ +\sin\left(-x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)G(R1,I1)\end{array}\right] + \\ \exp\left(x\sqrt{\frac{Sr}{T}}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l}\cos\left(x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)\left(1-F(R2,I2)\right) \\ +\sin\left(x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)G(R2,I2)\end{array}\right]\end{array}\right\}$$

$$-\frac{1}{2}H_1\sin(\omega t)\left\{\begin{array}{l} \exp\left(-x\sqrt{\frac{Sr}{T}}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l}\cos\left(-x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)G(R1,I1) \\ +\sin\left(-x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)\left(1-F(R1,I1)\right)\end{array}\right] + \\ \exp\left(x\sqrt{\frac{Sr}{T}}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l}-\cos\left(x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)G(R2,I2) \\ +\sin\left(x\sqrt{\frac{Sr}{T}}\sin\left(\frac{\theta}{2}\right)\right)\left(1-F(R2,I2)\right)\end{array}\right]\end{array}\right\} \tag{3.36}$$

Although the solution can be evaluated by a mathematics software, it is a long and complex solution. Therefore, an approximate solution method to the same problem was studied and will be presented in the next section.

3.3 Analytical Modeling of Transient Hydraulic Head in a Confined Aquifer by an Approximate Method

Jiao and Tang (1999) presented an approximate solution to a problem of groundwater response to tidal fluctuation in a leaky confined aquifer. This solution follows their method for an approximate transient seepage model in a confined aquifer. A schematic view of the model is shown in Fig. 3.2.

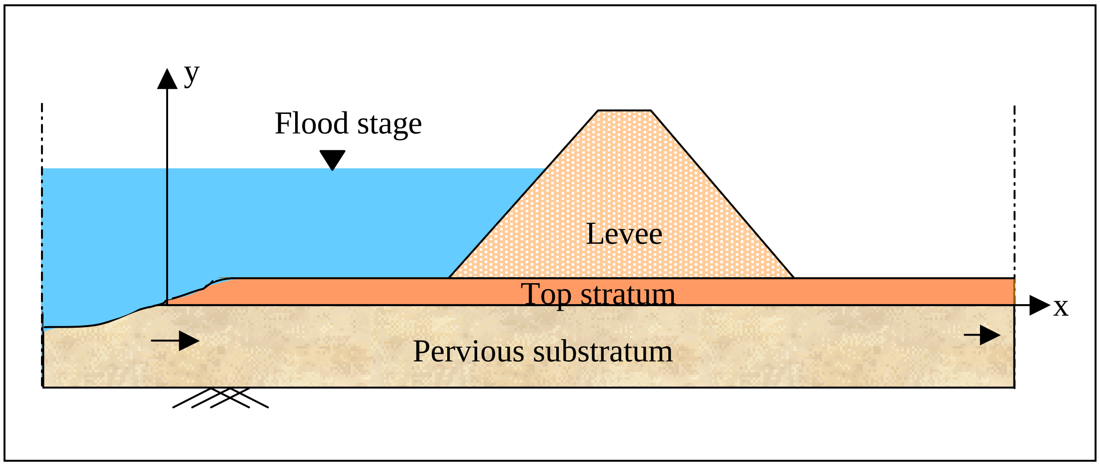


Fig. 3.2 A schematic view of confined flow under a levee for an approximate solution.

The governing equation for confined flow with initial and boundary conditions are

$$\frac{\partial h}{\partial t} = \frac{T}{S}\frac{\partial^2 h}{\partial x^2} \tag{3.37}$$

$$h(x,0) = h_0 \tag{3.38}$$

$$h(0,t) = h_0 + h_1 \sin(\omega t) \tag{3.39}$$

$$\lim_{x\to\infty} h(x,t) = h_0 \tag{3.40}$$

Let H=h-h_0, then the differential equation becomes as follows with initial and boundary conditions:

$$\frac{\partial H}{\partial t} = \frac{T}{S}\frac{\partial^2 H}{\partial x^2} \tag{3.41}$$

$$H(x,0) = 0 \tag{3.42}$$

$$H(0,t) = h_1 \sin(\omega t) \tag{3.43}$$

$$\lim_{x\to\infty} H(x,t) = 0 \tag{3.44}$$

Equation 3.43 is in the form of $H(0,t) = h_1 \operatorname{Im} e^{i(\omega t)}$, then the solution can be assumed as:

$$H(x,t) = h_1 e^{\lambda x} e^{i(\omega t)} \tag{3.45}$$

Substitute the solution in Equation 3.41,

$$\lambda^2 = \frac{i\omega S}{T} \tag{3.46}$$

Let $\lambda = -p + iq$, then

$$p = \sqrt{\frac{\omega S}{2T}} \tag{3.47}$$

$$q = -\frac{\omega S}{2pT} \tag{3.48}$$

$$H(x,t) = H_1 \operatorname{Im}[e^{-px} e^{i(\omega t + qx)}] \tag{3.49}$$

$$H(x,t) = h_1 e^{-px} \sin(\omega t + qx) \tag{3.50}$$

Back to the original problem

$$h(x,t) = h_0 + h_1 e^{-px} \sin\left(\omega t - \frac{\omega S}{2pT} x\right) \tag{3.51}$$

So, an approximate solution was found to the problem defined in Equations 3.37 through 3.40. This is an approximate solution because the final solution was initially assumed as shown in Equation 3.45. Also, the final solution, Equation 3.51, does not satisfy the initial condition specified in Equation 3.38. Thus, Equation 3.51 is called a quasi steady-state solution, which is applicable, when time is large enough that the initial condition is forgotten.

3.4 Results and Discussion

A typical levee section defined by the Army Corps is selected for analysis purpose (EM 1110-2-1913). The thickness of sandy alluvium under Mississippi River levees varies from 25 m to 45 m. The thickness of low permeable top layer under Mississippi

River levees ranges from 1.5 m to 37.5 m. The hydraulic conductivity of sandy alluvium ranges from 0.1 cm/sec to 0.2 cm/sec (Turnbull and Mansur, 1961). Typical storativity values for confined aquifers are $5x10^{-3}$, $5x10^{-4}$, $5x10^{-5}$ (Freeze and Cherry, 1979). In the 1993 floods, the net river level elevation change of the middle Mississippi River levees was recorded as 4.8 to 6.7 m (Mansur *et al*. 2000). A net head of 5 m and a fluctuation of 1.5 m were selected in the analysis. The typical levee section with selected aquifer parameters and hydraulic head is shown in Fig. 3.3.

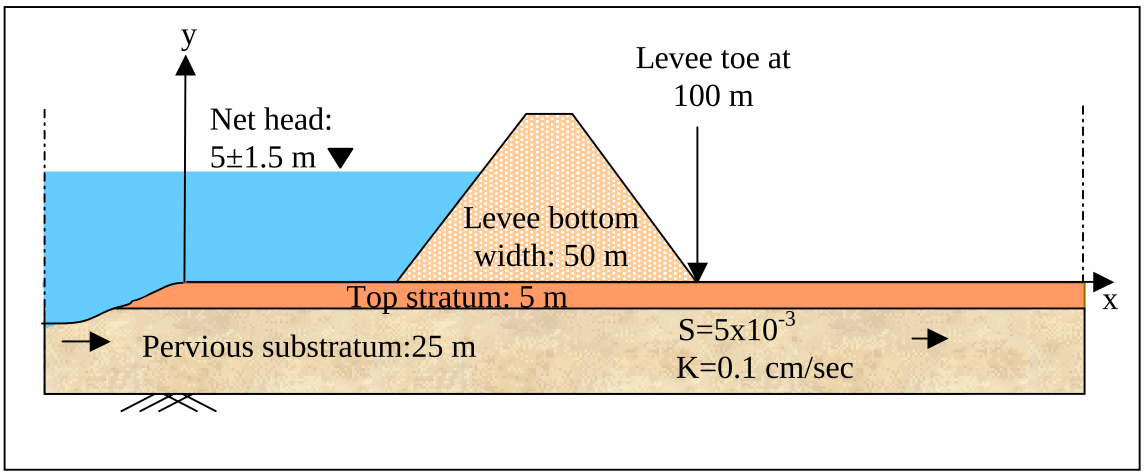


Fig. 3.3 A typical levee section with selected parameters (not in scale).

The flood duration was selected as 60 days. The net head starts at 5 m, rises to the peak of 6.5 m at time=30 days, and falls back to 5 m at time=60 days. Head development over a distance of 200 m was determined, which included 50 m at riverside, a 50 m levee base, and 100 m on the landside of the levee. The analysis was restricted to 100-m landside of the levee because, as noted in the literature review, Li *et al.*(1996) reported that there was no significant evidence of surface seepage beyond 100 m from the levee north of Cairo, Illinois after the 1993 high water. The exit gradient at the levee toe and landside of the levee was also calculated by taking the difference between the heads above and below the top stratum and dividing by the top stratum thickness. Calculations were performed by MathCad 2000 software. Figures 3.4, 3.5, 3.6 and 3.7 show the results by the Laplace transform method. Figures 3.8, 3.9, 3.10 and 3.11 show the results by the approximate method.

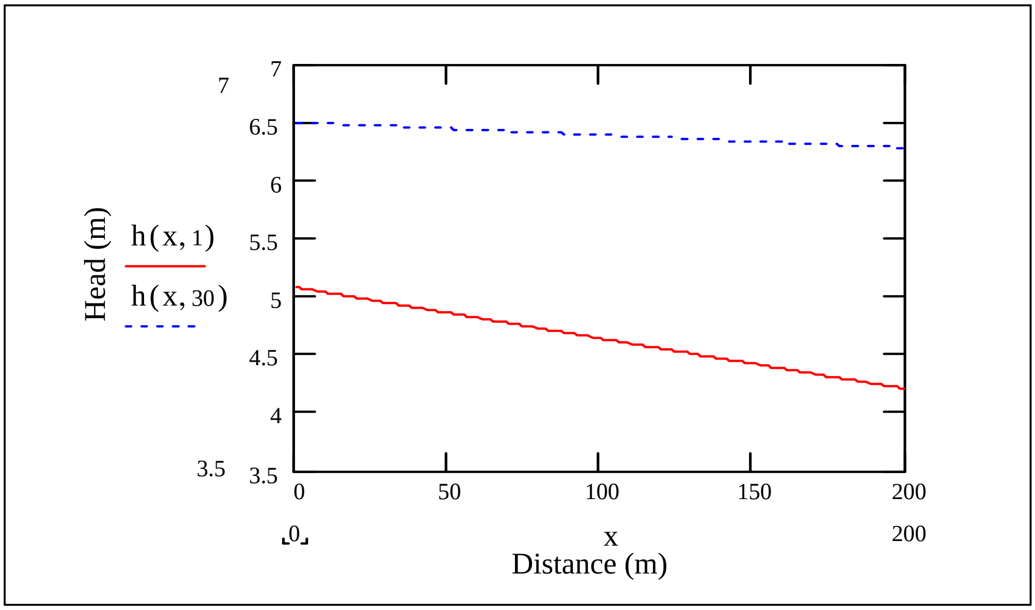


Fig. 3.4 Transient head development at t=1 day and 30 days by Laplace transform method.

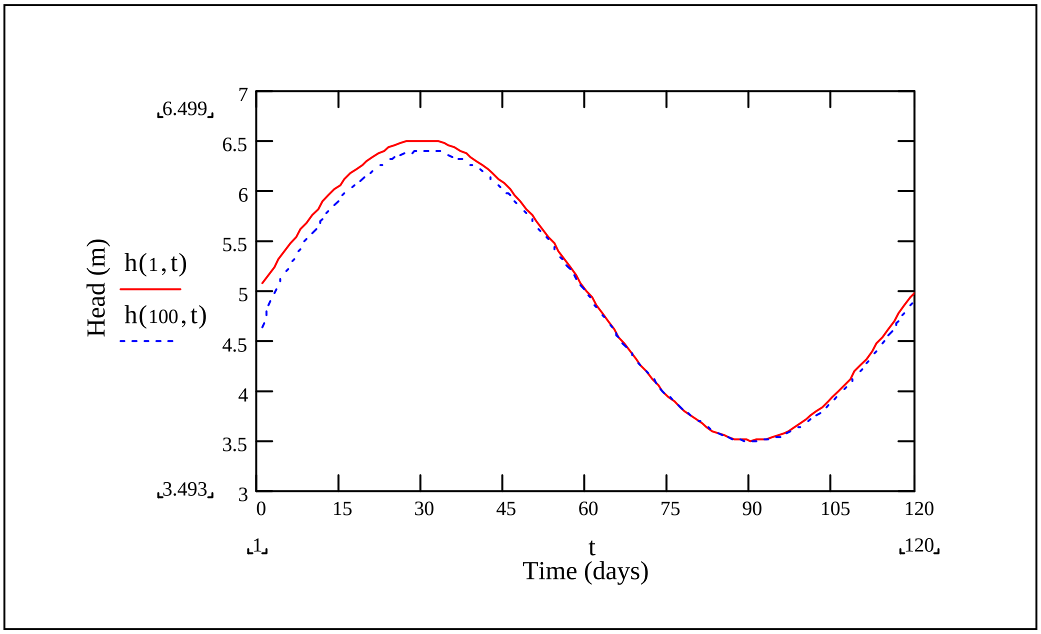


Fig. 3.5 Transient head development at x=1 m and x=100 m, levee toe, by Laplace transform method.

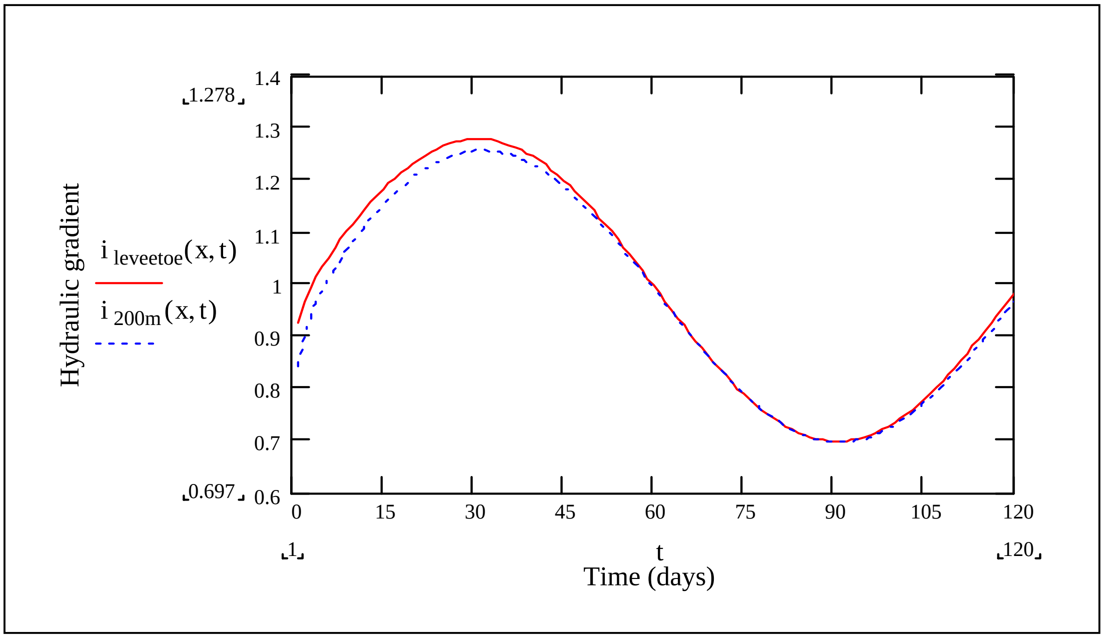


Fig. 3.6 Transient exit gradient at the levee toe and at 200-m landside of levee by Laplace transform method.

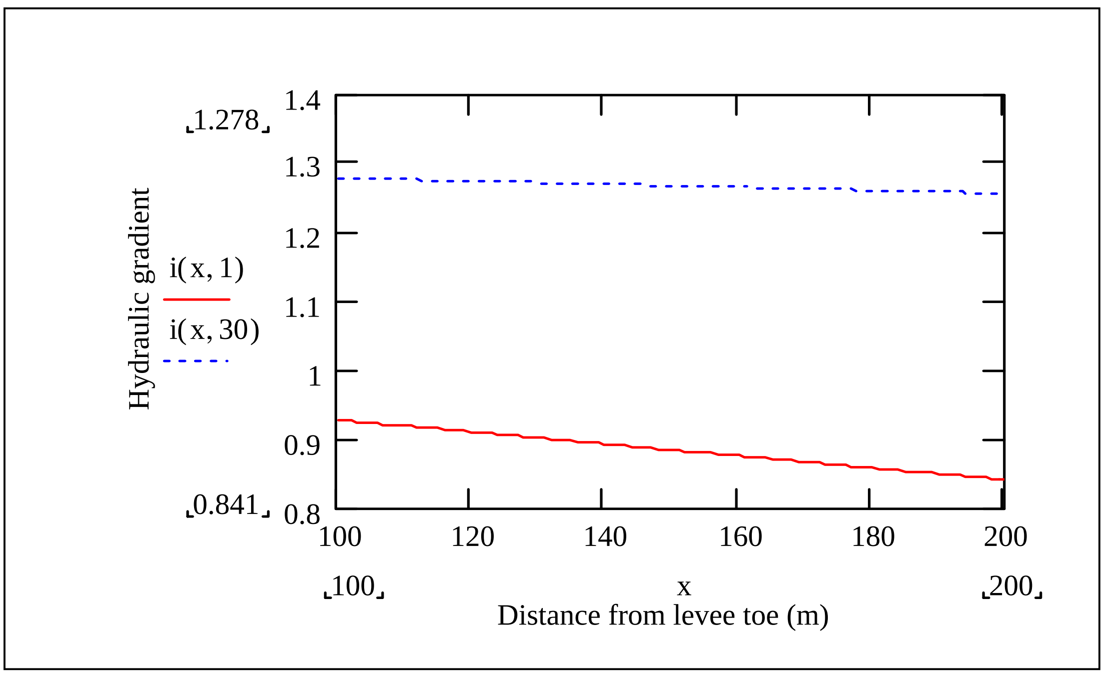


Fig. 3.7 Transient exit gradient at t=1 day and t=30 days at landside of the levee by Laplace transform method.

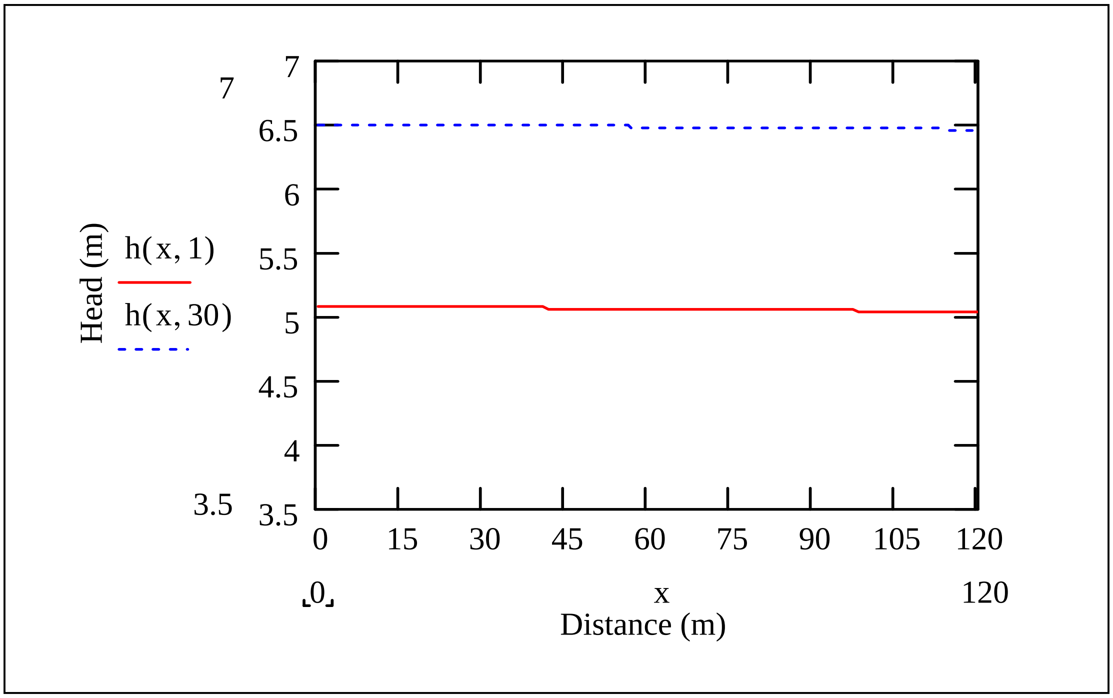


Fig. 3.8 Transient head development at t=1 day and t=30 days by the approximate method.

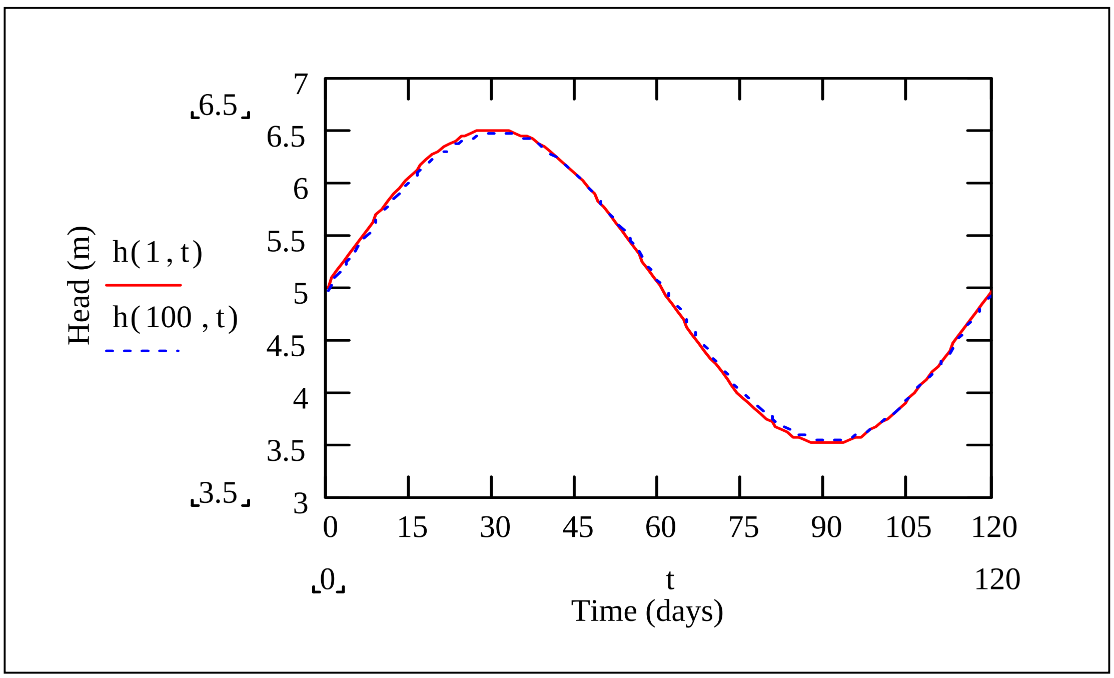


Fig. 3.9 Transient head development at x=1 m and x=100 m, levee toe, by the approximate method.

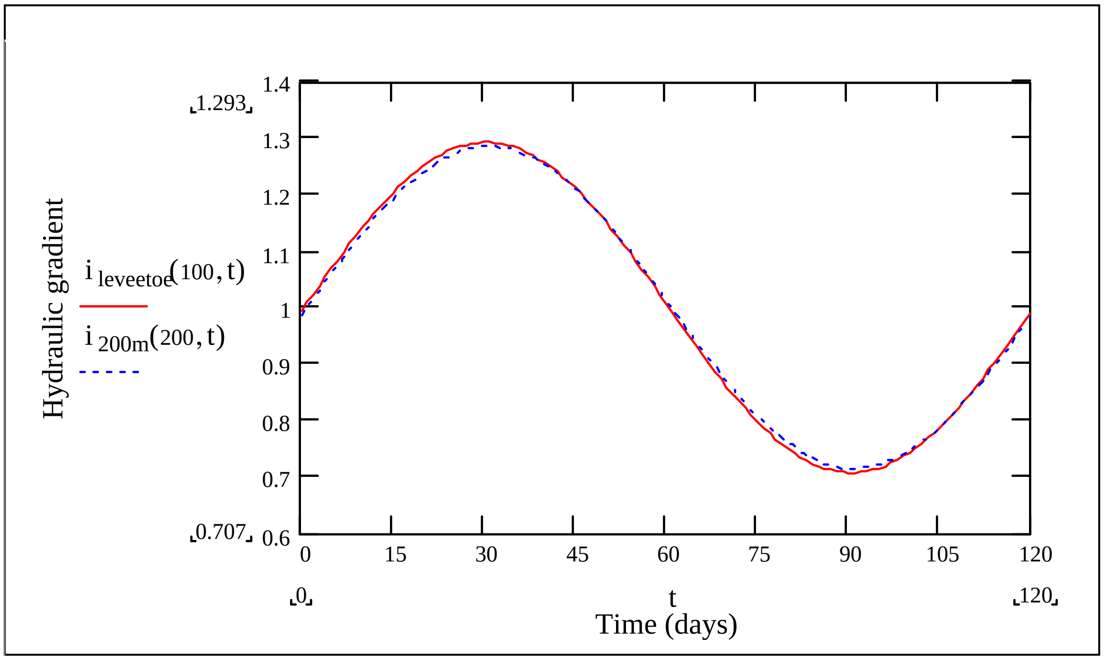


Fig. 3.10 Transient exit gradient at the levee toe and at 200-m landside of the levee by the approximate method.

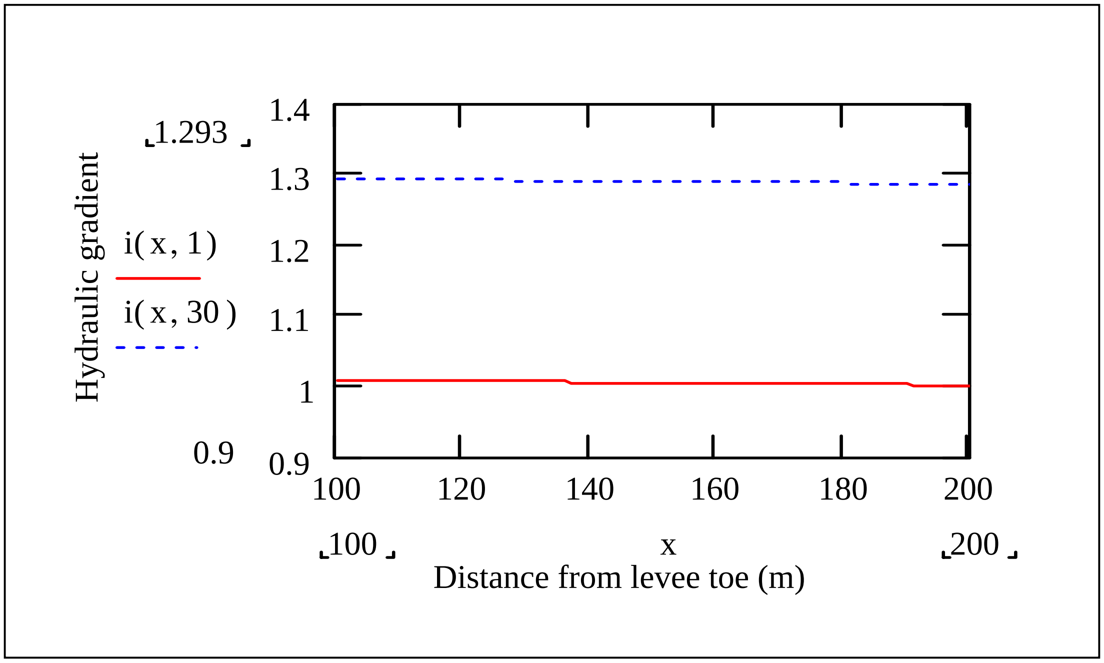


Fig. 3.11 Transient exit gradient at t=1 day and t=30 days at landside of the levee by the approximate method.

In general, both solutions give the expected 1.5 m sinusoidal head fluctuation with an initial head of 5 m, with a peak at 30 days, and the part of the graphs after 30 days represents the falling river stage (Figures 3.5 and 3.9). The approximate method performs well compared with Laplace transform solution. Both solutions give minor head dissipation with distance. Hydraulic head dissipates more rapidly at 100 m farther from the levee toe by Laplace transform solution than by the approximate solution. Both solutions assume a horizontal flow in semi-infinite layer. This assumption may be the reason for minor head dissipations with distance. Table 1.1 shows the summary of the results.

Table 3.1 Summary of the results by Laplace transform method and the approximate solution.

Head (m) and Hydraulic gradient	Time (day)	Laplace transform Method	Approximate Method
Head at levee toe (m)	1	4.64	5.04
	30	6.39	6.46
Head at 100 m farther than levee toe (m)	1	4.20	5.00
	30	6.28	6.43
Hydraulic gradient at levee toe	1	0.93	1.01
	30	1.28	1.30
Hydraulic gradient at 100 m farther than levee toe	1	0.84	1.00
	30	1.26	1.29

Time Lag in Head Development

One interesting common behavior is that both solutions show only a minor time lag between the peak points of sinusoidal head curves with distance. In other words, the peaks of head wave by Laplace transform solution (Fig. 3.5) and by the approximate solution (Fig. 3.9) correspond to about 30 days at the levee toe and also at 100 m farther than the levee toe. Based on Meehan's observations of levee failure on the Feather River, California, during the falling river stage in 1986 (reported in Chapter 2), one would expect to observe a time lag between the peak points of the head waves at varying distances. Figures 3.12 and 3.13 explore more on this subject.

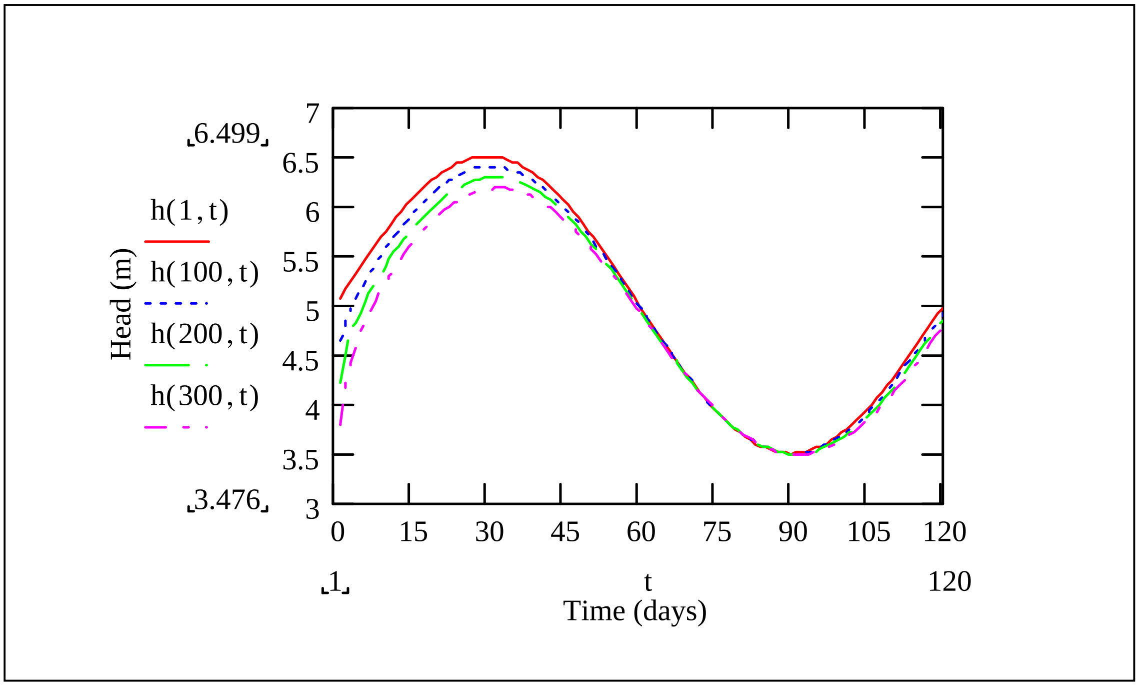


Fig. 3.12 Transient head development beneath the levee at various distances from the river by Laplace transform method.

The time of occurrence of the peak points of the river hydrograph and the peak hydraulic head of each head wave at various distances by Laplace transform and the approximate method are also summarized in Table 3.2.

Both solution methods show a minor time difference between the peak heads at various distances. As presented in Chapter 2, Ferris (1951) developed analytical expressions to determine the aquifer diffusivity (T/S) based on the observed values of amplitude, lag, velocity, and wavelength of the sinusoidal changes in groundwater level.

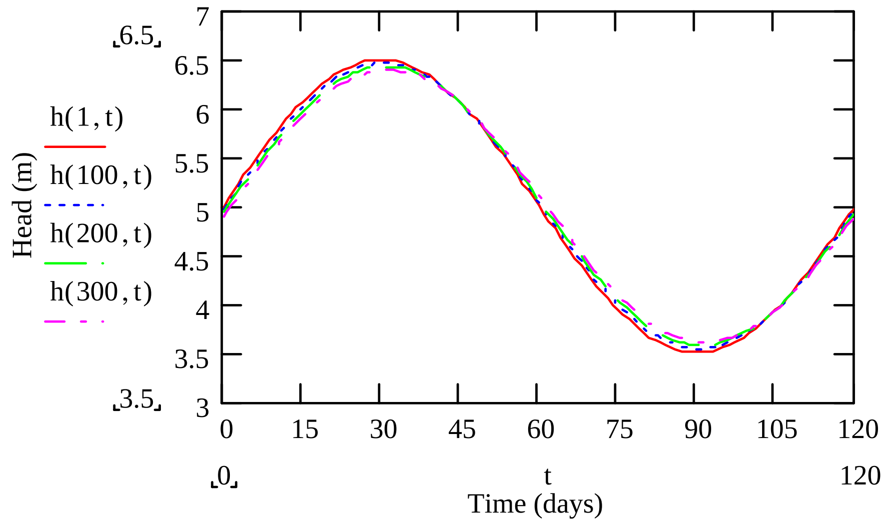


Fig. 3.13 Transient head development beneath the levee at various distances from the river by the approximate method.

Table 3.2 Time of occurrence of the peak points of head wave at variable distances.

Methods	Time and Head at peak	x=1 m	x=100m (levee toe)	x=200 m	x=300 m
Laplace Transform Method	Time (days)	30	31	31	32
	Head (m)	6.50	6.39	6.28	6.18
Approximate Method	Time (days)	30	30	31	31
	Head (m)	6.50	6.46	6.43	6.39

If the time lag between surface and groundwater maximum and minimum stages is known, then the aquifer diffusivity can be estimated by using the following formula (EM 1110-2-1421, Equation 6-9):

$$t_{lag} = d\sqrt{\frac{PS}{4\pi T}} \tag{3.52}$$

where t_{lag} is the lag time in the occurrence of the maximum groundwater stage following the occurrence of a similar surface stage, d is the distance from an observation well to the surface water, and P is the period of uniform tide or stage fluctuations. Equation 3.52 can be applied to time lag analysis of transient head development due to river fluctuations. If the same parameters as in the time lag analysis (d = 100 m, P = 60 days, S = 0.005, T = 2160 m^2/day) of Laplace transform and approximate methods were applied to Equation 3.52, the time lag would result in 0.33 days for every 100-m of distance.

Only field studies can confirm the reliability of time lags estimated by the transient flow models. As noted in the literature review, a levee collapse near Marysville, California, occurred one day after the peak of the flood stage of Feather River. Part of the time delay may have been due to the time required for sand boils to erode channels or pipes under the levee, undermine it, and accelerate its failure. At Louisiana State University Dairy Farm, however, an existing sand boil was reported to have responded very quickly with the river stage fluctuations.

Base on limited field studies and an analytical estimation, the time lag results presented in Table 1.2 appear to be reasonable.

3.5 Summary

Two transient flow models were developed to describe the hydraulic head development beneath the landside levee in response to head fluctuations in the river. The rising river stage was defined by a sinusoidally varying boundary condition. Both models consider one-dimensional saturated flow conditions in a homogenous isotropic confined aquifer. The first transient flow model was developed by solving the governing diffusion equation and the boundary conditions (Equation 3.1 through 3.4) by Laplace transform method. This solution method is complicated and can be evaluated only by a mathematical software. Therefore, an approximate solution was also presented. The results were evaluated for a typical levee section.

Both solutions result in expected head fluctuations. The approximate solution performs well compared with the Laplace transform method. Both solutions give minor head dissipation with time and distance. Both solutions also result in minor time lag between the peak points of head waves at various distances. The distinctions between the two solutions would become more apparent if the period of the river hydrograph decreased, and if the development of heads and gradients at small times was sought. Then the Laplace transform solution's performance would be enhanced over the performance of the approximate method.

The main objective of this chapter was to develop transient flow models by the Laplace transform method and by an approximate method. This objective was satisfied. The applicability and performance analysis of these flow models will be studied in the following chapters.

3.6 List of Symbols

a = constant in inverse Laplace transform

d = distance (L)

E(x, t) = an expression for a part of the hydraulic head function

f_n = function used to calculate error function

F = real function used to calculate an error function

g_n = function used to calculate error function

ε = error of approximation

G = imaginary function used to calculate an error function

h = hydraulic head (L)

$h(x, t)$ = hydraulic head function

$h_1(x, t)$ = imaginary part of hydraulic head function

$h_2(x, t)$ = real part of hydraulic head function

h_0 = initial hydraulic head (L)

H_0 = initial hydraulic head (L)

h_1 = amplitude of the variation from the initial hydraulic head (L)

H_1 = amplitude of the variation from the initial hydraulic head (L)

$\overline{H}(x,t)$ = Laplace transform of $h(x, t)$

i = imaginary unit where $i^2 = -1$

$I1, I2$ = imaginary part of a complex variable

n = index of summation

λ = a complex variable

p = real part of the complex variable λ

p = complex number in Laplace transform

P = period of uniform stage fluctuations (T)

r = inverse of length squared (L^{-2})

q = imaginary part of the complex variable λ

$R1, R2$ = real part of a complex variable

S = aquifer storativity (dimensionless)

t = time (T)

t_{lag} = time lag (T)

T = aquifer transmissivity (LT^{-2}), also time dimension

x = horizontal coordinate (L)

y = variable in error function

z_t = thickness of landside top stratum (L)

θ = phase angle for frequency ratio

ω = frequency of the flood wave (T^{-1})

CHAPTER 4 TRANSIENT FLOW MODEL WITH LEAKAGE OUT OF A CONFINED AQUIFER

4.1 Introduction

The objective of this chapter was to modify the analytical flow models developed in the previous chapter by considering leakage occurring out of the confined aquifer. This condition simulates the occurrence of loss of water by upward seepage and discharge through sand boils at the landside of a levee or a flood wall system. The sand boils develop at random points landside of the levee. The solution methods presented here describe a homogenous leakage out of a confined aquifer through the landside of a levee or a flood wall. The system considered is a subsurface confined aquifer with one-dimensional saturated flow and semi-permeable layer on top. The aquifer is assumed to be homogenous and isotropic. The models used a sinusoidally varying boundary condition to simulate the effects of the rising river stage. In these models, the governing equation is the diffusion equation that was developed under Darcy's law, and the law of conservation of mass. Two solutions were presented. The first solution used Laplace transform method and followed the same methodology outlined in Section 3.2. The second solution is an approximate solution and the same methodology outlined in Section 3.3 was followed. The analyses were extended to the falling limb of a flood wave due to the fact that some field observations indicated critical situations during the falling river stages (Section 2.3.1).

4.2 Analytical Modeling of Transient Hydraulic Head with Leakage Out of a Confined Aquifer by Laplace Transform Method

The model was set up considering a subsurface system with a leaky confined aquifer, and a semi-permeable layer on top representing the blanket layer (Fig. 4.1).

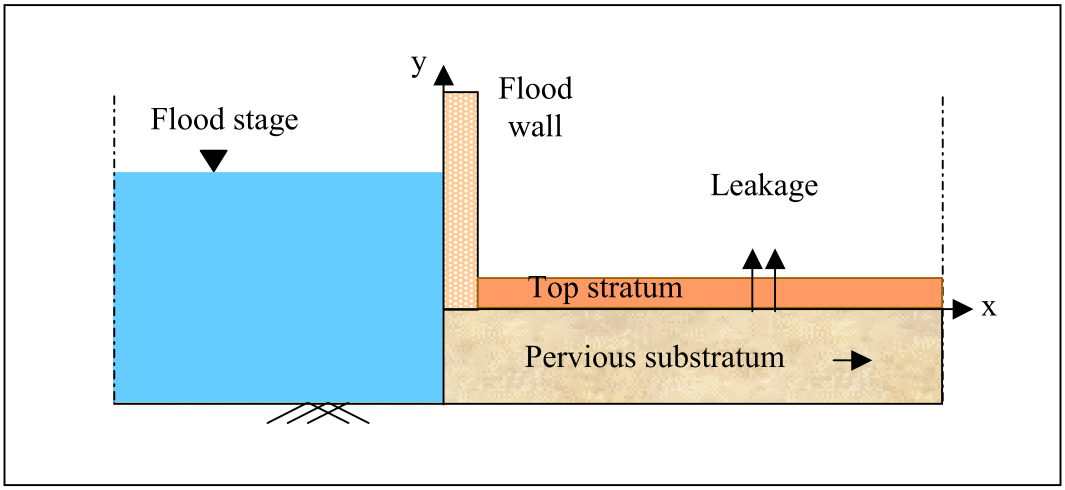


Fig. 4.1 Schematic view of confined flow under a flood wall with leakage out of an aquifer.

The initial head at time $t = 0$ is 0; assuming mean low river level is well below the origin which is the most common case. During high water, an initial head of h_0 is developed. The fluctuation of this head is typical and defined as $h_1 sin(\omega t)$ in the analysis. Another boundary condition is the head $h = 0$ when x approaches infinity which represents a condition in which there is no influence of head far landward. Under these conditions, the governing equation is:

$$\frac{\partial h}{\partial t} = \frac{T}{S}\frac{\partial^2 h}{\partial x^2} - \frac{L}{S}h \tag{4.1}$$

where h is the hydraulic head, T is the transmissivity, t is time, S is the storativity, L is the leakage, and x is the distance from the entrance to the confined aquifer. The initial and boundary conditions may be given as

$$h(x,0) = 0 \tag{4.2}$$

$$h(0,t) = h_0 + h_1 \sin(\omega t) \tag{4.3}$$

$$\lim_{x \to \infty} h(x,t) \to 0 \tag{4.4}$$

where h_0 is the initial hydraulic head applied to the aquifer, h_1 is the amplitude of the variation from the initial hydraulic head and ω is the frequency of the flood wave, $\omega = 2\pi/P$, where P is the fluctuation period. To make the problem realistic h_0 and h_1 are positive or zero with the constraint that $h_0 \geq h_1$. The leakage, L is the ratio of hydraulic conductivity of the semi-confining layer to the thickness of semi-confining layer. We apply the transform $h(x, t) = Y(x, t) \exp(-L\, t/S)$ to Equations 4.1 to 4.4 get a homogenous differential equation. The new set of equations becomes

$$\frac{\partial Y}{\partial t} = \frac{T}{S}\frac{\partial^2 Y}{\partial x^2} \tag{4.5}$$

$$Y(x,0) = 0 \tag{4.6}$$

$$Y(0,t) = h_0 \exp\left(\frac{L}{S}t\right) + h_1 \sin(\omega t) \exp\left(\frac{L}{S}t\right) \tag{4.7}$$

$$\lim_{x\to\infty} Y(x,t) = 0 \tag{4.8}$$

Now an approach similar to one followed by Ozisik (1968), and Alshawabkeh and Adrian (1997) and outlined in Section 3.2 is followed. A new problem is defined with dependent variable $Z(x,t)$ that is identical to Equations 4.5, 4.6, and 4.8 but the boundary condition is

$$Z(0,t) = h_0 \exp\left(\frac{L}{S}t\right) + h_1 \cos(\omega t) \exp\left(\frac{L}{S}t\right) \tag{9}$$

Each term in the first problem is multiplied by the complex number i where $i = \sqrt{-1}$, and the two problems are superimposed. Then, a new complex variable is introduced

$$\widetilde{H}(x,t) = Z(x,t) + iY(x,t) \tag{10}$$

where $Y(x,t)$, the imaginary part of solution, satisfies the original problem Equations 4.5-4.8, and $Z(x,t)$ the real part of the solution, satisfies the original problem with the boundary condition Equation 4.7 changed to Equation 4.9. The governing equation for the complex transient seepage becomes

$$\frac{\partial \tilde{H}}{\partial t} = \frac{T}{S}\frac{\partial^2 \tilde{H}}{\partial x^2} \tag{4.11}$$

$$\tilde{H}(x,0) = 0 \tag{4.12}$$

$$\tilde{H}(0,t) = (1+i)h_0 \exp\left(\frac{L}{S}t\right) + h_1 \exp(i\omega t)\exp\left(\frac{L}{S}t\right) \tag{4.13}$$

$$\lim_{x\to\infty} \tilde{H}(x,t) \to 0 \tag{4.14}$$

In Equation 4.13, Euler's relationship was used

$$\exp(i\omega t) = \cos(\omega t) + i\sin(\omega t) \tag{4.15}$$

The Laplace transform is applied to Equations 4.11 to 4.14 yielding

$$\frac{d^2\overline{H}}{dx^2} - \frac{pS}{T}\overline{H} = 0 \tag{4.16}$$

$$\overline{H}(0) = \frac{1+i}{p-\frac{L}{S}}h_0 + \frac{h_1}{p-\frac{L}{S}-i\omega} \tag{4.17}$$

$$\lim_{x\to\infty} \overline{H}(x) \to 0 \tag{4.18}$$

where the term $\overline{H}(x)$ is the Laplace transform of $\tilde{H}(x,t)$ and p is the parameter in the transform. The solution to Equation 4.16 subject to Equations 4.17 and 4.18 is

$$\overline{H}(x) = \left(\frac{1+i}{p-\frac{L}{S}}h_0 + \frac{h_1}{p-\left(i\omega+\frac{L}{S}\right)}\right)\exp\left(-x\sqrt{\frac{pS}{T}}\right) \tag{4.19}$$

The inverse Laplace transform from Carslaw and Jaeger (1963) applicable to Equation 4.19 in its original notation is

$$L^{-1}\left\{\frac{e^{-a\sqrt{p}}}{p-\omega}\right\}=\frac{1}{2}e^{\omega t}\left[e^{-a\sqrt{\omega}}\,erfc\left(\frac{a}{2\sqrt{t}}-\sqrt{\omega t}\right)+e^{a\sqrt{\omega}}\,erfc\left(\frac{a}{2\sqrt{t}}+\sqrt{\omega t}\right)\right] \tag{4.20}$$

When the inverse transform is applied to the Equation 4.19, the result is

$$\begin{aligned}\widetilde{H}(x,t)=&\left(\frac{1+i}{2}\right)h_0\exp\left(\frac{L}{S}t\right)\left[\begin{array}{l}\exp\left(-x\sqrt{\frac{L}{T}}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{\frac{L}{S}t}\right)+\\ \exp\left(x\sqrt{\frac{L}{T}}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{\frac{L}{S}t}\right)\end{array}\right]+\\ &\frac{1}{2}h_1\exp\left(i\omega+\frac{L}{S}\right)t\left[\begin{array}{l}\exp\left(-x\sqrt{\frac{S}{T}\left(i\omega+\frac{L}{S}\right)}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right)+\\ \exp\left(x\sqrt{\frac{S}{T}\left(i\omega+\frac{L}{S}\right)}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right)\end{array}\right]\end{aligned} \tag{4.21}$$

Equation 4.21 should be separated into its real and imaginary parts to be applicable to practical problems. The treatment of the real and imaginary parts of the complex function (Equation 4.21) is the same as the procedure of Fourier as cited by Tikhonov and Samarskii (1963) and detailed in Section 3.2. The same method is followed here. Separation of the expression

$$E(x,t)=\frac{1}{2}h_1\exp(i\omega t)\exp\left(\frac{L}{S}t\right)\left[\begin{array}{l}\exp\left(-x\sqrt{\frac{iS\omega}{T}+\frac{L}{T}}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right)+\\ \exp\left(x\sqrt{\frac{iS\omega}{T}+\frac{L}{T}}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right)\end{array}\right] \tag{4.22}$$

from Equation 21 into its real and imaginary parts is discussed term by term. By applying Euler's relationship

$$\exp\left(\mp x\sqrt{\frac{iS\omega}{T}+\frac{L}{T}}\right)=\exp\left(\mp\sqrt{\frac{Sr}{T}}\cos\frac{\theta}{2}\right)\left\{\cos\left(x\sqrt{\frac{Sr}{T}}\sin\frac{\theta}{2}\right)+i\sin\left(\mp\sqrt{\frac{Sr}{T}}\sin\frac{\theta}{2}\right)\right\} \quad (4.23)$$

where $r=\dfrac{\sqrt{(S\omega)^2+L^2}}{T}$ and $\theta=\arctan\left(\dfrac{S\omega}{L}\right)$.

Next, the complementary error function can be expanded as (Abramowitz and Stegun, 1965)

$$erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right)=erfc(R1+iI1) \quad (4.24)$$

$$erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{\left(i\omega+\frac{L}{S}\right)t}\right)=erfc(R2+iI2) \quad (4.25)$$

where

$$R1=\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{r_1 t}\cos\frac{\theta}{2} \quad (4.26)$$

$$R2=\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{r_1 t}\cos\frac{\theta}{2} \quad (4.27)$$

$$I1=-\sqrt{r_1 t}\sin\frac{\theta}{2} \quad (4.28)$$

$$I2=\sqrt{r_1 t}\sin\frac{\theta}{2} \quad (4.29)$$

where $r_1=\dfrac{\sqrt{(S\omega)^2+L^2}}{S}$ and θ are defined as in Equation 4.23.

To evaluate the complementary error function of a complex number, the following approximation is used (Abramowitz and Stegun, 1965):

$$erf(R+iI)=F(R,I)+iG(R,I)+\varepsilon(R,I) \quad (4.30)$$

where $erfc(y) = 1 - erf(y)$, and

$$F(R,I) = erf(R) + \frac{\exp(-R^2)}{2\pi R}\left(1-\cos(2RI)\right) + \frac{2}{\pi}\exp\left(-R^2\right)\sum_{n=1}^{\infty}\frac{\exp\left(-n^2/4\right)}{n^2+4R^2}f_n(R,I) \quad (4.31)$$

$$G(R,I) = \frac{\exp(-R^2)}{2\pi R}\sin(2RI) + \frac{2}{\pi}\exp\left(-R^2\right)\sum_{n=1}^{\infty}\frac{\exp\left(-n^2/4\right)}{n^2+4R^2}g_n(R,I) \quad (4.32)$$

$$f_n(R,I) = 2R - 2R\cosh(nI)\cos(2RI) + n\sinh(nI)\sin(2RI) \quad (4.33)$$

$$g_n(R,I) = 2R\cosh(nI)\sin(2RI) + n\sinh(nI)\cos(2RI) \quad (4.34)$$

and

$$\varepsilon \approx 10^{-16}\left|erf(R+iI)\right| \quad (4.35)$$

As $\varepsilon \approx 10^{-16}\left|erf(R+iI)\right|$, and $erf(R+iI)$ has a maximum value of 2, negligible error is introduced into the calculations when using Equation 4.30.

Now Equation 4.21can be separated into the portion applicable to the sine boundary condition, Equation 4.3 and cosine boundary condition, Equation 4.5. The solution to the original problem with sine boundary condition, Equations 4.1 through 4.4:

$$h(x,t) = \mathrm{Im}\left\{\widetilde{H}(x,t)\right\}\exp\left(-\frac{L}{S}t\right) \quad (4.36)$$

where $\mathrm{Im}\left\{\widetilde{H}(x,t)\right\}$ is the imaginary part of $\widetilde{H}(x,t)$ where

$$
\begin{aligned}
\operatorname{Im}\{\widetilde{H}(x,t)\} &= \frac{1}{2}h_0 \exp\left(\frac{L}{S}t\right)\left[\begin{array}{l} \exp\left(-x\sqrt{\frac{L}{T}}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}-\sqrt{\frac{L}{S}t}\right) \\ +\exp\left(x\sqrt{\frac{L}{T}}\right)erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}}+\sqrt{\frac{L}{S}t}\right)\end{array}\right] \\
&+\frac{1}{2}h_1\cos(\omega t)\exp\left(\frac{L}{S}t\right)\left\{\begin{array}{l} \exp\left(-x\sqrt{r}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l} -\cos\left(-x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)G(R1,I1) \\ +\sin\left(-x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R1,I1)\end{array}\right]+ \\ \exp\left(x\sqrt{r}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l} -\cos\left(x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)G(R2,I2) \\ +\sin\left(x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R2,I2)\end{array}\right]\end{array}\right\} \\
&+\frac{1}{2}h_1\sin(\omega t)\exp\left(\frac{L}{S}t\right)\left\{\begin{array}{l} \exp\left(-x\sqrt{r}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l} \cos\left(-x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R1,I1) \\ +\sin\left(-x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)G(R1,I1)\end{array}\right]+ \\ \exp\left(x\sqrt{r}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l} \cos\left(x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R2,I2) \\ \sin\left(x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)G(R2,I2)\end{array}\right]\end{array}\right\}
\end{aligned}
\tag{4.37}
$$

Similarly, the solution to the problem with cosine boundary condition, Equations 4.5, 4.6, 4.8, and 4.9 is

$$Z(x,t) = \operatorname{Re}\{\widetilde{H}(x,t)\}\exp\left(-\frac{L}{S}t\right) \tag{4.38}$$

where $\operatorname{Re}\{\widetilde{H}(x,t)\}$ is the real part of $\widetilde{H}(x,t)$.

$$
\begin{aligned}
\operatorname{Re}\{\widetilde{H}(x,t)\} &= \frac{1}{2}h_0 \exp\left(\frac{L}{S}t\right)\left[\begin{array}{l}\exp\left(-x\sqrt{\frac{L}{T}}\right) erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} - \sqrt{\frac{L}{S}t}\right)\\ + \exp\left(x\sqrt{\frac{L}{T}}\right) erfc\left(\frac{x}{2}\sqrt{\frac{S}{Tt}} + \sqrt{\frac{L}{S}t}\right)\end{array}\right] \\
&\frac{1}{2}h_1 \cos(\omega t)\exp\left(\frac{L}{S}t\right)\left\{\begin{array}{l}\exp\left(-x\sqrt{r}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l}\cos\left(-x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R1,I1))\\ +\sin\left(-x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)G(R1,I1)\end{array}\right]+\\ \exp\left(x\sqrt{r}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l}\cos\left(x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R2,I2))\\ +\sin\left(x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)G(R2,I2)\end{array}\right]\end{array}\right\} \\
&+\frac{1}{2}h_1 \sin(\omega t)\exp\left(\frac{L}{S}t\right)\left\{\begin{array}{l}\exp\left(-x\sqrt{r}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l}\cos\left(-x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)G(R1,I1)\\ -\sin\left(-x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R1,I1))\end{array}\right]+\\ \exp\left(x\sqrt{r}\cos\left(\frac{\theta}{2}\right)\right)\left[\begin{array}{l}\cos\left(x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)G(R2,I2)\\ -\sin\left(x\sqrt{r}\sin\left(\frac{\theta}{2}\right)\right)(1-F(R2,I2))\end{array}\right]\end{array}\right\}
\end{aligned}
\tag{4.39}
$$

Equation 4.39 is the solution to the problem introduced in Equations 4.1 through 4.4. This solution is applicable to determine time-dependent hydraulic head development beneath the levee when there is leakage out of the aquifer in response to the stage fluctuations observed in the river. Although the solution can be evaluated by mathematical software, it is a long and complex solution. Therefore, an approximate method to solve the same problem was studied and presented in the next section.

4.3 Analytical Modeling of Transient Hydraulic Head with Leakage Out of a Confined Aquifer by an Approximate Method

This solution follows the methodology outlined in Section 3.3 and originally presented by Jiao and Tang (1999) for an approximate solution to a problem of groundwater response to tidal fluctuation in a leaky confined aquifer. A schematic view of the model is shown in Fig. 4.2.

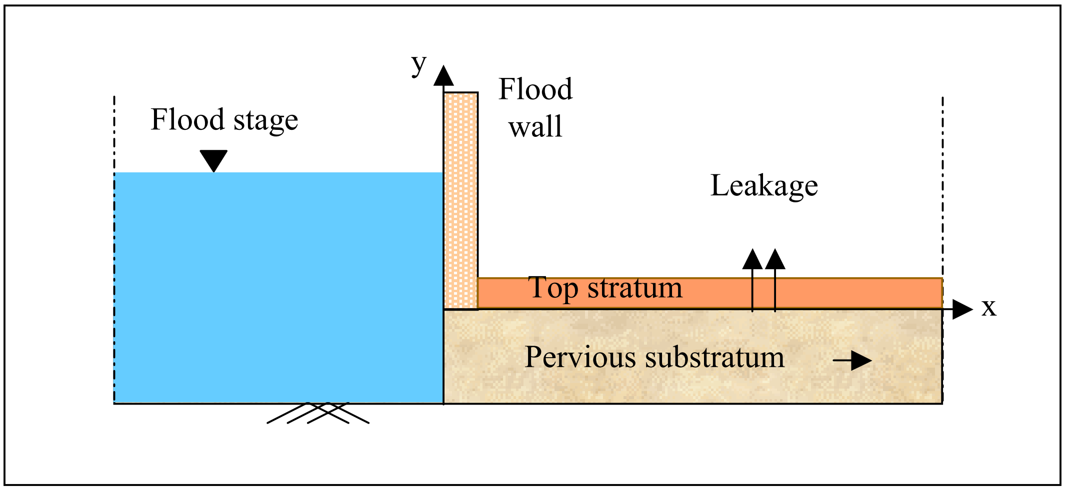


Fig. 4.2 Schematic view of confined flow with leakage out of aquifer for an approximate solution.

The governing equations for confined flow with initial and boundary conditions are

$$\frac{\partial h}{\partial t} = \frac{T}{S}\frac{\partial^2 h}{\partial x^2} - \frac{L}{S}(h_0 - h) \tag{4.40}$$

$$h(x,0) = h_0 \tag{4.41}$$

$$h(0,t) = h_0 + h_1 \sin(\omega t) \tag{4.42}$$

$$\lim_{x\to\infty} h(x,t) = h_0 \tag{4.43}$$

where h_0 is the initial head at $t = 0$, L is leakage, the ratio of hydraulic conductivity of the semi-confining layer to the thickness of semi-confining layer with units time^{-1}. Let

$H = h\text{-}h_0$, then the differential equation with initial and boundary conditions becomes:

$$\frac{\partial H}{\partial t} = \frac{T}{S}\frac{\partial^2 H}{\partial x^2} + \frac{L}{S}H \tag{4.44}$$

$$H(x,0) = 0 \tag{4.45}$$

$$H(0,t) = h_1 \sin(\omega t) \tag{4.46}$$

$$\lim_{x\to\infty} H(x,t) = 0 \tag{4.47}$$

Equation 4.40 is in the form of $H(0,t) = h_1 \operatorname{Im} e^{i(\omega t)}$, the solution can be assumed as

$$H(x,t) = h_1 e^{\lambda x} e^{i(\omega t)} \tag{4.48}$$

The assumed solution (Equation 4.48) is substituted in Equation 4.44, and λ^2 is derived

$$\lambda^2 = \frac{i\omega S}{T} - \frac{L}{T} \tag{4.49}$$

where λ must be a complex number. Let $\lambda = -p + iq$, then the real and imaginary parts of Equation 4.49 are equated and p and q are derived as

$$p = \frac{1}{\sqrt{2}}\left\{\left[\left(\frac{L}{T}\right)^2 + \left(\frac{\omega S}{T}\right)^2\right]^{1/2} - \frac{L}{T}\right\}^{1/2} \tag{4.50}$$

$$q = -\frac{\omega S}{2pT} \tag{4.51}$$

Substituting λ in Equation 4.48, and using the fluctuating boundary condition, Equation 4.46

$$H(x,t) = h_1 \operatorname{Im}[e^{-px} e^{i(\omega t + qx)}] \tag{4.52}$$

$$H(x,t) = h_1 e^{-px} \sin(\omega t + qx) \tag{4.53}$$

Back to the original problem, the solution of Equation 4.40 subject to boundary conditions Equation 4.42, 4.43 is

$$h(x,t) = h_0 + h_1 e^{-px} \sin\left(\omega t - \frac{\omega S}{2pT} x \right) \qquad (4.54)$$

where p is as defined in Equation 4.50.

Therefore, an approximate solution was found to the problem defined in Equations 4.40 through 4.43. This is an approximate solution because the final solution was initially assumed as shown in Equation 4.48. In addition, the final solution, Equation 4.54, does not satisfy the initial condition specified in Equation 4.41. Thus, the final solution is referred to as a quasi steady-state solution.

4.4 Results and Discussion

A typical levee section defined by the Army Corps is selected for analysis purposes (EM 1110-2-1913). The thickness of sandy alluvium under Mississippi River levees varies from 25 m to 45 m. The thickness of low permeable blanket layer under Mississippi River levees varies from 1.5 m to 37.5 m. The hydraulic conductivity of sandy alluvium ranges from 0.1 cm/sec to 0.2 cm/sec (Turnbull and Mansur 1961). Typical storativity values for confined aquifers are 5×10^{-3}, 5×10^{-4} and 5×10^{-5} (Freeze and Cherry, 1979). In the 1993 floods, the net river level elevation change of the middle Mississippi River levees was recorded as 4.8 to 6.7 m (Mansur *et al*. 2000). A net head of 5 m and a fluctuation of 1.5 m were selected in the analysis. The typical levee section with selected aquifer parameters and hydraulic head is shown in Fig. 4.3.

The flood duration was selected as 60 days. The net head starts at 5 m, rises to the peak of 6.5 m at time=30 days, and falls back to 5 m at time=60 days. Head development over a distance of 200 m was determined, which included 50 m at riverside, a 50 m levee base, and 100 m on the landside of the levee.

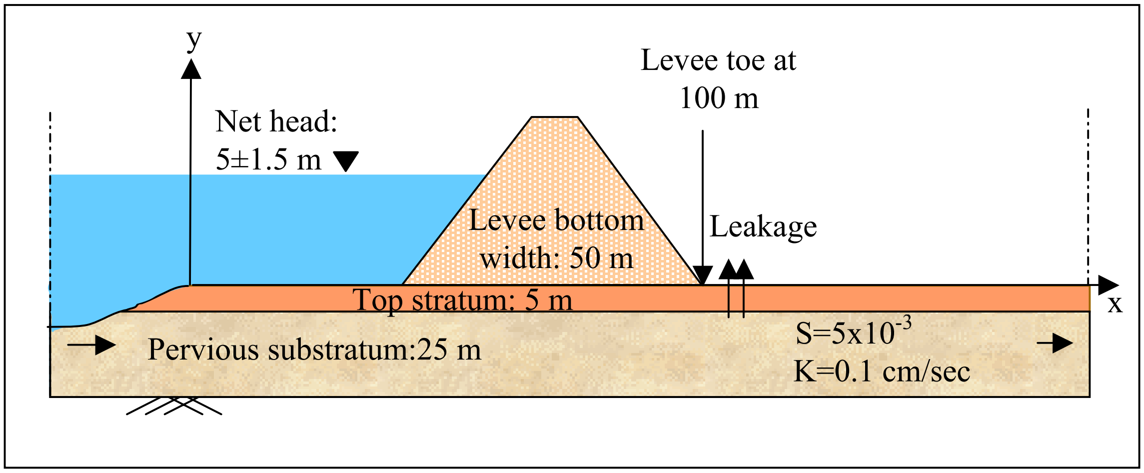


Fig. 4.3 Typical levee section with selected parameters (not in scale).

The analysis was restricted to 100-m landside of the levee because, as noted in the literature review, Li *et al.* (1996) reported that there was no significant evidence of surface seepage beyond 100 m from the levee north of Cairo, Illinois after the 1993 high water. Head development and exit gradients were calculated at the landside of the levee. Calculations were performed by MathCad 2000 software. The leakage amount was selected as 0.14 1/day/m, which corresponds to a 5 gal/min/100 feet of levee, reported by Turnbull and Mansur (1961) and presented in Table 2.1. Figure 4.4 shows the visual explanation for the estimation of leakage out of a confined aquifer. The upward leakage was estimated by Turnbull and Mansur (1961) using the general seepage formula:

$$Q = kiA \tag{4.55}$$

This horizontal seepage changes its direction and leaks out of the aquifer through semi-pervious top layer as in Figure 4.4. Then, hydraulic gradient under semi-permeable layer, i is estimated as $\Delta h/\Delta m$, where Δh is the hydraulic head difference between the river and landside of levee, and Δm is the thickness of top stratum. Recall that leakage is the ratio of vertical hydraulic conductivity of the semi-confining layer to the thickness of semi-confining layer, $L = k/\Delta m$. Here, a specific seepage is also defined as $Q_s = Q/h$ which corresponds to the computed natural seepage values, Q/h, which were reported by Turnbull and Mansur (1961). Therefore, seepage beneath the levee in terms of leakage is:

$$Q_s = L \Delta h A \tag{4.56}$$

where A is the unit area through which seepage passes. Using the maximum hydraulic head difference, $\Delta h = 6.5$ m, unit area, $A = 1$ m^2, and seepage amount, $Q_s = 0.9$ m^3/d/m, which corresponds to 5 gal/min/100 ft of levee, then leakage is estimated as, $L = 0.14$ 1/d /m of levee.

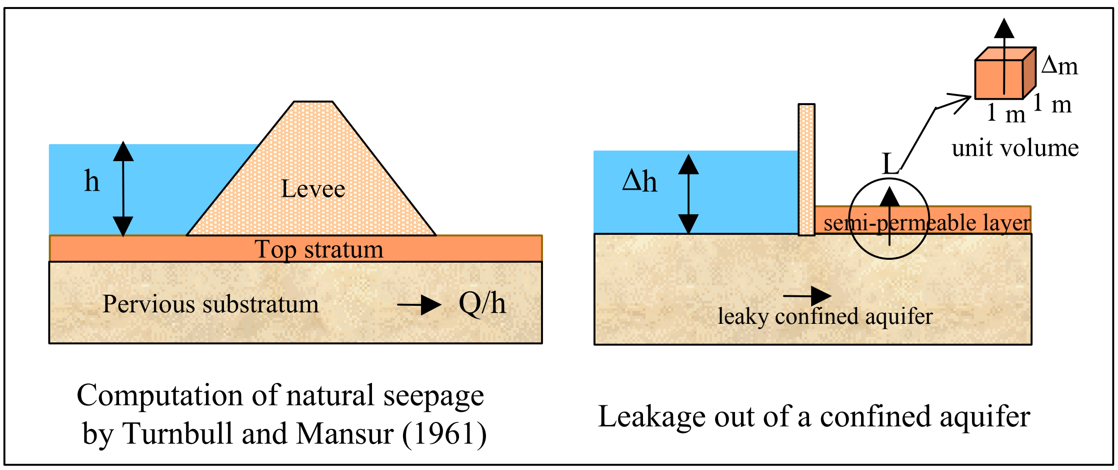


Fig. 4.4 Detailed figures related to the computation of upward leakage.

Figures 4.5, 4.6, 4.7, and 4.8 show head development and exit hydraulic gradient distributions by the Laplace transform method when there is a leakage of 0.14 1/day/m of levee. Similarly, Figures 4.9, 4.10, 4.11, and 4.12 show the results by the approximate method.

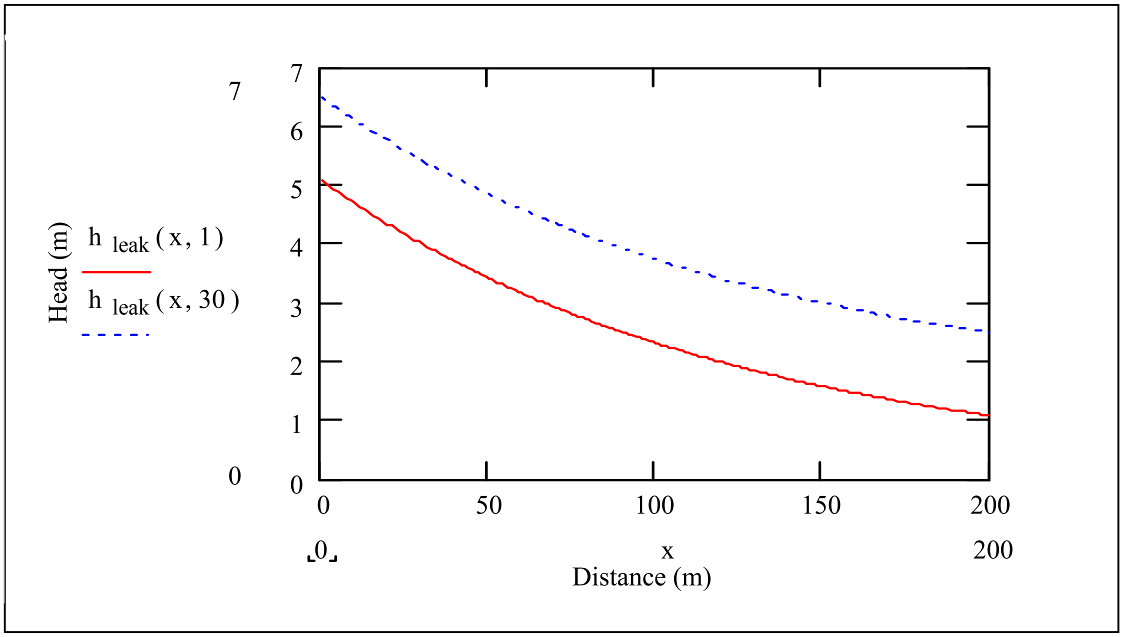


Fig. 4.5 Transient head development at t=1 day and 30 days by Laplace transform method with leakage, L=0.14 1/day/m of levee.

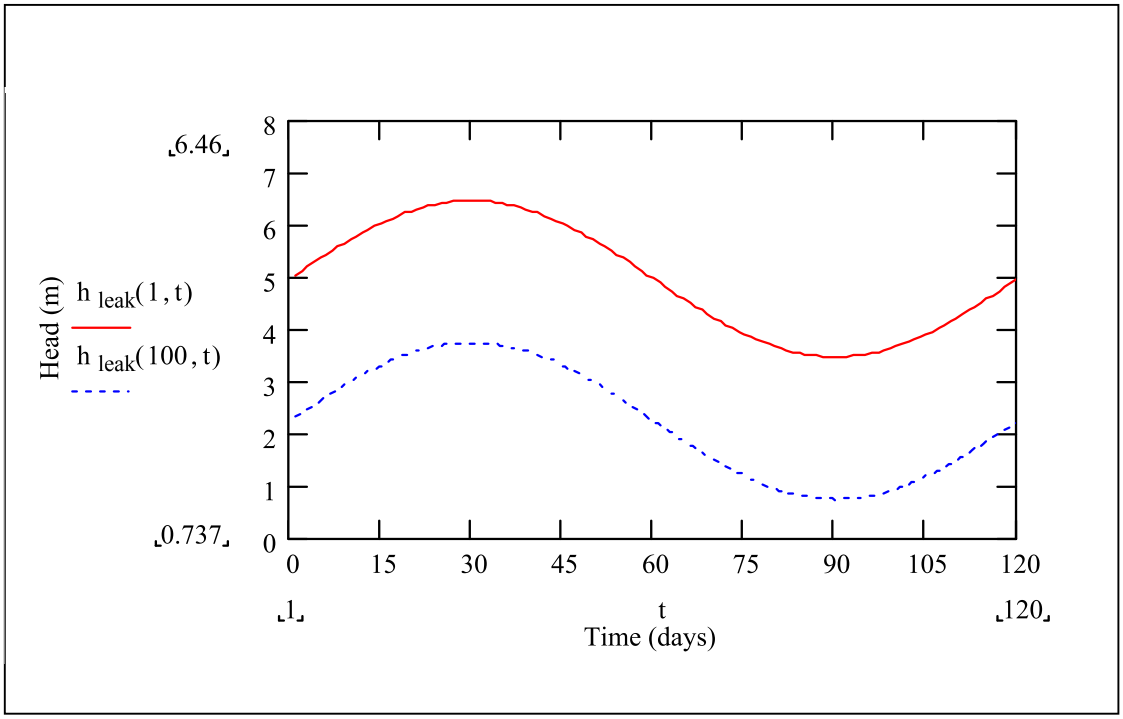


Fig. 4.6 Transient head development at x=1 m and x=100 m, levee toe, by Laplace transform method with leakage, L=0.14 1/day/m of levee.

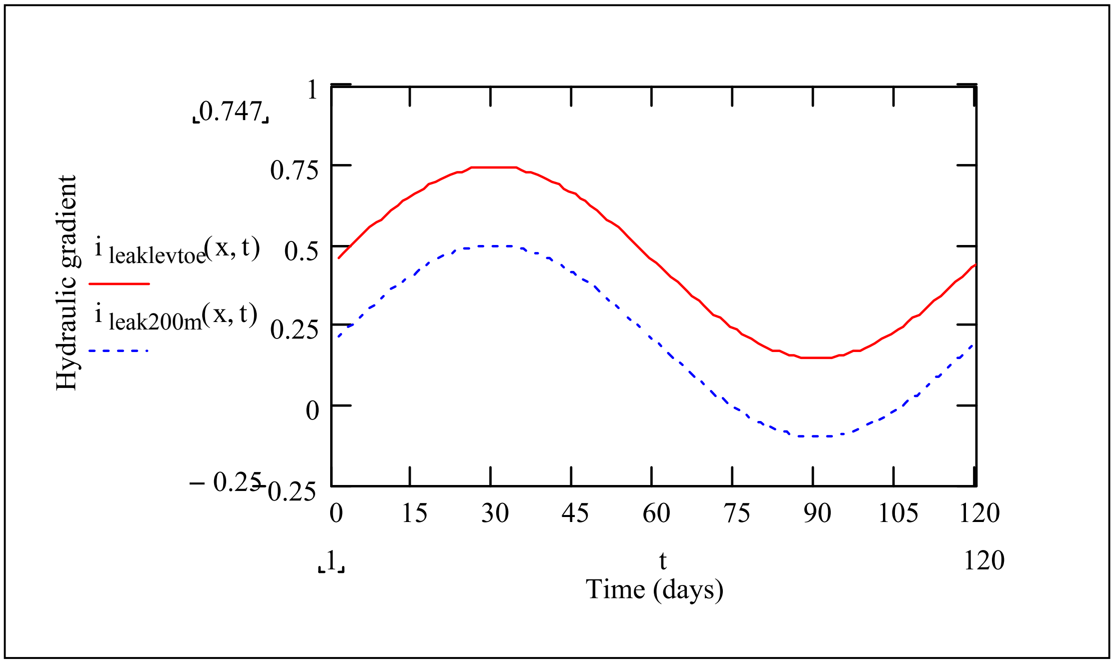


Fig. 4.7 Transient exit gradient at the levee toe and at 200 m landward of levee by Laplace transform method with leakage, L=0.14 1/day/m of levee.

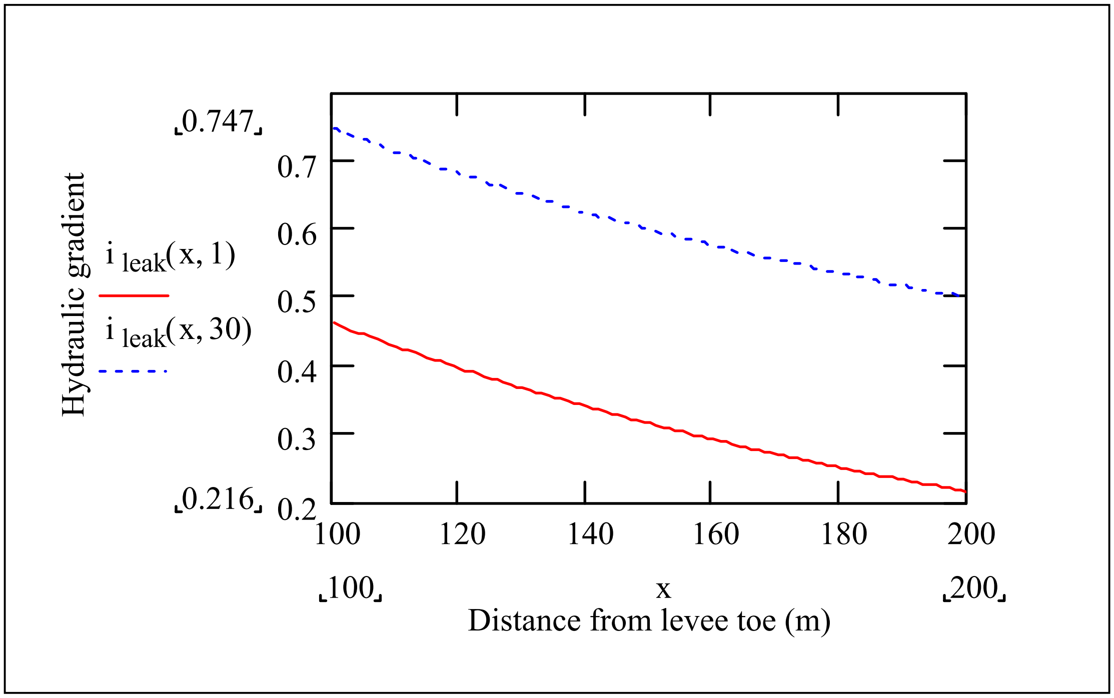


Fig. 4.8 Transient exit gradient at t=1 day and t=30 days at landside of the levee by Laplace transform method with leakage, L=0.14 1/day/m of levee.

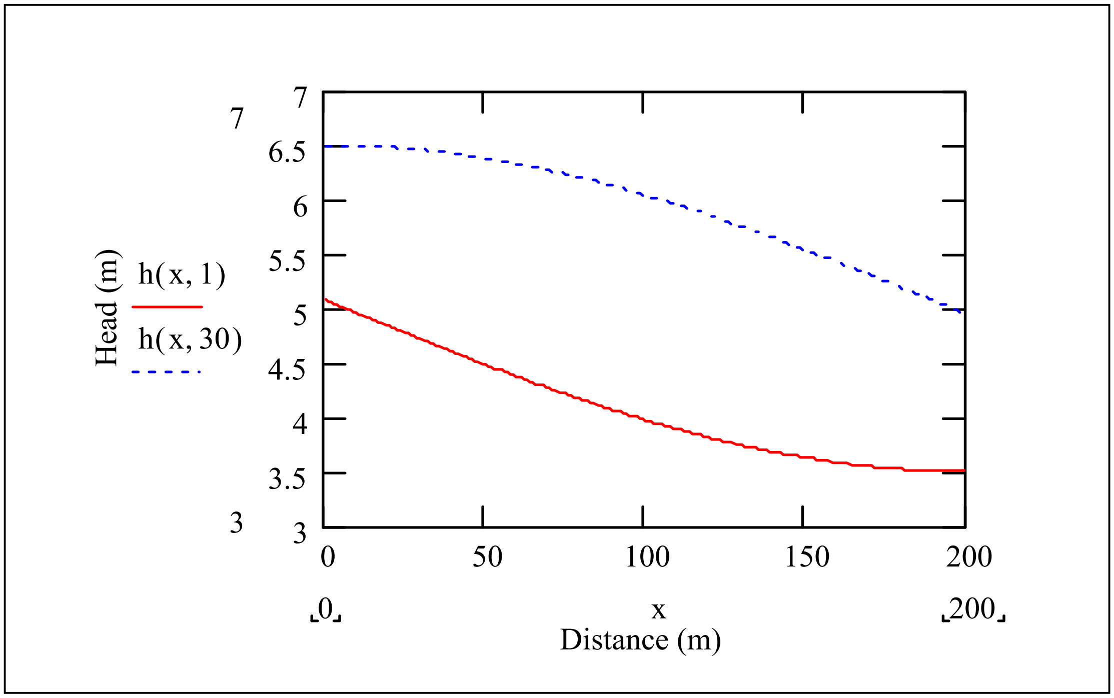


Fig. 4.9 Transient head development at t=1 day and 30 days by the approximate method with leakage, L=0.14 1/day/m of levee.

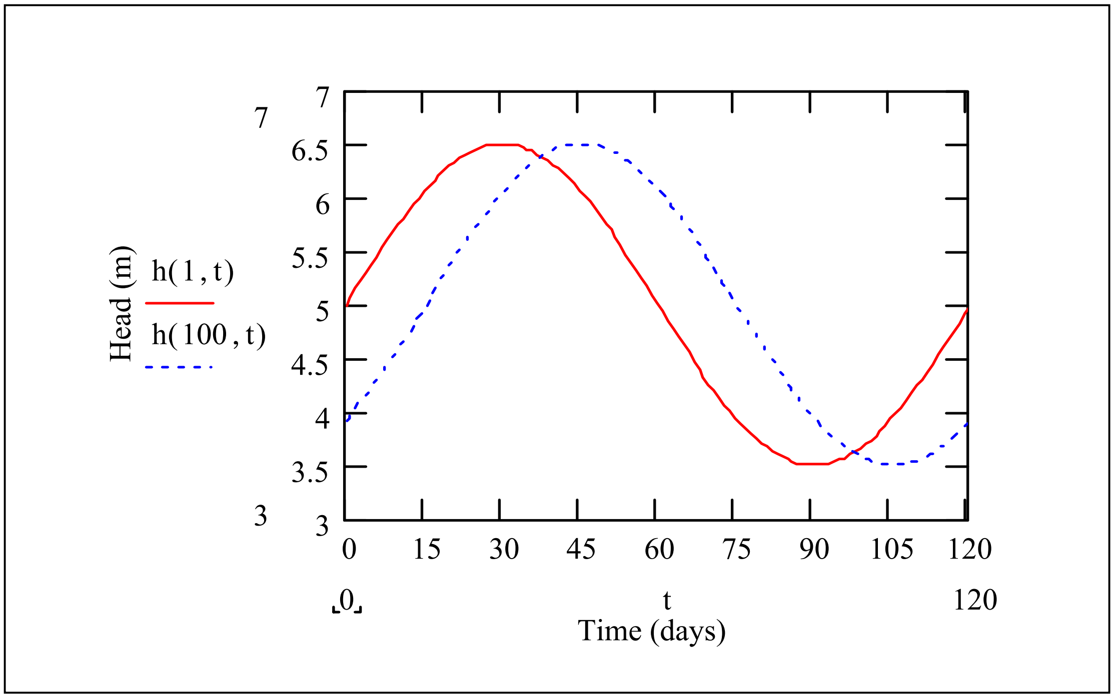


Fig. 4.10 Transient head development at x=1 m and x=100 m, levee toe, by the approximate method with leakage, L=0.14 1/day/m of levee.

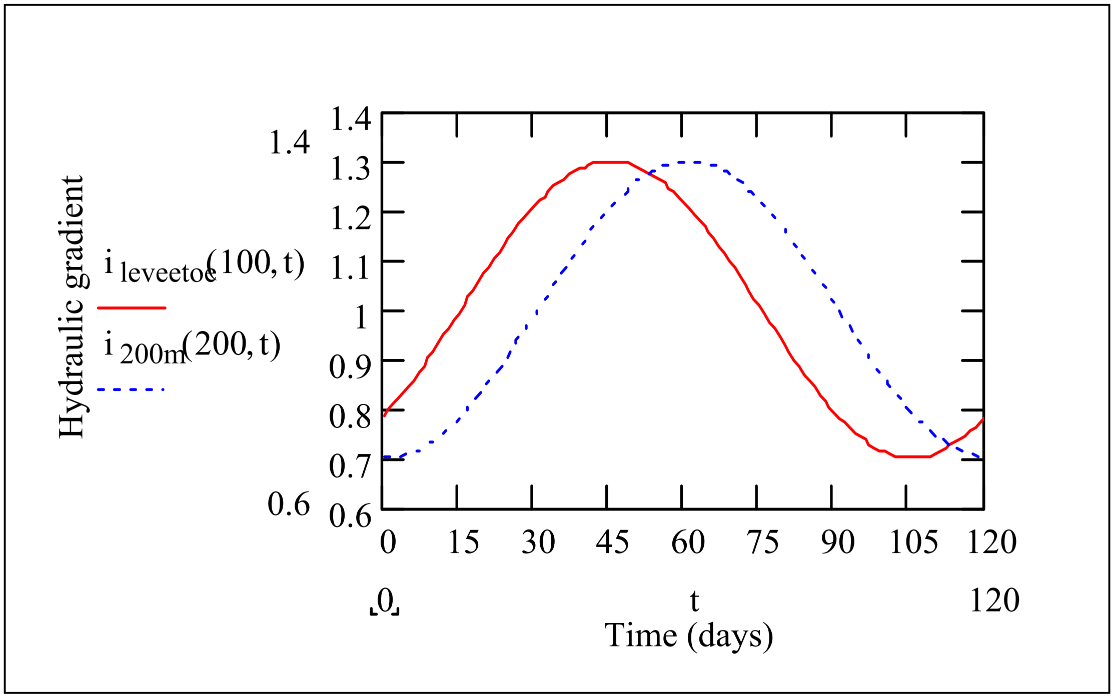


Fig. 4.11 Transient exit gradient at the levee toe and at 200 m landside of the levee by the approximate method with leakage, L=0.14 1/day/m of levee.

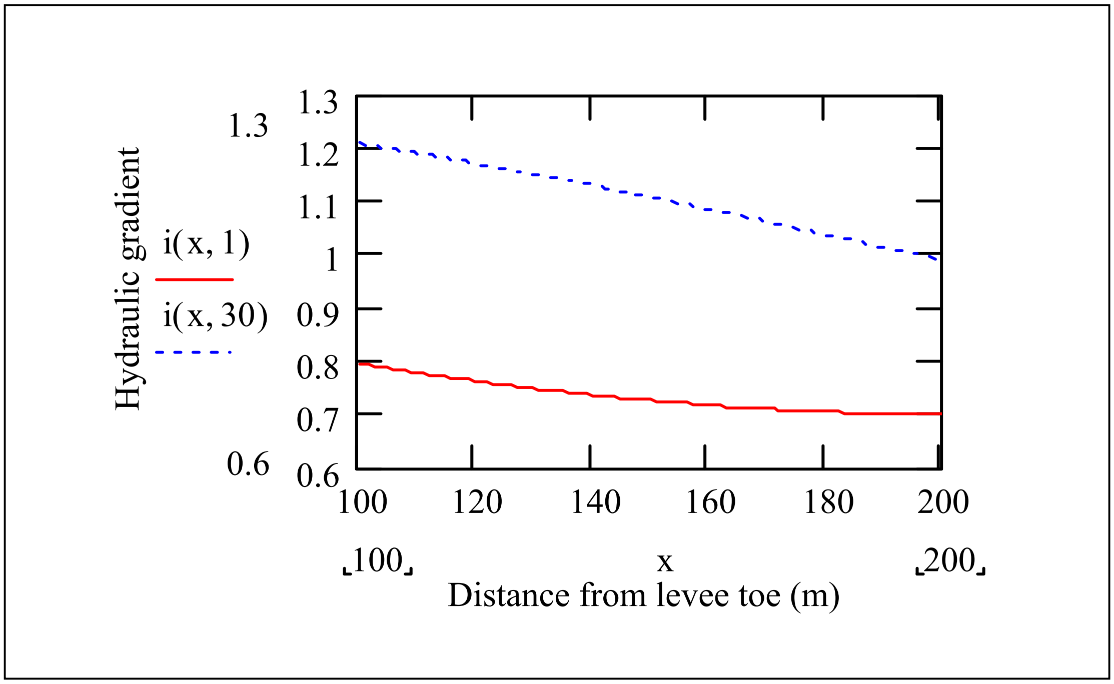


Fig. 4.12 Transient exit gradient at t=1 day and t=30 days at landside of the levee by the approximate method with leakage, L=0.14 1/day/m of levee.

In general, the Laplace transform solution gives higher decreases in head and hydraulic gradient with distance from the landside of the levee than does the approximate method does. The results are summarized in Table 4.1.

Table 4.1 Head and hydraulic gradient development by Laplace transform and approximate solution with a leakage of 0.14 1/day/m of levee.

	Time (days)	Laplace Transform Method	Approximate Method
Head at levee toe (m)	1	2.31	3.98
	30	3.73	6.04
Head at 100 m farther than levee toe (m)	1	1.08	3.50
	30	2.50	4.94
Hydraulic gradient at levee toe	1	0.46	0.80
	30	0.75	1.21
Hydraulic gradient at 100 m farther than levee toe	1	0.22	0.70
	30	0.50	0.99

Turnbull and Mansur (1962) reported that the exit gradient was in the range of 0.2 to 0.5 when there was 5 gal/min/100 feet of levee of seepage (Table 2.1). The Laplace transform solution results in an exit gradient of 0.75 at the levee toe and 0.22 at 100 m farther from the levee toe. As mentioned before, sand boils are most likely to occur within this distance. The approximate method results in an exit gradient in the range of 0.70 to 1.21, over the same distance, which is higher than the observed values in the field studies. Similarly, when there was 10 gal/min/100 feet of levee of seepage the exit gradient was reported to be in the range of 0.4 to 0.6 (Turnbull and Mansur, 1962). A seepage amount of 10 gal/min/100 feet of levee corresponds to a leakage of L = 0.28 1/day/m of levee (Equation 55). Figure 4.13 shows the exit gradient distribution by Laplace transform method for this case.

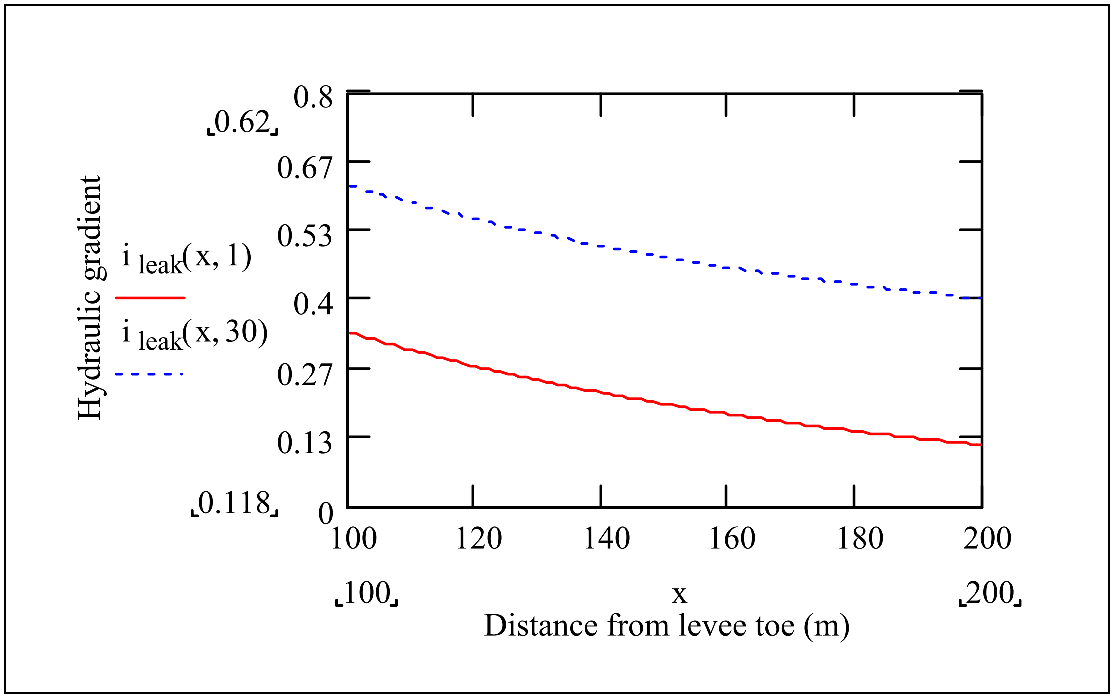


Fig. 4.13 Transient exit gradient at t=1 day and t=30 days at landside of the levee by Laplace transform method with leakage, L=0.28 1/day/m of levee.

As shown in Fig. 4.13, the exit gradient is in the range of 0.12 to 0.62 during the rising limb of flood wave from the levee toe to 100 m further than levee toe. The same condition is also analyzed by the approximate method. Figure 4.14 shows hydraulic gradient distribution by the approximate method when there is a leakage of 0.28 1/day/m of levee. Figure 4.14 shows that the exit gradient is in the range of 0.70 to 1.13 by the approximate method when there is a leakage corresponding to 10 gal/min/100 feet of levee. Table 4.2 summarizes this discussion. As shown in Table 4.2, the results of the transient analytical model with Laplace transform method coincide with the results of the limited number of field studies. However, the approximate method does not yield any close results to the field studies. In addition, the approximate solution shows very little dampening by time and distance as shown in Table 4.1 in response to upward leakage from the aquifer.

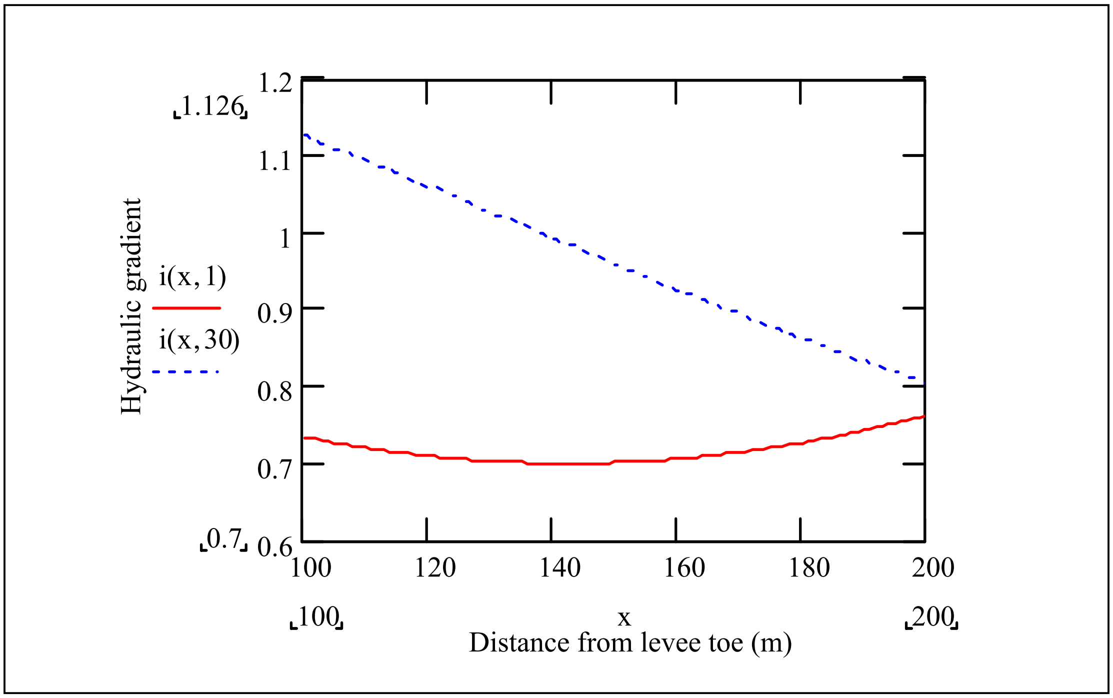


Fig. 4.14 Transient exit gradient at t=1 day and t=30 days at landside of the levee by the approximate method with leakage, L=0.28 1/day/m of levee.

Table 4.2 Exit gradient at landside of levee by Laplace transform method, approximate method and field observed values for Q=5 gal/min and 10 gal/min for 100 feet of levee.

Seepage Quantity (Leakage)	Location	Time (days)	Laplace Transform Method	Approximate method	Reported by Turnbull and Mansur (1961)
5 gal/min/100 feet of levee, (L=0.14 1/day/m of levee)	Levee toe	1	0.46	0.80	0.2-0.6
	100 m from levee toe	1	0.22	0.70	
	Levee toe	30	0.75	1.21	
	100 m from levee toe	30	0.50	0.99	
10 gal/min/100 feet of levee, (L=0.28 1/day/m of levee)	Levee toe	1	0.34	0.74	0.4-0.7
	100 m from levee toe	1	0.12	0.76	
	Levee toe	30	0.62	1.13	
	100 m from levee toe	30	0.40	0.85	

Both methods can be further investigated by using a more extensive summary of 1950 high water data at piezometer sites in the Lower Mississippi River Valley presented by Turnbull and Mansur (1961). The researchers concluded that the hydrostatic pressure ratio at the landside toe of the levee (h_0/H) varied from 20% to 75% depending on site and soil conditions. The same parameters were applied to the transient flow models and the results were presented in Table 4.3. The hydrostatic pressure ratio at the landside toe of the levee (h_0/H) varied from 21% to 75% by the Laplace transform method, and 3% to 99% by the approximate method (Table 4.3).

Table 4.3 Comparison of hydraulic head by Laplace transform method, approximate method and field observations of 1950 high water.

Site	H (ft)*	x (ft)*	Seepage (Q/H) (gpm/100 ft of levee)	h_0/H (%) (1950)	h_0/H (%) Laplace Trans. Method	h_0/H (%) Approx. Method
Caruthersville, MO	9.4	4,530	28	21	34	91
Gammon, AR	11.9	20,500	11.3	28	22	99
Commerce, MS	9.2	2,200	9.9	25	35	98
Trotters 51, MS	9.0	3,550	8.1	33	35	40
Trotters 54, MS	13.8	2,975	9.1	22	23	83
Stoval, MS	14.9	3,600	10	44	21	91
Farrell, MS	6.8	5,500	5.5	28	46	82
Upper Francis, MS	8.3	7,250	8.8	21	37	47
Lower Francis, MS	13.6	1,675	25.2	13	23	96
Bolivar, MS	6.5	1,830	15.6	37	49	3
Eutaw, MS	6.2	2,950	4.3	65	52	81
L'Argent, LA	16.4	2,880	1.1	35	20	98
Hole in the Wall, LA	10.4	2,600	3.5	13	31	57
Kelson, LA	16.7	1,180	0.015	28	75	96
Baton Rouge, LA	17.4	710	1.1	73	33	74

* H: height of flood stage, x: distance from landside toe of the levee to effective source of seepage entry.

In Table 4.3 seepage values were computed by using Bennett's (1946) analytical solutions as presented in The Army Engineer Manual (EM) 1110-2-1913 (Turnbull and Mansur, 1961). They also stated that about 64% of seepage flow rises to the surface between the landside levee toe and the effective seepage exit according to the blanket formulas. Therefore in the analysis, the leakage value was estimated as 64% of the computed seepage value for each site. According to the results presented in Tables 4.2

and 4.3, the Laplace Transform method performs well compared with the field observations.

Time Lag in Head Development

In the field, one would expect to observe a time difference in head development between the river, at the levee toe, and with distance on the landside of the levee. The Laplace Transform solution does not yield any significant time differences in head development at various distances (Fig. 4.15). This figure shows considerable dampening in head development by time due to leakage, however, little time lag occurs between the head curves at various distances.

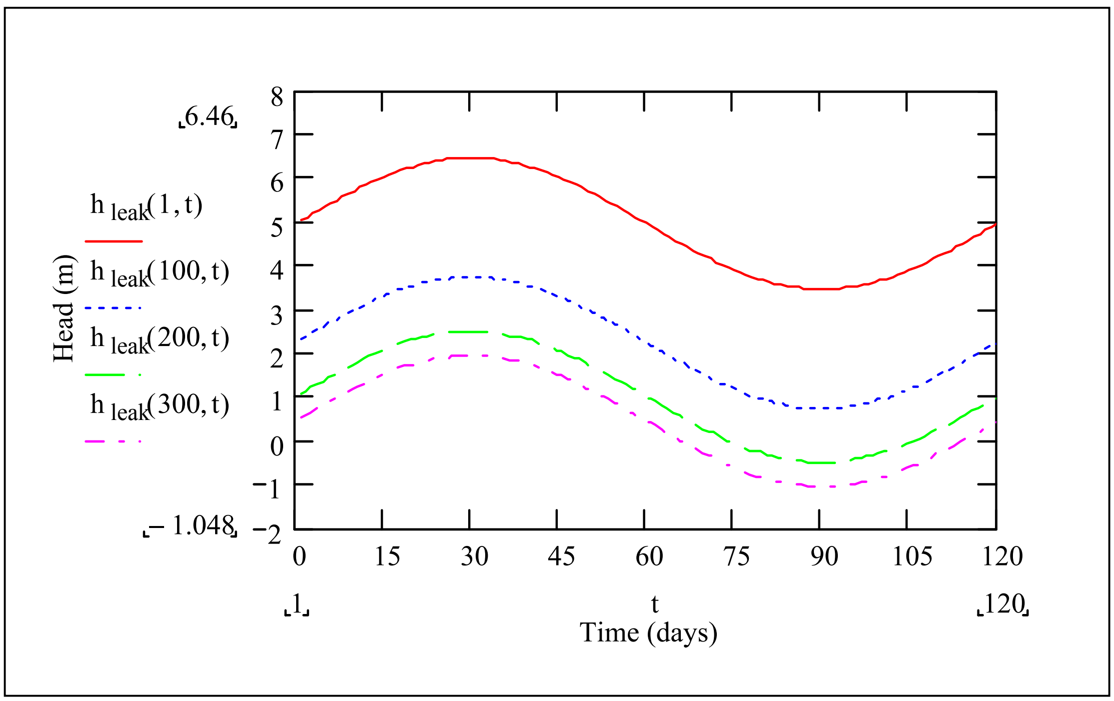


Fig. 4.15 Transient head development beneath the levee at various distances from the river by Laplace transform method.

As noted in Chapter 2 and Chapter 3, Ferris (1951) presented analytical expressions to determine aquifer diffusivity (T/S) based on the observed values of amplitude, lag, velocity, and wavelength of the sinusoidal changes in groundwater level.

If the time lag between river and groundwater maximum and minimum stages is known then aquifer diffusivity can be estimated by using the following formula (Engineer Manual, EM 1110-2-1421, Equation 6-9)

$$t_{lag} = d\sqrt{\frac{PS}{4\pi T}} \tag{4.56}$$

where t_{lag} is the lag time in the occurrence of the maximum groundwater stage following the occurrence of a similar surface stage, d is the distance from an observation well to the river, and P is the period of uniform tide or stage fluctuations. Equation 4.56 can be applied to time lag analysis of transient head development due to river fluctuations. If the same parameters as in the time lag analysis (d = 100 m, P = 60 days, S = 0.005, T = 2160 m^2/day) of the Laplace transform solution and the approximate method were applied to Equation 4.56, the time lag would result in 0.33 days for every 100-m of distance. This expression does not consider any leakage out of an aquifer. However, one would expect smaller time lags than 0.33 days between the head waves when leakage out of an aquifer occurs.

In addition, as noted in the literature review, according to the observations of a levee collapse near Marysville, California, there was one-day difference between the peak of the flood stage in Feather River and the collapse of the levee. Sand boils were also observed before the collapse of the levee. Part of the time delay may have been due to the time required for sand boils to erode channels or pipes under the levee, undermine it, and accelerate its failure. Also, at Louisiana State University, Dairy Farm, head and seepage rate in one existing sand boil responded very quickly to the river stage fluctuations. Therefore, the lack of time lag shown by the Laplace transform solution in Fig. 4.15 may not be unreasonable.

On the other hand, the approximate solution shows a significant time lag between head fluctuations. Figure 4.16 shows about a 15-day time difference between the peak points of head fluctuations for every 100-m distance from the river. A prediction of time lag between head waves determined from Equation 4.56 and limited field observations suggests that a 15-day time lag between the river and 100 m beyond the levee toe is not reasonable.

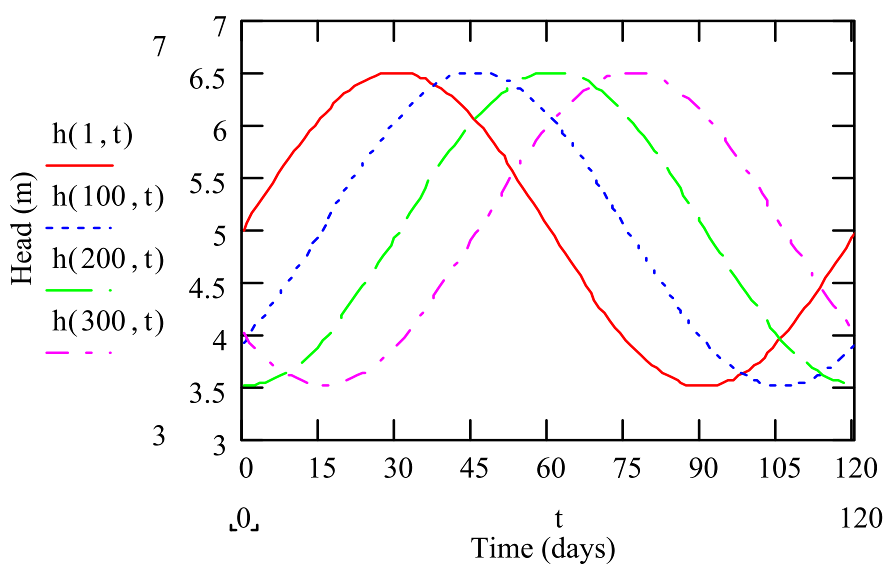


Fig. 4.16 Transient head development beneath the levee at various distances from the river by the approximate method.

The approximate solution was not nearly as accurate as the Laplace Transform solution and the field studies for estimating hydraulic head developments in a confined aquifer with an upward leakage. Therefore, the approximate solution was eliminated from further analysis of transient flow problems in this research.

4.5 Summary

Two transient flow models were developed to describe the hydraulic head development at the landside of a flood wall in response to head fluctuations in the river when there is leakage out of a confined aquifer. This situation simulates surface seepage and sand boil formation. The rising river stage was defined by a sinusoidally varying boundary condition. Both models consider one-dimensional saturated flow conditions in a homogenous isotropic confined aquifer. The first transient flow model was developed by solving the governing diffusion equation and the boundary conditions (Equation 4.1 through 4.4) with the Laplace transform method. This solution method is complicated and can only be evaluated by a mathematical software. Therefore, an approximate solution was also presented. The results were evaluated for a typical levee section.

The Laplace transform solution resulted in considerable head dissipation with time and distance in response to the upward seepage out of the aquifer. The hydraulic gradient by the Laplace transform method was evaluated for different leakage quantities as reported by Turnbull and Mansur (1962). The results were in agreement compared with the field studies. However, the Laplace transform solution did not show any significant time lag between the peak points of head waves at various distances. In other words, the effect of head fluctuations in the river was felt quickly at various distances from the landside of the levee when surface seepage was expected. According to very limited field observations, this was a reasonable result.

The approximate solution did not perform well compared with the limited field studies and the Laplace transform method. The solution showed little dampening in hydraulic head in response to the leakage out of the aquifer. It also showed an unreasonable time lag between head waves at various distances.

The main objective of this chapter was to develop transient flow models for leakage out of a confined aquifer by the Laplace transform method and by an approximate method. This objective was satisfied. The results of the analysis lead us to eliminate the approximate method from further analysis. The applicability and performance analysis of the transient flow model with Laplace transform method will be studied in the following chapters.

4.6 List of Symbols

a = constant in inverse Laplace Transform

A = unit area (L^2)

d = distance (L)

E(x, t) = an expression for a part of hydraulic head function

f_n = function used to calculate error function

F = real function used to calculate an error function

g_n = function used to calculate error function

ε = error of approximation

G = imaginary function used to calculate an error function

h = hydraulic head (L)

h(x, t) = hydraulic head function

Δh = hydraulic head difference (L)

h_0 = initial hydraulic head (L)

h_0 = head beneath top stratum at landside toe of levee (L)

H = height of flood stage (L)

H_0 = initial hydraulic head (L)

h_1 = amplitude of the variation from the initial hydraulic head (L)

H_1 = amplitude of the variation from the initial hydraulic head (L)

$\widetilde{H}(x,t)$ = a complex variable to define transformed hydraulic head function

$\overline{H}(x,t)$ = Laplace transform of $\widetilde{H}(x,t)$

i = imaginary unit where $i^2 = -1$

L = leakage (T^{-1})

I1, I2= imaginary part of a complex variable

n = index of summation

λ = a complex variable

p = real part of the complex variable λ

p = complex number in Laplace transform

P = period of uniform stage fluctuations (T)

r = inverse of length squared (L^{-2})

r_1 = frequency of a wave (T^{-1})

q = imaginary part of the complex variable λ

Q = seepage (L^3T^{-1})

R1, R2= real part of a complex variable

S = aquifer storativity (dimensionless)

t = time (T)

t_{lag} = time lag (T)

T = aquifer transmissivity (LT^{-2})

x = horizontal coordinate (L)

x = distance from landside toe of the levee to effective source of seepage entry (L)

y = variable in error function

Y(x, t) = transformed hydraulic head function (imaginary part of $\widetilde{H}(x,t)$)

z_t = thickness of landside top stratum

Z(x, t) = transformed hydraulic head function (real part of $\widetilde{H}(x,t)$)

θ = phase angle for frequency ratio

ω = frequency of the flood wave

CHAPTER 5 CONSTRUCTION OF TRANSIENT FLOW NETS

5.1 Introduction

The flow of water through soil is represented by flow nets. A flow net is formed by the network of flow lines and equipotential lines that illustrates graphically how the head or energy varies as water flows through a pervious medium. Flow lines characterize the average flow path of a particle of water from the upstream water to the downstream. The energy of flow is described by lines of equal potential called equipotential lines. A simple method to obtain a flow net is sketching. Other methods besides sketching include mathematical solutions, electrical analogs, viscous-flow models, small-scale laboratory flow models, the method of fragments, and numerical methods (Holtz and Kovacs, 1981).

The objective of this chapter was to construct time-dependent flow nets. The geometry of flow nets is not expected to change with time. Only the numerical values assigned to equipotential and flow lines change with time. The main reason to include such an analysis is because the literature provides little guidance on transient flow nets. To develop equations to construct time dependent flow nets could be an interesting contribution to the literature.

An analytical solution expressed as a flow net is actually a graphical solution of Laplace's equation in two dimensions:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 \tag{5.1}$$

In this analysis, time-dependent streamline and equipotential line equations were derived analytically by using complex variables. While complex variables have long been associated with two-dimensional steady flow, there are conditions in which time dependent boundary conditions can be introduced. The time dependent boundary condition on the riverside of the levee is

$$h(0, y, t) = h_0 + h_1 \sin(\omega t) \tag{5.2}$$

Here, two solutions of transient flow nets were presented; one for infinite-depth aquifers, and one for finite-depth aquifers. Mathematical analyses presented by Polubarinova-Kochina (1962) were followed. For transient flow nets in an infinite-depth aquifer case, Polubarinova-Kochina (1962) presented a problem with wave actions at both headwater and tail water of a hydraulic structure on a soil of infinite depth. Her examples were for standing waves such as a hydraulic jump that was a function of distance, but not time. Here, her analysis was modified for a time-dependent boundary condition representing a flood-wave. This solution allows us to draw a time-dependent flow net in an infinite-depth semi-confined aquifer. Polubarinova-Kochina (1962) also presented an analytical solution for flow net construction under a hydraulic structure on a layer of finite-depth confined aquifer. Again, her examples were for standing waves as a hydraulic jump that was a function of distance, but not time. The same methodology was followed and a time-dependent head term was introduced into her solution.

5.2 Construction of Transient Flow Nets for Infinite Depth Aquifers

Seepage flow in an infinite depth aquifer under a levee due to fluctuating river head is considered in this section (Fig. 5.1).

The complex potential is defined as $\omega(z) = \phi + i\psi$, which is a function of the complex variable, $z = x + iy$. A constant value of ϕ represents a line of constant head while a constant value of ψ represents a particular streamline.

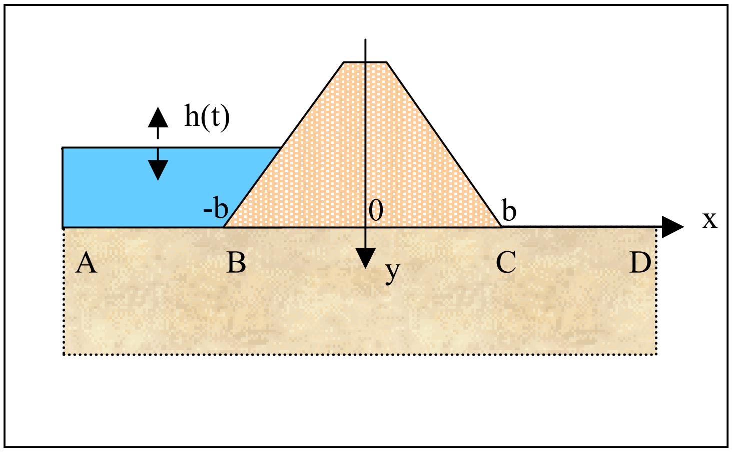


Fig. 5.1 Flow region in a soil of infinite-depth aquifer.

Polubarinova-Kochina (1962) introduced the complex function representing the conditions of the complex potential in the flow region

$$f(z) = \frac{\omega(z,t)}{\sqrt{z^2 - b^2}} \tag{5.3}$$

Polubarinova-Kochina (1962) explained the development of a velocity function representing the flow in a soil of infinite depth. A similar analogy is used in the development of the complex potential function, Equation 5.3. As is known

$$\sqrt{z^2 - b^2} = (z-b)^{1/2}(z+b)^{1/2} \tag{5.4}$$

The function (Equation 5.4) is real for $z < -b$ and $z > b$, and imaginary for $-b < z < b$. This expression satisfies the conditions in the flow region: along segment AB and CD, complex potential is real, $\psi = 0$, and along segment BC, complex potential is imaginary, $\phi = 0$. Now the complex potential function will be evaluated by applying Cauchy's integral formula,

$$f(a) = \frac{1}{2\pi i}\oint_C \frac{f(z)dz}{z-a} \tag{5.5}$$

where *f(z)* is an analytic function within and on a closed contour *C* of a simply connected region *R*, and point *a* is interior to *C*. Here, the value of function in the lower half-plane is evaluated

$$\frac{\omega(z,t)}{\sqrt{z^2-b^2}} = -\frac{1}{\pi i}\int_{-\infty}^{-b}\frac{\omega(\varsigma,t)d\varsigma}{\varsigma - z} \tag{5.6}$$

where

$$\omega(\varsigma,t) = \frac{\phi(\varsigma,t)}{\sqrt{\varsigma^2-b^2}} \tag{5.7}$$

The potential is defined in terms of the hydraulic conductivity and head as

$$\phi(\varsigma,t) = -k_h h(\varsigma,t) \tag{5.8}$$

where head fluctuation is represented by

$$h(\varsigma,t) = h_0 + h_1 \sin(\omega t) \tag{5.9}$$

Equations 5.6, 5.7, 5.8, and 5.9 lead to

$$\omega(z,t) = -\frac{k_h\sqrt{z^2-b^2}}{\pi i}\left\{h_0\int_{-\infty}^{-b}\frac{d\varsigma}{\sqrt{\varsigma^2-b^2}\,(\varsigma - z)} + h_1\sin(\omega t)\int_{-\infty}^{-b}\frac{d\varsigma}{\sqrt{\varsigma^2-b^2}\,(\varsigma - z)}\right\} \tag{5.10}$$

The solution of the integral in Equation 5.10 is listed by Petit Bois (1961)

$$\int\frac{dx}{(r^2x+pq)\sqrt{r^2x^2-q^2}} = -\frac{1}{qr\sqrt{r^2-p^2}}\arcsin\frac{prx+qr}{r^2x+pq} \tag{5.11}$$

If $r = 1$, $q = b$ and $p = -z/b$, the integral is evaluated as

$$\int_{-\infty}^{-b}\frac{d\varsigma}{\sqrt{\varsigma^2-b^2}\,(\varsigma - z)} = -\frac{1}{\sqrt{b^2-z^2}}\left(\arcsin\left(-\frac{z}{b}\right)-\frac{\pi}{2}\right) \tag{5.12}$$

Equation 5.12 is substituted into Equation 5.10 to obtain the complex potential

$$\omega(z,t) = -\frac{k_h\sqrt{z^2-b^2}}{\pi i}\left\{\begin{array}{l}\dfrac{-1}{\sqrt{b^2-z^2}}h_0\left(\dfrac{\pi}{2}-\arcsin\left(\dfrac{z}{b}\right)\right)\\[2ex]+\dfrac{-1}{\sqrt{b^2-z^2}}h_1\sin(\omega t)\left(\dfrac{\pi}{2}-\arcsin\left(\dfrac{z}{b}\right)\right)\end{array}\right\} \tag{5.13}$$

where

$$\arccos\left(\frac{z}{b}\right) = \frac{\pi}{2}-\arcsin\left(\frac{z}{b}\right) \tag{5.14}$$

so $\omega(z,t)$ is reduced to,

$$\omega(z,t) = -\frac{k}{\pi}(h_0 + h_1\sin(\omega t))\arccos\left(\frac{z}{b}\right) \tag{5.15}$$

and

$$z = b\cos\frac{\omega(z,t)\pi}{k_h(h_0 + h_1\sin(\omega t))} \tag{5.16}$$

Equation 5.16 can be separated into real and imaginary parts by using the following properties $z = x + iy$ and $\omega(z,t) = \phi(z,t) + i\psi(z,t)$. These properties lead to Equation 5.16 becoming

$$\cos(\omega) = \cos\phi\cos\psi - i\sin\phi\sin\psi \tag{5.17}$$

and

$$x = b\cos\phi_1\cosh\psi_1 \tag{5.18}$$

$$y = -b\sin\phi_1\sinh\psi_1 \tag{5.19}$$

where

$$\phi_1 = \frac{\phi\pi}{k_h(h_0 + h_1\sin(\omega t))} \tag{5.20}$$

$$\psi_1 = \frac{\psi\pi}{k_h(h_0 + h_1\sin(\omega t))} \tag{5.21}$$

The streamline and equipotential line equations are derived from the relationships:

$\sin^2\phi_1 + \cos^2\phi_1 = 1$ and $\cosh^2\psi_1 - \sinh^2\psi_1 = 1$ with the results:

$$\frac{x^2}{b^2\cosh^2\psi_1} + \frac{y^2}{b^2\sinh^2\psi_1} = 1 \tag{5.22}$$

which gives ellipses for the stream lines, and

$$\frac{x^2}{b^2\cos^2\phi_1} - \frac{y^2}{b^2\sin^2\phi_1} = 1 \tag{5.23}$$

which gives hyperbolas for the equipotential lines. Equations 5.22 and 5.23 are used to draw flow nets for a confined flow under a levee on soil of infinite depth aquifer with a fluctuating reservoir boundary.

The velocity distribution can be evaluated by taking the derivative of the complex potential given by Equation 5.15:

$$\frac{d}{dz}\omega(z,t) = -\frac{k_h}{\pi}(h_0 + h_1\sin(\omega t))\frac{d}{dz}\arccos\left(\frac{z}{b}\right) \tag{5.24}$$

$$\frac{d}{dz}\omega(z,t) = -\frac{k_h}{\pi}(h_0 + h_1\sin(\omega t))\frac{-1}{\sqrt{1-\frac{z^2}{b^2}}}\frac{1}{b} \tag{5.25}$$

The relationships $\frac{d}{dz}\omega(z,t) = u + iv$ where u and v are the velocity components in the x and y directions, respectively, give the result

$$u(z,t) + iv(z,t) = \frac{k_h}{\pi}(h_0 + h_1\sin(\omega t))\frac{1}{\sqrt{b^2 - z^2}} \tag{5.26}$$

As mentioned above z is a complex variable so that Equation 5.26 becomes:

$$u(z,t) + iv(z,t) = \frac{k_h}{\pi}(h_0 + h_1\sin(\omega t))\frac{1}{\sqrt{b^2 - x^2 - i2xy + y^2}} \tag{5.27}$$

Along the landside of levee, along CD in Fig. 5.1, $y = 0$ is substituted into Equation 5.27 to obtain the horizontal component of velocity:

$$u(x,0,t) = \frac{k_h}{\pi}(h_0 + h_1 \sin(\omega t))\frac{1}{\sqrt{b^2 - x^2}} \tag{5.28}$$

and the vertical component of the velocity is derived by multiplying numerator and denominator of Equation 5.28 by complex number, $i = \sqrt{-1}$ to obtain

$$v(x,0,t) = \frac{k_h}{\pi}(h_0 + h_1 \sin(\omega t))\frac{1}{\sqrt{x^2 - b^2}} \tag{5.29}$$

The exit gradient, i_e, is evaluated by using the relationship, $v = k_h i_e$

$$i_e = \frac{1}{\pi}(h_0 + h_1 \sin(\omega t))\frac{1}{\sqrt{x^2 - b^2}} \tag{5.30}$$

Equation 5.30 is used to calculate the exit gradient along the landside of the levee where $x \geq b$. This equation implies that in the vicinity of $x = b$, the toe of the levee as seen in Fig. 5.1, the exit gradient is unbounded, and there exists in this area the danger of piping. Of course, as the velocity becomes greater, Darcy's equation is no longer valid so a prediction of an infinite velocity at the levee toe is not literally true. Still the levee toe is a vulnerable location for high velocity and piping.

5.3 Construction of Transient Flow Nets for Finite Depth Aquifers

Flow in a finite depth aquifer is considered. Equations to draw transient flow nets for a confined flow under a levee on soil of finite depth aquifer are developed. The strip flow region in the z-plane is mapped onto the lower ζ half plane (Fig. 5.2). The Schwartz-Christoffel formula is used for the transformation (Harr, 1962):

$$z = Mk^2 \int_0^{\varsigma} \frac{d\varsigma}{1 - k^2 \varsigma^2} \tag{5.31}$$

where M and k are some numbers and will be determined after further analysis. The integral in Equation 5.31 is evaluated as

$$z = \frac{M}{2k} \ln \frac{1 + k\varsigma}{1 - k\varsigma} \tag{5.32}$$

The length of the base, BC is *2b.* For $\zeta = \pm 1$, $z = \pm b$, then

$$l = \frac{M}{2k} \ln \frac{1 + k}{1 - k} \tag{5.33}$$

Walking around the point $\zeta = 1/k$ in the lower half plane in Fig. 5.2 corresponds to jumping from segment CD to DE in the z-plane, and gives an increase of $-\pi i$. This value also corresponds to the change in the imaginary part of z, from $y = 0$ to $y = -B$, which is the thickness of the aquifer. Therefore,

$$\Delta z = -Bi = -\frac{M}{2k} \pi i \tag{5.34}$$

So, M is found as

$$M = \frac{2kB}{\pi} \tag{5.35}$$

Then, M is substituted into Equation 5.33 to obtain

$$l = \frac{B}{\pi} \ln \frac{1 + k}{1 - k} \tag{5.36}$$

and k is found as

$$k = \tanh \frac{\pi b}{2B} \tag{5.37}$$

In order to solve for z, we use elliptic integrals. The elliptic integral of the first kind in canonical form is

$$u = \int_0^{\zeta} \frac{d\zeta}{\sqrt{(1 - \zeta^2)(1 - k^2 \zeta^2)}} \tag{5.38}$$

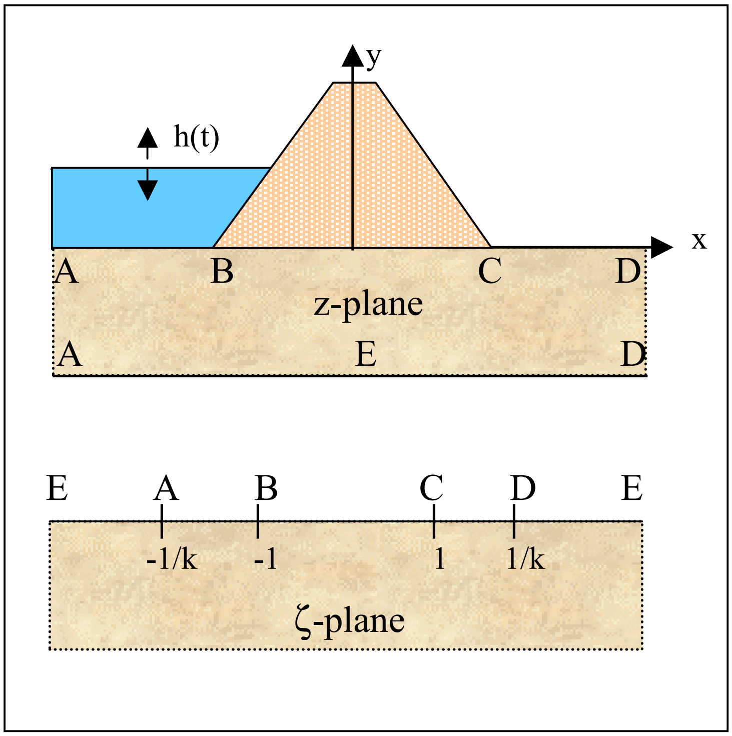


Fig. 5.2 Flow region in z-plane and ζ-plane.

where the elliptic sine is also introduced as

$$\varsigma = sn\, u \tag{5.39}$$

and

$$u = \frac{2K\omega}{k_h h(x,t)} \tag{5.40}$$

where K is complete elliptic integral of the first kind with modulus m, k_h is hydraulic conductivity of the aquifer, and

$$h(x,t) = h_0 + h_1 \sin(\omega t) \tag{5.41}$$

Then z is developed as

$$z = \frac{B}{\pi} \ln \frac{1 + k\, sn\, u}{1 - k\, sn\, u} \tag{5.42}$$

Equation 5.42 is differentiated and evaluated as

$$z' = \frac{B}{\pi} 2k \frac{cn\,u}{dn\,u} \tag{5.43}$$

where elliptic functions; $cn\,u = \sqrt{1 - sn^2 u}$ and $dn\,u = \sqrt{1 - k^2 sn^2 u}$, and the ratio $\frac{cn\,u}{dn\,u}$ is developed into the trigonometric series as

$$z = \frac{4B}{\pi}\left\{ \frac{\cos\left(\frac{\pi\omega}{k_h h(x,t)}\right)}{\sinh\left(\frac{\pi K'}{2K}\right)} + \frac{\cos\left(\frac{3\pi\omega}{k_h h(x,t)}\right)}{3\sinh\left(\frac{3\pi K'}{2K}\right)} + \frac{\cos\left(\frac{5\pi\omega}{k_h h(x,t)}\right)}{5\sinh\left(\frac{5\pi K'}{2K}\right)} + \ldots \right\} \tag{5.44}$$

where *B* is the depth of aquifer, K' is the complete elliptic integral of the first kind with complementary modulus m' and *K* is the complete elliptic integral of the first kind with modulus *m.* Harr (1962) presents a table for complete elliptic integrals of the first kind.

As mentioned before, $\omega(z) = \phi + i\psi$ is a function of the complex variable, $z = x + iy$, where ϕ and ψ are constants representing constant potential and stream functions. Equation 5.48 can be separated into its real and imaginary parts:

$$x = \frac{4B}{\pi}\left\{ \frac{\cos\left(\frac{\pi\phi}{k_h h(x,t)}\right)\cosh\left(\frac{\pi\psi}{k_h h(x,t)}\right)}{\sinh\left(\frac{\pi K'}{2K}\right)} + \frac{\cos\left(\frac{3\pi\phi}{k_h h(x,t)}\right)\cosh\left(\frac{3\pi\psi}{k_h h(x,t)}\right)}{3\sinh\left(\frac{3\pi K'}{2K}\right)} + \ldots \right\} \tag{5.45}$$

$$y = -\frac{4B}{\pi}\left\{ \frac{\sin\left(\frac{\pi\phi}{k_h h(x,t)}\right)\sinh\left(\frac{\pi\psi}{k_h h(x,t)}\right)}{\sinh\left(\frac{\pi K'}{2K}\right)} + \frac{\sin\left(\frac{3\pi\phi}{k_h h(x,t)}\right)\sinh\left(\frac{3\pi\psi}{k_h h(x,t)}\right)}{3\sinh\left(\frac{3\pi K'}{2K}\right)} + \ldots \right\} \tag{5.46}$$

Along the boundary CD of Fig. 5.1, the velocity is

$$v = \frac{k_h h(x,t)\pi}{4KB} \frac{\cosh\left(\frac{\pi b}{2B}\right)}{\sqrt{\sinh\left(\frac{\pi(b+x)}{2B}\right)\sinh\left(\frac{\pi(x-b)}{2B}\right)}} \tag{5.47}$$

Then, the exit gradient, i_e, is evaluated by using the relationship, $v = k_h i_e$, so that

$$i_e = \frac{h(x,t)\pi}{4KB} \frac{\cosh\left(\frac{\pi b}{2B}\right)}{\sqrt{\sinh\left(\frac{\pi(b+x)}{2B}\right)\sinh\left(\frac{\pi(x-b)}{2B}\right)}} \tag{5.48}$$

In conclusion, Equations 5.45 and 5.46 are used to draw flow nets for a confined flow under a levee on soil of finite depth aquifer with a fluctuating reservoir boundary. Equation 5.48 is used to calculate the exit gradient along the landside of the levee.

5.4 Results and Discussion

Exit gradients on the landside of the levee on an infinite depth aquifer can be calculated using Equation 5.30. A schematic view of the problem is in Fig. 5.3.

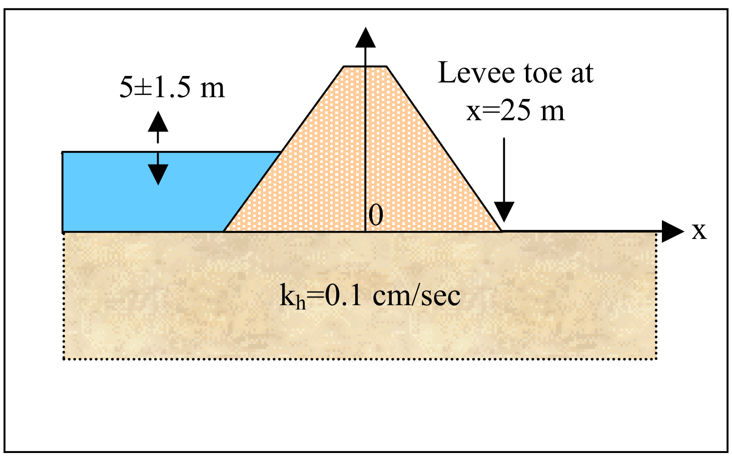


Fig. 5.3 A schematic view of the problem (not in scale).

A net head of 5 m, and a fluctuation of 1.5 m were selected in the analysis. The flood duration was selected as 60 days. The initial head of 5 m rises to the peak of 6.5 m at time=30 days, and falls back to 5 m at time=60 days. The base width of the levee was selected as 50 m. As shown in Equation 5.30, the exit gradient for infinite depth aquifers is not dependent on the thickness of the aquifer. The hydraulic gradient distribution for the confined flow in a soil of an infinite depth aquifer is shown in Fig. 5.4 and 5.5.

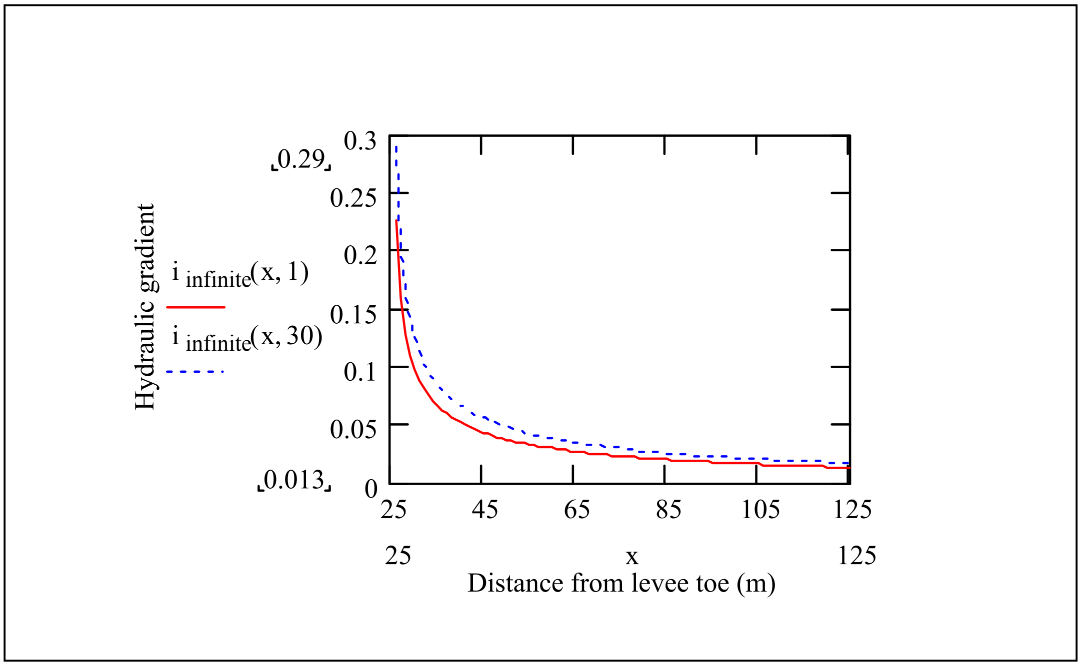


Fig. 5.4 Transient exit gradient at t=1 day and t=30 days on landside of the levee on a soil of infinite depth aquifer.

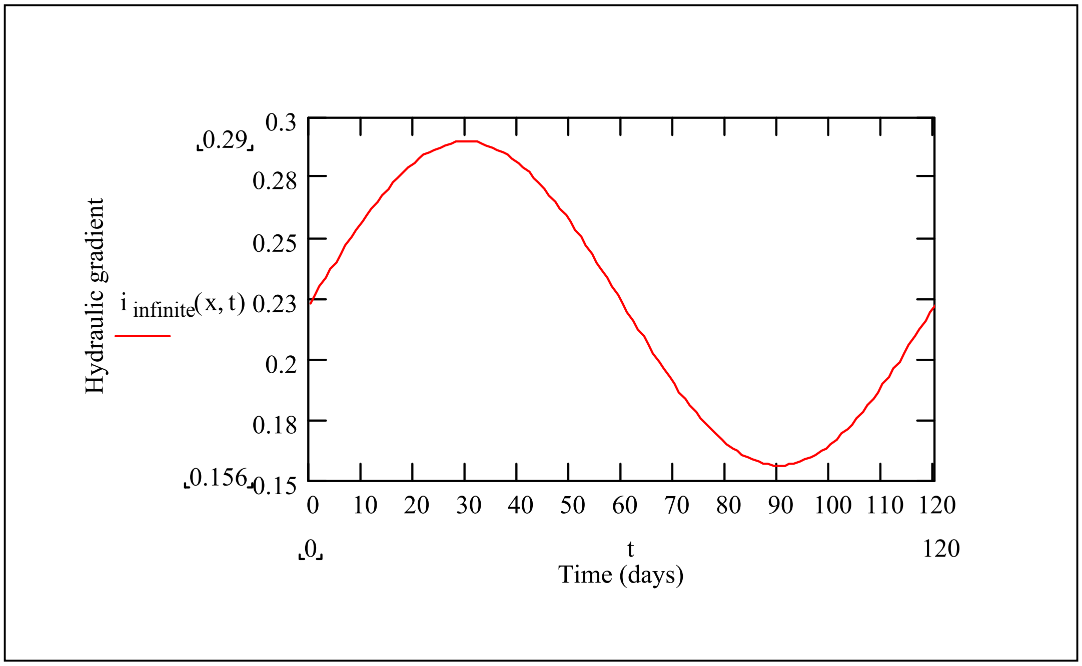


Fig. 5.5 Transient exit gradient at the levee toe on a soil of infinite depth aquifer.

A transient flow net for infinite depth aquifers can be drawn by using Equation 5.22 and 5.23. Figure 5.6 shows the flow net for horizontal and vertical hydraulic conductivity of k_h = 0.1 cm/sec, and time, t = 30 days, when the head fluctuation makes its peak, h = 6.5 m in the river. Although transient flow net equations were used to draw the flow net, there exists only one flow net for a certain cross section of levee. In other words, the shape of the flow net does not change with time but the numerical values of the streamlines and equipotential lines change with time.

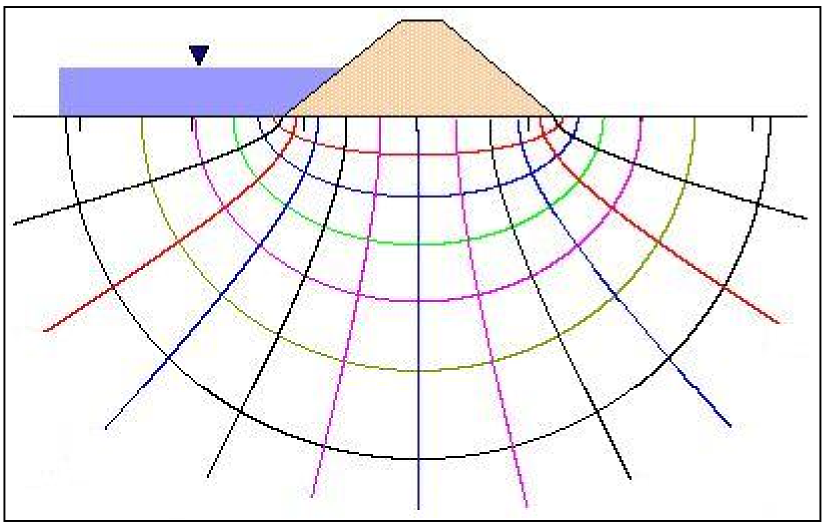


Fig. 5.6 Transient flow net for infinite depth aquifers, h=6.5 m in the river, k=0.1 cm/sec, t=30 days.

The aquifer thickness for the finite depth aquifer case is taken as 50 m. A scheme of the problem is shown in Fig. 5.7. Equation 5.48 is used to calculate the hydraulic gradient distribution for the confined flow in a soil of finite depth aquifer. The results are shown in Fig. 5.8 and 5.9. If a scaled flow net is drawn, the exit gradient shown in Fig. 5.8 is reasonable, and it fluctuates depending on the fluctuations in the river as shown in Fig. 5.9.

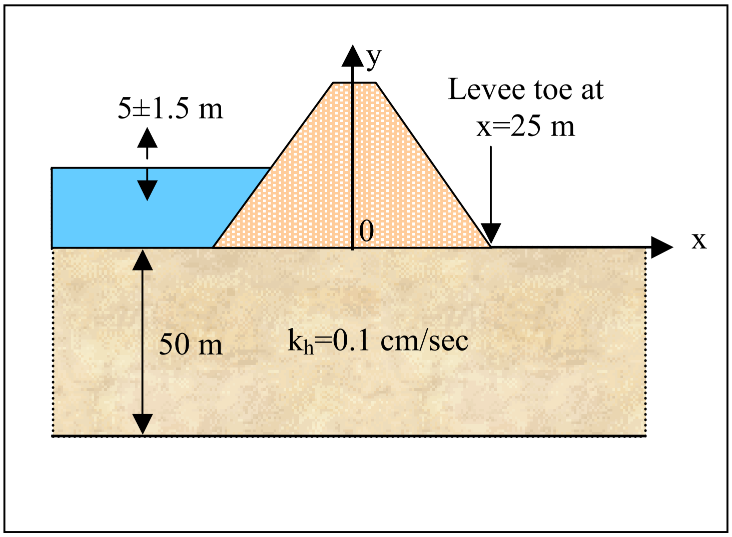


Fig. 5.7 A schematic view of the problem (not in scale).

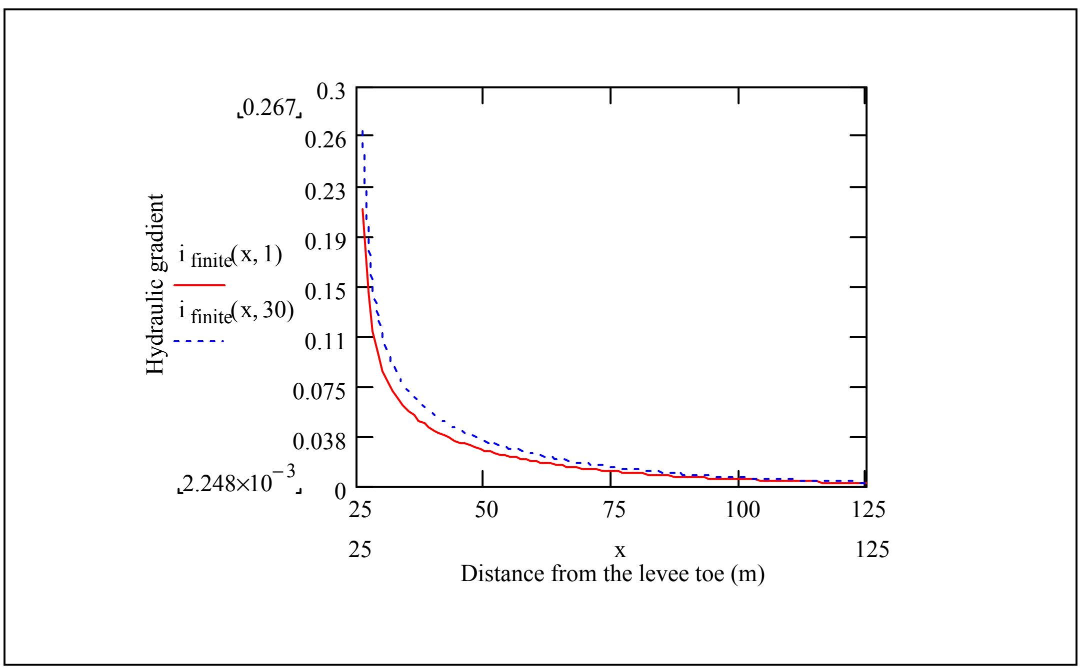


Fig. 5.8 Transient exit gradient at t=1 day and t=30 days on landside of the levee on a soil of finite depth aquifer.

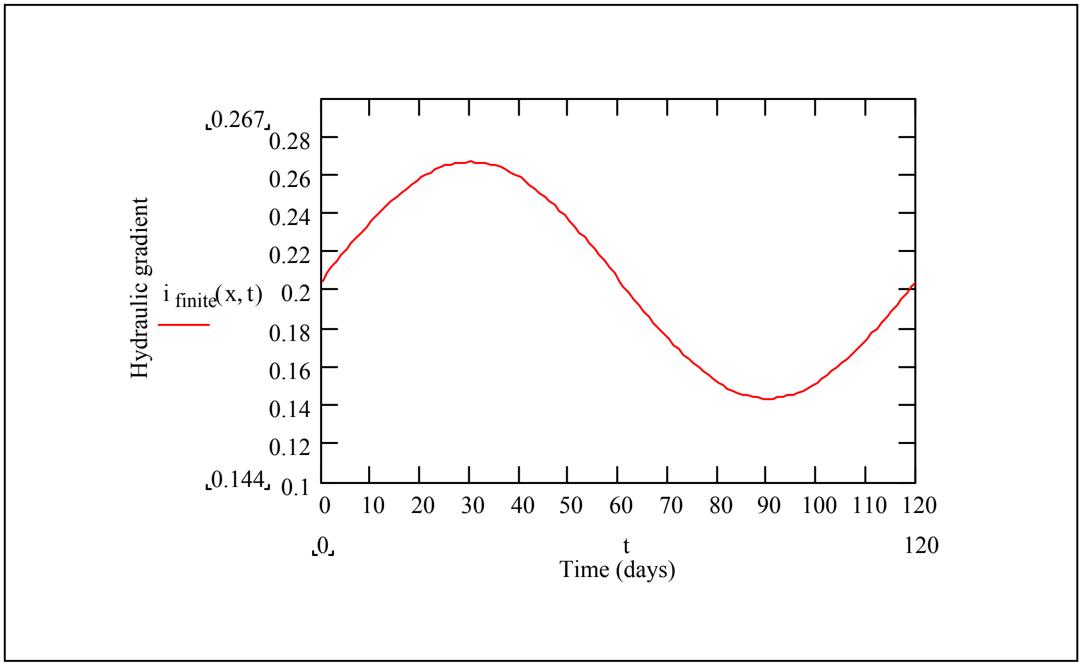


Fig. 5.9 Transient exit gradient at the levee toe on a soil of finite depth aquifer.

A transient flow net for finite depth aquifers can be drawn by using Equations 5.45 and 5.46. Figure 5.10 shows the flow net for vertical and horizontal hydraulic conductivity, k_h = 0.1 cm/sec, and time, t = 30 days, when the head fluctuation makes its peak, h = 6.5 m in the river.

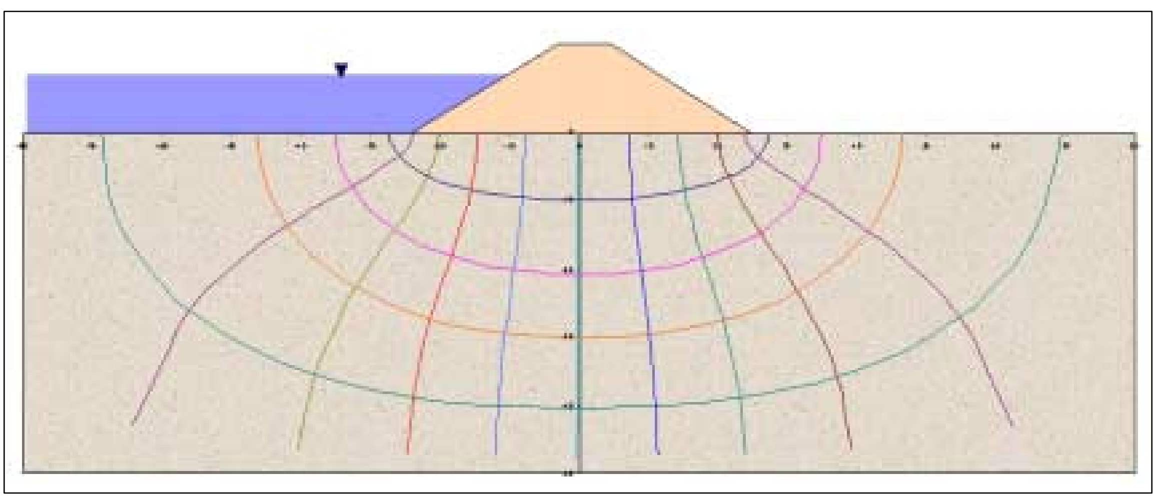


Fig. 5.10 Transient flow net for finite depth aquifers, h=6.5 m in the river, k=0.1 cm/sec, t=30 days, aquifer depth=50 m.

Again, although transient flow net equations were used to draw the flow net, there exists only one flow net for a certain cross section of levee. However, the numerical values assigned to equipotential and flow lines change with time depending on the river head fluctuations

5.5 Summary

In this chapter, time dependent flow nets were constructed. Two solutions were provided; one for infinite depth aquifers and one for finite depth aquifers. The methodologies given by Polubarinova-Kochina (1962) were followed in both solutions. The assumptions and the conditions in her solutions were maintained for the coordinate $y = 0$; a downward vertical flow on the riverside of the levee, a horizontal flow under the levee, and an upward vertical flow at the landside of the levee.

The flow nets were constructed for isotropic flow conditions. Exit gradients were also evaluated. The results look very reasonable. As noted before, the geometry of the flow nets does not change with time, however the numerical values assigned to the equipotential lines and flow lines change with time due to head fluctuations. The governing equations to the two-dimensional transient flow problem did not contain storage terms so the streamlines and equipotential lines responded instantaneously to changes in flood elevation.

The main objective of this chapter was to construct transient flow nets. This objective was satisfied. An analytical solution for a transient flow net has not been reported in the literature. The solutions presented here could be interesting to the engineering community.

5.6 List of Symbols

b = horizontal distance (L)

B = vertical distance (L)

cn u, dn u, sn u = Jacobian elliptic functions

$f(z)$ = complex function

h = hydraulic head (L)

h_0 = initial hydraulic head (L)

h_1 = amplitude of the variation from the initial hydraulic head (L)

i = imaginary unit where $i^2 = -1$

i_e = exit hydraulic gradient

k_h = hydraulic conductivity of soil

K = complete elliptic integral of the first kind with modulus m

K' = complete elliptic integral of the first kind with complementary modulus m'

M, k, l, ζ = constants used in Schwartz-Christoffel formula

p, q, r = constants used in the solution of an integral (Eqn. 5.11)

t = time (T)

T = time dimension

u, u(z,t), u(x,t) = velocity component in x-direction

u = elliptic integral function

v, v(z,t) = velocity component in y-direction

x = horizontal coordinate (L)

y = vertical coordinate (L)

φ = potential function

ψ = stream function

ζ = complex variable

$\omega(z)$, $\omega(z, t)$ = complex potential

ω = frequency (T^{-1})

z = complex variable

CHAPTER 6 PERFORMANCE ANALYSIS

6.1 Introduction

The objective of this chapter was to compare hydraulic head and exit gradient development beneath a levee by the transient flow models developed in Chapters 3 and 4 with commonly used seepage analysis methods. This section also explored whether transient effects are critical to the development of exit hydraulic gradients, which may lead to sand boil formation.

The transient flow model developed in Chapter 3 is applicable to homogeneous confined aquifers while the flow model developed in Chapter 4 is applicable for a leaky confined aquifer. These transient models were compared with the steady-state models: Army Corps EM 1110-2-1913 method and SEEP2D finite element analysis.

Two-dimensional transient flow net analysis was not used for comparisons. The main focus of this research is one-dimensional transient flow study. A comparison of two-dimensional transient flow net analysis with one-dimensional transient flow models would not be applicable.

Performance of the transient flow models was analyzed using the parameters of the cross section of a typical Mississippi Valley confined aquifer. A typical levee section was selected according to the dimensions set in the Department of Army, Engineer Manual, Design and Construction of Levees, EM 1110-2-1913 (2000). The thickness of sandy alluvium under Mississippi River levees changes from 25 m to 45 m. Horizontal hydraulic conductivity of pervious medium is in the range of 0.1-0.2 cm/sec (Turnbull and Mansur 1961). Typical storativity values for confined aquifers are $5x10^{-3}$, $5x10^{-4}$, $5x10^{-5}$ (Freeze and Cherry, 1979). In 1993, the net hydraulic head of the middle Mississippi River levees during floods were recorded as 4.8 m to 6.7 m above the landside of the levee (Mansur *et al*. 2000). Therefore, a net head of 5 m, and a fluctuation of 1.5 m are selected in our analysis. The typical levee section with selected aquifer parameters and hydraulic head is shown in Fig. 6.1.

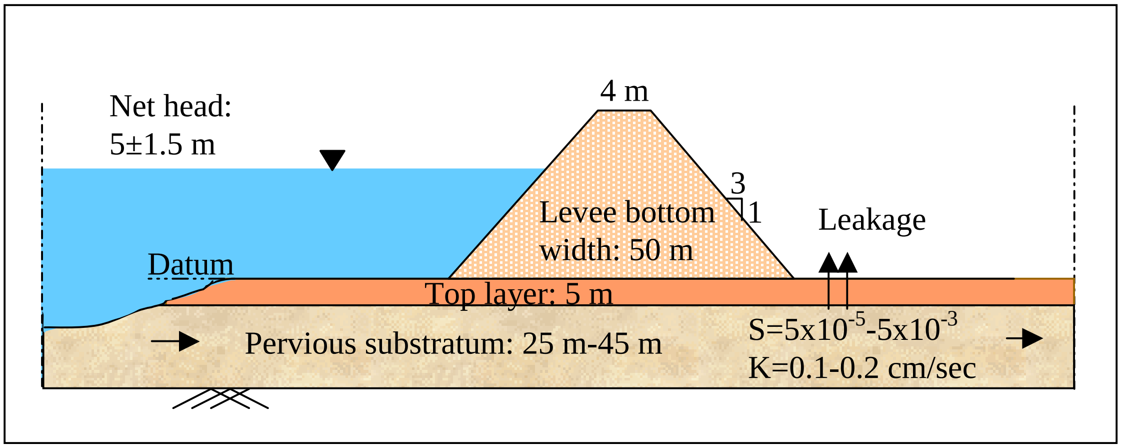


Fig. 6.1 A typical levee section with selected parameters (not in scale).

Two sets of comparisons were carried out. The first set of analyses compared the results of underseepage analysis with the transient flow model, the Army Corps EM 1110-2-1913 method, and SEEP2D finite element analysis. The second set of comparisons analyzed the results of seepage analysis with leakage out of a confined aquifer case. This set includes the results of the transient flow model with leakage and SEEP2D finite element analysis. The Army Corps method does not examine a leakage out of a confined aquifer case. Therefore, it is not applicable for the second set of comparisons.

A brief introduction was provided to the Army Corps EM 1110-2-1913 method and SEEP2D finite element software.

- **Army Corps EM 1110-2-1913 method.** The Department of Army, Engineer Manual, EM 1110-2-1913, Design and Construction of Levees (2000) details the mathematical analysis of underseepage and substratum pressure for levees. The equations contained in the manual were developed during a study of piezometric data, reported in a technical memorandum, USACE Waterways Experiment Station (WES) TM 3-424 (1956), and confirmed by model studies. The procedures to evaluate the quantity of underseepage, uplift pressures and hydraulic gradients were developed based on closed-form solutions for differential equations of seepage flow presented by Bennett (1946). The equations in this engineer manual were developed considering a two-layer foundation, which is a typical geological condition in Lower Mississippi River Valley. The following simplifying assumptions were set in this seepage analysis (Engineer Manual, EM 1110-2-1913):

> “a. seepage may enter the pervious substratum at any point in the foreshore (usually at riverside borrow pits) and/or through the riverside top stratum,
>
> b. flow through the top stratum is vertical,
>
> c. flow through the pervious substratum is horizontal,
>
> d. the levee and the portion of the top stratum beneath it is impervious,
>
> e. all seepage is laminar.”

The equations are presented for several cases: no top stratum, impervious top stratum both riverside and landside, impervious riverside top stratum and no landside top stratum, impervious landside top stratum and no riverside top stratum, semipervious riverside top stratum and no landside top stratum, semipervious landside top stratum and no riverside top stratum, semipervious top stratum both riverside and landside. Two more cases were added by Cunny *et al.* (1989) in a Technical Report REMR-GT-13. These cases are: impervious riverside top stratum with semipervious landside top stratum and semipervious riverside top stratum with impervious landside top stratum. In this chapter, out of these nine cases, the most critical case, which is the seventh case listed in EM

1110-2-1913, semipervious top stratum at riverside and landside of levee with a pervious substratum was considered for analysis purpose. A cross-section of the levee with required parameters is shown in Fig. 6.2.

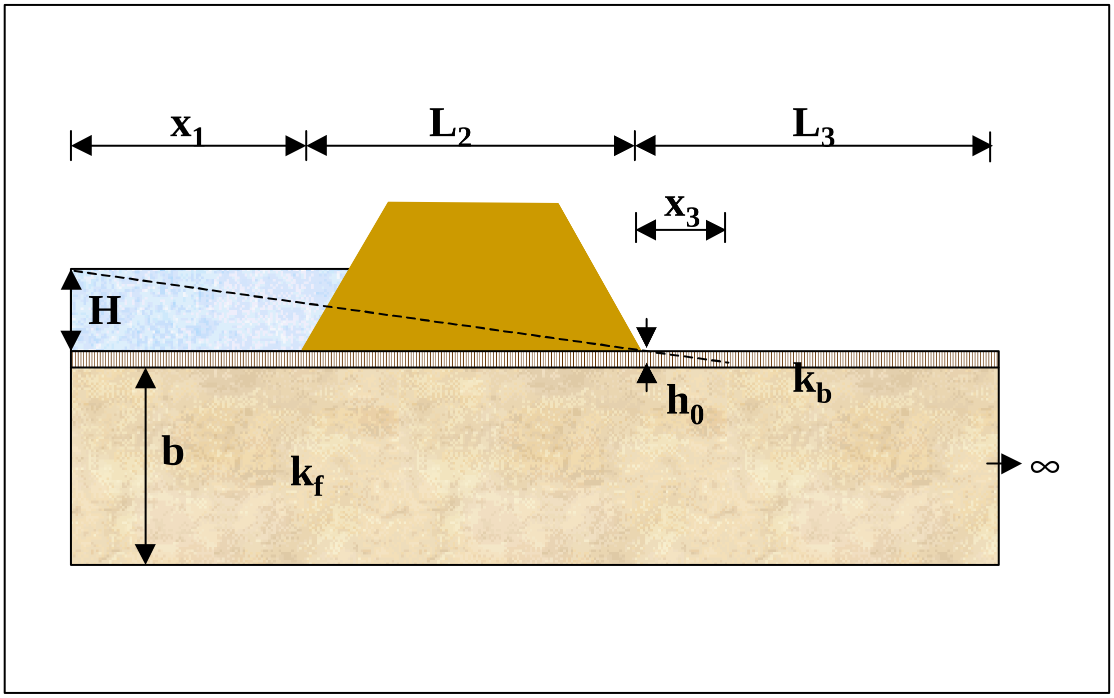


Fig. 6.2 Basic scheme of levee with design parameters as presented in the Army Corps EM 1110-2-1913.

The hydrostatic head beneath the top stratum on the landside toe of levee, h_0 is calculated as

$$h_0 = H\left(\frac{x_3}{x_1 + L_2 + x_3}\right) \tag{6.1}$$

where x_1 is effective length of riverside blanket, L_2 is base width of levee, and x_3 is distance from the landside levee toe to the effective seepage exit. If L_3, landward extent of top stratum measured from landside levee toe, is considered as it goes to infinity, then x_3 is estimated as

$$x_3 = \frac{1}{c} \tag{6.2}$$

$$c = \sqrt{\frac{k_b}{k_f z_b b}} \tag{6.3}$$

where k_b is vertical hydraulic conductivity of the top stratum, k_f is horizontal hydraulic conductivity of the pervious layer, z_b is thickness of the top stratum, and b is thickness of the pervious layer. Then, head beneath the top stratum at distance x from landside levee toe is estimated as

$$h_x = h_0 e^{-cx} \tag{6.4}$$

The hydraulic gradient through the top stratum at the landside of the levee is estimated as

$$i_x = \frac{h_x}{z_b} \tag{6.5}$$

- **SEEP2D Seepage Analysis Model.** The SEEP2D software was developed by USACE Waterways Experiment Station to model a variety of problems including seepage. In this research, the SEEP2D model is used in conjunction with the GMS (Groundwater Modeling System). GMS was developed by the Brigham Young University in cooperation with WES. Several conditions can be modeled by using SEEP2D. These conditions include isotropic/anisotropic soil properties, confined/unconfined flow profile models, saturated/unsaturated flow for unconfined profile models, confined flow for plan models, and heterogeneous soil conditions. SEEP2D cannot model transient or time varying problems and unconfined plan models. In the modeling process, a finite element mesh is constructed, boundary conditions are defined, hydraulic conductivities are entered, and then the model is run by SEEP2D and viewed by GMS. A partial aquifer modeled by SEEP2D is shown in Fig. 6.3.

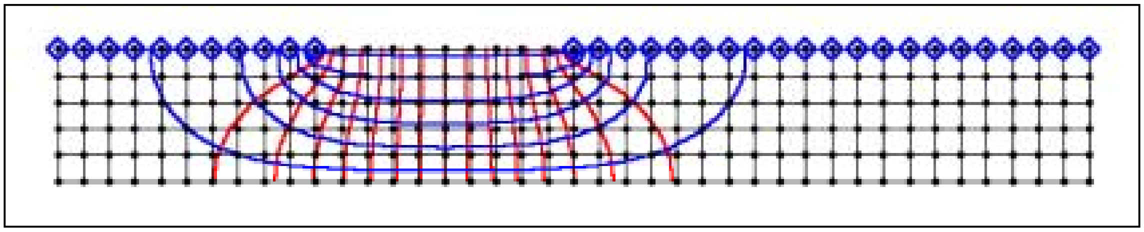


Fig. 6.3 A sample SEEP2D model.

This model applied in Fig. 6.3 represents a simple confined flow problem. Constant heads were applied to the boundaries where trapezoid shapes were placed. The other boundaries are "no flow" boundaries where the flow direction is parallel to those regions. Isotropic soil conditions at the soil medium resulted in a familiar flow net for part of the aquifer as shown in Fig. 6.3.

6.2 Performance Analysis of Transient Flow Model in a Confined Aquifer

The parameters were selected as shown in Fig. 6.4.

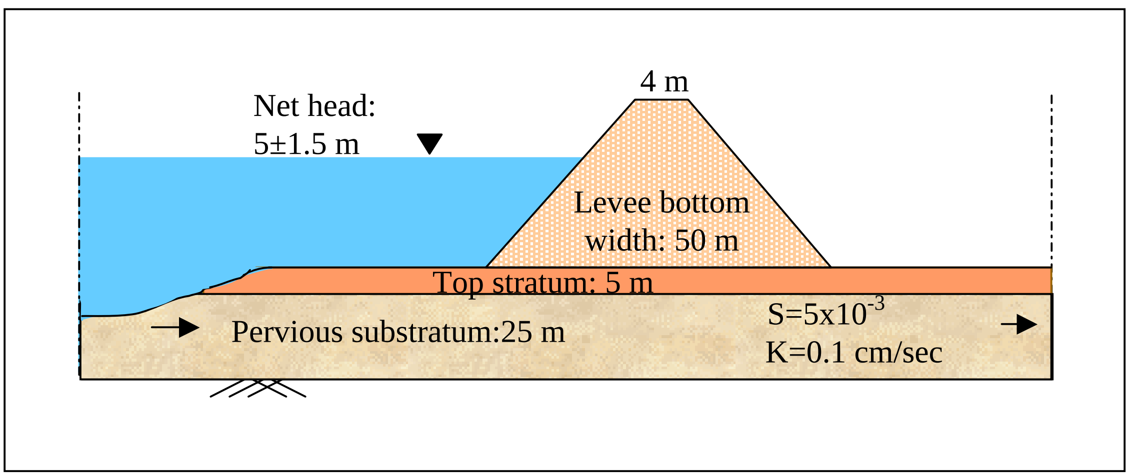


Fig. 6.4 A levee cross section with selected parameters for performance analysis (not in scale).

The Laplace transform solution considers seepage through the pervious substratum. The thickness of top stratum is taken into account only for calculating the exit hydraulic gradients. As noted before, the Army Corps method and SEEP2D model are applicable for steady-state analysis. Therefore a certain time was selected for comparison purpose. The time of the analysis was chosen as 30 days, when the river head makes its peak, which is 6.5 m. Therefore a constant head of 6.5 m was applied for the steady-state methods. In Fig. 6.5, the hydraulic head and hydraulic gradient distribution beneath the levee toe by the Laplace transform solution is shown.

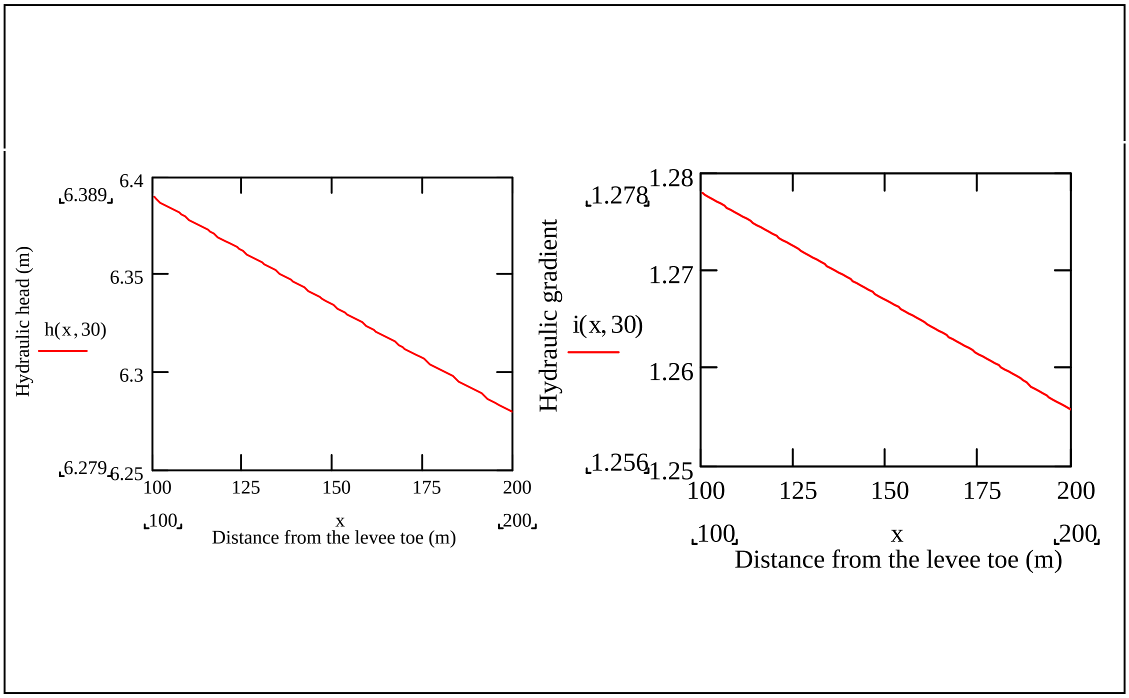


Fig. 6.5 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer at t=30 days by the transient flow model, Laplace transform method.

In Fig. 6.5, exit hydraulic gradients were evaluated by dividing the difference in hydraulic heads by the thickness of the top layer, which was chosen as 5 m. The same methodology was followed in the applications of the Army Corps method and SEEP2D model.

The Army Corps solution considers hydraulic conductivity of the top layer (Equation 6.3). Therefore, a vertical hydraulic conductivity of 1×10^{-4} cm/sec was assigned to the top layer of the soil medium for the applications of USACE method. The results are seen in Fig. 6.6.

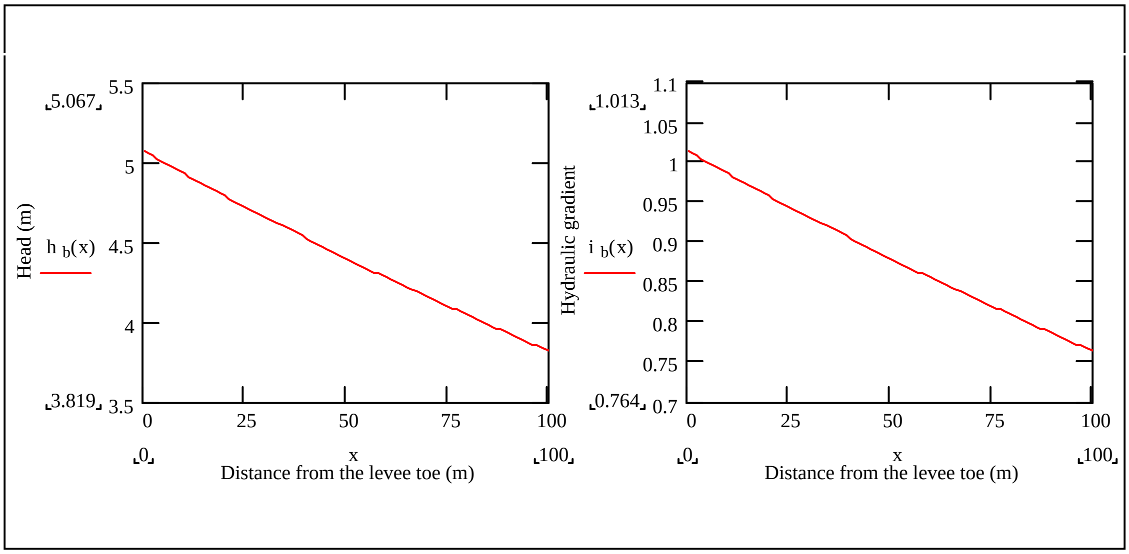


Fig. 6.6 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer by the Army Corps EM 1110-2-1913 method.

In the SEEP2D finite element model, an aquifer depth of 30 m with hydraulic conductivities as seen in Fig. 6.4 were defined. Hydraulic head development at 5 m below the landside levee and hydraulic gradients through the landside levee are plotted in Fig. 6.7. The results presented in Figures 6.5 through 6.7 are summarized in Table 6.1, which shows that there are significant differences between the results of the methods.

The analytical transient flow model developed by the Laplace transform method showed the most conservative results compared with the Army Corps method and SEEP2D model. The Laplace transform method assumes that seepage flow travels horizontally in an infinite flow medium. The model does not allow any upward leakage from the flow medium. In addition, as presented in Chapter 3, hydraulic head fluctuations dissipate very slowly. Therefore, high hydraulic gradients were calculated through the top layer.

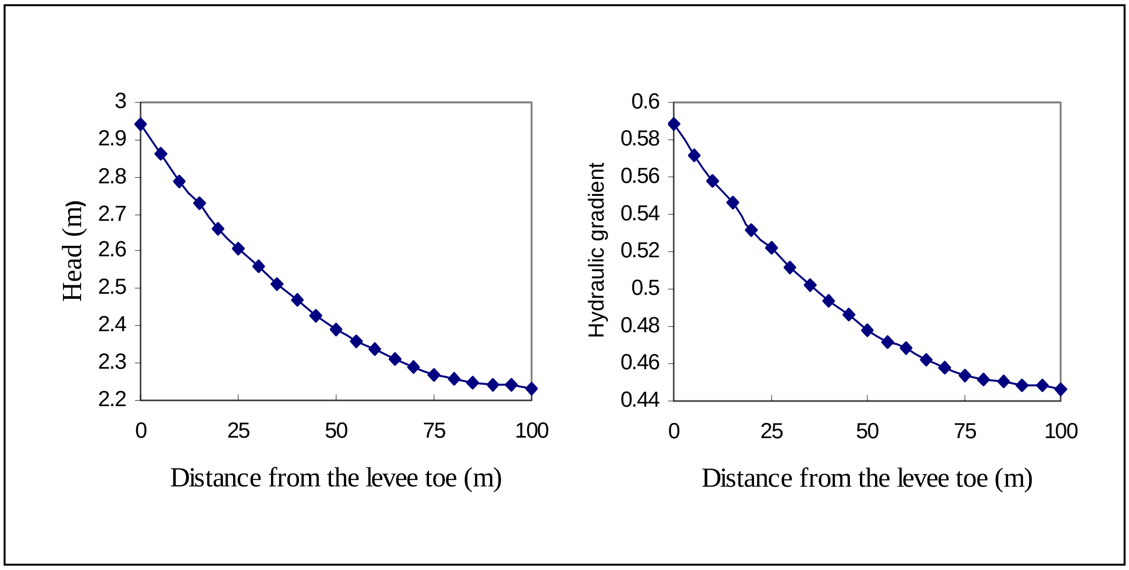


Fig. 6.7 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer by SEEP2D modeling.

Table 6.1 Hydraulic head and gradient beneath the levee for a confined aquifer by various methods.

Methods	$h_{levee\ toe}$ (m)	$h_{100\ m}$ (m)	$i_{levee\ toe}$	$i_{100\ m}$
Transient flow model	6.39	6.28	1.28	1.26
The Army Corps method	5.07	3.82	1.01	0.76
SEEP2D model	2.94	2.23	0.59	0.45

The SEEP2D finite element model was run under the confined aquifer medium, however the program allows a portion of seepage flow to exit vertically through the top blanket. This upward seepage reduced hydraulic head development on the landside of the levee, and reduces the hydraulic gradient through the top layer.

Gabr *et al.* (1995) presented a study on the comparison between finite element analysis and simplified analysis of levee underseepage. They used LEVSEEP and LEVEEMSU computer programs for simplified analysis of levee underseepage. As discussed in the second chapter, both computer programs were based on Bennett's (1946) analytical solutions and both methods were expected to give results close to those outlined in Levee Design Manual, EM 1110-2-1913, which is the Army Corps method analyzed in this research. Gabr *et al.* (1995) used PCSEEP and SEEP finite element computer programs in their study. SEEP is an older version of the SEEP2D model used in this dissertation. The researchers found significant differences between the results of LEVSEEP and LEVEEMSU and those from the two-dimensional finite element models. They concluded that exit hydraulic gradients predicted from simplified LEVSEEP and LEVEEMSU for the cases studied were conservative as compared with those predicted from the finite element model. They noted that there were no available piezometer data for high-water levels to verify the results from the finite element models. They also noted that a comprehensive parameter study and investigation of several case histories were needed before the conclusions they presented could be generalized. Table 6.1 also shows conservative results from the Army Corps method compared with the SEEP2D model.

So far, the comparisons of the flow models were based on steady-state conditions. The Army Corps method and the SEEP2D model can be solved for various heads and the results of these steady-state flow models can be compared with the results of the transient flow model. A flood wave of 60-day duration with a net head of 5 m and a fluctuation of 1.5 m were used for this purpose. The flood wave and corresponding hydraulic gradient development at the levee toe by the Laplace transform method are shown in Fig. 6.8. The hydraulic gradient curve in Fig. 6.8 was divided into certain ranges, and then corresponding head values in the river were calculated. The Army Corps method was solved by using these head values and the range of hydraulic gradients were calculated. The results were presented in Table 6.2.

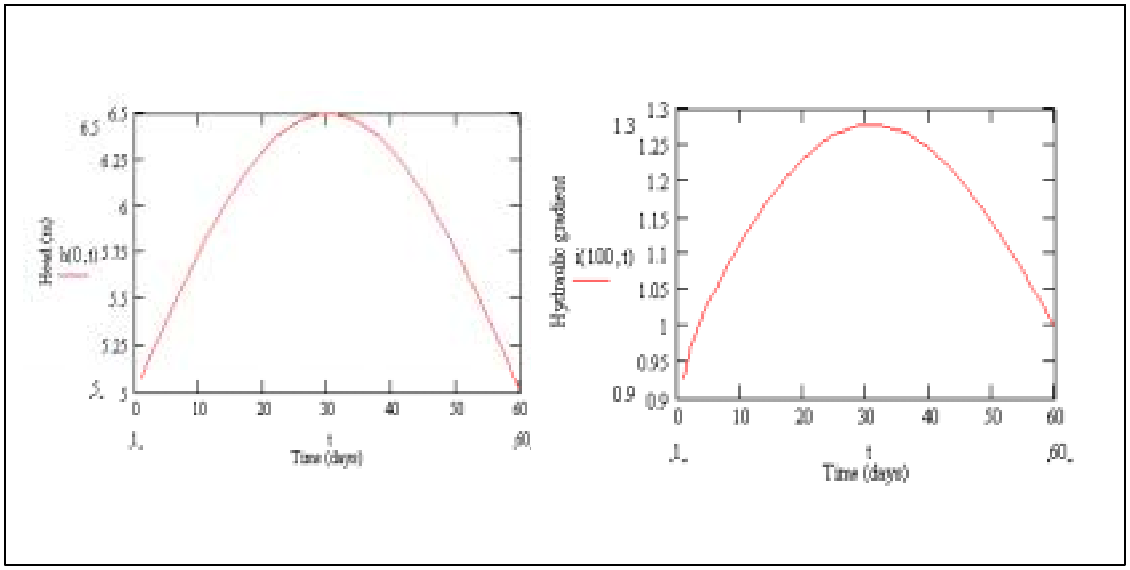


Fig. 6.8 Flood wave in the river and hydraulic gradient development at the levee toe by Laplace transform method.

Table 6.2 Summary of the range of hydraulic gradient and corresponding range of hydraulic head with time duration at the levee toe by Laplace transform method and the Army Corps method.

Time Range (days)	Duration (days)	Range of Hydraulic Head in the River (m)	Range of Hydraulic Gradient at the Levee Toe	
			Laplace Transform Method	Army Corps Method
1-3	3	5.08-5.24	0.93-0.99	0.79-0.82
4-8	5	5.31-5.61	1.01-1.09	0.83-0.88
9-16	8	5.68-6.12	1.10-1.19	0.89-0.95
17-30 31-45	29	6.17-6.50 6.50-6.10	1.20-1.28 1.28-1.20	0.96-1.01 1.01-0.95
46-53	8	6.00-5.54	1.19-1.10	0.94-0.86
54-59	6	5.46-5.08	1.09-1.01	0.85-0.79
60	1	5.00	1.00	0.78

The SEEP2D model was not used for this analysis because hydraulic gradient at the levee toe by SEEP2D model was significantly lower than the results calculated by the Army Corps and transient flow models (Table 6.1). The analysis shown in Table 6.2 can be useful to determine critical times during a flood. For example, if a hydraulic gradient of 0.85 is considered to be the initiation threshold of a sand boil, according to the transient flow model by Laplace transform solution, the whole high water event is critical, while according to the Army Corps method, the first and the last couple of days of the high water event is not critical. In general, the transient flow model by Laplace transform method and the Army Corps model resulted in close hydraulic gradients, however higher hydraulic gradients were determined by the transient flow model than by the U.S. Army Corps of Engineers method.

6.3 Performance Analysis of Transient Flow Model with Leakage Out of a Confined Aquifer

The parameters were selected as shown in Fig. 6.9.

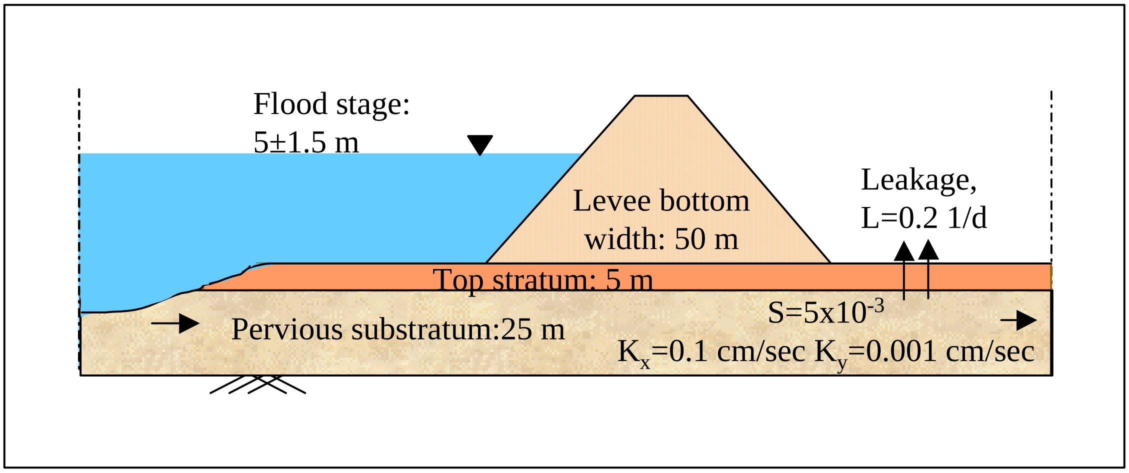


Fig. 6.9 A levee cross section with selected parameters for performance analysis (not in scale).

The Laplace transform solution considers seepage through the pervious substratum. In SEEP2D modeling, a constant head boundary was defined at the riverside of the levee and an exit face boundary was defined on the landside of the levee. After the model was run, the flow rates on the landside of the levee were examined. As expected, the highest flow rate occurred at the levee toe. The total flow below the landward levee was averaged through the landside of the levee to find a leakage amount to be used in the transient flow model. This leakage was found to be, L=0.2 1/day per meter of levee. Therefore, a leakage amount of L=0.2 1/day per meter of levee was selected for comparison purposes. In Fig. 6.10, the hydraulic head beneath the landside of the levee, and the hydraulic gradient distribution through the top layer by Laplace transform solution are shown. Hydraulic head and exit gradient distribution beneath the levee by SEEP2D are shown in Fig. 6.11. Table 6.3 summarizes the results presented in Figures 6.10 and 6.11.

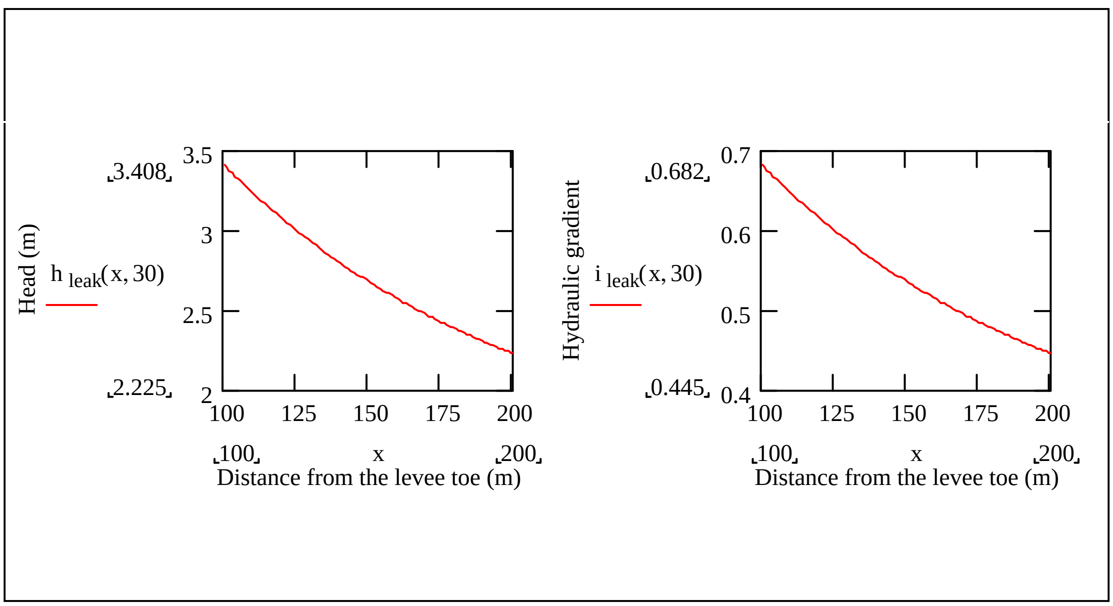


Fig. 6.10 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer by the transient flow model, Laplace transform method, with leakage, L=0.2 1/day/m of levee.

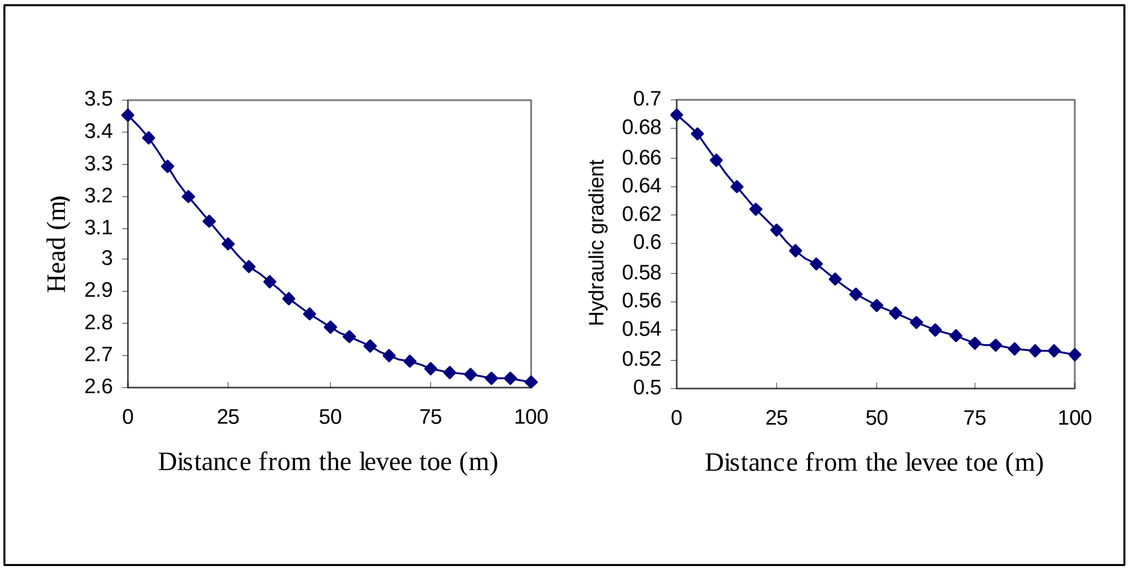


Fig. 6.11 Hydraulic head beneath the landside of the levee, and the hydraulic gradient development through the top layer by SEEP2D modeling with leakage, L=0.2 1/day/m of levee.

Table 6.3 Hydraulic head beneath the levee, and the hydraulic gradient through the top layer for a confined aquifer with leakage, L=0.2 1/day/m of levee, by analytical model and finite element analysis.

Methods	$h_{levee\ toe}$ (m)	$h_{100\ m}$ (m)	$i_{levee\ toe}$	$i_{100\ m}$
Transient flow model	3.41	2.23	0.68	0.45
SEEP2D model	3.45	2.62	0.69	0.52

Table 6.3 shows that hydraulic head and gradient values are closely matched with the transient flow model developed by the Laplace transform method and SEEP2D finite element analysis when there is an upward leakage of 0.2 1/day/m of levee. This agreement can be further investigated by using different leakage quantities. As discussed in the fourth chapter, there are field studies reported by Turnbull and Mansur (1962) on seepage quantities and corresponding exit gradients. The same seepage values can be achieved by the SEEP2D model by changing the driving hydraulic forces and/or

hydraulic conductivity of the medium. The investigated leakage quantities are 5 gal/min /100 ft of levee (L=0.14 1/day/m of levee) and 10 gal/min/100 ft of levee (L=0.28 1/day/m of levee). The results are shown in Table 6.4.

Table 6.4 Hydraulic head beneath the levee and the hydraulic gradient through the top layer for a confined aquifer with leakage by analytical model and finite element analysis.

Leakage (1/day/m of levee)	**Methods**	$h_{levee\ toe}$ (m)	$h_{100\ m}$ (m)	$i_{levee\ toe}$	$i_{100\ m}$
0.14	Transient flow model (K_x=0.1 cm/sec)	3.73	2.50	0.75	0.50
	SEEP2D model (K_x=0.063 cm/sec)	3.49	2.56	0.70	0.51
0.28	Transient flow model (K_x=0.1 cm/sec)	3.10	2.01	0.62	0.40
	SEEP2D model (K_x=0.148 cm/sec)	3.36	2.69	0.68	0.54

Table 6.4 shows that the results from the transient flow model and finite element analysis are still in agreement for different leakage quantities. Here, in SEEP2D analysis, the horizontal hydraulic conductivity of the medium was adjusted in order to get the target leakage quantities at the exit face, which is the landside of the levee. In reality, the hydraulic conductivity of the medium may also change due to the mechanisms involved in the underseepage process. Therefore, adjusting the hydraulic conductivity of the medium in order to get target leakage quantities can be considered as a reasonable approach. However, it should be noted that the results presented in Table 6.4 do not correspond to exactly the same conditions as used for comparison of transient flow and SEEP2D models.

So far, the comparisons of the flow models were based on steady-state conditions. SEEP2D model can be solved for various heads and the results of these steady-state flow models can be compared with the results of transient flow model. As in Section 6.2, a flood wave of 60 days, a net head of 5 m, a fluctuation of 1.5 m, and a homogenous upward leakage of 0.14 1/day/m of levee were selected for this purpose. The flood wave and corresponding hydraulic gradient development at the levee toe by the Laplace Transform method is shown in Fig. 6.12.

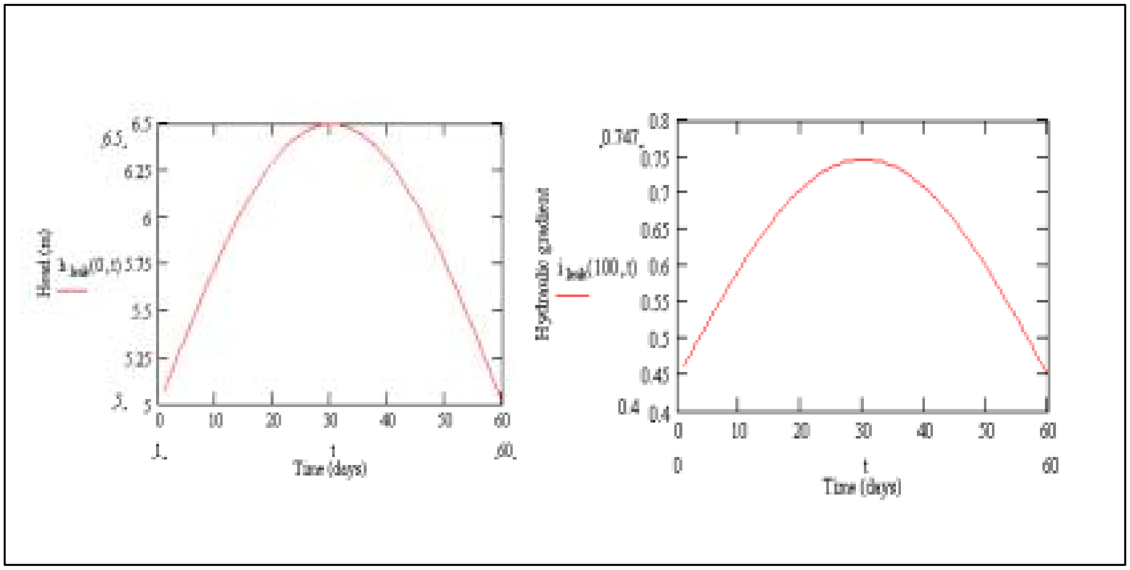


Fig. 6.12 Flood wave in the river and hydraulic gradient development at the levee toe by Laplace transform method with leakage, 0.14 1/day/m of levee.

The hydraulic gradient curve in Fig. 6.12 was divided into certain ranges, and corresponding head values in the river were calculated. A series of SEEP2D models were solved by using these head values, and the range of hydraulic gradients were calculated. In SEEP2D analysis, horizontal hydraulic conductivity of the medium was adjusted in order to get the target leakage quantity at the landside of the levee. The results are presented in Table 6.5.

Table 6.5 Summary of the range of hydraulic gradient with corresponding range of hydraulic head with time duration at the levee toe by Laplace transform method and SEEP2D model with leakage, L=0.14 1/day/m of levee.

Time Range (days)	Duration (days)	Range of Hydraulic Head in the River (m)	Range of Hydraulic Gradient at the Levee Toe	
			Laplace Transform Method	SEEP2D Model
1-3	3	5.04-5.20	0.46-0.49	0.54-0.55
4-10	7	5.27-5.71	0.51-0.60	0.56-0.61
11-19	9	5.78-6.22	0.61-0.70	0.62-0.67
20-30 31-40	21	6.26-6.46 6.46-6.26	0.71-0.75 0.75-0.71	0.67-0.69 0.69-0.67
41-49	9	6.22-5.78	0.70-0.61	0.67-0.62
50-56	7	5.71-5.27	0.60-0.51	0.61-0.56
57-60	4	5.20-4.96	0.49-0.45	0.55-0.54

As shown in Table 6.5, the results from the transient flow model and finite element analysis are still in agreement during the assumed high water event. Again, it should be noted that in SEEP2D modeling, the horizontal hydraulic conductivity value was adjusted for each hydraulic head in the river to get the target upward leakage quantity. This analysis simulates the pressure relief due to formation of sand boils during a flood, and can be useful to examine the sites with relief wells.

6.4 Summary and Conclusions

The main objective of this chapter was to show the performance of the analytical seepage model developed by Laplace transform method. The results from the analytical model were presented and compared with other seepage analysis methods. The Army Corps method outlined in Army Engineer Manual, EM 1110-2-1913 and SEEP2D finite element analysis were selected for comparison purposes.

Two sets of comparisons were conducted. In the first set, one-dimensional flow in the confined aquifer case was studied. The transient analytical model by Laplace Transform method resulted in higher exit gradients than the steady-state analysis models: the Army Corps method and SEEP2D finite element analysis. In the second set of comparisons, the Laplace transform method and SEEP2D analysis were compared for one-dimensional flow with leakage out of a confined aquifer case. The results are in agreement for different leakage quantities. The assigned upward leakage term refers to seepage flowing out through sand boils. This situation resembles relief wells and causes decreases in head development beneath the levee compared to the no leakage case.

Transient head development was also simulated by the steady-state models. The Army Corps method and SEEP2D model were analyzed for certain increments of head values and the results were compared with the transient flow model. This type of analysis can also be useful to predict the occurrence of sand boils and the performance of the sites where relief wells have been installed during a possible high water event.

The predictability of the models can only be measured and the results presented in this chapter can only be generalized with field measurements. Besides, even though a simple cross-section is compared, the comparisons do not reflect identical conditions due to the fact that each method was developed under its own assumptions. With this performance analysis, the main objective of this chapter was satisfied.

This chapter also investigated the question of whether or not transient effects are critical in the development of hydraulic gradients. The performance analysis presented in this chapter clearly shows that the transient flow models developed by Laplace transform method give reasonable results compared with the commonly used steady-state seepage analysis applications. Therefore, the transient flow models are worthwhile to consider during an underseepage study of levees and prediction of sand boil formations at the landside of the levee.

6.5 List of Symbols

b = thickness of pervious layer (L)

c = a variable to define x_3 (L^{-1})

h_0 = hydraulic head beneath top stratum landside toe of the levee (L)

H = total head loss (L)

h_x = head beneath top stratum at distance x from landside toe of the levee (L)

i_c = critical hydraulic gradient (dimensionless)

i_x = hydraulic gradient beneath top stratum at landside of the levee (dimensionless)

k_b = vertical hydraulic conductivity of top stratum (LT^{-2})

k_f = horizontal hydraulic conductivity of pervious layer (LT^{-2})

K_x = horizontal hydraulic conductivity of pervious layer (LT^{-2})

K_y = vertical hydraulic conductivity of pervious layer (LT^{-2})

L = leakage ($T^{-1}L^{-1}$)

L = length dimension (L)

L_2 = base width of levee (L)

L_3 = landside extent of top stratum measured from landside levee toe (L)

S = aquifer storativity (dimensionless)

x_1 = effective length of riverside blanket (L)

x_3 = distance from landside levee toe to effective seepage exit (L)

z_b = thickness of landside top stratum

CHAPTER 7 EVALUATION OF CUMULATIVE EFFECTS

7.1 Introduction

The objective of this chapter was to use the transient flow models and steady-state seepage analysis methods to evaluate possible cumulative effects caused by repetitive flood events.

In the case of piping problems under levees, the pore size may increase with time as fine soil particles are washed away due to underseepage. The increased pore size may enable the migration of larger sized soil particles. If the unobservable process proceeds and sufficient soil is transported, an internal channel may develop. A sand boil at the location where the seepage exits is an indication that an internal channel has formed, even though the channel is of small size. After a sand boil has formed, fine soil is usually discharged with the flowing water. This continued discharge of fine material might suggest the eroded internal channel is migrating from the landside of the levee toward the riverside. As an internal channel develops, enlarges, and lengthens due to cumulative effects, several parameters that are important in seepage analysis are expected to change. The thickness of pervious layer, soil porosity, soil hydraulic conductivity, and saturation degree are some of those parameters. Out of these parameters, soil porosity and degree of saturation directly effects the hydraulic conductivity of the soil layer.

In this research hydraulic conductivity of the soil medium was assumed as the most important parameter in the evaluation of possible cumulative effects due to underseepage. Therefore, a range of hydraulic conductivity values for the soil medium was assumed and then exit hydraulic gradients were evaluated for corresponding hydraulic conductivity values.

In Chapter 3, a transient analytical model was developed by the Laplace transform method. The main soil property in this model is aquifer diffusivity value, which is transmissivity over storativity ratio (T/S). The model can be run for a range of T/S ratios to examine the effect of changes in hydraulic conductivity of the soil medium. Typical Mississippi Valley aquifer parameters were considered and a range of aquifer diffusivity values (T/S) were selected for analysis purposes. The thickness of sandy alluvium under Mississippi River levees changes from 25 m to 45 m. The hydraulic conductivity of sandy alluvium is in the range of 0.1-0.2 cm/sec (Turnbull and Mansur 1961). Typical storativity values for confined aquifers are $5x10^{-3}$, $5x10^{-4}$, $5x10^{-5}$ (Freeze and Cherry, 1979). In the 1993 floods, the net change in river level elevation of the middle Mississippi River levees was recorded as 4.8 to 6.7 m (Mansur *et al*. 2000). A net head of 5 m and a fluctuation of 1.5 m were selected in the analysis. The typical levee section with selected aquifer parameters and hydraulic head is presented in Fig. 7.1.

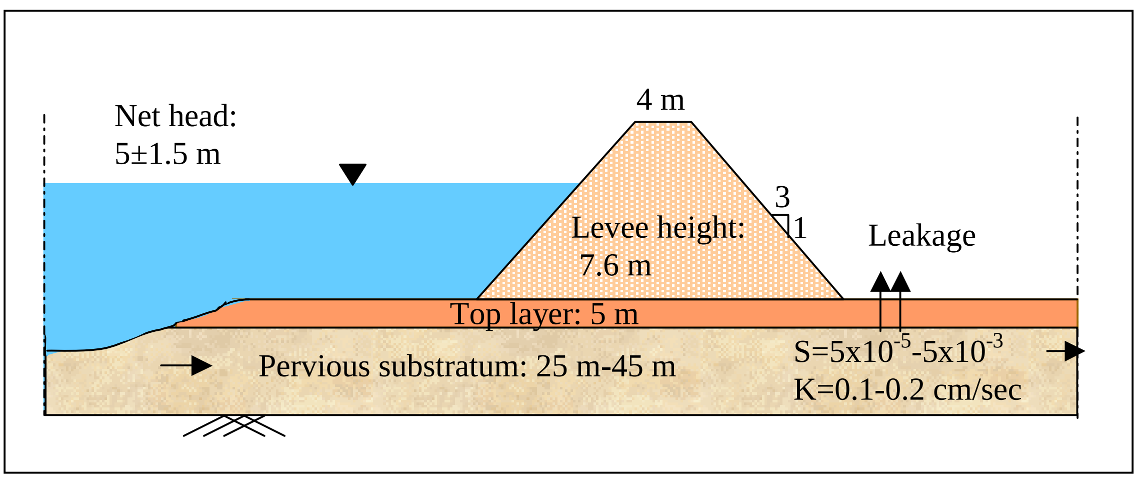


Fig. 7.1 A typical levee section with selected parameters (not in scale).

The range of typical aquifer diffusivities for cumulative analysis purpose is shown in Table 7.1.

Table 7.1 Selected aquifer diffusivities used in cumulative effect analysis.

Aquifer diffusivity, T/S ratio	Hydraulic conductivity, K (cm/sec)	Thickness of aquifer (m)	Transmissivity, T (m^2/sec)	Storativity (dimensionless)
5	0.1	25	0.025	$5x10^{-3}$
18	0.2	45	0.090	$5x10^{-3}$
500	0.1	25	0.025	$5x10^{-5}$
1800	0.2	45	0.090	$5x10^{-5}$

Two sets of analyses were conducted to evaluate possible cumulative effects of piping under levees. The first set of analyses included the following methods: transient analytical model by Laplace transform method, the Army Corps method, and SEEP2D finite element model. The second set of analyses was applied when there was leakage out of a confined aquifer, which simulates the loss of water by upward seepage and discharge through sand boils. For this situation, the transient flow model by Laplace transform method and SEEP2D finite element analysis were studied.

7.2 Cumulative Analysis for Underseepage in a Confined Aquifer

The transient flow model applying the Laplace transform method was solved for various aquifer diffusivity values selected in Table 7.1. Hydraulic head development beneath the landside of the levee when the river head makes its peak is shown in Fig. 7.2. Hydraulic gradient development is shown in Fig. 7.3.

As aquifer diffusivity increases higher hydraulic heads and hydraulic gradients are observed on the landside of the levee (Figures 7.2 and 7.3). The results of hydraulic head and gradient development are tabulated in Table 7.2.

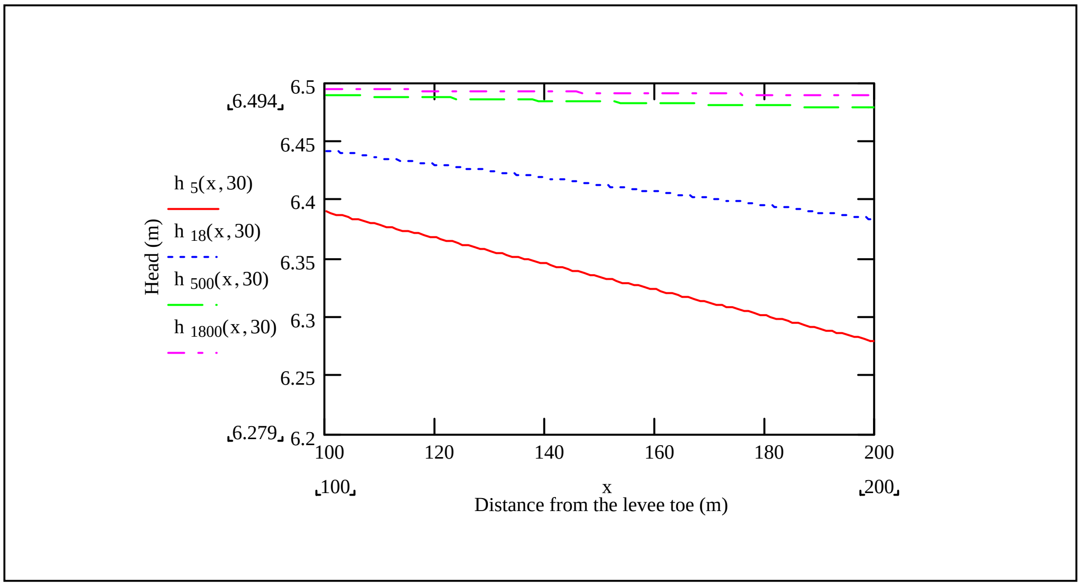


Fig. 7.2 Hydraulic head development at t=30 days by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500, and 1800.

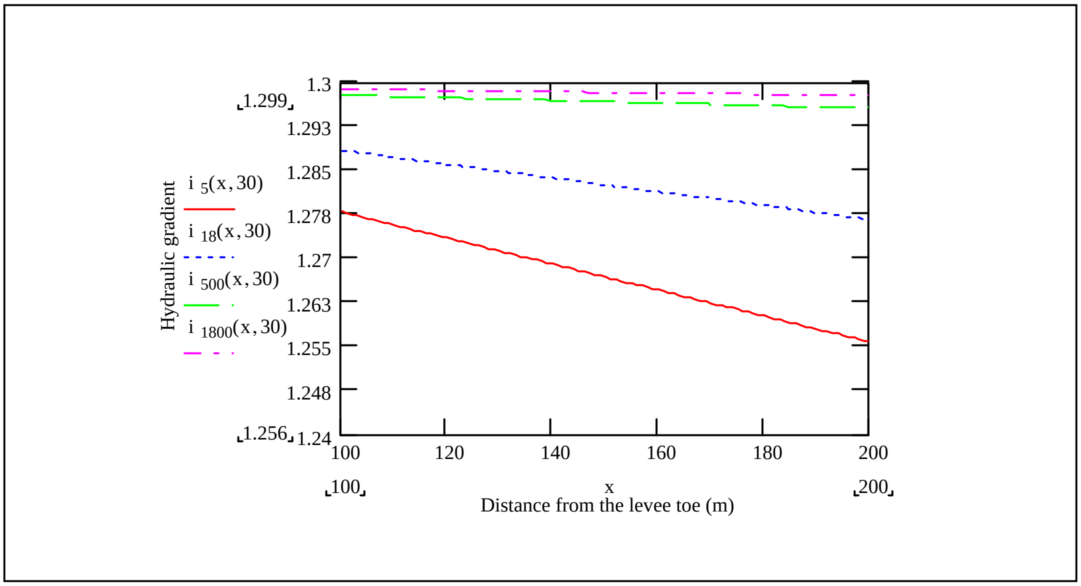


Fig. 7.3 Hydraulic gradient development at t=30 days by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500, and 1800.

Table 7.2 Hydraulic head beneath the landside of the levee and gradient through the top layer of a confined aquifer by transient flow model for various aquifer diffusivities.

Aquifer diffusivity (T/S)	$h_{levee\ toe}$ (m)	$h_{100\ m}$ (m)	$i_{levee\ toe}$	$i_{100\ m}$
5 (T=0.025 m^2/sec, S=5x10^{-3})	6.389	6.279	1.278	1.256
18 (T=0.090 m^2/sec, S=5x10^{-3})	6.442	6.383	1.288	1.277
500 (T=0.025 m^2/sec, S=5x10^{-5})	6.489	6.478	1.298	1.296
1800 (T=0.090 m^2/sec, S=5x10^{-5})	6.494	6.488	1.299	1.298

As shown in Table 7.2, the transient flow model by the Laplace transform solution results in slight increases in hydraulic head beneath the landside of the levee and the gradient through the top layer as hydraulic diffusivity of the pervious medium increases.

The Army Corps method as outlined in Engineer Manual, EM 1110-2-1913 was detailed in the sixth chapter. The formulation of the solution considers horizontal hydraulic conductivity and the depth of the pervious medium. Therefore, only aquifer transmissivity (T) of the pervious medium was increased for analysis purpose. The peak hydraulic head of 6.5 m was considered at the river. Figure 7.4 and 7.5 show hydraulic head and gradients at the landside of the levee when the aquifer transmissivities are 0.025 m^2/sec and 0.090 m^2/sec, respectively.

The same parameters used in the Army Corps method were also used for SEEP2D modeling. Figures 7.6 and 7.7 show the results when the aquifer transmissivities are 0.025 m^2/sec and 0.090 m^2/sec, respectively, by SEEP2D finite element analysis.

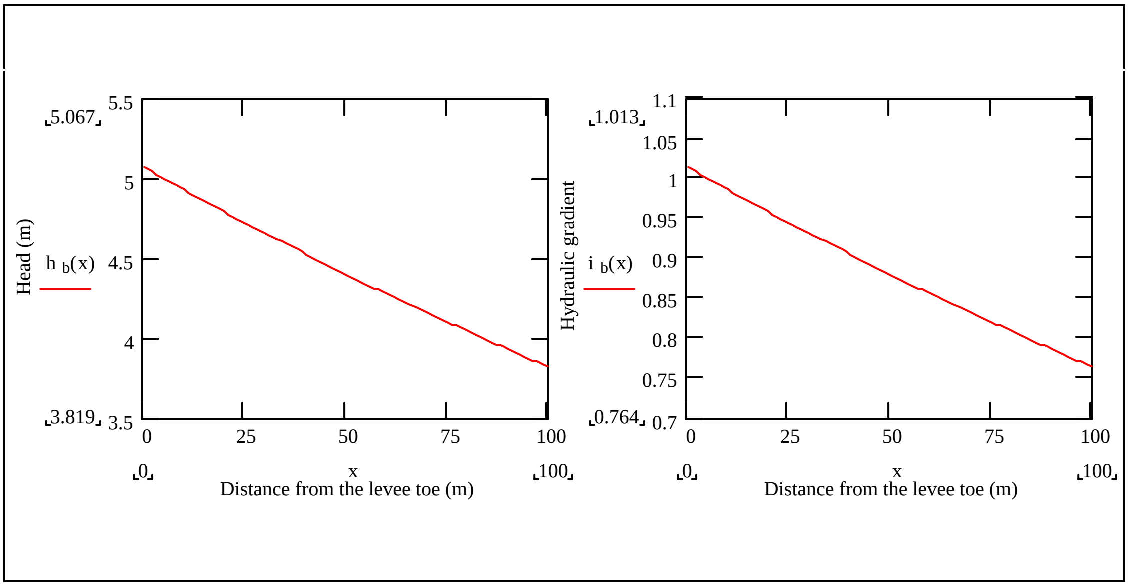


Fig. 7.4 Hydraulic head beneath the landside of the levee and gradient development through the top layer by the USACE method for aquifer transmissivity (T) of 0.025 m^2/sec.

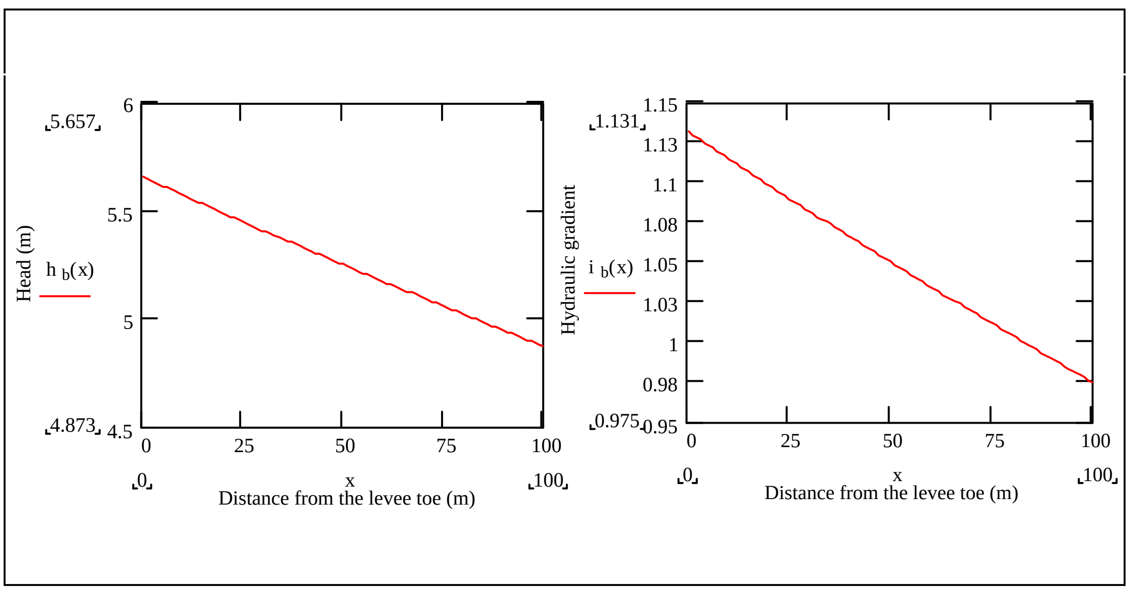


Fig. 7.5 Hydraulic head beneath the landside of the levee and gradient development through the top layer by the USACE method for aquifer transmissivity (T) of 0.090 m^2/sec.

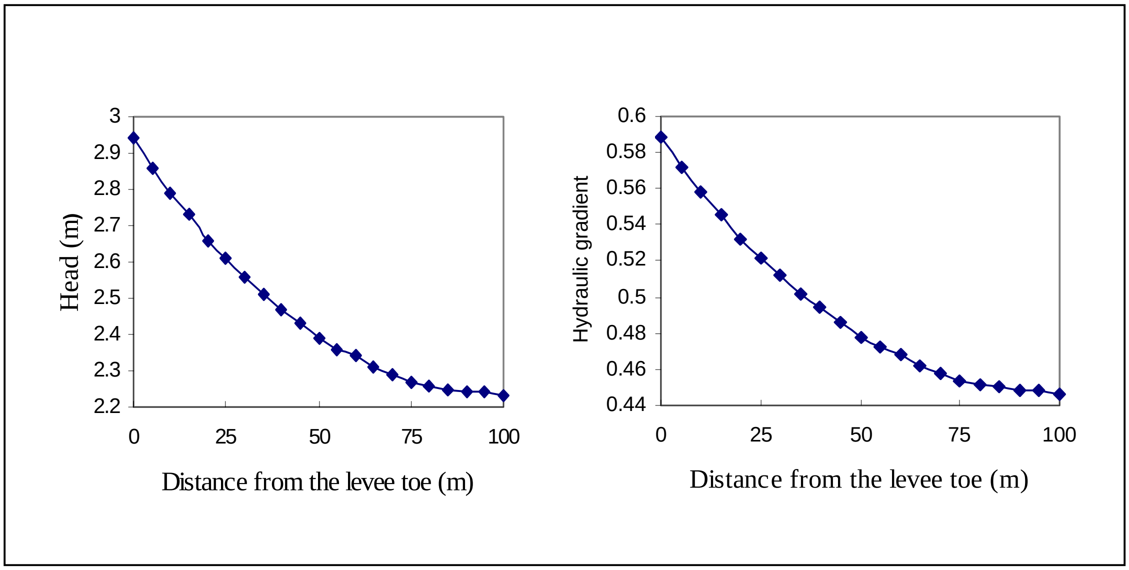


Fig. 7.6 Hydraulic head and gradient development beneath the landside levee by SEEP2D modeling for aquifer transmissivity (T) of 0.025 m^2/sec.

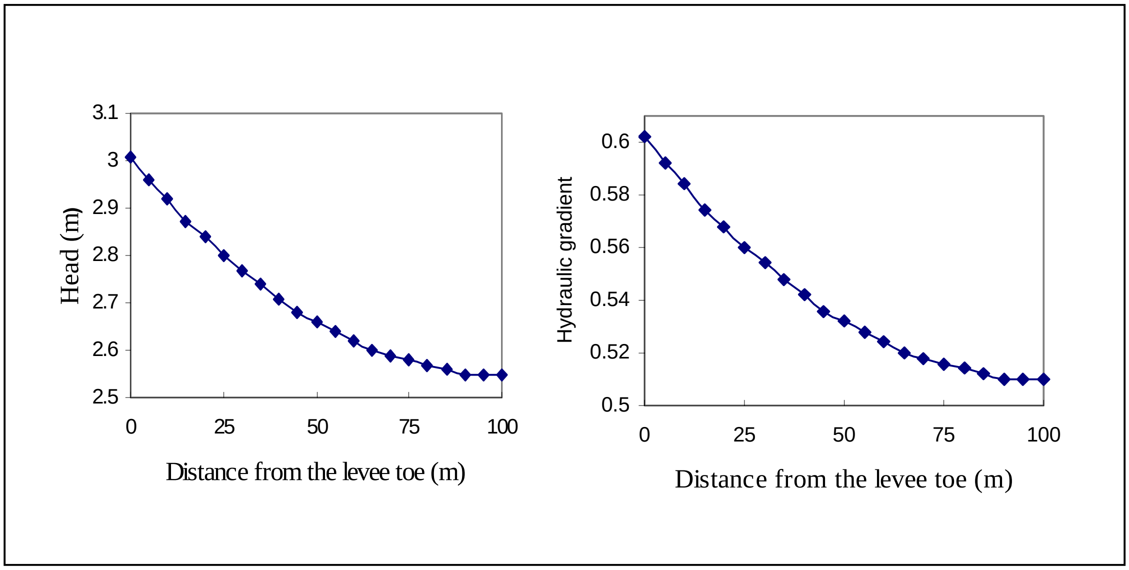


Fig. 7.7 Hydraulic head and gradient development beneath the landside levee by SEEP2D modeling for aquifer transmissivity (T) of 0.090 m^2/sec.

The changes in hydraulic gradients due to the changes in aquifer transmissivities by three of the analysis methods are summarized in Table 7.3.

Table 7.3 Increases in hydraulic gradients (%) through the top layer on the landside of the levee by the transient flow model, the Army Corps method and SEEP2D modeling for different aquifer transmissivities.

Methods	Aquifer transmissivity, T (m^2/sec)	$i_{levee\ toe}$	Increase (%)	$i_{100\ m}$	Increase (%)
Transient flow model ($S=5x10^{-3}$)	0.025	1.278		1.256	
	0.090	1.288	0.78	1.277	1.67
Transient flow model ($S=5x10^{-5}$)	0.025	1.298		1.296	
	0.090	1.299	0.08	1.298	0.15
Army Corps method	0.025	1.013		0.764	
	0.090	1.131	11.65	0.975	27.62
SEEP2D model	0.025	0.588		0.446	
	0.090	0.602	2.38	0.510	14.35

As discussed in Chapter 6, the transient flow model using the Laplace transform solution and the Army Corps method result in more conservative hydraulic gradients than SEEP2D finite element analysis (Table 7.3). This table also shows that the Laplace transform solution gives only minor changes in the exit hydraulic gradient as hydraulic diffusivity of the pervious medium changes. The Army Corps method is the most sensitive solution to the changes in transmissivity of the pervious medium.

The Laplace transform solution assumes flow over an infinite horizontal distance in the medium. Therefore, increases in aquifer transmissivity affect the head development very slightly in this assumed infinite soil medium within the first 100 m of landside levee. The Army Corps method assumes there is an upward flow on the landside of the levee. In

SEEP2D analysis, a confined aquifer was modeled, however, the program still allowed upward leakage concentrated at the levee toe and through the top layer on the landside of the levee. Probably, due to this upward flow in the Army Corps method and SEEP2D model, hydraulic conductivity of the medium affects the exit gradients in both models.

A change in hydraulic conductivity has an affect on exit hydraulic gradients. However, exit hydraulic gradients at a location distant from the landside of the levee were affected more than those closer to the levee.

7.3 Cumulative Analysis for Underseepage with Leakage Out of a Confined Aquifer

The transient flow model utilizing the Laplace transform solution and SEEP2D finite element analysis are capable of analyzing hydraulic head developments when there is an upward seepage emerging at the landside of the levee. Two separate SEEP2D models were constructed using aquifer transmissivities of 0.025 m^2/sec and 0.090 m^2/sec, respectively. The model with an aquifer transmissivity of 0.025 m^2/sec resulted in an average leakage of 0.20 1/day per meter of levee, and the model with an aquifer transmissivity of 0.090 m^2/sec resulted in an average leakage of 0.36 1/day per meter of levee. Therefore, two transient flow models were run with each leakage quantity for cumulative analysis and also for comparison purposes with SEEP2D finite element modeling. The first model of transient flow analysis used aquifer diffusivities as set in Table 7.1 and an upward leakage of 0.20 1/day/m of levee. With these parameters, hydraulic head development beneath the landside of the levee when the river head makes its peak is shown in Fig. 7.8. Hydraulic gradient development for this case is also shown in Fig. 7.9. It is important to note that hydraulic head and gradient development for aquifer diffusivities (T/S) of 5 and 500, and 18 and 1800 almost identical (Fig. 7.8 and 7.9).

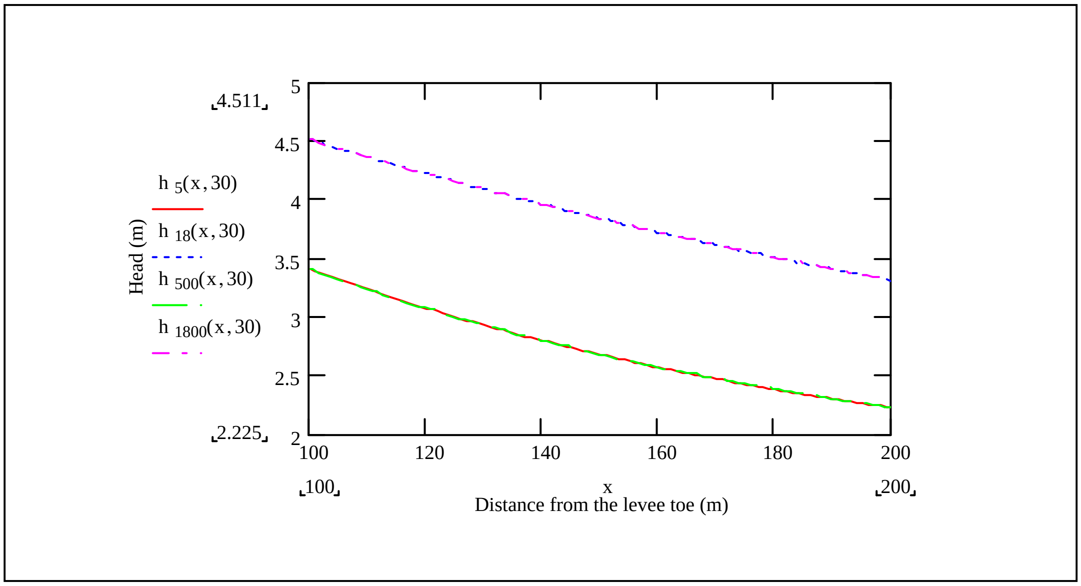


Fig. 7.8 Hydraulic head development beneath the landside of the levee by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500 and 1800 with a leakage of 0.20 1/day/m of levee.

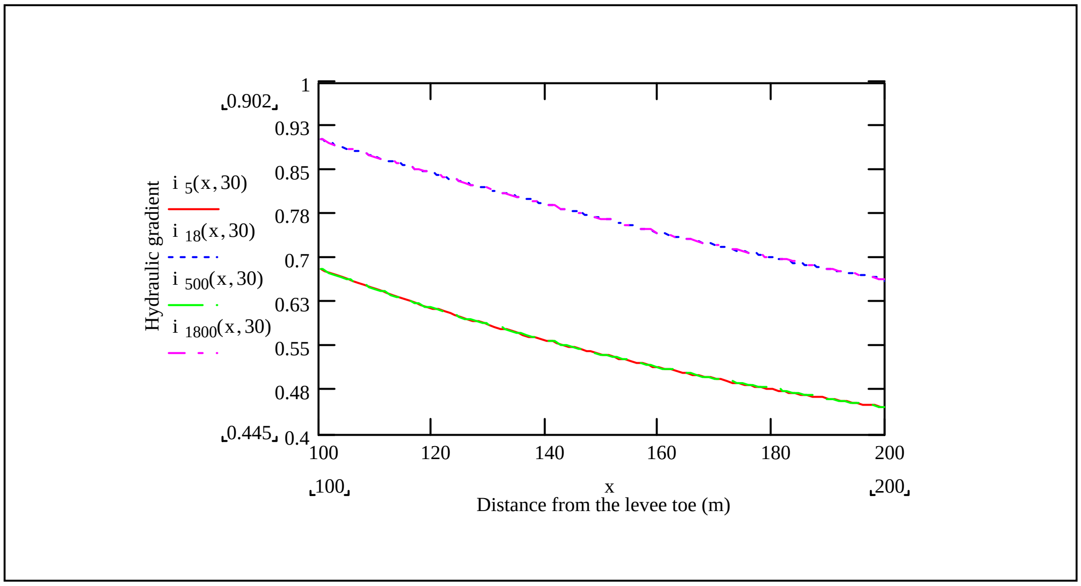


Fig. 7.9 Hydraulic gradient development through the top layer on the landside of the levee by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500 and 1800 with a leakage of 0.20 1/day/m of levee.

The second model of transient flow analysis also used the same aquifer diffusivities, as set in Table 7.1 and a leakage of 0.36 1/day/m of levee. With these parameters, hydraulic head development beneath the landside of the levee when the river head makes its peak is shown in Fig. 7.10, and hydraulic gradient development is shown in Fig. 7.11. Again, the hydraulic head and gradient development for aquifer diffusivities (T/S) of 5 and 500, and 18 and 1800 almost identical (Fig. 7.10 and 7.11). The results of the transient flow models as shown in Figures 7.8 through 7.11 are also tabulated in Table 7.4.

Figures 7.8 through 7.11 and Table 7.4 show that aquifer transmissivity, T, plays a more important role than does the aquifer diffusivity, T/S, in the transient flow model developed by the Laplace transform method. When the transmissivity was kept constant, the transient flow model resulted in almost identical hydraulic heads beneath the landside of the levee regardless of changes in storativity of the medium. In addition, the results indicated a considerable increase in hydraulic head and gradient development through the top layer at the landside of the levee as transmissivity of the medium increases when there is leakage out of the aquifer.

The same analysis was also studied by using SEEP2D finite element modeling. Two models were constructed. One has an aquifer depth of 25 m with a hydraulic conductivity of 0.1 cm/sec, and the other one has an aquifer depth of 45 m with a hydraulic conductivity of 0.2 cm/sec. In both models, an exit face was defined at the landside of the levee to allow upward seepage. Figures 7.12 and 7.13 show hydraulic head beneath the landside of the levee and gradient development through the top layer for aquifer transmissivities of 0.025 m^2/sec and 0.090 m^2/sec, respectively.

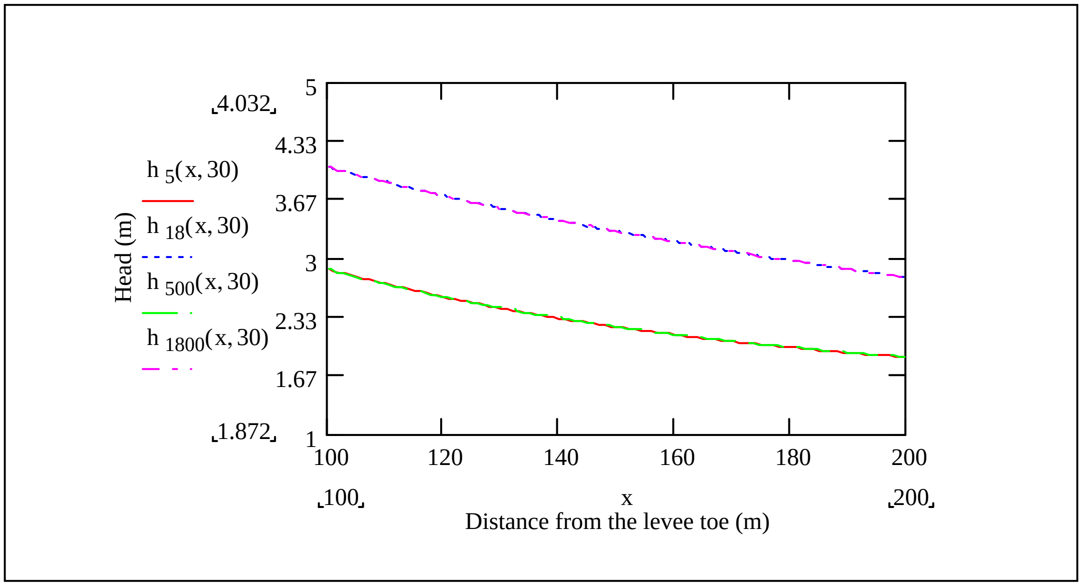


Fig. 7.10 Hydraulic head development beneath the landside of the levee by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500 and 1800 with a leakage of 0.36 1/day/m of levee.

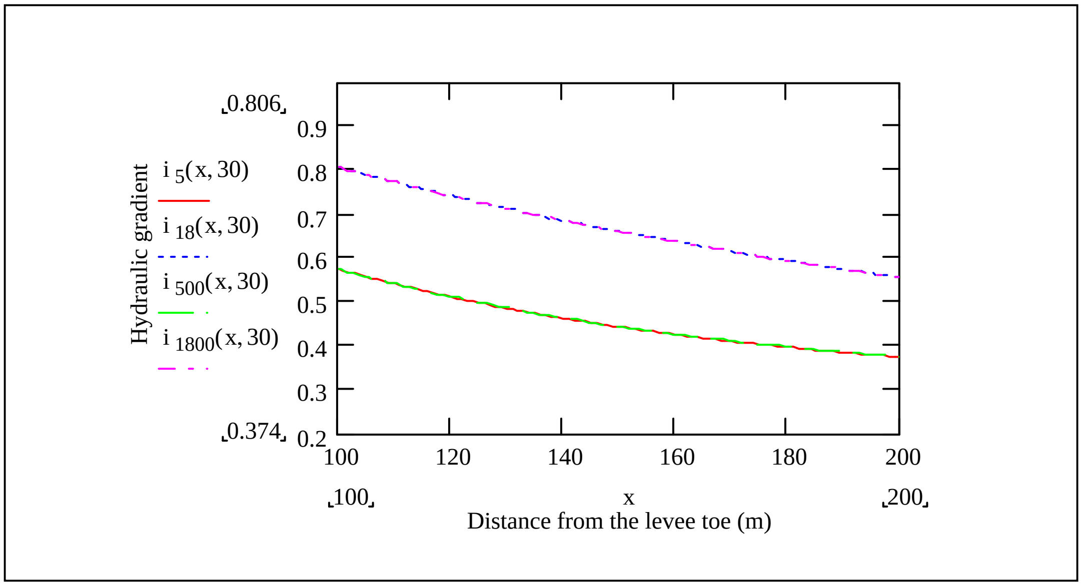


Fig. 7.11 Hydraulic gradient development through the top layer on the landside of the levee by transient flow model for aquifer diffusivities (T/S) of 5, 18, 500 and 1800 with a leakage of 0.36 1/day/m of levee.

Table 7.4 Hydraulic head beneath the landside of the levee and gradient through the top layer by transient flow model for various aquifer diffusivities when there is a leakage out of a confined aquifer.

Aquifer diffusivity (T/S)	Leakage (1/day/m of levee)	$h_{levee\ toe}$ (m)	$h_{100\ m}$ (m)	$i_{levee\ toe}$	$i_{100\ m}$
5 (T=0.025 m^2/sec, S=5x10^{-3})	0.20	3.408	2.225	0.682	0.445
18 (T=0.090 m^2/sec, S=5x10^{-3})		4.510	3.312	0.902	0.662
500 (T=0.025 m^2/sec, S=5x10^{-5})		3.410	2.229	0.682	0.446
1800 (T=0.090 m^2/sec, S=5x10^{-5})		4.511	3.313	0.902	0.663
5 (T=0.025 m^2/sec, S=5x10^{-3})	0.36	2.872	1.872	0.574	0.374
18 (T=0.090 m^2/sec, S=5x10^{-3})		4.031	2.781	0.806	0.556
500 (T=0.025 m^2/sec, S=5x10^{-5})		2.875	1.878	0.575	0.376
1800 (T=0.090 m^2/sec, S=5x10^{-5})		4.032	2.782	0.806	0.556

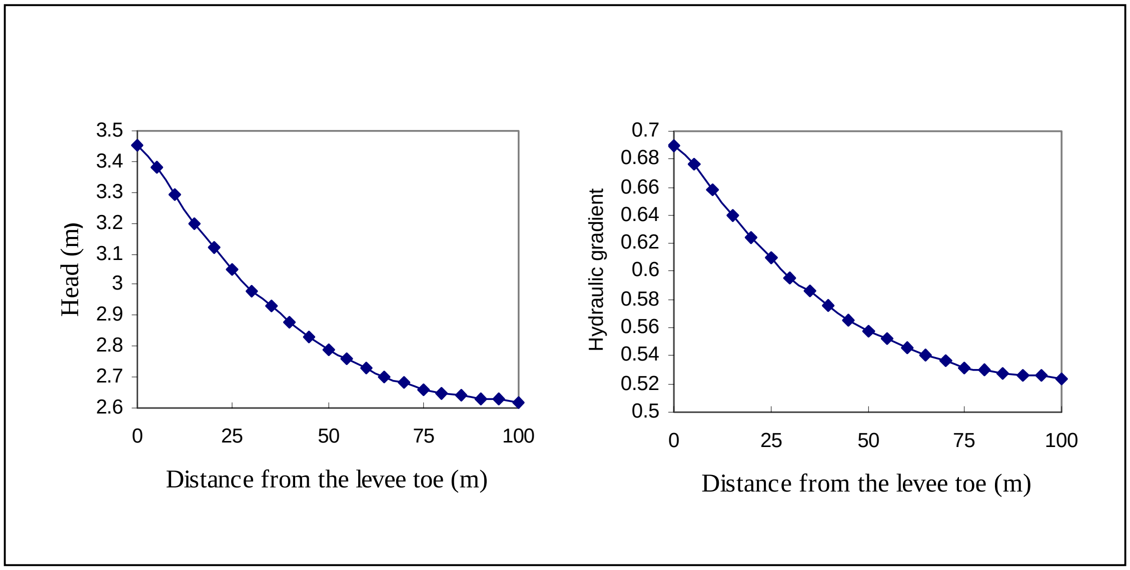


Fig. 7.12 Hydraulic head and gradient development beneath the landside of the levee by SEEP2D modeling for aquifer transmissivity (T) of 0.025 m^2/sec with a leakage of 0.2 1/day/m of levee.

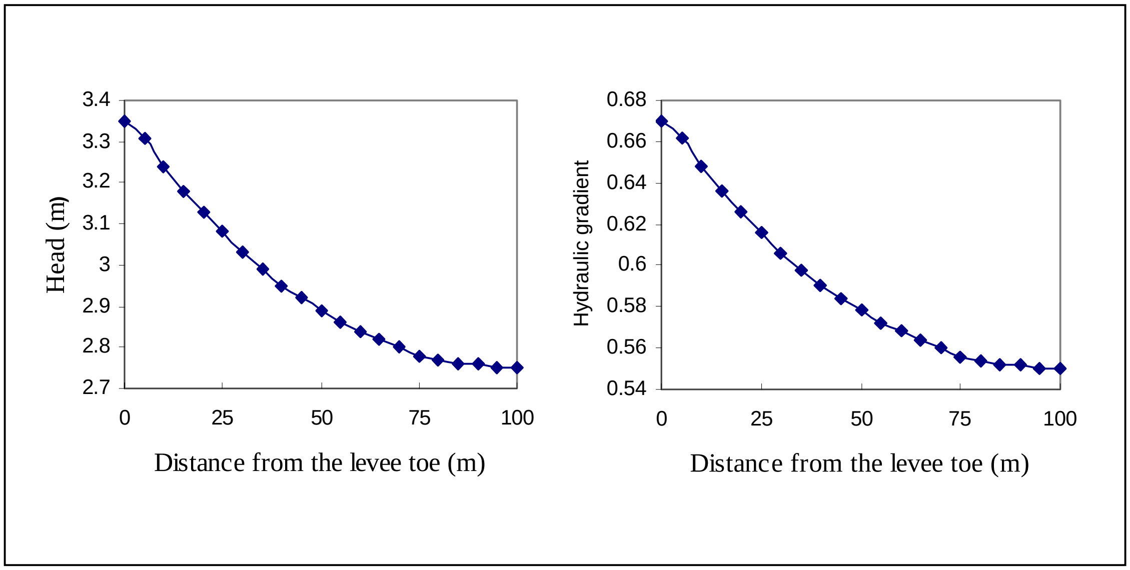


Fig. 7.13 Hydraulic head and gradient development beneath the landside of the levee by SEEP2D modeling for aquifer transmissivity (T) of 0.090 m^2/sec with a leakage of 0.36 1/day/m of levee.

The increases in hydraulic gradients developed through the top layer on the landside of the levee by the changes in aquifer transmissivities by transient flow model and SEEP2D analysis are summarized in Table 7.5. The transient flow model solved by the Laplace transform method shows that hydraulic gradients through the top layer on the landside of the levee significantly increase as transmissivity of the medium increases when there is seepage emerging at the landside of the levee. SEEP2D finite element analysis does not show this trend. The main reason that the software fails to do this is that the models were constructed in such a way that upward seepage cannot be kept constant while the transmissivity of the layer changes. Therefore, the results of SEEP2D analysis cannot be generalized. One common trend is that the changes in hydraulic conductivity effect exit hydraulic gradients at a location distant from the landside of the levee more than those closer to the levee. The same trend was also observed when there was no seepage allowed on the landside of the levee as discussed in the previous section.

Table 7.5 Increases in hydraulic gradients (%) through the top layer on the landside of the levee by the transient flow model and SEEP2D analysis for different aquifer transmissivities.

Methods	Aquifer transmissivity T (m^2/sec)	Leakage (1/day/m of levee)	$i_{levee\ toe}$	Increase (%)	$i_{100\ m}$	Increase (%)
Transient flow model	0.025 T/S = 5, 500	0.20	0.682		0.445	
	0.090 T/S = 8, 1800	0.20	0.902	32.3	0.663	49.0
Transient flow model	0.025 T/S = 5, 500	0.36	0.575		0.375	
	0.090 T/S = 8, 1800	0.36	0.806	40.2	0.556	48.3
SEEP2D model	0.025	0.20	0.690		0.524	
SEEP2D model	0.090	0.36	0.670	-3.0	0.550	5.0

Table 7.5 also shows reasonable agreement of the exit gradients by both transient flow model and SEEP2D analysis for the same aquifer transmissivity and leakage quantities.

Further cumulative analysis can be conducted by assuming incremental changes in hydraulic conductivity of the medium. For this purpose, an incremental increase of 0.01 cm/sec was assumed in a 25-m and 45-m depth of aquifers after each flood. An upward leakage of 0.2 1/day/m of levee was assumed. Table 7.6 presents the changes in hydraulic gradient at the levee toe and 100-m farther at the landside of the levee with the Laplace transform solution.

Table 7.6 Increases in hydraulic gradients (%) through the top layer on the landside of the levee by the transient flow model due to an incremental increase in hydraulic conductivity of the medium.

K (m/sec)	Aquifer thickness = 25 m				Aquifer thickness = 45 m			
	$i_{levee\ toe}$	Increase (%)	$i_{100\ m}$	Increase (%)	$i_{levee\ toe}$	Increase (%)	$i_{100\ m}$	Increase (%)
0.0010	0.682		0.445		0.788		0.538	
0.0011	0.699	2.5	0.459	3.1	0.804	2.0	0.554	3.0
0.0012	0.715	2.3	0.472	2.8	0.819	1.9	0.570	2.9
0.0013	0.730	2.1	0.484	2.5	0.833	1.7	0.584	2.5
0.0014	0.743	1.8	0.496	2.5	0.845	1.4	0.597	2.2
0.0015	0.756	1.7	0.507	2.2	0.857	1.4	0.610	2.2
0.0016	0.767	1.5	0.518	2.2	0.867	1.2	0.621	1.8
0.0017	0.778	1.4	0.528	1.9	0.877	1.2	0.633	1.9
0.0018	0.788	1.3	0.538	1.9	0.886	1.0	0.643	1.6
0.0019	0.797	1.1	0.547	1.7	0.894	0.9	0.653	1.6
0.0020	0.806	1.1	0.556	1.6	0.902	0.9	0.662	1.4

Table 7.6 shows that the hydraulic gradient at the levee toe increases from 0.682 to 0.806 after possible cumulative effects of assumed repetitive flood events causing an increase in hydraulic conductivity of the medium. This table also supports the trend that the changes in hydraulic conductivity effect exit hydraulic gradients at a location distant from the landside of the levee more than those closer to the levee. Table 7.6 also shows that the 25-m depth aquifer is more sensitive to possible cumulative effects than the 45-m depth aquifer suggesting the thickness of the aquifer is important factor in predicting cumulative effects.

7.4 Summary and Conclusions

This chapter discusses the possible cumulative effects due to repetitive underseepage processes. In Chapter 3, a transient flow model was developed by the Laplace transform method. In Chapter 4, the model was revised when there was an upward seepage out of the aquifer. In this chapter, cumulative effects were evaluated with and without an upward seepage at the landside of the levee.

For cumulative analysis of underseepage in a confined aquifer, the transient flow model by the Laplace transform method, the Army Corps method and SEEP2D finite element analysis were used. The results indicated that the transient flow model did not show any considerable increase in exit gradients as the aquifer transmissivity increases. The Army Corps method and SEEP2D analysis showed considerable increases in exit gradients in response to increases in aquifer transmissivities.

For cumulative analysis of underseepage with leakage out of a confined aquifer, the transient flow model by the Laplace transform method and SEEP2D finite element analysis were used. The results indicated that the transient flow model showed significant increases in exit hydraulic gradients in response to increases in aquifer diffusivities during seepage emerging at the landside of the levee. This result implies that the regions where sand boils were observed may experience more dramatic underseepage problems in the next flood event due to cumulative effects. A similar trend cannot be associated with the results of SEEP2D finite element analysis. However, the increases in exit gradients by SEEP2D analysis are not expected to be as significant as the increases that resulted from the transient flow model when there is an upward seepage at the landside of the levee. The exit gradients are also in agreement when comparing the transient flow model and SEEP2D finite element analysis.

An interesting common trend in cumulative analysis is that the cumulative effects seem to result in higher exit gradients farther from the landside of the levee than at the toe of the levee. This trend leads us to expect that critical underseepage problems may develop farther from the landside of the levee due to cumulative effects of underseepage. As presented in Section 2.3.1, sand boils were reported up to 2.4-km landside from the Mississippi River levees. Cumulative effects may be among the reasons for the occurrence of sand boil formations at surprisingly far distances from the levees. However, this argument is applicable to the assumption of a homogenous increase in hydraulic conductivity of the pervious medium along the landside of the levee.

The objective of this chapter was satisfied with the analysis presented. This chapter also examined one of the main questions of this research: how transient flow analysis in conjunction with current underseepage analysis tools responds to possible cumulative effects problem. As noted in the literature survey, there is no published study on cumulative effects of underseepage problems associated with sand boils. The approach followed in this chapter helps to evaluate possible cumulative effects by the tools developed and used in this research. Long term site monitoring is needed in the field to confirm the application and the results of the tools used in this chapter.

CHAPTER 8 CONCLUDING REMARKS

The phenomena of seepage under hydraulic structures and formation of sand boils is quite complicated by a variety of factors including complex geological features and other discontinuities due to man made works, natural processes and organic agencies. As discussed in Chapter 2, qualitative and quantitative models and a number of tools exist to successfully perform underseepage analysis of levees. However, in literature, transient conditions associated with sand boil problems have not been studied in detail. This study investigated transient effects of seepage flow under levees associated with sand boil formation. The results of this research allow practicing engineers:

(1) to develop hydraulic gradient profile through the landside of a levee for rising and falling river stages,

(2) to consider possible site-specific cumulative effects due to repetitive flood, and

(3) to be aware of a time-lag between the river head fluctuations and the formation of uplift and sand boils at the landside of a levee.

Two transient flow models were developed: one was for the transient hydraulic head development in a confined aquifer and the other was for the transient hydraulic head development with leakage out of a confined aquifer. The second model simulated the occurrence of loss of water by upward seepage and discharge through sand boils. Two different solutions were presented for each model, and the exact solution, Laplace transform solution, was studied in detail. With the development of transient flow models the first and the second objectives of this research presented in Chapter1 were satisfied.

The developed flow models are practical tools to examine transient cases. In general, the models performed well. The transient flow model in confined aquifers is more conservative than the Army Corps method and SEEP2D finite element program.

The transient flow model with homogenous upward leakage out of confined aquifers is in good agreement with the SEEP2D finite element model.

Two-dimensional transient flow nets were also constructed based on analytical solutions to the governing equations, and they provide useful information to investigate head development beneath the landside of a levee. In addition, the solutions provide an analytical benchmark against which to compare numerical contributions to formulations of the flow nets. The third objective of this research was satisfied with this task.

Cumulative effects due to repetitive flood events were discussed. The response of transient flow models and the current underseepage analysis tools make it possible to evaluate some of the cumulative effects that may be associated with sand boil enlargement and piping from a series of floods. The transient flow model with leakage out of a confined aquifer showed significant increases in exit hydraulic gradients in response to cumulative effects.

This dissertation explored the following two questions that were set in Chapter 1: (1) Is transient flow analysis due to river head fluctuations critical in the development of exit hydraulic gradients and the subsequent sand boil formation? and (2) If sand boils develop more frequently due to cumulative effects associated with repetitive flood events, how can transient flow analysis in conjunction with current underseepage analysis tools respond to this problem?

The first question was explored in Chapter 6. This chapter also satisfied the fourth objective of this research. The transient flow analysis can provide critical information in the development of exit hydraulic gradients and subsequent sand boil formation. However, a combination of further field, laboratory, and model studies are needed to document changes in exit gradients with a series of floods. The second question was discussed in Chapter 7. This chapter also satisfied the fifth objective of this research. The transient flow analysis with upward leakage responded significantly to possible cumulative effects of repetitive underseepage of levees. For the case of no upward leakage, the Army Corps method and SEEP2D finite element analysis are more susceptible to the changes in the aquifer transmissivities than the transient flow model.

The present models can be further investigated for case studies. Some modifications can be considered in the application of transient flow models according to the site-specific underseepage history. Some of the modifications that appear warranted are adjustment in upward leakage quantity, use of both transient flow models, with and without upward leakage, and considering a time lag in head development between the river head and landside of the levee. Analysis in the sites with relief wells would also be very useful to test transient flow model with upward leakage.

The Army Corps method for underseepage analysis of levees is the state-of-art practice. Therefore, the Army Corps method can be taken as a base for comparison with the transient flow models. Currently, the Laplace transform solution without upward leakage case provides more conservative results than the Army Corps method. An error range can be determined for the transient flow models with extensive site-specific studies.

Other than experimental and field studies, transient and cumulative effects of repetitive high water events can also be further investigated by analytical methods. Transient models can be applied to the underseepage analysis in conjunction with the migration of wetting front. The changes in soil parameters due to saturation and migration of fines can be incorporated into transient flow models in order to determine the effects of prolonged high water. One subject that would be beneficial to study is the migration characteristics of different sized particles in natural strata under levees.

Overall, transient seepage flow analysis due to fluctuating river head conditions can be an important view point to adopt in the study of underseepage of levees associated with sand boil problems. Further analytical, field and laboratory studies are recommended to address the transient and cumulative effects of seepage under levees.

REFERENCES

Abramowitz M., and Stegun I.A. (Editors) (1965). Handbook of Mathematical Functions. Dover Publications, NY.

Bear J. (1972). Dynamics of Fluids in Porous Media. American Elsevier, New York.

Adrian D.D., Alshawabkeh A.N., and Ozkan S. (2001). Tracer Transport in a Soil Column for Sine Wave Loading. Physical and Chemical Processes of Water and Solute Transport Retention in Soils, Edited by H. Magdi Selim and Donald Sparks, Soil Science Society of America Special Publication, No.56, Madison, WI, pp. 169-188.

Alshawabkeh A.N., and Adrian D.D. (1997). Analytical Water Quality Model for a Sinusiodally Varying BOD Discharge Concentration. Water Research, 31(5), pp. 1207-1215.

Barlow P.M., DeSimone L.A., and Moench A.F. (2000). Aquifer Response to Stream-Stage and Recharge Variations. II. Convolution Method and Applications. Journal of Hydrology, V. 230, pp. 211-229.

Bennett P.T. (1946). The Effect of Blankets on Seepage Through Pervious Foundations. ASCE Transactions, Vol. 11, Paper No. 2270, pp. 215-252.

Bligh W.G. (1927). The Practical Design of Irrigation Works. Van Nostrand Co., New York.

Brizendine A.L., Taylor H.M., and Gabr M.A.(1995). LEVSEEP: Analysis Software for Levee Underseepage and Rehabilitation. USACE Waterways Experiment Station, Technical Report, GL-95-10, United States Army Corps of Engineers, Washington, DC.

Budhu, M. (2000). Soil Mechanics and Foundations. John Wiley & Sons, Inc.

Casagrande A.(1937). Seepage Through Dams. Journal of the New England Water Works Association, republished in Contributions to Soil Mechanics 1925-1940, Boston Society of Civil Engineers, Boston, MA, pp. 295-336.

Carslaw H.S., and Jaeger J.C. (1959). Conduction of Heat in Solids, Second Edition. Oxford University Press, London, England.

Carslaw H.S., and Jaeger J.C. (1963). Operational Methods in Applied Mathematics. Dover Publications, NY.

Churchill R. V. (1958). Complex Variables and Applications. McGraw-Hill, New York, NY.

Cooper H.H., and Rorabaugh M.I. (1963). Groundwater Movements in Bank Storage due to Flood Stages in Surface Streams. U.S. Geol. Survey Water Supply Paper 1536-J, U.S. Government Printing Office, Washington, D.C., pp. 343-366.

Cunny R.W. (1980). Documentation and Analysis of Rock Island Underseepage Data. USACE Waterways Experiment Station, Technical Report, GL-80-3, Vicksburg, MS.

Cunny R.W., Agostinelli V.M., and Taylor H.M., Jr. (1989). Levee Underseepage Software User Manual and Validation. Technical Report REMR-GT-13. USACE Waterways Experiment Station, Vicksburg, MS

Daniel D.E. (1985). Review of Piezometric Data for Various Ranges in the Rock Island District. USACE Waterways Experiment Station, Vicksburg, MS.

Desai C.S. (1970). Seepage in Mississippi River Banks, Analysis of Transient Seepage Using a Viscous-Flow Model and Numerical Methods, Miscellanous Paper S-70-3, Report 1. USACE Waterways Experiment Station, Vicksburg, MS.

Desai C.S. (1973). Seepage in Mississippi River Banks, Analysis of Transient Seepage Using a Viscous-Flow Model and Finite Difference and Finite Element Methods, Technical Report S-73-S, Report 1. USACE Waterways Experiment Station, Vicksburg, MS.

DeWiest R.J.M. (1965). Geohydrology. John Wiley and Sons, Inc. New York.

De Wit J.M., Sellmeijer J.B., and Penning A. (1981). Laboratory Testing on Piping. Proceedings of the Tenth International Conference on Soil Mechanics and Foundation Engineering, 15-19 June 1981, Stockholm, Part I, A.A. Balkema Publishers, The Netherlands, pp. 517-520.

Farlow S.J. (1982). Partial Differential Equations for Scientists and Engineers, John Wiley and Sons, Inc. New York.

Ferris J.G. (1952). Cyclic Fluctuations of Water Level as a Basis for Determining Aquifer Transmissibility. pp. 1-17. In Contribution No. 1, Ground Water Hydraulics Section, Ground Water Branch, U.S. Geol. Surv., Washington, D.C.

Franklin, P. (1958). Functions of Complex Variables, Prentice-Hall, Englewood Cliffs, NJ.

Freeze R.A., and Cherry J.A. (1979). Groundwater. Prentice-Hall Inc., New Jersey.

Gabr M.A., Wolff T.F., Taylor H.M., and Brizendine A.L (1995). LEVEEMSU: Numerical Analysis Software for Levee Underseepage and Rehabilitation. USACE Waterways Experiment Station, Technical Report, GL-95-9, Vicksburg, MS.

Gabr M.A., Brizendine A.L., and Taylor H.M (1995). Comparison Between Finite Element Study and Simplified Analysis of Levee Underseepage. USACE Waterways Experiment Station, Technical Report, GL-95-11, Vicksburg, MS.

Gabr M.A., Wolff T.F., Brizendine A.L., and Taylor H.M (1996). Underseepage Analysis of Levees on Two-layer and Three-layer Foundation. Computers and Geotechnics, 18(2), pp. 85-107.

Gradshteyn I. S., and Ryzhik I. M. (1980). Table of Integrals, Series, and Products. Translated from Russian by Scripta Technica, Inc., edited by Alan Jeffrey, Academic Press, New York, NY.

GMS/SEEP2D, Finite Element Seepage Analysis, Brigham Young University, Scientific Software Group, Washington, DC.

Hall F.R., and Moench A.G. (1972). Application of the Convolution Equation to Stream Aquifer Relationships. Water Resources Research, 8 (2), pp. 487-493.

Hantush M.S., and Jacob C.E. (1955). Nonsteady Radial Flow in an Infinite Leaky Aquifer. Eos Trans, AGU, 36 (1), pp. 95-100.

Harr M.E. (1962). Groundwater and Seepage, McGraw-Hill Inc., New York, NY.

Hartono S. (2002). Prediction of Transient Head on Seepage Path Using Boundary Fitted Coordinate (BFC) System. A master's thesis, Louisiana State University, Baton Rouge, LA.

Holtz R.D., and Kovacs W.D. (1981). An Introduction to Geotechnical Engineering. Prentice-Hall Inc., New Jersey.

Horenstein W. (1945). Quarterly Applied Math, Vol. 3, 183.

Jiao J.J., and Tang Z. (1999). An Analytical Solution of Groundwater Response to Tidal Fluctuation in a Leaky Confined Aquifer. Water Resources Research, 35(3), pp. 747-751.

Kirkham D., and Powers W.L. (1972). Advanced Soil Physics, John Wiley and Sons, Inc., N.Y.

Kohler H.J. (1993). The influence of Hydraulic Head and Hydraulic Gradient on the Filtration Process. In Filters in Geotechnical and Hydraulic Engineering, edited by Brauns J., Heibaum H., and Shuler U. Karlsruhe, Germany. October 1992. A.A. Balkema, Rotterdam, The Netherlands, pp. 225-240.

Kolb C.R. (1976). Geologic Control of Sand Boils Along Mississippi River Levees. Geomorphology and Engineering, 7. Geomorphology Symposium, Binghamton, NY.

Lane E.W. (1935). Security from Underseepage: Masonary Dams on Earth Foundation. Transactions ASCE, Vol. 100, pp. 1235-1272.

Li Y., Craven J., Schweig E.S., and Obermeir S.F. (1996). Sand Boils Induced by the 1993 Mississippi River Flood: Could They One Day be Misinterpreted as Earthquake-Induced Liquefaction. Geology, 24 (2), pp. 171-174.

Logan J.D., and Zlotnik V.A. (1995). The Convective-Diffusion Equation with Periodic Boundary Conditions. Applied Math. Lett., 8, pp. 55-61.

Logan J.D., Zlotnik V.A., and Cohn S. (1996). Transport in Fractured Porous Media with Time-Periodic Boundary Condition. Mathematical and Computer Modeling, 24(9).

Meehan, R. (2001). Class notes of CE 297: Geotechnical and Environmental Failures, Stanford University, California, http://www.stanford.edu/~meehan/flood/peak.html.

Mansur C.I., Kaufman R.I., and Schultz J.R. (1956). Investigation of Underseepage and Its Control, Lower Mississippi River Levees, 2 vols. USACE Waterways Experiment Station, Technical Memo, 3-424, Vicksburg, MS.

Mansur C.I., Postol G., and Salley J.R. (2000). Performance of Relief Well Systems Along Mississippi River Levees. Journal of Geotechnical and Geoenvironmental Engineering, 126(8), pp. 727-738.

Moench A.F., and Barlow P.M. (2000). Aquifer Response to Stream-Stage and Recharge Variations. I. Analytical Step-Response Functions, Journal of Hydrology, V. 230, pp. 192-210.

Oberhettinger F., and Badii L. (1973). Tables of Laplace Transforms. Springer - Verlag, New York, NY.

Ojha C.S.P, Singh V.P., and Adrian D.D. (2001). Influence of Porosity on Piping Models of Levee Failure. ASCE, Journal of Geotechnical and Geoenvironmental Engineering, 120 (12), pp. 1071-1074.

Oppenheimer S.F., Adrian D.D., and Alshawabkeh A.N. (1999). A River Water Quality Model for Time Varying BOD Discharge Concentration. Math. Probl. Eng., 5, pp. 193-221.

Ozisik M.N. (1963). Boundary Value Problems of Heat Conduction, International Textbook Co., Scranton, PA.

Peter P. (1982). Canal and River Levees. Developments of Civil Engineering 29, Bratislava, Slovakia, Elsevier/North-Holland, Inc., NY.

Petit Bois G. (1961). Tables of Indefinite Integrals. Dover Pub., New York, NY.

Pinder G.F., Bredehoeft J.D., and Cooper H.H. (1969). Determination of Aquifer Diffusivity from Aquifer Response to Fluctuations in River Stage. Water Resources Research 5 (4), pp. 850-855.

Polubarinova-Kochina P.Ya. (1962). Theory of Ground Water Movement. Translated from the Russian by J.M. Roger De Wiest, Princeton University Press, Princeton, NJ.

SEEP/W for Finite Element Seepage Analysis (1995-2000). Geo-Slope Office Version 4, Geo-Slope Int. Ltd., Alberta, Canada.

Sellmeijer J.B., and Koenders M.A. (1991). A Mathematical Model for Piping. Appl. Math. Modelling, 15 (6), pp. 646-651.

Scott, E. J. (1955). Transform Calculus with an Introduction to Complex Variables. Harper & Brothers, New York, NY.

Sherard J.L., Woodward R.J., Gizienski S.F., and Clevenger W.A. (1963). Earth and Earth-Rock Dams, Engineering Problems of Design and Construction. John Wiley and Sons, Inc., NY.

Sherard J.L., Decker R.S., and Ryker N.L. (1972). Specialty Conference on Performance of Earth and Earth-Supported Structures. ASCE, Vol.1, Part 1, pp 589-626.

Singh, V.P. (1992). Elementary Hydrology. Prentice-Hall, Inc., New Jersey.

Terzaghi K. (1929). Effect of Minor Geologic Details on the Safety of Dams. Bulletin of American Institute of Mining and Metallurgical Engineers, Technical Publication 215, Class I, Mining Geology, No. 26, pp. 31-46.

Thompson J.F., Warsi Z.U.A., and Mastin C.W. (1985). Numerical Grid Generation: Foundation and Applications, Elsevier, New York.

Thompson J.F., and Warsi Z.U.A. (1982). Boundary–fitted Coordinate Systems for Numerical Solution of Partial Differential Equations. Journal of Computational Physics 47: 1-108.

Thompson J.F., Thames F.C., and Mastin C.W. (1977). Boundary-fitted Curvilinear Coordinate Systems for the Solution of Partial Differential Equations on Fields Containing Any Number of Arbitrary Two-dimensional Bodies. NASA CR-2729, National Aeronautics and Space Administration.

Tomlinson S.S., and Vaid Y.P. (2000). Seepage Forces and Confining Pressure Effects on Piping Erosion. Canadian Geotechnical Journal, 37 (1), pp. 1-13.

Tracy F.T. (1973a). A Plane and Axisymmetric Finite Element Program for Steady-State and Transient Seepage Problems, Miscellaneous Paper K-73-4. USACE Waterways Experiment Station, Vicksburg, MS.

Tracy F.T. (1973b). A Three Dimensional Finite Element Program for Steady-State and Transient Seepage Problems, Miscellaneous Paper K-73-3. USACE Waterways Experiment Station, Vicksburg, MS.

Turnbull W.J., and Mansur C.I. (1961). Investigation of Underseepage-Mississippi River Levees. Transactions, ASCE, 126 (1), pp. 1429-1485.

Turner G. A. (1972). Heat and Concentration Waves, Academic Press, New York, NY, pp. 196-200.

U.S. Army Corps of Engineers (1956). TM 3-424, Underseepage and Its Control, Lower Mississippi River Levees (1956). USACE Waterways Experiment Station, Vicksburg, MS.

U.S. Army Corps of Engineers (1963). EM 1110-2-1905, Design of Finite Relief Well Systems. Department of the Army, USACE , Washington, D.C.

U.S. Army Corps of Engineers (1986, 1993). EM 1110-2-1901, Seepage Analysis and Control for Dams. Department of the Army, USACE, Washington, D.C.

U.S. Army Corps of Engineers (1992). EM 1110-2-1914, Design, Construction and Maintenance of Relief Wells. Department of the Army, USACE, Washington, D.C.

U.S. Army Corps of Engineers, New Orleans District Office (1992). Mississippi River Levees LSU-Duncan Point Seepage Study, Item M-227.5 to L-217.1, Pontchartrain Levee District.

U.S. Army Corps of Engineers (1994). CSEEP:Seepage Package. USACE Waterways Experiment Station, Vicksburg, MS.

U.S. Army Corps of Engineers (1997). ETL 1110-2-555, Design Guidance on Levees. Department of Army, USACE, Washington, DC.

U.S. Army Corps of Engineers (1999). EM 1110-2-1421, Engineering and Design – Groundwater Hydrology. Department of the Army, USACE, Washington, DC.

U.S. Army Corps of Engineers (2000). EM 1110-2-1913, Engineering and Design - Design and Construction of Levees. Department of the Army, USACE, Washington, DC.

Van Genuchten M.T., and Alves W. J. (1982). Analytical Solutions of the One-Dimensional Convective-Dispersive Solute Transport Equation. Technical Bulletin 1661, U. S. Department of Agriculture, Agricultural Research Service, Washington, DC.

Van Zyl D., and Harr M.E. (1981). Seepage Erosion Analysis of Structures. Proceedings of the Tenth International Conference on Soil Mechanics and Foundation Engineering, 15-19 June 1981, Stockholm, Part I, A.A. Balkema Publishers, The Netherlands, pp. 503-509.

Werner P. W., and Noren D. (1951). Progressive Waves in Non-Artesian Aquifers. Transaction*s*, American Geophysical Union, 32(2), pp. 238-244.

Wolff T.F. (1987). Levee Underseepage Analysis for Special Foundation Conditions. Research report prepared for USACE Waterways Experiment Station, Michigan State University, East Lansing, MI.

Wolff T.F. (1989). LEVEEMSU: A Software Package Designed for Levee Underseepage Analysis. Technical Report GL-89-13. USACE Waterways Experiment Station, Michigan State University, East Lansing, MI.

Wolff T.F., and Taylor H.M. (1991). Critical Review of Levee Underseepage. Technical Report prepared for USACE Waterways Experiment Station, Michigan State University, East Lansing, MI.

Wolff T.F. (2002). Performance of Levee Underseepage Controls: A Critical Review. USACE Engineer Research and Development Center, ERDC/GSL TR-02-19, Washington, DC.

Yu F. X., Adrian D. D., and Singh V.P. (1991). Modeling River Quality by Superposition Method. J. Environmental Systems, 20(4), pp. 1-16.

APPENDIX A CALCULATIONS AND GRAPHS IN CHAPTER 3 AND 4

Calculations and Graphs in Chapter 3

Transient Flow Model by Laplace Transform Method

$S := 0.005$ dimensionless $\qquad T := 0.025\,86400$ m^2/day

$\omega := \frac{\pi}{60} \qquad r := \omega \qquad \theta := \frac{\pi}{2} \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad m := 100$

$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot \cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R,I) := \frac{\exp(-R^2)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp(-R^2)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \operatorname{erf}(R) + \frac{\exp(-R^2)}{2\cdot\pi\cdot R}\cdot(1-\cos(2\cdot R\cdot I))\ \ldots$$
$$+\frac{2}{\pi}\cdot\exp(-R^2)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$R2(x,t) := \sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$H_0 := 5$ meter

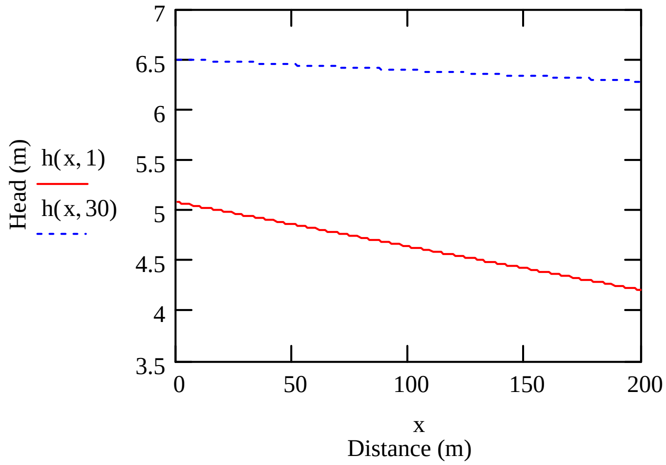
$H_1 := 1.5$ meter

$$h_{im}(x,t) := \frac{1}{2}\cdot H_1\cdot\cos(\omega\cdot t)\cdot\left[\begin{array}{l}\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\ \ldots\\ +\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t)))\end{array}\right]\ \ldots\\ +\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\ \ldots\\ +\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t)))\end{array}\right]\end{array}\right]\ \ldots$$
$$+\frac{1}{2}\cdot H_1\cdot\sin(\omega\cdot t)\cdot\left[\begin{array}{l}\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t)))\ \ldots\\ +\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\end{array}\right]\ \ldots\\ +\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t)))\ \ldots\\ +\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\end{array}\right]\end{array}\right]$$

Figure 3.4

$$h(x,t) := H_0 \cdot \mathrm{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}}\right) + h_{im}(x,t)$$

$x := 0, 1 .. 200$ m



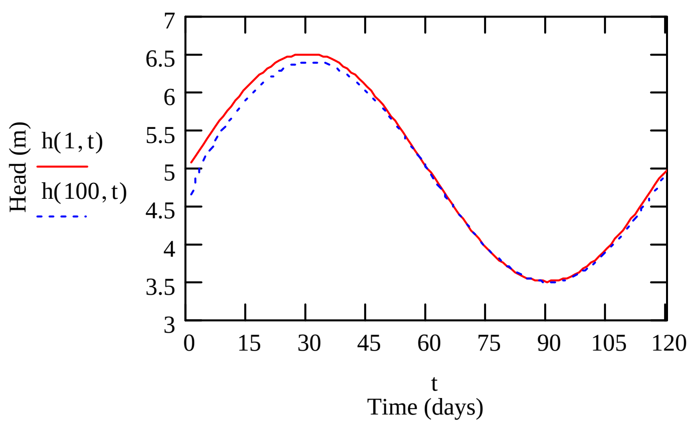
$h(0,1) = 5.079$ $h(0,30) = 6.5$

$h(100,1) = 4.638$ $h(100,30) = 6.389$

$h(200,1) = 4.203$ $h(200,30) = 6.279$

Figure 3.5

$t := 0 .. 120$



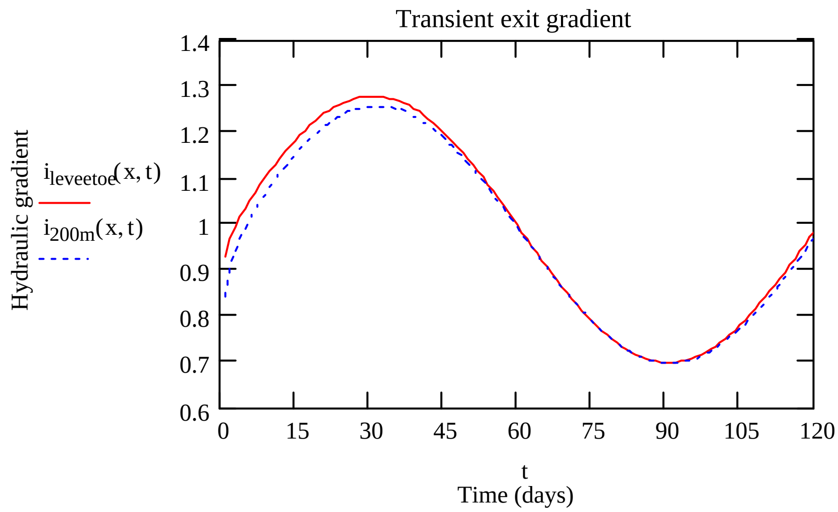
$h(1,30) = 6.499$ $h(100,30) = 6.389$

Figure 3.6

$x := 100$ $t := 0 .. 120$

Thickness of upper layer is assumed as 5 m

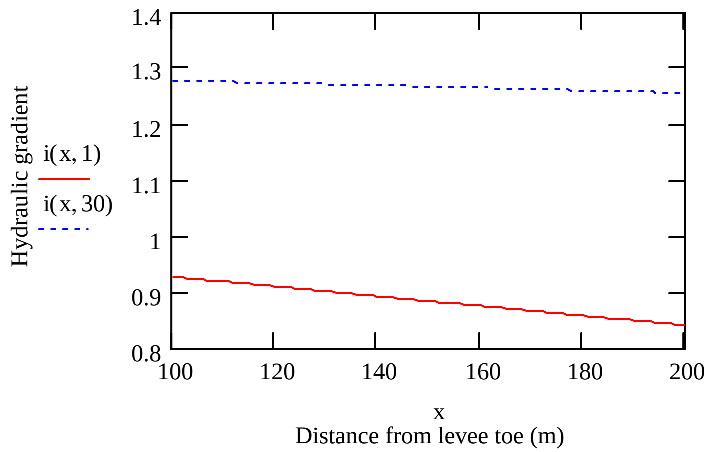
$$i_{leveetoe}(x,t) := \frac{h(100,t)}{5} \qquad i_{200m}(x,t) := \frac{h(200,t)}{5}$$



$i_{leveetoe}(x,30) = 1.278$ $\quad$ $i_{200m}(x,30) = 1.256$

Figure 3.7

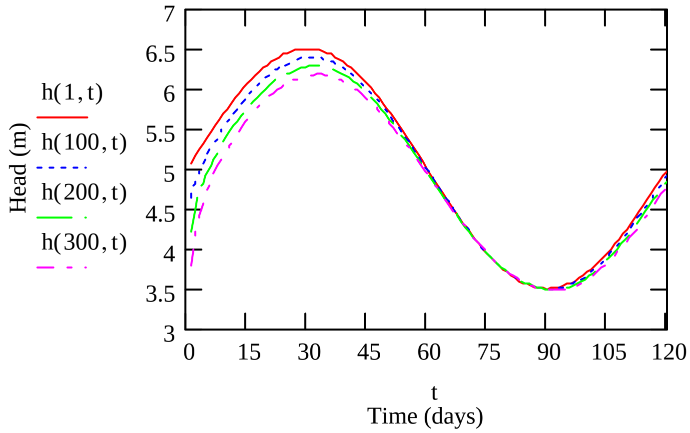
$i(x,t) := \dfrac{h(x,t)}{5}$ $\quad$ $x := 100..200$



$i(200,1) = 0.841$ $\quad$ $i(200,30) = 1.256$ $\quad$ $i(100,1) = 0.928$ $\quad$ $i(100,30) = 1.278$

Figure 3.12

$t := 0..120$



t := 29.. 33

h(100, t) =	h(200, t) =	h(300, t) =
6.384	6.271	6.157
6.389	6.279	6.168
6.39	6.283	6.175
6.387	6.283	6.178
6.38	6.279	6.177

Transient Flow Model by an Approximate Method

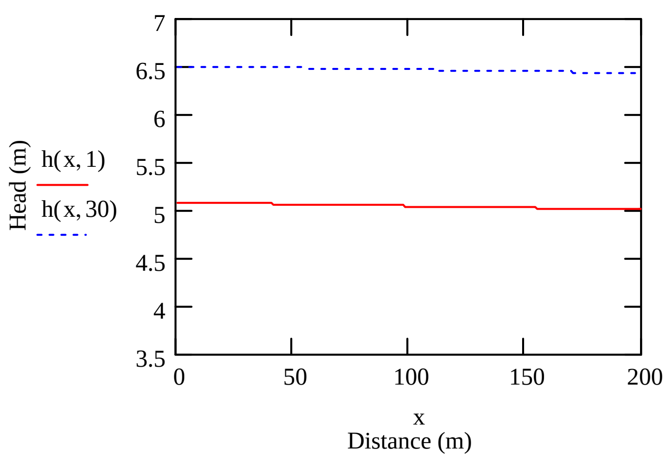
$S := 0.005$ dimensionless $\qquad T := 0.025\,86400$ m^2/day

$$\omega := \frac{\pi}{60} \qquad p := \sqrt{\frac{\omega \cdot S}{2 \cdot T}} \qquad h_0 := 5\ \text{m} \qquad h_1 := 1.5\ \text{m}$$

$$h(x,t) := h_0 + h_1 \cdot e^{-p \cdot x} \cdot \sin\left(\omega \cdot t - \frac{\omega \cdot S}{2 \cdot p \cdot T} \cdot x\right)$$

Figure 3.8

$t := 1 \qquad x := 0, 1 .. 200$ m

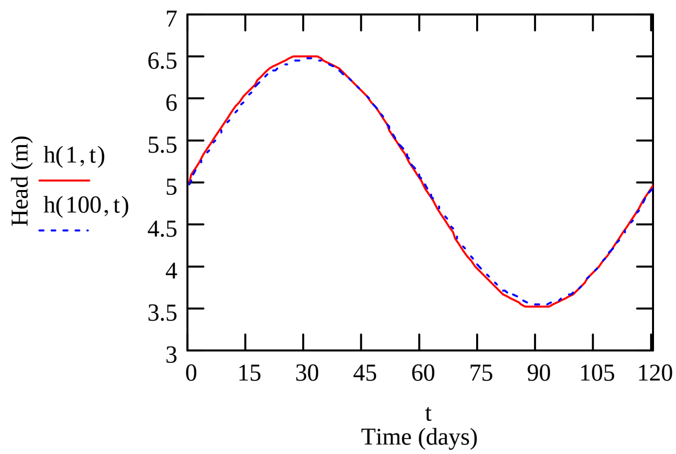


$h(100, 1) = 5.041 \qquad h(100, 30) = 6.463$

$h(200, 1) = 5.004 \qquad h(200, 30) = 6.426$

Figure 3.9

$t := 0, 1..120$

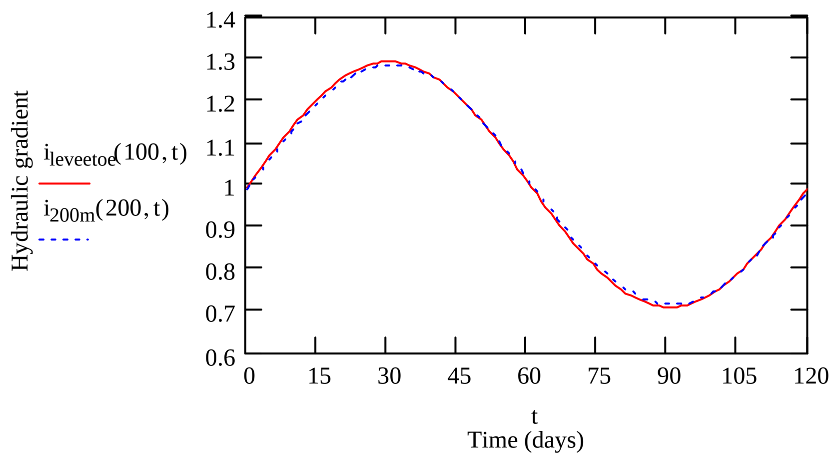


$h(1, 30) = 6.5$ $\quad h(100, 30) = 6.463$

Figure 3.10

$t := 0..120$ days $\quad$ Thickness of upper layer is assumed as 5 m

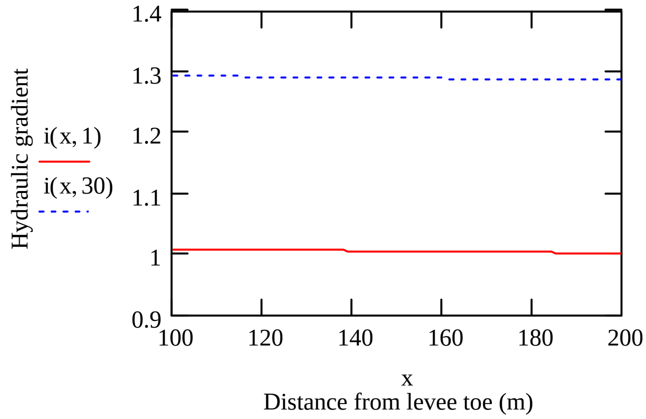
$i_{leveetoe}(x, t) := \frac{h(100, t)}{5}$ $\quad i_{200m}(x, t) := \frac{h(200, t)}{5}$



$i_{leveetoe}(100, 0) = 0.993$ $\quad i_{200m}(200, 90) = 0.715$

Figure 3.11

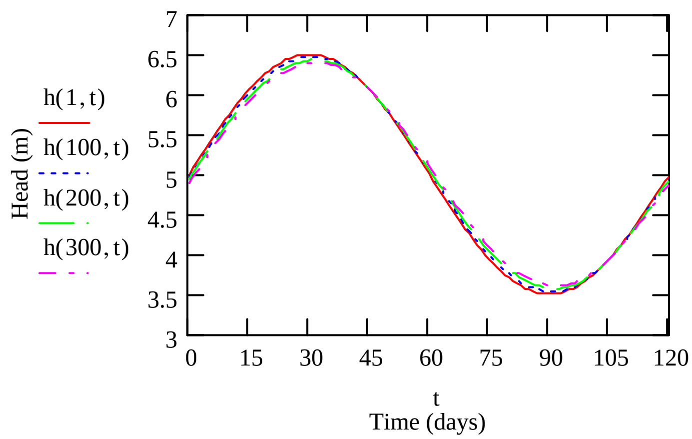
$i(x, t) := \frac{h(x, t)}{5}$ $\quad x := 100..200$



$i(100,1) = 1.008$ $i(200,1) = 1.001$ $i(100,30) = 1.293$ $i(200,30) = 1.285$

Figure 3.13

$t := 0..120$



$t := 29..33$

$h(100,t) =$	$h(200,t) =$	$h(300,t) =$
6.459	6.421	6.382
6.463	6.426	6.389
6.463	6.428	6.393
6.459	6.426	6.393
6.451	6.42	6.388

Calculations and Graphs in Chapter 4

Transient Flow Model by Laplace Transform Method with Leakage Out of Confined Aquifer

$S := 0.005$ dimensionless $T := 0.025\,86400$ m^2/day $L := 0.14$ $\omega := \frac{\pi}{60}$

$m := 100$

$$\theta := \operatorname{atan}\left(\frac{S\cdot\omega}{L}\right) \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad r := \frac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2\,\omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$$

$$g_n(R, I, n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$$

$$G(R, I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R, I, n)$$

$$F(R, I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1 - \cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R, I, n)\right)$$

$$R1(x,t) := -\sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$$

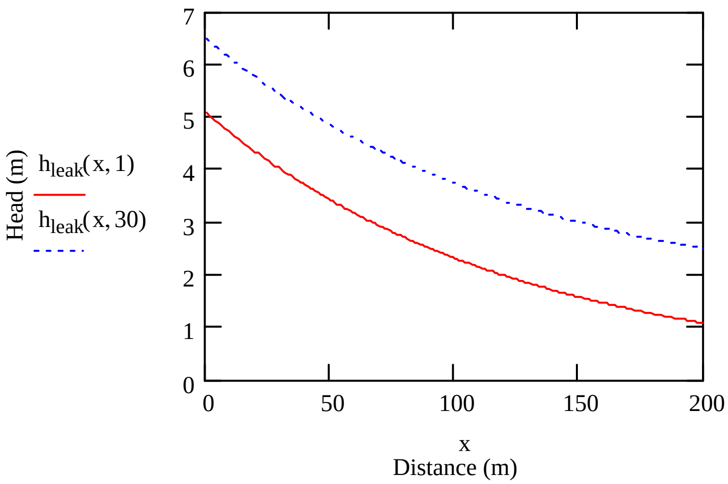
$$R2(x,t) := \sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$$

$$h_0 := 5 \;\; \text{meter} \qquad h_1 := 1.5 \;\; \text{meter}$$

$$\begin{aligned}
h_{leak}(x,t) := {} & \frac{1}{2}\cdot h_1\cdot\cos(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t), I1(t)) \ldots \\
& \qquad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t), I1(t)))\Bigg] \ldots \\
& \quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t), I2(t)) \ldots \\
& \qquad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t), I2(t)))\Bigg]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_1\cdot\sin(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t), I1(t))) \ldots \\
& \qquad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t), I1(t))\Bigg] \ldots \\
& \quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t), I2(t))) \ldots \\
& \qquad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t), I2(t))\Bigg]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_0\cdot\left(\exp\left(-x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} - \sqrt{\frac{L}{S}\cdot t}\right) + \exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} + \sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}$$

Figure 4.4

$x := 0, 1 .. 200\ m$



$h_{leak}(100, 1) = 2.314$ $h_{leak}(200, 1) = 1.078$ $h_{leak}(100, 30) = 3.733$ $h_{leak}(200, 30) = 2.496$

Figure 4.5

$t := 0 .. 120$

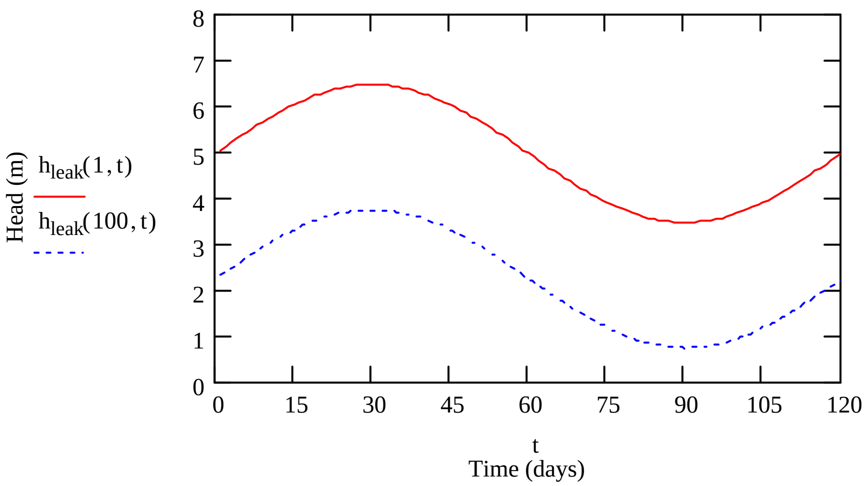
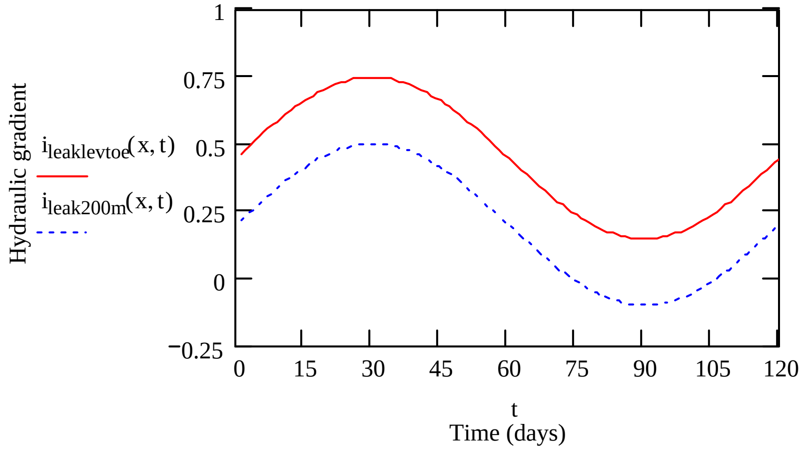


Figure 4.6

$x := 100 \quad t := 0 .. 120$

$$i_{leaklevtoe}(x, t) := \frac{h_{leak}(100, t)}{5} \quad i_{leak200m}(x, t) := \frac{h_{leak}(200, t)}{5}$$

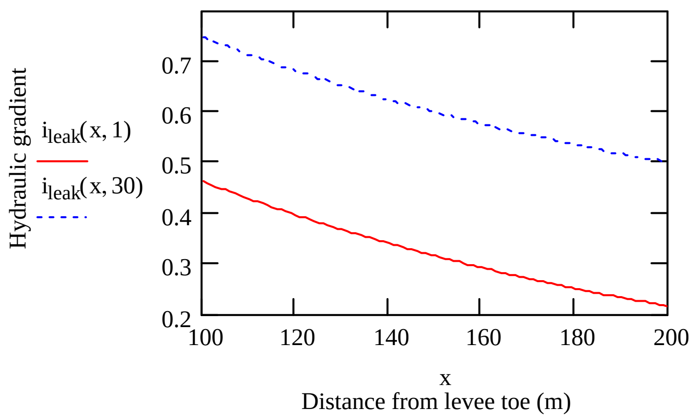


$i_{leaklevtoe}(x,120) = 0.447$ $i_{leak200m}(x,120) = 0.2$

Figure 4.7

$$i_{leak}(x,t) := \frac{h_{leak}(x,t)}{5}$$

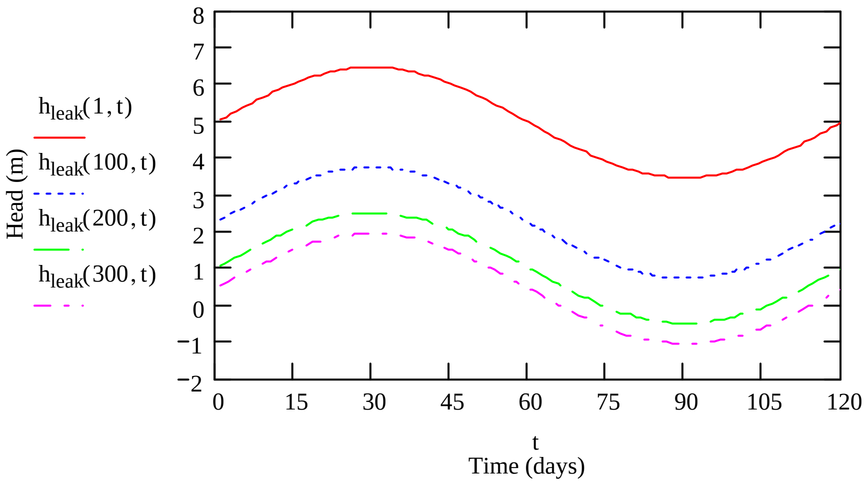
$x := 100..200$



$i_{leak}(200,1) = 0.216$ $i_{leak}(200,30) = 0.499$ $i_{leak}(100,1) = 0.463$ $i_{leak}(100,30) = 0.747$

Figure 4.14

$t := 0..120$



$t := 29..32$

$h_{leak}(1,t) =$ $h_{leak}(100,t) =$ $h_{leak}(200,t) =$ $h_{leak}(300,t) =$

6.458	3.731	2.494	1.939
6.46	3.733	2.496	1.941
6.458	3.731	2.494	1.939
6.452	3.725	2.487	1.933

Calculations for Figure 4.12, L=0.28 1/day

$S := 0.005$ dimensionless $\qquad T := 0.025\,86400$ m^2/day $\qquad L := 0.28 \quad \omega := \frac{\pi}{60}$

$m := 100$

$\theta := \operatorname{atan}\left(\frac{S\cdot\omega}{L}\right) \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad r := \frac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2\,\omega^2 + L^2}}{S}$

$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1-\cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

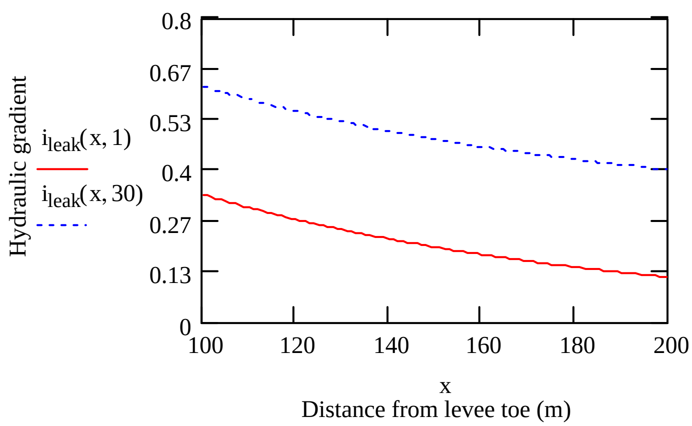
$R2(x,t) := \sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$h_0 := 5$ meter $\qquad h_1 := 1.5$ meter

$$
\begin{aligned}
h_{leak}(x,t) := {} & \frac{1}{2}\cdot h_1\cdot \cos(\omega\cdot t)\cdot\left[\begin{aligned}
& \exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{aligned}
& -\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t), I1(t)) \ldots \\
& + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t), I1(t)))
\end{aligned}\right] \ldots \\
& + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{aligned}
& -\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t), I2(t)) \ldots \\
& + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t), I2(t)))
\end{aligned}\right]
\end{aligned}\right] \ldots \\
& + \frac{1}{2}\cdot h_1\cdot \sin(\omega\cdot t)\cdot\left[\begin{aligned}
& \exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{aligned}
& \cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t), I1(t))) \ldots \\
& + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t), I1(t))
\end{aligned}\right] \ldots \\
& + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{aligned}
& \cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t), I2(t))) \ldots \\
& + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t), I2(t))
\end{aligned}\right]
\end{aligned}\right] \ldots \\
& + \frac{1}{2}\cdot h_0\cdot\left(\exp\left(-x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} - \sqrt{\frac{L}{S}\cdot t}\right) + \exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} + \sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}
$$

Figure 4.12

$$i_{leak}(x,t) := \frac{h_{leak}(x,t)}{5} \qquad x := 100 .. 200$$



$i_{leak}(200,1) = 0.118 \quad i_{leak}(200,30) = 0.402 \quad i_{leak}(100,1) = 0.336 \quad i_{leak}(100,30) = 0.62$

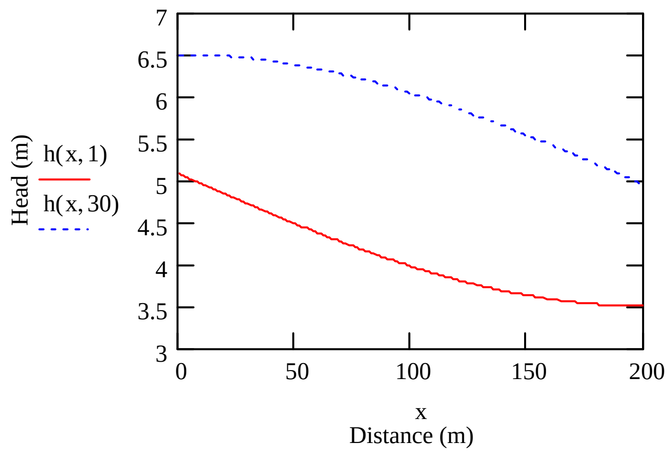
Transient Flow Model by an Approximate Method with Leakage Out of Confined Aquifer

$S := 0.005$ dimensionless $\quad T := 0.025\,86400$ m^2/day $\quad L := 0.14$1/day $\quad \omega := \frac{\pi}{60} \quad h_0 := 5$ m $h_1 := 1.5$ m

$$p := \frac{1}{\sqrt{2}} \cdot \left[\left[\left(\frac{L}{T} \right)^2 + \left(\frac{S \cdot \omega}{T} \right)^2 \right]^{\frac{1}{2}} - \frac{L}{T} \right]^{\frac{1}{2}} \qquad h(x,t) := h_0 + h_1 \cdot e^{-p \cdot x} \cdot \sin\left(\omega \cdot t - \frac{\omega \cdot S}{2 \cdot p \cdot T} \cdot x \right)$$

Figure 4.8

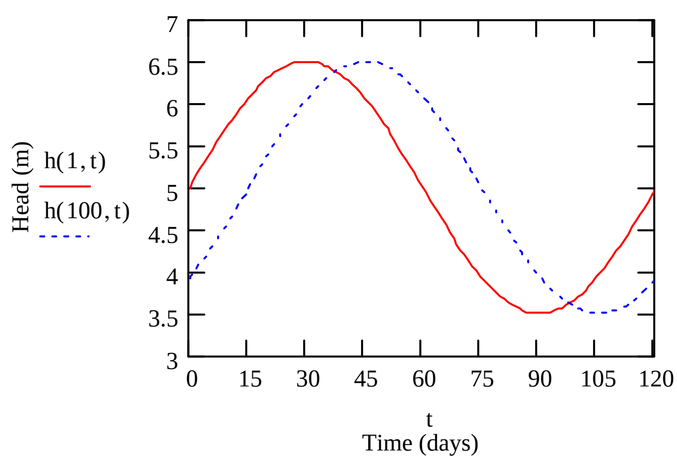
$t := 1 \qquad x := 0, 1 .. 200$ m



$h(100,1) = 3.975 \quad h(200,1) = 3.502 \quad h(100,30) = 6.039 \quad h(200,30) = 4.941$

Figure 4.9

$t := 0, 1 .. 120$ days

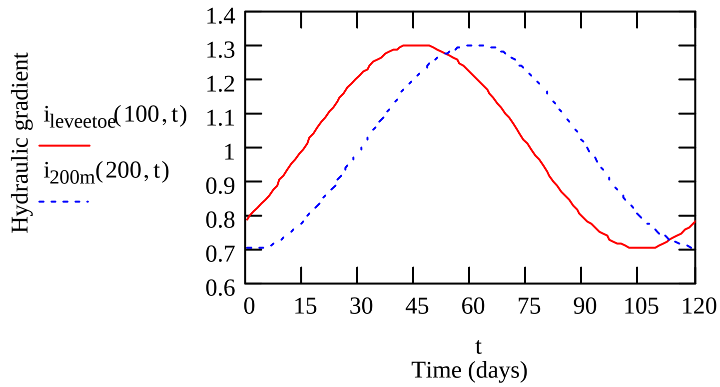


$h(100,48) = 6.485 \quad h(1,30) = 6.5$

Figure 4.10

$t := 0 .. 120$ days

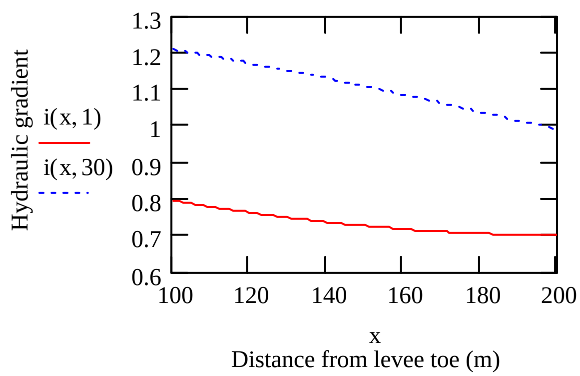
$$i_{leveetoe}(x,t) := \frac{h(100,t)}{5} \qquad i_{200m}(x,t) := \frac{h(200,t)}{5}$$



$i_{leveetoe}(100, 50) = 1.291 \quad i_{200m}(200, 68) = 1.278$

Figure 4.11

$i(x, t) := \frac{h(x, t)}{5} \qquad x := 100..\, 200$



$i(100, 1) = 0.795 \quad i(200, 1) = 0.7 \quad i(100, 30) = 1.208 \quad i(200, 30) = 0.988$

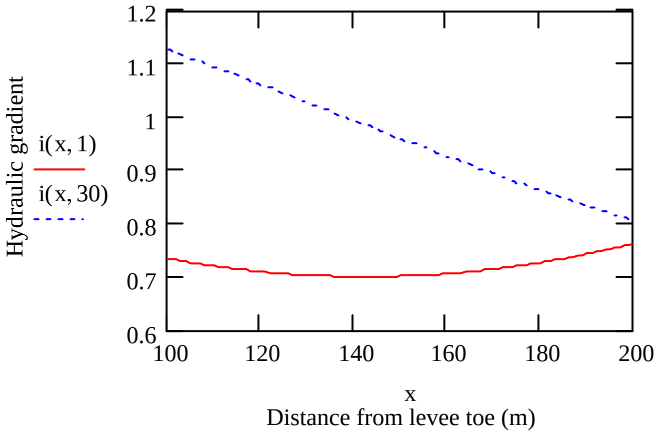
Calculations for Figure 4.13, L=0.28 1/day

$S := 0.005$ dimensionless $\quad T := 0.025\,86400$ m^2/day $\quad L := 0.28$ 1/day $\quad \omega := \frac{\pi}{60} \quad h_0 := 5\text{ m} \quad h_1 := 1.5\text{ m}$

$$p := \frac{1}{\sqrt{2}} \cdot \left[\left[\left(\frac{L}{T} \right)^2 + \left(\frac{S \cdot \omega}{T} \right)^2 \right]^{\frac{1}{2}} - \frac{L}{T} \right]^{\frac{1}{2}} \qquad h(x, t) := h_0 + h_1 \cdot e^{-p \cdot x} \cdot \sin\left(\omega \cdot t - \frac{\omega \cdot S}{2 \cdot p \cdot T} \cdot x \right)$$

Figure 4.13

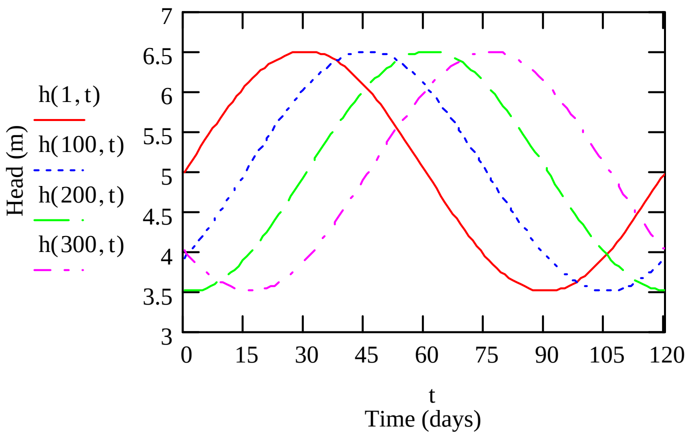
$i(x, t) := \frac{h(x, t)}{5} \qquad x := 100..\, 200$



i(100, 1) = 0.735   i(200, 1) = 0.762   i(100, 30) = 1.126   i(200, 30) = 0.805

Figure 4.15

t := 0.. 120



APPENDIX B CALCULATIONS AND GRAPHS IN CHAPTER 5

$\omega := \frac{\pi}{60}$ $h_0 := 5\text{ m}$ $h_1 := 1.5\text{ m}$ $b := 25\text{ m}$

$h(t) := h_0 + h_1 \cdot \sin(\omega \cdot t)$ $i_{infinite}(x,t) := \frac{h(t)}{\pi\sqrt{x^2 - b^2}}$

Figure 5.3

$x := 25..125$ m

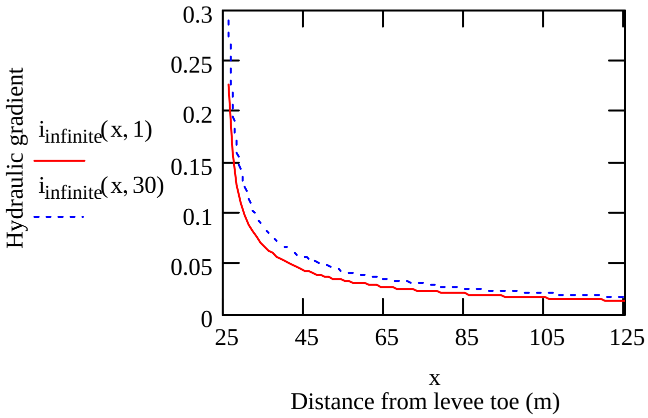
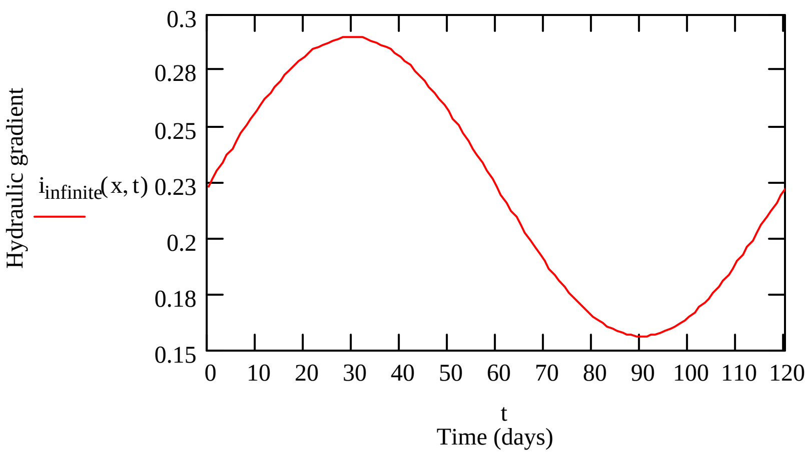


Figure 5.4

$t := 0..120$ day $x := 26$ m



Transient flow net for infinite depth aquifer:

Equipotential lines:

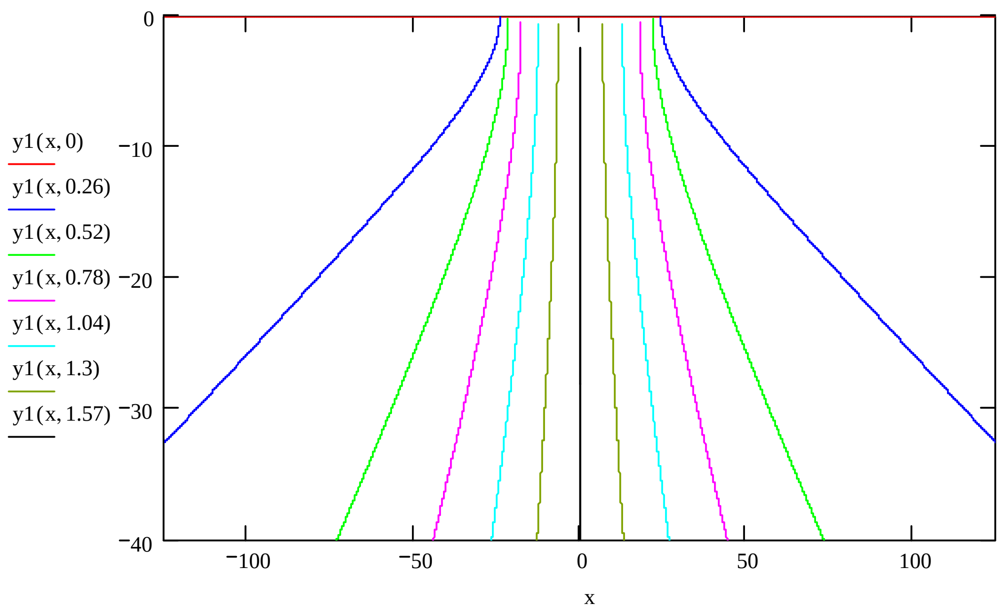
$b := 25$ $\omega := \frac{\pi}{60}$ $h_0 := 5$ $h_1 := 1.5$ $t := 10$ $k := 86.4\ \frac{m}{d}$

$h := h_0 + h_1 \cdot \sin(\omega \cdot t)$ $x := 125, 124.99..-125$

$\phi := 0, 41..246$ $\quad \phi_1(\phi, k, h) := \frac{\pi \cdot \phi}{k \cdot h}$ $\quad y1(x, \phi_1) := -\sqrt{x^2 \cdot \tan(\phi_1)^2 - b^2 \cdot \sin(\phi_1)^2}$

$\phi_1(\phi, k, h) =$

0
0.259
0.519
0.778
1.037
1.296
1.556



Streamlines:

$x := 125, 124.99..-125$ $\quad \psi := 0, 41..246$ $\quad \psi_1(\psi, k, h) := \frac{\pi \cdot \psi}{k \cdot h}$

$y2(x, \psi_1) := -\sqrt{b^2 \cdot \sinh(\psi_1)^2 - x^2 \cdot \tanh(\psi_1)^2}$

$\psi_1(\psi, k, h) =$

0
0.259
0.519
0.778
1.037
1.296
1.556

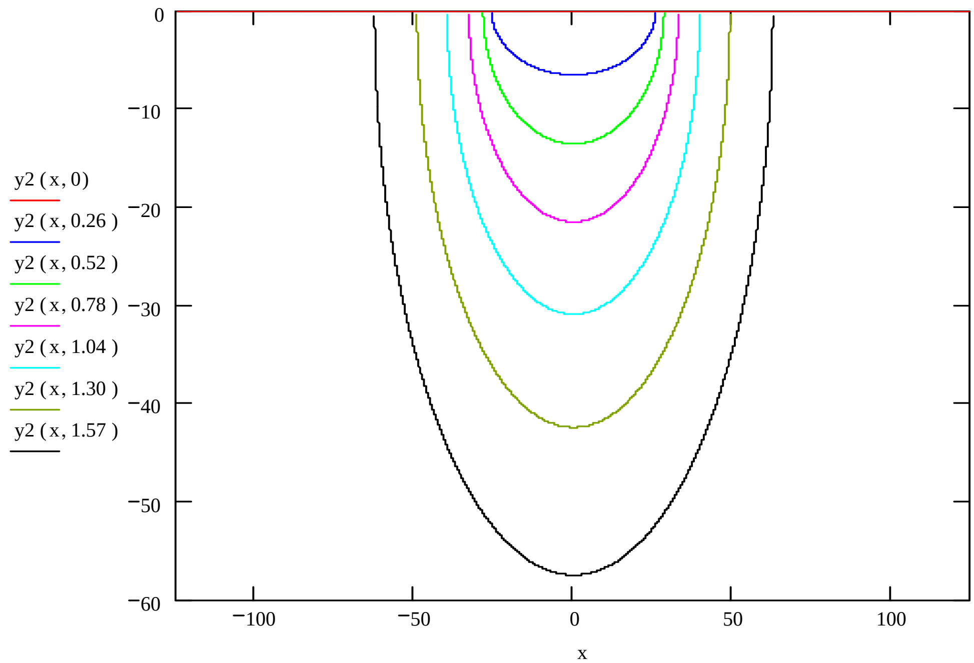

y2 (x, 0)
y2 (x, 0.26)
y2 (x, 0.52)
y2 (x, 0.78)
y2 (x, 1.04)
y2 (x, 1.30)
y2 (x, 1.57)
x

Figure 5.5

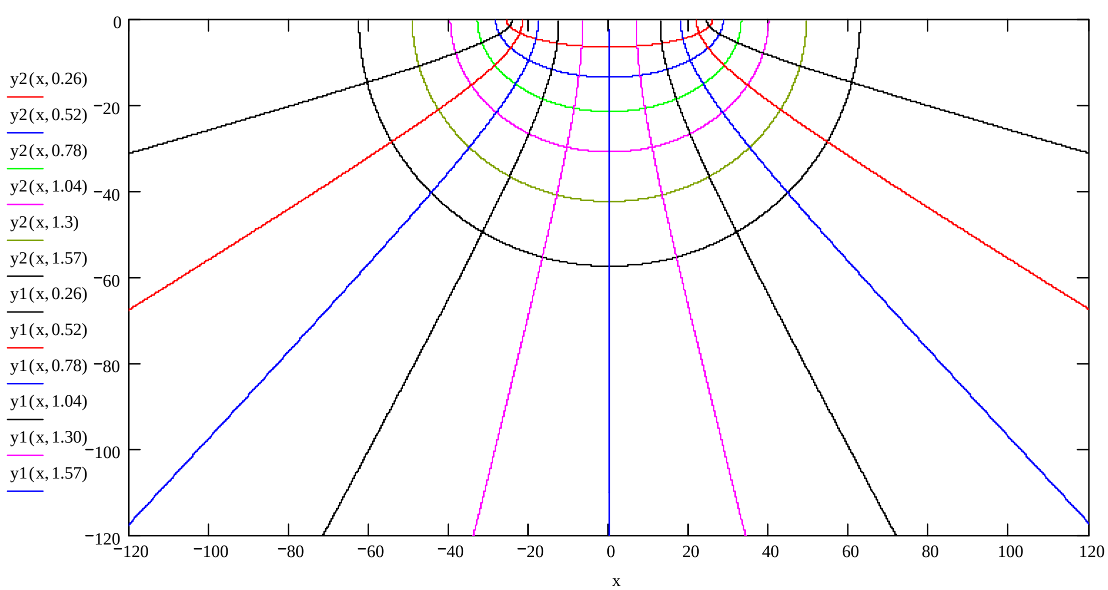

y2(x, 0.26)
y2(x, 0.52)
y2(x, 0.78)
y2(x, 1.04)
y2(x, 1.3)
y2(x, 1.57)
y1(x, 0.26)
y1(x, 0.52)
y1(x, 0.78)
y1(x, 1.04)
y1(x, 1.30)
y1(x, 1.57)
x

Figure 5.6

Finite depth aquifers:

$b := 25 \quad \omega := \frac{\pi}{60} \quad h_0 := 5\ \mathrm{m} \quad h_1 := 1.5\ \mathrm{m} \quad T := 50\ \mathrm{m}$

$z := \tanh\left(\frac{\pi \cdot b}{2 \cdot T}\right) \quad h(t) := h_0 + h_1 \cdot \sin(\omega \cdot t) \quad z^2 = 0.43 \quad K := 1.799$

$$i_{finite}(x,t) := \frac{h(t)\cdot\pi}{4\cdot K\cdot T}\cdot\frac{\cosh\left(\frac{\pi\cdot b}{2\cdot T}\right)}{\sqrt{\sinh\left[\pi\cdot\frac{(b+x)}{2\cdot T}\right]\cdot\sinh\left[\pi\cdot\frac{(x-b)}{2\cdot T}\right]}}$$

$x := 26..125$

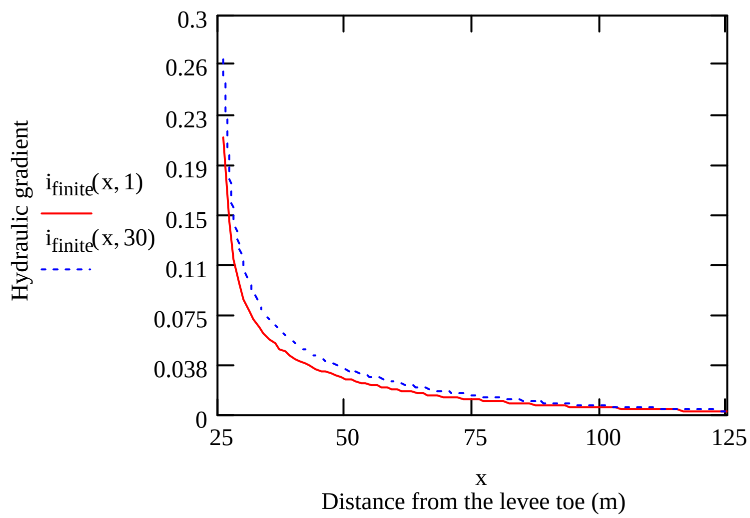
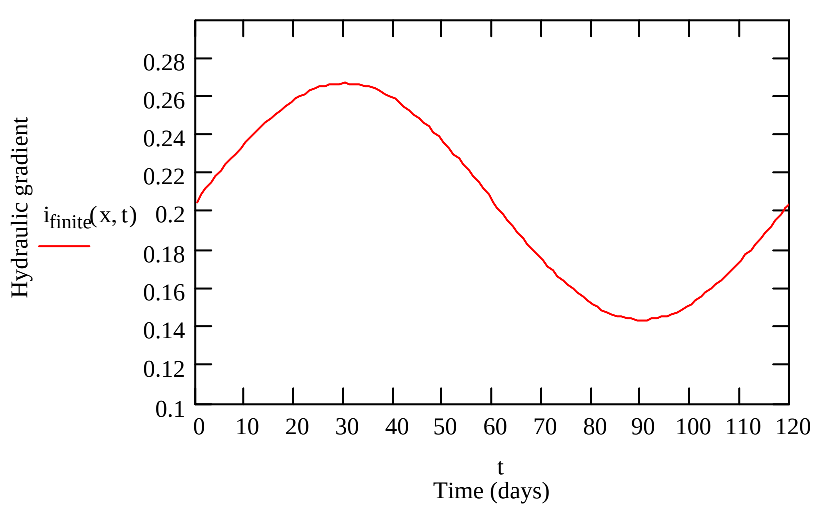


Figure 5.7

$x := 26\ \mathrm{m} \quad t := 0..120\ \mathrm{day}$



Transient flow net for finite depth aquifer:

$t := 10 \quad \omega := \dfrac{\pi}{60} \quad h_0 := 5 \quad h_1 := 1.5 \quad K := 1.799 \quad K_1 := 1.918 \quad T := 50 \quad l := 25$

$z := \tanh\left(\dfrac{\pi \cdot l}{2 \cdot T}\right) \quad h(t) := h_0 + h_1 \cdot \sin(\omega \cdot t) \quad z = 0.656 \quad z^2 = 0.43$

$\alpha := \dfrac{\pi \cdot K_1}{2 \cdot K} \quad k := 86.4$

$\phi := 0, 20 .. 500 \quad \psi := 0, 100 .. 800$

$\phi_1(\phi, h) := \dfrac{\phi}{k \cdot h(t)} \quad \psi_1(\psi, h) := \dfrac{\psi}{k \cdot h(t)}$

$$X(h, \phi, \psi) := \frac{4 \cdot T}{\pi} \cdot \left[\sum_{n=0}^{20} \frac{\cos\left[(2 \cdot n + 1)\pi \cdot \phi_1(\phi, h)\right] \cdot \cosh\left[(2 \cdot n + 1) \cdot \psi_1(\psi, h)\right]}{(2 \cdot n + 1) \cdot \sinh\left[(2 \cdot n + 1) \cdot \alpha\right]} \right]$$

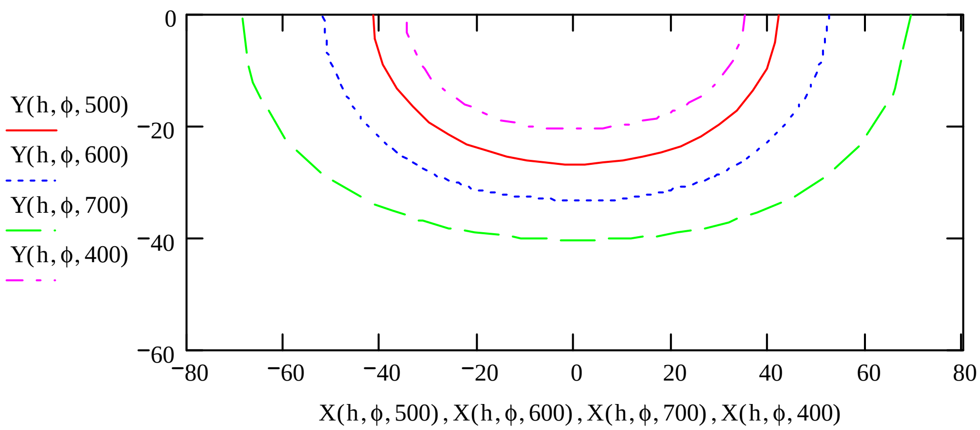
$$Y(h, \phi, \psi) := \frac{-4 \cdot T}{\pi} \cdot \left[\sum_{n=0}^{20} \frac{\sin\left[(2 \cdot n + 1)\pi \cdot \phi_1(\phi, h)\right] \cdot \sinh\left[(2 \cdot n + 1) \cdot \psi_1(\psi, h)\right]}{(2 \cdot n + 1) \cdot \sinh\left[(2 \cdot n + 1) \cdot \alpha\right]} \right]$$

Figure 5.8

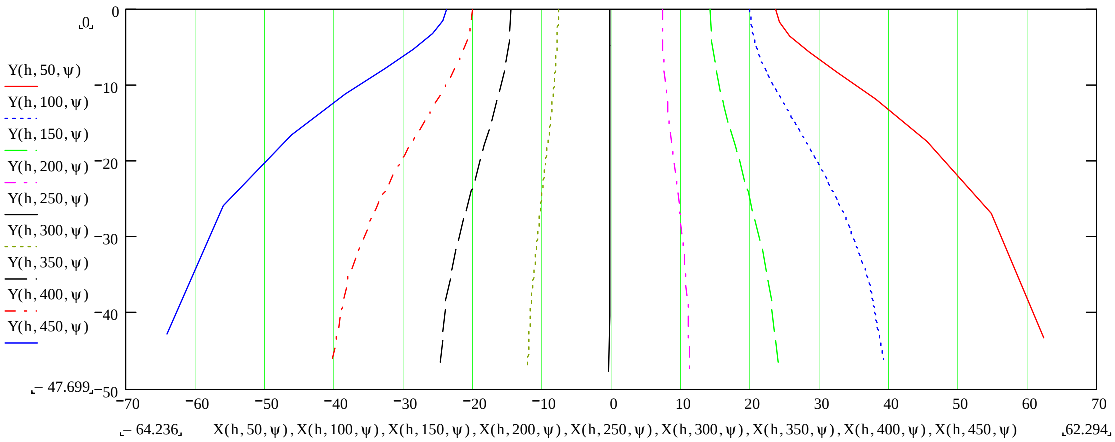
Note: Microsoft Excel was used to create the final figure.

$t := 10$ days

$\phi := 0, 20 .. 500$



$\psi := 0, 100 .. 800$


Y(h, 50, ψ)
Y(h, 100, ψ)
Y(h, 150, ψ)
Y(h, 200, ψ)
Y(h, 250, ψ)
Y(h, 300, ψ)
Y(h, 350, ψ)
Y(h, 400, ψ)
Y(h, 450, ψ)
0
−10
−20
−30
−40
−50
−47.699
−70
−60
−50
−40
−30
−20
−10
0
10
20
30
40
50
60
70
−64.236
X(h, 50, ψ), X(h, 100, ψ), X(h, 150, ψ), X(h, 200, ψ), X(h, 250, ψ), X(h, 300, ψ), X(h, 350, ψ), X(h, 400, ψ), X(h, 450, ψ)
62.294

APPENDIX C CALCULATIONS AND GRAPHS IN CHAPTER 6

Transient Analytical Model by Laplace Transform Method

$S := 0.005$ dimensionless $\qquad T := 0.025\,86400$ m^2/day

$\omega := \frac{\pi}{60} \qquad r := \omega \qquad \theta := \frac{\pi}{2} \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}}$

$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$m := 100$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1-\cos(2\cdot R\cdot I)) \ldots$$
$$+\frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$R2(x,t) := \sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$H_0 := 5$ meter

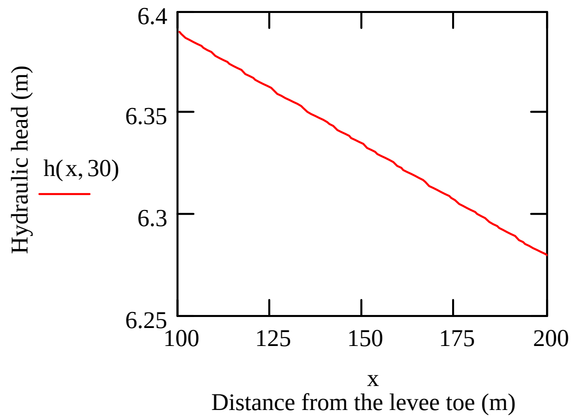
$H_1 := 1.5$ meter

$$h_{im}(x,t) := \frac{1}{2}\cdot H_1\cdot\cos(\omega\cdot t)\cdot\left[\begin{array}{l}\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ldots \\ +\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t)))\end{array}\right] \ldots \\ +\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ldots \\ +\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t)))\end{array}\right]\end{array}\right] \ldots$$
$$+\frac{1}{2}\cdot H_1\cdot\sin(\omega\cdot t)\cdot\left[\begin{array}{l}\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t))) \ldots \\ +\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\end{array}\right] \ldots \\ +\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t))) \ldots \\ +\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\end{array}\right]\end{array}\right]$$

Figure 6.5

$$h(x,t) := H_0 \cdot \mathrm{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}}\right) + h_{im}(x,t)$$

$x := 100..200$ m



$$i(x,t) := \frac{h(x,t)}{5}$$

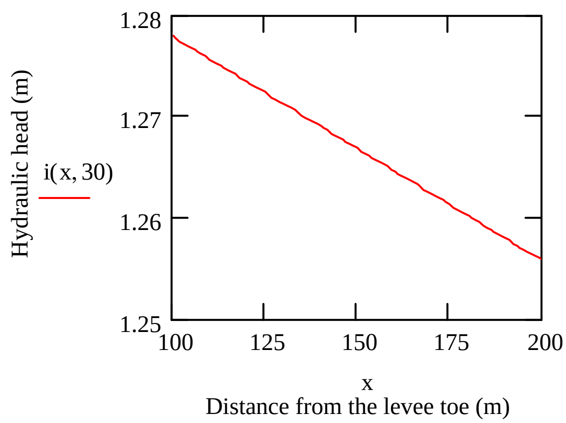
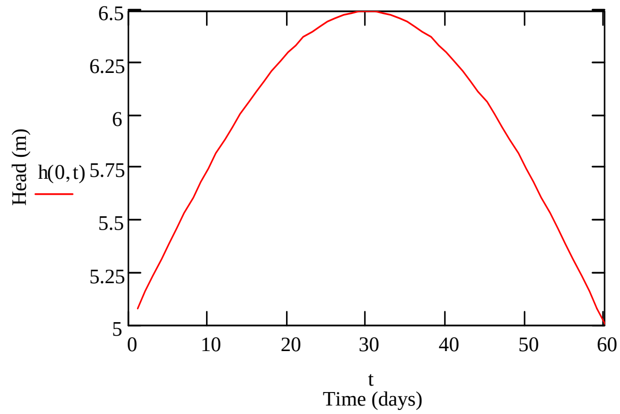


Figure 6.8

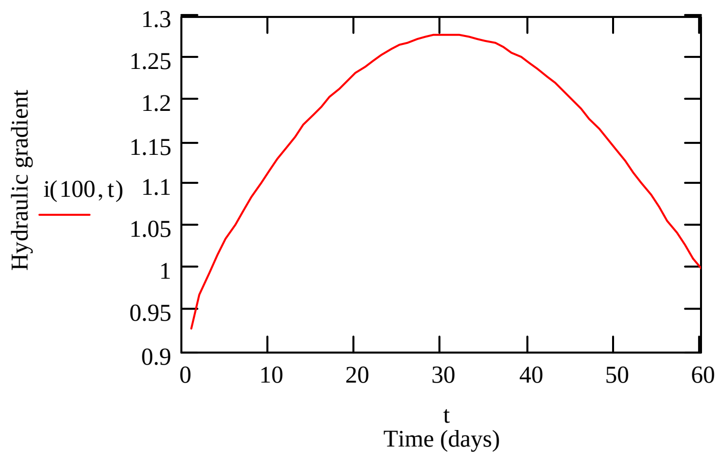
t := 0.. 60



x := 100 Thickness of upper layer is assumed as 5 m

t := 0.. 60

$$i(x,t) := \frac{h(100,t)}{5}$$



Calculation of Substratum Pressures by the Army Corps Method

EM 1110-2-1913: Design and Construstion of Levees details the underseepage analysis. The equations contained in the manual were developed during a study reported in (U.S. Army Engineer Waterways Experiment Station TM 3-424, Appendix A) of piezometric data and seepage mesurements along the Lower Mississippi River and confirmed by model studies.

Case 7, which is a semipervious top strata both riverside and landside was selected.

$H := 6.5m$ head at the riverside $x_1 := 50m$ $L_2 := 50m$

$d := 25m$ assumed thickness of pervious aquifer

$z_b := 5m$ assumed thickness of top layer

$k_f := 0.1 \cdot 10^{-2} \frac{m}{s}$ hydraulic conductivity of pervious substratum

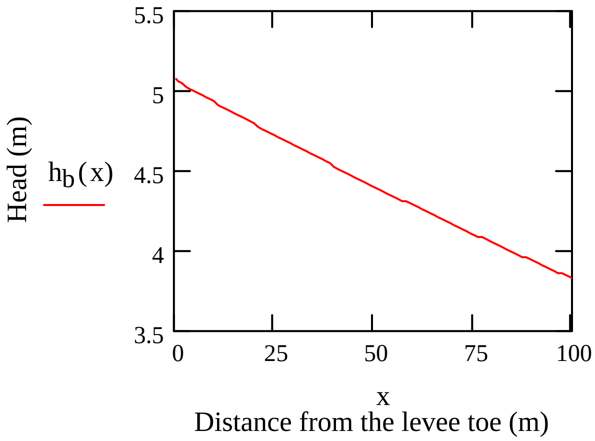
$k_b := 1 \cdot 10^{-6} \frac{m}{s}$ hydraulic conductivity of top substratum

$c := \sqrt{\frac{k_b}{k_f \cdot z_b \cdot d}}$ $x_3 := \frac{1}{c}$ $h_0 := \frac{H \cdot x_3}{x_1 + L_2 + x_3}$ $h_b(x) := h_0 \cdot e^{-c \cdot x}$

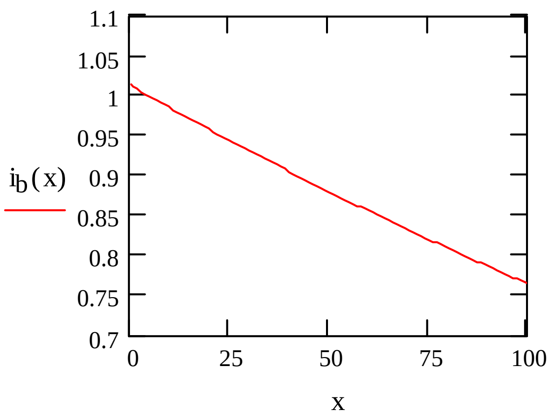
$h_0 = 5.067m$ head beneath top stratum at landside levee toe

Figure 6.6

$x := 0 .. 100$ distance from landside levee toe



$$i_b(x) := \frac{h_0 \cdot e^{-c \cdot x}}{z_b}$$



Transient Analytical Model by Laplace Transform Method with Leakage out of a Confined Aquifer

$S := 0.005$ dimensionless $\qquad T := 0.025\,86400$ m^2/day

$L := 0.2 \qquad \omega := \frac{\pi}{60} \qquad m := 100 \qquad \theta := \operatorname{atan}\left(\frac{S\cdot\omega}{L}\right) \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}}$

$r := \frac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2\,\omega^2 + L^2}}{S}$

$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1-\cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$R2(x,t) := \sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

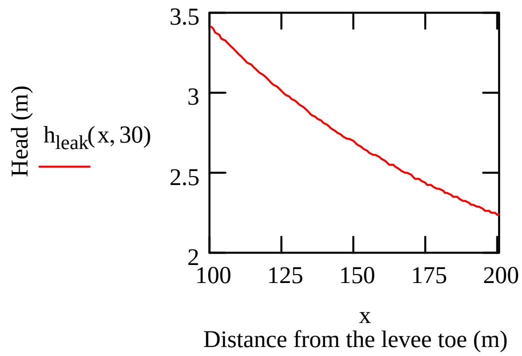
$h_0 := 5$ meter

$h_1 := 1.5$ meter

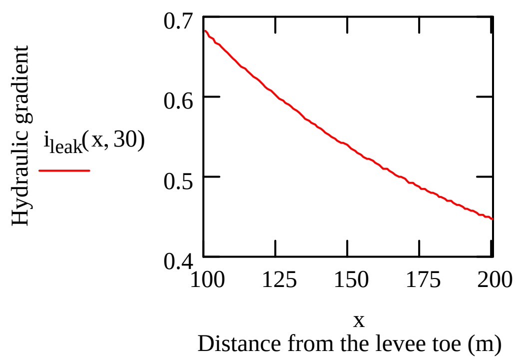
$$\begin{aligned}
h_{leak}(x,t) := {} & \frac{1}{2}\cdot h_1\cdot\cos(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\ \ldots \\
& \quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t)))\Bigg]\ \ldots \\
& \quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\ \ldots \\
& \quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t)))\Bigg]\Bigg]\ \ldots \\
& + \frac{1}{2}\cdot h_1\cdot\sin(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t)))\ \ldots \\
& \quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\Bigg]\ \ldots \\
& \quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t)))\ \ldots \\
& \quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\Bigg]\Bigg]\ \ldots \\
& + \frac{1}{2}\cdot h_0\cdot\left(\exp\left(-x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} - \sqrt{\frac{L}{S}\cdot t}\right) + \exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} + \sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}$$

Figure 6.9

$x := 100..200$ m



$$i_{leak}(x,t) := \frac{h_{leak}(x,t)}{5}$$



Transient Analytical Model by Laplace Transform Method with Leakage out of a Confined Aquifer

$S := 0.005$ dimensionless $\qquad T := 0.025 \cdot 86400$ m^2/day

$L := 0.14 \qquad \omega := \frac{\pi}{60} \qquad m := 100 \qquad \theta := \operatorname{atan}\left(\frac{S\cdot\omega}{L}\right) \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}}$

$$r := \frac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2\,\omega^2 + L^2}}{S}$$

$$f_n(R, I, n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$$

$$g_n(R, I, n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$$

$$G(R, I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R, I, n)$$

$$F(R, I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1 - \cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R, I, n)\right)$$

$$R1(x,t) := -\sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$$

$$R2(x,t) := \sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$$

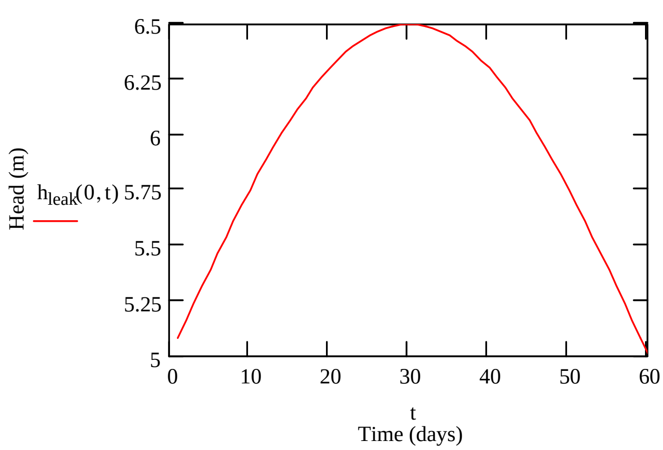
$h_0 := 5 \quad \text{meter}$

$h_1 := 1.5 \ \ \text{meter}$

$$\begin{aligned}
h_{leak}(x,t) := \frac{1}{2}\cdot h_1\cdot\cos(\omega\cdot t)\cdot\Bigg[& \exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l} -\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ \ldots \\ +\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t))) \end{array}\right] \ \ldots \\
& +\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l} -\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ \ldots \\ +\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t))) \end{array}\right]\Bigg] \ \ldots \\
+\frac{1}{2}\cdot h_1\cdot\sin(\omega\cdot t)\cdot\Bigg[& \exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l} \cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t))) \ \ldots \\ +\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \end{array}\right] \ \ldots \\
& +\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l} \cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t))) \ \ldots \\ +\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \end{array}\right]\Bigg] \ \ldots \\
+\frac{1}{2}\cdot h_0\cdot & \left(\exp\left(-x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}}-\sqrt{\frac{L}{S}\cdot t}\right)+\exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}}+\sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}$$

Figure 6.12

$t := 0..\,60$



$$i_{leak}(x,t) := \frac{h_{leak}(100,t)}{5}$$

$t := 0..\ 60$

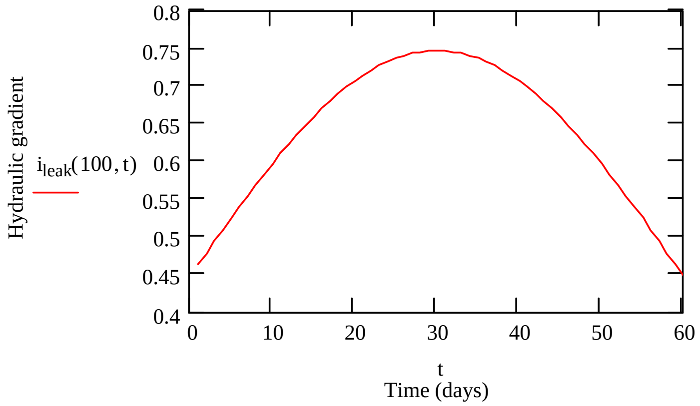
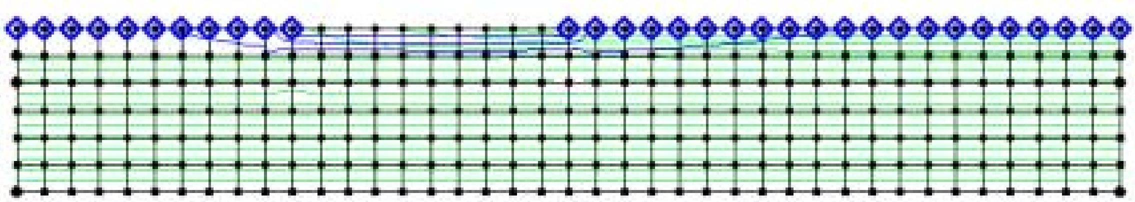


Fig. 6.7

SEEP2D Model
A confined aquifer with a depth of 30 m, and hydraulic conductivities of k_h=0.1 cm/sec, k_v=0.0001 cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head was defined at riverside and landside of the levee. The figure of the model is below:



Note: Node numbers 142 to 282 are located at 5 m below the landside of the levee.

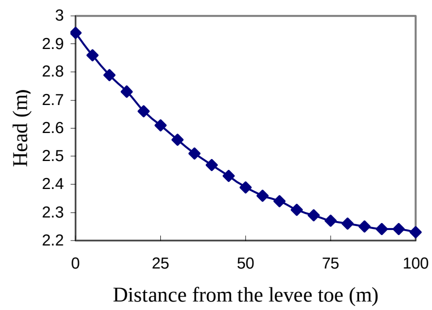
Model Output

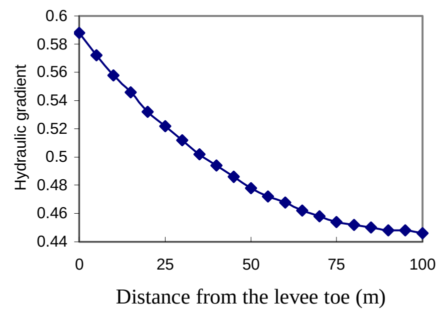
Plane flow problem
Confined aquifer, 30 m.
Number of nodal points------ 287
Number of elements---------- 240
Number of diff. materials--- 1
Elevation of datum--------- 0.000
Unsaturated flow option----- 0
Material Properties

30 m depth confined aquifer, kh=0.1 cm/sec, kv=0.0001 cm/sec

Node	Distance (m)	Head	Head-30	i=h/z
142	0	32.94	2.94	0.588
149	5	32.86	2.86	0.572
156	10	32.79	2.79	0.558
163	15	32.73	2.73	0.546
170	20	32.66	2.66	0.532
177	25	32.61	2.61	0.522
184	30	32.56	2.56	0.512
191	35	32.51	2.51	0.502
198	40	32.47	2.47	0.494
205	45	32.43	2.43	0.486
212	50	32.39	2.39	0.478
219	55	32.36	2.36	0.472
226	60	32.34	2.34	0.468
233	65	32.31	2.31	0.462
240	70	32.29	2.29	0.458
247	75	32.27	2.27	0.454
254	80	32.26	2.26	0.452
261	85	32.25	2.25	0.45
268	90	32.24	2.24	0.448
275	95	32.24	2.24	0.448
282	100	32.23	2.23	0.446

Flow = 21.907





Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.8640E+02	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

Node Point Information

Node	BC	X	Y	Flow-head
1	1	0.00	30.00	36.50
2	0	0.00	25.00	0.00
3	0	0.00	20.00	0.00
4	0	0.00	15.00	0.00
5	0	0.00	10.00	0.00
6	0	0.00	5.00	0.00
7	0	0.00	0.00	0.00
8	1	5.00	30.00	36.50
9	0	5.00	25.00	0.00
10	0	5.00	20.00	0.00
11	0	5.00	15.00	0.00
12	0	5.00	10.00	0.00
13	0	5.00	5.00	0.00
14	0	5.00	0.00	0.00
15	1	10.00	30.00	36.50
16	0	10.00	25.00	0.00
17	0	10.00	20.00	0.00
18	0	10.00	15.00	0.00
19	0	10.00	10.00	0.00
20	0	10.00	5.00	0.00
21	0	10.00	0.00	0.00
22	1	15.00	30.00	36.50
23	0	15.00	25.00	0.00
24	0	15.00	20.00	0.00
25	0	15.00	15.00	0.00
26	0	15.00	10.00	0.00
27	0	15.00	5.00	0.00
28	0	15.00	0.00	0.00
29	1	20.00	30.00	36.50
30	0	20.00	25.00	0.00
31	0	20.00	20.00	0.00
32	0	20.00	15.00	0.00
33	0	20.00	10.00	0.00
34	0	20.00	5.00	0.00
35	0	20.00	0.00	0.00
36	1	25.00	30.00	36.50
37	0	25.00	25.00	0.00

38	0	25.00	20.00	0.00
39	0	25.00	15.00	0.00
40	0	25.00	10.00	0.00
41	0	25.00	5.00	0.00
42	0	25.00	0.00	0.00
43	1	30.00	30.00	36.50
44	0	30.00	25.00	0.00
45	0	30.00	20.00	0.00
46	0	30.00	15.00	0.00
47	0	30.00	10.00	0.00
48	0	30.00	5.00	0.00
49	0	30.00	0.00	0.00
50	1	35.00	30.00	36.50
51	0	35.00	25.00	0.00
52	0	35.00	20.00	0.00
53	0	35.00	15.00	0.00
54	0	35.00	10.00	0.00
55	0	35.00	5.00	0.00
56	0	35.00	0.00	0.00
57	1	40.00	30.00	36.50
58	0	40.00	25.00	0.00
59	0	40.00	20.00	0.00
60	0	40.00	15.00	0.00
61	0	40.00	10.00	0.00
62	0	40.00	5.00	0.00
63	0	40.00	0.00	0.00
64	1	45.00	30.00	36.50
65	0	45.00	25.00	0.00
66	0	45.00	20.00	0.00
67	0	45.00	15.00	0.00
68	0	45.00	10.00	0.00
69	0	45.00	5.00	0.00
70	0	45.00	0.00	0.00
71	1	50.00	30.00	36.50
72	0	50.00	25.00	0.00
73	0	50.00	20.00	0.00
74	0	50.00	15.00	0.00
75	0	50.00	10.00	0.00
76	0	50.00	5.00	0.00
77	0	50.00	0.00	0.00
78	0	55.00	30.00	0.00
79	0	55.00	25.00	0.00
80	0	55.00	20.00	0.00
81	0	55.00	15.00	0.00
82	0	55.00	10.00	0.00
83	0	55.00	5.00	0.00
84	0	55.00	0.00	0.00
85	0	60.00	30.00	0.00
86	0	60.00	25.00	0.00
87	0	60.00	20.00	0.00
88	0	60.00	15.00	0.00
89	0	60.00	10.00	0.00
90	0	60.00	5.00	0.00
91	0	60.00	0.00	0.00
92	0	65.00	30.00	0.00
93	0	65.00	25.00	0.00
94	0	65.00	20.00	0.00
95	0	65.00	15.00	0.00
96	0	65.00	10.00	0.00
97	0	65.00	5.00	0.00
98	0	65.00	0.00	0.00
99	0	70.00	30.00	0.00
100	0	70.00	25.00	0.00
101	0	70.00	20.00	0.00
102	0	70.00	15.00	0.00
103	0	70.00	10.00	0.00
104	0	70.00	5.00	0.00
105	0	70.00	0.00	0.00
106	0	75.00	30.00	0.00
107	0	75.00	25.00	0.00
108	0	75.00	20.00	0.00
109	0	75.00	15.00	0.00
110	0	75.00	10.00	0.00
111	0	75.00	5.00	0.00
112	0	75.00	0.00	0.00
113	0	80.00	30.00	0.00
114	0	80.00	25.00	0.00
115	0	80.00	20.00	0.00
116	0	80.00	15.00	0.00
117	0	80.00	10.00	0.00
118	0	80.00	5.00	0.00
119	0	80.00	0.00	0.00
120	0	85.00	30.00	0.00
121	0	85.00	25.00	0.00
122	0	85.00	20.00	0.00
123	0	85.00	15.00	0.00
124	0	85.00	10.00	0.00
125	0	85.00	5.00	0.00
126	0	85.00	0.00	0.00
127	0	90.00	30.00	0.00
128	0	90.00	25.00	0.00
129	0	90.00	20.00	0.00
130	0	90.00	15.00	0.00
131	0	90.00	10.00	0.00
132	0	90.00	5.00	0.00
133	0	90.00	0.00	0.00
134	0	95.00	30.00	0.00
135	0	95.00	25.00	0.00
136	0	95.00	20.00	0.00
137	0	95.00	15.00	0.00
138	0	95.00	10.00	0.00
139	0	95.00	5.00	0.00
140	0	95.00	0.00	0.00
141	1	100.00	30.00	30.00
142	0	100.00	25.00	0.00
143	0	100.00	20.00	0.00
144	0	100.00	15.00	0.00
145	0	100.00	10.00	0.00
146	0	100.00	5.00	0.00
147	0	100.00	0.00	0.00
148	1	105.00	30.00	30.00
149	0	105.00	25.00	0.00
150	0	105.00	20.00	0.00
151	0	105.00	15.00	0.00
152	0	105.00	10.00	0.00
153	0	105.00	5.00	0.00
154	0	105.00	0.00	0.00
155	1	110.00	30.00	30.00
156	0	110.00	25.00	0.00
157	0	110.00	20.00	0.00
158	0	110.00	15.00	0.00
159	0	110.00	10.00	0.00
160	0	110.00	5.00	0.00
161	0	110.00	0.00	0.00
162	1	115.00	30.00	30.00
163	0	115.00	25.00	0.00
164	0	115.00	20.00	0.00
165	0	115.00	15.00	0.00
166	0	115.00	10.00	0.00
167	0	115.00	5.00	0.00
168	0	115.00	0.00	0.00
169	1	120.00	30.00	30.00
170	0	120.00	25.00	0.00
171	0	120.00	20.00	0.00
172	0	120.00	15.00	0.00
173	0	120.00	10.00	0.00
174	0	120.00	5.00	0.00
175	0	120.00	0.00	0.00
176	1	125.00	30.00	30.00
177	0	125.00	25.00	0.00

178	0	125.00	20.00	0.00
179	0	125.00	15.00	0.00
180	0	125.00	10.00	0.00
181	0	125.00	5.00	0.00
182	0	125.00	0.00	0.00
183	1	130.00	30.00	30.00
184	0	130.00	25.00	0.00
185	0	130.00	20.00	0.00
186	0	130.00	15.00	0.00
187	0	130.00	10.00	0.00
188	0	130.00	5.00	0.00
189	0	130.00	0.00	0.00
190	1	135.00	30.00	30.00
191	0	135.00	25.00	0.00
192	0	135.00	20.00	0.00
193	0	135.00	15.00	0.00
194	0	135.00	10.00	0.00
195	0	135.00	5.00	0.00
196	0	135.00	0.00	0.00
197	1	140.00	30.00	30.00
198	0	140.00	25.00	0.00
199	0	140.00	20.00	0.00
200	0	140.00	15.00	0.00
201	0	140.00	10.00	0.00
202	0	140.00	5.00	0.00
203	0	140.00	0.00	0.00
204	1	145.00	30.00	30.00
205	0	145.00	25.00	0.00
206	0	145.00	20.00	0.00
207	0	145.00	15.00	0.00
208	0	145.00	10.00	0.00
209	0	145.00	5.00	0.00
210	0	145.00	0.00	0.00
211	1	150.00	30.00	30.00
212	0	150.00	25.00	0.00
213	0	150.00	20.00	0.00
214	0	150.00	15.00	0.00
215	0	150.00	10.00	0.00
216	0	150.00	5.00	0.00
217	0	150.00	0.00	0.00
218	1	155.00	30.00	30.00
219	0	155.00	25.00	0.00
220	0	155.00	20.00	0.00
221	0	155.00	15.00	0.00
222	0	155.00	10.00	0.00
223	0	155.00	5.00	0.00
224	0	155.00	0.00	0.00
225	1	160.00	30.00	30.00
226	0	160.00	25.00	0.00
227	0	160.00	20.00	0.00
228	0	160.00	15.00	0.00
229	0	160.00	10.00	0.00
230	0	160.00	5.00	0.00
231	0	160.00	0.00	0.00
232	1	165.00	30.00	30.00
233	0	165.00	25.00	0.00
234	0	165.00	20.00	0.00
235	0	165.00	15.00	0.00
236	0	165.00	10.00	0.00
237	0	165.00	5.00	0.00
238	0	165.00	0.00	0.00
239	1	170.00	30.00	30.00
240	0	170.00	25.00	0.00
241	0	170.00	20.00	0.00
242	0	170.00	15.00	0.00
243	0	170.00	10.00	0.00
244	0	170.00	5.00	0.00
245	0	170.00	0.00	0.00
246	1	175.00	30.00	30.00
247	0	175.00	25.00	0.00
248	0	175.00	20.00	0.00
249	0	175.00	15.00	0.00
250	0	175.00	10.00	0.00
251	0	175.00	5.00	0.00
252	0	175.00	0.00	0.00
253	1	180.00	30.00	30.00
254	0	180.00	25.00	0.00
255	0	180.00	20.00	0.00
256	0	180.00	15.00	0.00
257	0	180.00	10.00	0.00
258	0	180.00	5.00	0.00
259	0	180.00	0.00	0.00
260	1	185.00	30.00	30.00
261	0	185.00	25.00	0.00
262	0	185.00	20.00	0.00
263	0	185.00	15.00	0.00
264	0	185.00	10.00	0.00
265	0	185.00	5.00	0.00
266	0	185.00	0.00	0.00
267	1	190.00	30.00	30.00
268	0	190.00	25.00	0.00
269	0	190.00	20.00	0.00
270	0	190.00	15.00	0.00
271	0	190.00	10.00	0.00
272	0	190.00	5.00	0.00
273	0	190.00	0.00	0.00
274	1	195.00	30.00	30.00
275	0	195.00	25.00	0.00
276	0	195.00	20.00	0.00
277	0	195.00	15.00	0.00
278	0	195.00	10.00	0.00
279	0	195.00	5.00	0.00
280	0	195.00	0.00	0.00
281	1	200.00	30.00	30.00
282	0	200.00	25.00	0.00
283	0	200.00	20.00	0.00
284	0	200.00	15.00	0.00
285	0	200.00	10.00	0.00
286	0	200.00	5.00	0.00
287	0	200.00	0.00	0.00

Nodal Flows and Heads

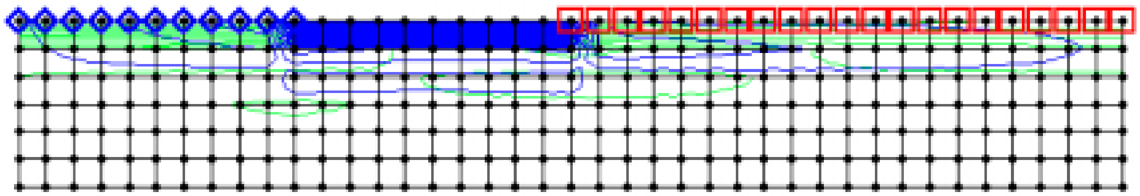
Node	Head	Percentage of available head	Flow
1	0.3650E+02	100.0 %	0.2234E+00
2	0.3241E+02	37.0 %	
3	0.3242E+02	37.2 %	
4	0.3244E+02	37.5 %	
5	0.3243E+02	37.4 %	
6	0.3243E+02	37.4 %	
7	0.3243E+02	37.4 %	
8	0.3650E+02	100.0 %	0.4473E+00
9	0.3240E+02	37.0 %	
10	0.3242E+02	37.2 %	
11	0.3244E+02	37.5 %	
12	0.3243E+02	37.4 %	
13	0.3243E+02	37.4 %	
14	0.3243E+02	37.4 %	
15	0.3650E+02	100.0 %	0.4488E+00
16	0.3239E+02	36.8 %	
17	0.3242E+02	37.3 %	
18	0.3244E+02	37.5 %	
19	0.3243E+02	37.4 %	
20	0.3243E+02	37.4 %	

21	0.3243E+02	37.4 %	
22	0.3650E+02	100.0 %	0.4512E+00
23	0.3238E+02	36.6 %	
24	0.3243E+02	37.3 %	
25	0.3243E+02	37.5 %	
26	0.3243E+02	37.4 %	
27	0.3243E+02	37.4 %	
28	0.3243E+02	37.4 %	
29	0.3650E+02	100.0 %	0.4547E+00
30	0.3235E+02	36.2 %	
31	0.3243E+02	37.4 %	
32	0.3243E+02	37.4 %	
33	0.3243E+02	37.4 %	
34	0.3243E+02	37.4 %	
35	0.3243E+02	37.4 %	
36	0.3650E+02	100.0 %	0.4592E+00
37	0.3232E+02	35.7 %	
38	0.3244E+02	37.6 %	
39	0.3243E+02	37.4 %	
40	0.3243E+02	37.4 %	
41	0.3243E+02	37.4 %	
42	0.3243E+02	37.4 %	
43	0.3650E+02	100.0 %	0.4647E+00
44	0.3229E+02	35.2 %	
45	0.3245E+02	37.7 %	
46	0.3243E+02	37.4 %	
47	0.3243E+02	37.4 %	
48	0.3243E+02	37.4 %	
49	0.3243E+02	37.4 %	
50	0.3650E+02	100.0 %	0.4713E+00
51	0.3224E+02	34.5 %	
52	0.3246E+02	37.9 %	
53	0.3242E+02	37.3 %	
54	0.3243E+02	37.4 %	
55	0.3243E+02	37.4 %	
56	0.3243E+02	37.4 %	
57	0.3650E+02	100.0 %	0.4790E+00
58	0.3219E+02	33.7 %	
59	0.3248E+02	38.2 %	
60	0.3242E+02	37.2 %	
61	0.3243E+02	37.4 %	
62	0.3243E+02	37.4 %	
63	0.3243E+02	37.4 %	
64	0.3650E+02	100.0 %	0.4878E+00
65	0.3213E+02	32.8 %	
66	0.3250E+02	38.4 %	
67	0.3242E+02	37.2 %	
68	0.3244E+02	37.5 %	
69	0.3243E+02	37.4 %	
70	0.3243E+02	37.4 %	
71	0.3650E+02	100.0 %	0.1752E+02
72	0.3207E+02	31.8 %	
73	0.3252E+02	38.7 %	
74	0.3241E+02	37.1 %	
75	0.3244E+02	37.5 %	
76	0.3243E+02	37.4 %	
77	0.3243E+02	37.4 %	
78	0.3582E+02	89.5 %	
79	0.3217E+02	33.4 %	
80	0.3249E+02	38.3 %	
81	0.3242E+02	37.2 %	
82	0.3244E+02	37.5 %	
83	0.3243E+02	37.4 %	
84	0.3243E+02	37.4 %	
85	0.3515E+02	79.2 %	
86	0.3227E+02	35.0 %	
87	0.3247E+02	38.0 %	
88	0.3242E+02	37.3 %	
89	0.3243E+02	37.4 %	
90	0.3243E+02	37.4 %	
91	0.3243E+02	37.4 %	
92	0.3450E+02	69.2 %	
93	0.3236E+02	36.3 %	
94	0.3245E+02	37.7 %	
95	0.3243E+02	37.3 %	
96	0.3243E+02	37.4 %	
97	0.3243E+02	37.4 %	
98	0.3243E+02	37.4 %	
99	0.3385E+02	59.3 %	
100	0.3244E+02	37.6 %	
101	0.3243E+02	37.4 %	
102	0.3243E+02	37.4 %	
103	0.3243E+02	37.4 %	
104	0.3243E+02	37.4 %	
105	0.3243E+02	37.4 %	
106	0.3321E+02	49.4 %	
107	0.3252E+02	38.8 %	
108	0.3242E+02	37.2 %	
109	0.3243E+02	37.4 %	
110	0.3243E+02	37.4 %	
111	0.3243E+02	37.4 %	
112	0.3243E+02	37.4 %	
113	0.3258E+02	39.7 %	
114	0.3260E+02	40.0 %	
115	0.3240E+02	36.9 %	
116	0.3244E+02	37.5 %	
117	0.3243E+02	37.4 %	
118	0.3243E+02	37.4 %	
119	0.3243E+02	37.4 %	
120	0.3194E+02	29.9 %	
121	0.3268E+02	41.2 %	
122	0.3238E+02	36.7 %	
123	0.3244E+02	37.5 %	
124	0.3243E+02	37.4 %	
125	0.3243E+02	37.4 %	
126	0.3243E+02	37.4 %	
127	0.3130E+02	20.0 %	
128	0.3276E+02	42.5 %	
129	0.3237E+02	36.4 %	
130	0.3244E+02	37.6 %	
131	0.3243E+02	37.4 %	
132	0.3243E+02	37.4 %	
133	0.3243E+02	37.4 %	
134	0.3066E+02	10.1 %	
135	0.3285E+02	43.8 %	
136	0.3235E+02	36.1 %	
137	0.3245E+02	37.7 %	
138	0.3243E+02	37.3 %	
139	0.3243E+02	37.4 %	
140	0.3243E+02	37.4 %	
141	0.3000E+02	0.0 %	-0.1670E+02
142	0.3294E+02	45.2 %	
143	0.3232E+02	35.7 %	
144	0.3246E+02	37.8 %	
145	0.3243E+02	37.3 %	
146	0.3243E+02	37.4 %	
147	0.3243E+02	37.4 %	
148	0.3000E+02	0.0 %	-0.3283E+00
149	0.3286E+02	44.0 %	
150	0.3234E+02	36.0 %	
151	0.3245E+02	37.7 %	
152	0.3243E+02	37.3 %	
153	0.3243E+02	37.4 %	
154	0.3243E+02	37.4 %	
155	0.3000E+02	0.0 %	-0.3177E+00
156	0.3279E+02	42.9 %	
157	0.3236E+02	36.3 %	
158	0.3245E+02	37.6 %	
159	0.3243E+02	37.4 %	
160	0.3243E+02	37.4 %	

161	0.3243E+02	37.4 %	
162	0.3000E+02	0.0 %	-0.3080E+00
163	0.3273E+02	41.9 %	
164	0.3238E+02	36.6 %	
165	0.3244E+02	37.6 %	
166	0.3243E+02	37.4 %	
167	0.3243E+02	37.4 %	
168	0.3243E+02	37.4 %	
169	0.3000E+02	0.0 %	-0.2990E+00
170	0.3266E+02	41.0 %	
171	0.3239E+02	36.8 %	
172	0.3244E+02	37.5 %	
173	0.3243E+02	37.4 %	
174	0.3243E+02	37.4 %	
175	0.3243E+02	37.4 %	
176	0.3000E+02	0.0 %	-0.2908E+00
177	0.3261E+02	40.1 %	
178	0.3240E+02	37.0 %	
179	0.3244E+02	37.5 %	
180	0.3243E+02	37.4 %	
181	0.3243E+02	37.4 %	
182	0.3243E+02	37.4 %	
183	0.3000E+02	0.0 %	-0.2833E+00
184	0.3256E+02	39.3 %	
185	0.3241E+02	37.1 %	
186	0.3243E+02	37.4 %	
187	0.3243E+02	37.4 %	
188	0.3243E+02	37.4 %	
189	0.3243E+02	37.4 %	
190	0.3000E+02	0.0 %	-0.2764E+00
191	0.3251E+02	38.6 %	
192	0.3242E+02	37.3 %	
193	0.3243E+02	37.4 %	
194	0.3243E+02	37.4 %	
195	0.3243E+02	37.4 %	
196	0.3243E+02	37.4 %	
197	0.3000E+02	0.0 %	-0.2702E+00
198	0.3247E+02	38.0 %	
199	0.3243E+02	37.4 %	
200	0.3243E+02	37.4 %	
201	0.3243E+02	37.4 %	
202	0.3243E+02	37.4 %	
203	0.3243E+02	37.4 %	
204	0.3000E+02	0.0 %	-0.2646E+00
205	0.3243E+02	37.4 %	
206	0.3244E+02	37.5 %	
207	0.3243E+02	37.4 %	
208	0.3243E+02	37.4 %	
209	0.3243E+02	37.4 %	
210	0.3243E+02	37.4 %	
211	0.3000E+02	0.0 %	-0.2595E+00
212	0.3239E+02	36.8 %	
213	0.3244E+02	37.6 %	
214	0.3243E+02	37.4 %	
215	0.3243E+02	37.4 %	
216	0.3243E+02	37.4 %	
217	0.3243E+02	37.4 %	
218	0.3000E+02	0.0 %	-0.2551E+00
219	0.3236E+02	36.4 %	
220	0.3245E+02	37.7 %	
221	0.3243E+02	37.3 %	
222	0.3243E+02	37.4 %	
223	0.3243E+02	37.4 %	
224	0.3243E+02	37.4 %	
225	0.3000E+02	0.0 %	-0.2511E+00
226	0.3234E+02	35.9 %	
227	0.3245E+02	37.7 %	
228	0.3243E+02	37.3 %	
229	0.3243E+02	37.4 %	
230	0.3243E+02	37.4 %	
231	0.3243E+02	37.4 %	
232	0.3000E+02	0.0 %	-0.2476E+00
233	0.3231E+02	35.6 %	
234	0.3246E+02	37.8 %	
235	0.3243E+02	37.3 %	
236	0.3243E+02	37.4 %	
237	0.3243E+02	37.4 %	
238	0.3243E+02	37.4 %	
239	0.3000E+02	0.0 %	-0.2447E+00
240	0.3229E+02	35.2 %	
241	0.3246E+02	37.8 %	
242	0.3243E+02	37.3 %	
243	0.3243E+02	37.4 %	
244	0.3243E+02	37.4 %	
245	0.3243E+02	37.4 %	
246	0.3000E+02	0.0 %	-0.2422E+00
247	0.3227E+02	35.0 %	
248	0.3246E+02	37.9 %	
249	0.3243E+02	37.3 %	
250	0.3243E+02	37.4 %	
251	0.3243E+02	37.4 %	
252	0.3243E+02	37.4 %	
253	0.3000E+02	0.0 %	-0.2402E+00
254	0.3226E+02	34.8 %	
255	0.3246E+02	37.9 %	
256	0.3243E+02	37.3 %	
257	0.3243E+02	37.4 %	
258	0.3243E+02	37.4 %	
259	0.3243E+02	37.4 %	
260	0.3000E+02	0.0 %	-0.2386E+00
261	0.3225E+02	34.6 %	
262	0.3247E+02	37.9 %	
263	0.3243E+02	37.3 %	
264	0.3243E+02	37.4 %	
265	0.3243E+02	37.4 %	
266	0.3243E+02	37.4 %	
267	0.3000E+02	0.0 %	-0.2375E+00
268	0.3224E+02	34.5 %	
269	0.3247E+02	37.9 %	
270	0.3243E+02	37.3 %	
271	0.3243E+02	37.4 %	
272	0.3243E+02	37.4 %	
273	0.3243E+02	37.4 %	
274	0.3000E+02	0.0 %	-0.2369E+00
275	0.3224E+02	34.4 %	
276	0.3247E+02	38.0 %	
277	0.3243E+02	37.3 %	
278	0.3243E+02	37.4 %	
279	0.3243E+02	37.4 %	
280	0.3243E+02	37.4 %	
281	0.3000E+02	0.0 %	-0.1183E+00
282	0.3223E+02	34.4 %	
283	0.3247E+02	38.0 %	
284	0.3243E+02	37.3 %	
285	0.3243E+02	37.4 %	
286	0.3243E+02	37.4 %	
287	0.3243E+02	37.4 %	

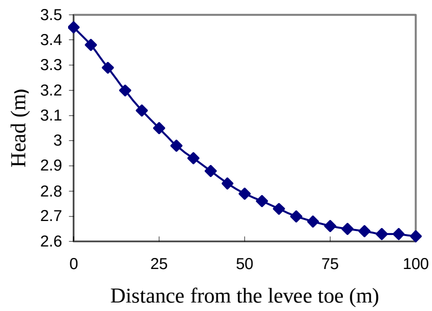
Flow = 2.1907E+01

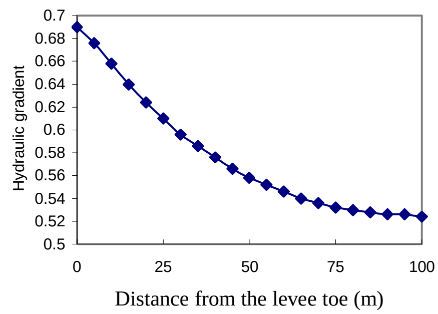
Fig. 6.11
SEEP2D Model
An unconfined aquifer with a depth of 30 m, and hydraulic conductivities of k_h=0.1 cm/sec, k_v=0.0001 cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head boundary was defined at riverside and exit face boundary was defined at landside of the levee. The figure of the model is shown below:



30 m depth unconfined, exit face landside levee, kh=0.1 cm/sec, kv=0.0001 cm/sec

Node	Distance (m)	Head (m)	Head-30	i=h/5
142	0	33.45	3.45	0.69
149	5	33.38	3.38	0.676
156	10	33.29	3.29	0.658
163	15	33.2	3.2	0.64
170	20	33.12	3.12	0.624
177	25	33.05	3.05	0.61
184	30	32.98	2.98	0.596
191	35	32.93	2.93	0.586
198	40	32.88	2.88	0.576
205	45	32.83	2.83	0.566
212	50	32.79	2.79	0.558
219	55	32.76	2.76	0.552
226	60	32.73	2.73	0.546
233	65	32.7	2.7	0.54
240	70	32.68	2.68	0.536
247	75	32.66	2.66	0.532
254	80	32.65	2.65	0.53
261	85	32.64	2.64	0.528
268	90	32.63	2.63	0.526
275	95	32.63	2.63	0.526
282	100	32.62	2.62	0.524





Note: Node numbers 142 to 282 are located at 5 m below the landside of the levee.

Model Output

Plane flow problem
30 m exit face
Number of nodal points------ 287
Number of elements---------- 240
Number of diff. materials--- 1
Elevation of datum---------- 0.000
Unsaturated flow option----- 0
Material Properties

Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.8640E+02	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

Node Point Information

Node	BC	X	Y	Flow-head
1	1	0.00	30.00	36.50
2	0	0.00	25.00	0.00
3	0	0.00	20.00	0.00
4	0	0.00	15.00	0.00
5	0	0.00	10.00	0.00
6	0	0.00	5.00	0.00
7	0	0.00	0.00	0.00
8	1	5.00	30.00	36.50
9	0	5.00	25.00	0.00
10	0	5.00	20.00	0.00
11	0	5.00	15.00	0.00
12	0	5.00	10.00	0.00
13	0	5.00	5.00	0.00
14	0	5.00	0.00	0.00
15	1	10.00	30.00	36.50
16	0	10.00	25.00	0.00
17	0	10.00	20.00	0.00
18	0	10.00	15.00	0.00
19	0	10.00	10.00	0.00
20	0	10.00	5.00	0.00
21	0	10.00	0.00	0.00
22	1	15.00	30.00	36.50
23	0	15.00	25.00	0.00
24	0	15.00	20.00	0.00
25	0	15.00	15.00	0.00
26	0	15.00	10.00	0.00
27	0	15.00	5.00	0.00
28	0	15.00	0.00	0.00
29	1	20.00	30.00	36.50
30	0	20.00	25.00	0.00
31	0	20.00	20.00	0.00
32	0	20.00	15.00	0.00
33	0	20.00	10.00	0.00
34	0	20.00	5.00	0.00
35	0	20.00	0.00	0.00
36	1	25.00	30.00	36.50
37	0	25.00	25.00	0.00
38	0	25.00	20.00	0.00
39	0	25.00	15.00	0.00
40	0	25.00	10.00	0.00
41	0	25.00	5.00	0.00
42	0	25.00	0.00	0.00
43	1	30.00	30.00	36.50
44	0	30.00	25.00	0.00
45	0	30.00	20.00	0.00
46	0	30.00	15.00	0.00
47	0	30.00	10.00	0.00
48	0	30.00	5.00	0.00
49	0	30.00	0.00	0.00
50	1	35.00	30.00	36.50
51	0	35.00	25.00	0.00
52	0	35.00	20.00	0.00
53	0	35.00	15.00	0.00
54	0	35.00	10.00	0.00
55	0	35.00	5.00	0.00
56	0	35.00	0.00	0.00
57	1	40.00	30.00	36.50
58	0	40.00	25.00	0.00
59	0	40.00	20.00	0.00
60	0	40.00	15.00	0.00
61	0	40.00	10.00	0.00
62	0	40.00	5.00	0.00
63	0	40.00	0.00	0.00
64	1	45.00	30.00	36.50
65	0	45.00	25.00	0.00
66	0	45.00	20.00	0.00
67	0	45.00	15.00	0.00
68	0	45.00	10.00	0.00
69	0	45.00	5.00	0.00
70	0	45.00	0.00	0.00
71	1	50.00	30.00	36.50
72	0	50.00	25.00	0.00
73	0	50.00	20.00	0.00
74	0	50.00	15.00	0.00
75	0	50.00	10.00	0.00
76	0	50.00	5.00	0.00
77	0	50.00	0.00	0.00
78	0	55.00	30.00	0.00
79	0	55.00	25.00	0.00
80	0	55.00	20.00	0.00
81	0	55.00	15.00	0.00
82	0	55.00	10.00	0.00
83	0	55.00	5.00	0.00
84	0	55.00	0.00	0.00
85	0	60.00	30.00	0.00
86	0	60.00	25.00	0.00
87	0	60.00	20.00	0.00
88	0	60.00	15.00	0.00
89	0	60.00	10.00	0.00
90	0	60.00	5.00	0.00
91	0	60.00	0.00	0.00
92	0	65.00	30.00	0.00
93	0	65.00	25.00	0.00
94	0	65.00	20.00	0.00
95	0	65.00	15.00	0.00
96	0	65.00	10.00	0.00
97	0	65.00	5.00	0.00
98	0	65.00	0.00	0.00
99	0	70.00	30.00	0.00
100	0	70.00	25.00	0.00
101	0	70.00	20.00	0.00
102	0	70.00	15.00	0.00
103	0	70.00	10.00	0.00
104	0	70.00	5.00	0.00
105	0	70.00	0.00	0.00
106	0	75.00	30.00	0.00
107	0	75.00	25.00	0.00
108	0	75.00	20.00	0.00
109	0	75.00	15.00	0.00
110	0	75.00	10.00	0.00
111	0	75.00	5.00	0.00
112	0	75.00	0.00	0.00
113	0	80.00	30.00	0.00
114	0	80.00	25.00	0.00
115	0	80.00	20.00	0.00
116	0	80.00	15.00	0.00
117	0	80.00	10.00	0.00
118	0	80.00	5.00	0.00
119	0	80.00	0.00	0.00
120	0	85.00	30.00	0.00
121	0	85.00	25.00	0.00
122	0	85.00	20.00	0.00
123	0	85.00	15.00	0.00
124	0	85.00	10.00	0.00
125	0	85.00	5.00	0.00
126	0	85.00	0.00	0.00
127	0	90.00	30.00	0.00

128	0	90.00	25.00	0.00
129	0	90.00	20.00	0.00
130	0	90.00	15.00	0.00
131	0	90.00	10.00	0.00
132	0	90.00	5.00	0.00
133	0	90.00	0.00	0.00
134	0	95.00	30.00	0.00
135	0	95.00	25.00	0.00
136	0	95.00	20.00	0.00
137	0	95.00	15.00	0.00
138	0	95.00	10.00	0.00
139	0	95.00	5.00	0.00
140	0	95.00	0.00	0.00
141	2	100.00	30.00	0.00
142	0	100.00	25.00	0.00
143	0	100.00	20.00	0.00
144	0	100.00	15.00	0.00
145	0	100.00	10.00	0.00
146	0	100.00	5.00	0.00
147	0	100.00	0.00	0.00
148	2	105.00	30.00	0.00
149	0	105.00	25.00	0.00
150	0	105.00	20.00	0.00
151	0	105.00	15.00	0.00
152	0	105.00	10.00	0.00
153	0	105.00	5.00	0.00
154	0	105.00	0.00	0.00
155	2	110.00	30.00	0.00
156	0	110.00	25.00	0.00
157	0	110.00	20.00	0.00
158	0	110.00	15.00	0.00
159	0	110.00	10.00	0.00
160	0	110.00	5.00	0.00
161	0	110.00	0.00	0.00
162	2	115.00	30.00	0.00
163	0	115.00	25.00	0.00
164	0	115.00	20.00	0.00
165	0	115.00	15.00	0.00
166	0	115.00	10.00	0.00
167	0	115.00	5.00	0.00
168	0	115.00	0.00	0.00
169	2	120.00	30.00	0.00
170	0	120.00	25.00	0.00
171	0	120.00	20.00	0.00
172	0	120.00	15.00	0.00
173	0	120.00	10.00	0.00
174	0	120.00	5.00	0.00
175	0	120.00	0.00	0.00
176	2	125.00	30.00	0.00
177	0	125.00	25.00	0.00
178	0	125.00	20.00	0.00
179	0	125.00	15.00	0.00
180	0	125.00	10.00	0.00
181	0	125.00	5.00	0.00
182	0	125.00	0.00	0.00
183	2	130.00	30.00	0.00
184	0	130.00	25.00	0.00
185	0	130.00	20.00	0.00
186	0	130.00	15.00	0.00
187	0	130.00	10.00	0.00
188	0	130.00	5.00	0.00
189	0	130.00	0.00	0.00
190	2	135.00	30.00	0.00
191	0	135.00	25.00	0.00
192	0	135.00	20.00	0.00
193	0	135.00	15.00	0.00
194	0	135.00	10.00	0.00
195	0	135.00	5.00	0.00
196	0	135.00	0.00	0.00
197	2	140.00	30.00	0.00
198	0	140.00	25.00	0.00
199	0	140.00	20.00	0.00
200	0	140.00	15.00	0.00
201	0	140.00	10.00	0.00
202	0	140.00	5.00	0.00
203	0	140.00	0.00	0.00
204	2	145.00	30.00	0.00
205	0	145.00	25.00	0.00
206	0	145.00	20.00	0.00
207	0	145.00	15.00	0.00
208	0	145.00	10.00	0.00
209	0	145.00	5.00	0.00
210	0	145.00	0.00	0.00
211	2	150.00	30.00	0.00
212	0	150.00	25.00	0.00
213	0	150.00	20.00	0.00
214	0	150.00	15.00	0.00
215	0	150.00	10.00	0.00
216	0	150.00	5.00	0.00
217	0	150.00	0.00	0.00
218	2	155.00	30.00	0.00
219	0	155.00	25.00	0.00
220	0	155.00	20.00	0.00
221	0	155.00	15.00	0.00
222	0	155.00	10.00	0.00
223	0	155.00	5.00	0.00
224	0	155.00	0.00	0.00
225	2	160.00	30.00	0.00
226	0	160.00	25.00	0.00
227	0	160.00	20.00	0.00
228	0	160.00	15.00	0.00
229	0	160.00	10.00	0.00
230	0	160.00	5.00	0.00
231	0	160.00	0.00	0.00
232	2	165.00	30.00	0.00
233	0	165.00	25.00	0.00
234	0	165.00	20.00	0.00
235	0	165.00	15.00	0.00
236	0	165.00	10.00	0.00
237	0	165.00	5.00	0.00
238	0	165.00	0.00	0.00
239	2	170.00	30.00	0.00
240	0	170.00	25.00	0.00
241	0	170.00	20.00	0.00
242	0	170.00	15.00	0.00
243	0	170.00	10.00	0.00
244	0	170.00	5.00	0.00
245	0	170.00	0.00	0.00
246	2	175.00	30.00	0.00
247	0	175.00	25.00	0.00
248	0	175.00	20.00	0.00
249	0	175.00	15.00	0.00
250	0	175.00	10.00	0.00
251	0	175.00	5.00	0.00
252	0	175.00	0.00	0.00
253	2	180.00	30.00	0.00
254	0	180.00	25.00	0.00
255	0	180.00	20.00	0.00
256	0	180.00	15.00	0.00
257	0	180.00	10.00	0.00
258	0	180.00	5.00	0.00
259	0	180.00	0.00	0.00

260	2	185.00	30.00	0.00
261	0	185.00	25.00	0.00
262	0	185.00	20.00	0.00
263	0	185.00	15.00	0.00
264	0	185.00	10.00	0.00
265	0	185.00	5.00	0.00
266	0	185.00	0.00	0.00
267	2	190.00	30.00	0.00
268	0	190.00	25.00	0.00
269	0	190.00	20.00	0.00
270	0	190.00	15.00	0.00
271	0	190.00	10.00	0.00
272	0	190.00	5.00	0.00
273	0	190.00	0.00	0.00
274	2	195.00	30.00	0.00
275	0	195.00	25.00	0.00
276	0	195.00	20.00	0.00
277	0	195.00	15.00	0.00
278	0	195.00	10.00	0.00
279	0	195.00	5.00	0.00
280	0	195.00	0.00	0.00
281	2	200.00	30.00	0.00
282	0	200.00	25.00	0.00
283	0	200.00	20.00	0.00
284	0	200.00	15.00	0.00
285	0	200.00	10.00	0.00
286	0	200.00	5.00	0.00
287	0	200.00	0.00	0.00

Nodal Flows and Heads

Node	Head	Percentage of available head	Flow
1	0.3650E+02	100.0 %	0.2029E+00
2	0.3279E+02	43.0 %	
3	0.3285E+02	43.8 %	
4	0.3286E+02	44.0 %	
5	0.3285E+02	43.9 %	
6	0.3285E+02	43.9 %	
7	0.3285E+02	43.9 %	
8	0.3650E+02	100.0 %	0.4062E+00
9	0.3279E+02	42.9 %	
10	0.3285E+02	43.8 %	
11	0.3286E+02	44.0 %	
12	0.3285E+02	43.9 %	
13	0.3285E+02	43.9 %	
14	0.3285E+02	43.9 %	
15	0.3650E+02	100.0 %	0.4076E+00
16	0.3278E+02	42.8 %	
17	0.3285E+02	43.9 %	
18	0.3286E+02	44.0 %	
19	0.3285E+02	43.9 %	
20	0.3285E+02	43.9 %	
21	0.3285E+02	43.9 %	
22	0.3650E+02	100.0 %	0.4098E+00
23	0.3277E+02	42.6 %	
24	0.3286E+02	43.9 %	
25	0.3286E+02	43.9 %	
26	0.3285E+02	43.9 %	
27	0.3285E+02	43.9 %	
28	0.3285E+02	43.9 %	
29	0.3650E+02	100.0 %	0.4130E+00
30	0.3275E+02	42.2 %	
31	0.3286E+02	44.0 %	
32	0.3285E+02	43.9 %	
33	0.3285E+02	43.9 %	
34	0.3285E+02	43.9 %	
35	0.3285E+02	43.9 %	
36	0.3650E+02	100.0 %	0.4172E+00
37	0.3272E+02	41.8 %	
38	0.3287E+02	44.1 %	
39	0.3285E+02	43.9 %	
40	0.3285E+02	43.9 %	
41	0.3285E+02	43.9 %	
42	0.3285E+02	43.9 %	
43	0.3650E+02	100.0 %	0.4223E+00
44	0.3268E+02	41.3 %	
45	0.3288E+02	44.3 %	
46	0.3285E+02	43.8 %	
47	0.3285E+02	43.9 %	
48	0.3285E+02	43.9 %	
49	0.3285E+02	43.9 %	
50	0.3650E+02	100.0 %	0.4283E+00
51	0.3264E+02	40.7 %	
52	0.3289E+02	44.5 %	
53	0.3285E+02	43.8 %	
54	0.3285E+02	43.9 %	
55	0.3285E+02	43.9 %	
56	0.3285E+02	43.9 %	
57	0.3650E+02	100.0 %	0.4355E+00
58	0.3260E+02	39.9 %	
59	0.3291E+02	44.7 %	
60	0.3284E+02	43.7 %	
61	0.3286E+02	43.9 %	
62	0.3285E+02	43.9 %	
63	0.3285E+02	43.9 %	
64	0.3650E+02	100.0 %	0.4436E+00
65	0.3254E+02	39.1 %	
66	0.3292E+02	45.0 %	
67	0.3284E+02	43.7 %	
68	0.3286E+02	44.0 %	
69	0.3285E+02	43.9 %	
70	0.3285E+02	43.9 %	
71	0.3650E+02	100.0 %	0.1727E+02
72	0.3248E+02	38.2 %	
73	0.3294E+02	45.3 %	
74	0.3283E+02	43.6 %	
75	0.3286E+02	44.0 %	
76	0.3285E+02	43.9 %	
77	0.3285E+02	43.9 %	
78	0.3583E+02	89.6 %	
79	0.3259E+02	39.9 %	
80	0.3292E+02	44.9 %	
81	0.3284E+02	43.7 %	
82	0.3286E+02	44.0 %	
83	0.3285E+02	43.9 %	
84	0.3285E+02	43.9 %	
85	0.3517E+02	79.5 %	
86	0.3270E+02	41.5 %	
87	0.3289E+02	44.5 %	
88	0.3284E+02	43.7 %	
89	0.3286E+02	43.9 %	
90	0.3285E+02	43.9 %	
91	0.3285E+02	43.9 %	
92	0.3452E+02	69.5 %	
93	0.3279E+02	42.9 %	

94	0.3287E+02	44.2 %	
95	0.3285E+02	43.8 %	
96	0.3286E+02	43.9 %	
97	0.3285E+02	43.9 %	
98	0.3285E+02	43.9 %	
99	0.3387E+02	59.6 %	
100	0.3288E+02	44.3 %	
101	0.3285E+02	43.9 %	
102	0.3285E+02	43.9 %	
103	0.3285E+02	43.9 %	
104	0.3285E+02	43.9 %	
105	0.3285E+02	43.9 %	
106	0.3324E+02	49.8 %	
107	0.3297E+02	45.7 %	
108	0.3284E+02	43.6 %	
109	0.3286E+02	43.9 %	
110	0.3285E+02	43.9 %	
111	0.3285E+02	43.9 %	
112	0.3285E+02	43.9 %	
113	0.3260E+02	40.0 %	
114	0.3306E+02	47.0 %	
115	0.3282E+02	43.3 %	
116	0.3286E+02	44.0 %	
117	0.3285E+02	43.9 %	
118	0.3285E+02	43.9 %	
119	0.3285E+02	43.9 %	
120	0.3196E+02	30.2 %	
121	0.3315E+02	48.4 %	
122	0.3280E+02	43.1 %	
123	0.3286E+02	44.1 %	
124	0.3285E+02	43.9 %	
125	0.3285E+02	43.9 %	
126	0.3285E+02	43.9 %	
127	0.3132E+02	20.3 %	
128	0.3324E+02	49.8 %	
129	0.3278E+02	42.7 %	
130	0.3287E+02	44.1 %	
131	0.3285E+02	43.9 %	
132	0.3285E+02	43.9 %	
133	0.3285E+02	43.9 %	
134	0.3067E+02	10.2 %	
135	0.3334E+02	51.4 %	
136	0.3275E+02	42.4 %	
137	0.3287E+02	44.2 %	
138	0.3285E+02	43.8 %	
139	0.3285E+02	43.9 %	
140	0.3285E+02	43.9 %	
141	0.3000E+02	0.0 %	-0.1698E+02
142	0.3345E+02	53.0 %	
143	0.3273E+02	41.9 %	
144	0.3288E+02	44.3 %	
145	0.3285E+02	43.8 %	
146	0.3286E+02	43.9 %	
147	0.3285E+02	43.9 %	
148	0.3000E+02	0.0 %	-0.4273E+01
149	0.3338E+02	52.1 %	
150	0.3274E+02	42.2 %	
151	0.3288E+02	44.3 %	
152	0.3285E+02	43.8 %	
153	0.3285E+02	43.9 %	
154	0.3285E+02	43.9 %	
155	0.3016E+02	2.4 %	0.1137E-12
156	0.3329E+02	50.5 %	
157	0.3277E+02	42.6 %	
158	0.3287E+02	44.2 %	
159	0.3285E+02	43.8 %	
160	0.3285E+02	43.9 %	
161	0.3285E+02	43.9 %	
162	0.3030E+02	4.6 %	0.2842E-12
163	0.3320E+02	49.2 %	
164	0.3279E+02	42.9 %	
165	0.3287E+02	44.1 %	
166	0.3285E+02	43.9 %	
167	0.3285E+02	43.9 %	
168	0.3285E+02	43.9 %	
169	0.3043E+02	6.5 %	-0.3979E-12
170	0.3312E+02	48.0 %	
171	0.3281E+02	43.2 %	
172	0.3286E+02	44.0 %	
173	0.3285E+02	43.9 %	
174	0.3285E+02	43.9 %	
175	0.3285E+02	43.9 %	
176	0.3054E+02	8.3 %	0.1137E-12
177	0.3305E+02	46.9 %	
178	0.3282E+02	43.4 %	
179	0.3286E+02	44.0 %	
180	0.3285E+02	43.9 %	
181	0.3285E+02	43.9 %	
182	0.3285E+02	43.9 %	
183	0.3065E+02	10.0 %	-0.5684E-13
184	0.3298E+02	45.9 %	
185	0.3284E+02	43.7 %	
186	0.3285E+02	43.9 %	
187	0.3285E+02	43.9 %	
188	0.3285E+02	43.9 %	
189	0.3285E+02	43.9 %	
190	0.3074E+02	11.4 %	-0.2842E-12
191	0.3293E+02	45.0 %	
192	0.3285E+02	43.8 %	
193	0.3285E+02	43.9 %	
194	0.3285E+02	43.9 %	
195	0.3285E+02	43.9 %	
196	0.3285E+02	43.9 %	
197	0.3083E+02	12.7 %	-0.2842E-12
198	0.3288E+02	44.3 %	
199	0.3286E+02	44.0 %	
200	0.3285E+02	43.9 %	
201	0.3285E+02	43.9 %	
202	0.3285E+02	43.9 %	
203	0.3285E+02	43.9 %	
204	0.3090E+02	13.9 %	0.5684E-13
205	0.3283E+02	43.6 %	
206	0.3287E+02	44.1 %	
207	0.3285E+02	43.8 %	
208	0.3285E+02	43.9 %	
209	0.3285E+02	43.9 %	
210	0.3285E+02	43.9 %	
211	0.3097E+02	14.9 %	-0.5684E-13
212	0.3279E+02	43.0 %	
213	0.3287E+02	44.2 %	
214	0.3285E+02	43.8 %	
215	0.3285E+02	43.9 %	
216	0.3285E+02	43.9 %	
217	0.3285E+02	43.9 %	
218	0.3103E+02	15.8 %	-0.2274E-12
219	0.3276E+02	42.4 %	
220	0.3288E+02	44.3 %	
221	0.3285E+02	43.8 %	
222	0.3285E+02	43.9 %	
223	0.3285E+02	43.9 %	
224	0.3285E+02	43.9 %	
225	0.3108E+02	16.6 %	0.0000E+00

226	0.3273E+02	42.0 %	
227	0.3288E+02	44.3 %	
228	0.3285E+02	43.8 %	
229	0.3285E+02	43.9 %	
230	0.3285E+02	43.9 %	
231	0.3285E+02	43.9 %	
232	0.3113E+02	17.3 %	0.1137E-12
233	0.3270E+02	41.6 %	
234	0.3288E+02	44.4 %	
235	0.3285E+02	43.8 %	
236	0.3285E+02	43.9 %	
237	0.3285E+02	43.9 %	
238	0.3285E+02	43.9 %	
239	0.3116E+02	17.9 %	0.1137E-12
240	0.3268E+02	41.3 %	
241	0.3289E+02	44.4 %	
242	0.3285E+02	43.8 %	
243	0.3285E+02	43.9 %	
244	0.3285E+02	43.9 %	
245	0.3285E+02	43.9 %	
246	0.3120E+02	18.4 %	0.1137E-12
247	0.3266E+02	41.0 %	
248	0.3289E+02	44.4 %	
249	0.3285E+02	43.8 %	
250	0.3285E+02	43.9 %	
251	0.3285E+02	43.9 %	
252	0.3285E+02	43.9 %	
253	0.3122E+02	18.8 %	0.1705E-12
254	0.3265E+02	40.8 %	
255	0.3289E+02	44.5 %	
256	0.3285E+02	43.8 %	
257	0.3285E+02	43.9 %	
258	0.3285E+02	43.9 %	
259	0.3285E+02	43.9 %	
260	0.3124E+02	19.1 %	-0.1705E-12
261	0.3264E+02	40.6 %	
262	0.3289E+02	44.5 %	
263	0.3285E+02	43.8 %	
264	0.3285E+02	43.9 %	
265	0.3285E+02	43.9 %	
266	0.3285E+02	43.9 %	
267	0.3126E+02	19.3 %	-0.5684E-13
268	0.3263E+02	40.5 %	
269	0.3289E+02	44.5 %	
270	0.3285E+02	43.8 %	
271	0.3285E+02	43.9 %	
272	0.3285E+02	43.9 %	
273	0.3285E+02	43.9 %	
274	0.3127E+02	19.5 %	0.1705E-12
275	0.3263E+02	40.4 %	
276	0.3289E+02	44.5 %	
277	0.3285E+02	43.8 %	
278	0.3285E+02	43.9 %	
279	0.3285E+02	43.9 %	
280	0.3285E+02	43.9 %	
281	0.3127E+02	19.5 %	-0.2274E-12
282	0.3262E+02	40.4 %	
283	0.3289E+02	44.5 %	
284	0.3285E+02	43.8 %	
285	0.3285E+02	43.9 %	
286	0.3285E+02	43.9 %	
287	0.3285E+02	43.9 %	

Flow = 2.1252E+01

APPENDIX D CALCULATIONS AND GRAPHS IN CHAPTER 7

Transient Analytical Model by Laplace Transform Method Cumulative Analysis

a. T/S = 5

$S := 0.005$ dimensionless $\qquad T := 0.025\ 86400$ m^2/day

$\omega := \frac{\pi}{60} \qquad r := \omega \qquad \theta := \frac{\pi}{2} \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad m := 100$

$$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$$

$$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$$

$$G(R,I) := \frac{\exp(-R^2)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp(-R^2)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \operatorname{erf}(R) + \frac{\exp(-R^2)}{2\cdot\pi\cdot R}\cdot(1-\cos(2\cdot R\cdot I)) \ldots$$
$$+\frac{2}{\pi}\cdot\exp(-R^2)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$R2(x,t) := \sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$H_0 := 5$ meter

$H_1 := 1.5$ meter

$$h1a(x,t) := \frac{1}{2}\cdot H_1\cdot\cos(\omega\cdot t)\cdot\left[\begin{array}{l}\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ldots\\ +\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t)))\end{array}\right] \ldots\\ +\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ldots\\ +\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t)))\end{array}\right]\end{array}\right] \ldots$$
$$+\frac{1}{2}\cdot H_1\cdot\sin(\omega\cdot t)\cdot\left[\begin{array}{l}\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t))) \ldots\\ +\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\end{array}\right] \ldots\\ +\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{array}{l}\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t))) \ldots\\ +\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\end{array}\right]\end{array}\right]$$

$$h_5(x,t) := H_0 \cdot \mathrm{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}}\right) + h1a(x,t)$$

b. T/S = 18

$S := 0.005$ dimensionless $\quad T := 0.09\cdot 86400$ m^2/day

$\omega := \frac{\pi}{60} \quad r := \omega \quad \theta := \frac{\pi}{2} \quad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \quad m := 100$

$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \left[\mathrm{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1-\cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$R2(x,t) := \sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$H_0 := 5$ meter

$H_1 := 1.5$ meter

$$\begin{aligned}
h1b(x,t) := {} & \frac{1}{2}\cdot H_1\cdot\cos(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ldots \\
& \quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t)))\Bigg] \ldots \\
& \quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ldots \\
& \quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t)))\Bigg]\Bigg] \ldots \\
& + \frac{1}{2}\cdot H_1\cdot\sin(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t))) \ldots \\
& \quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\Bigg] \ldots \\
& \quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t))) \ldots \\
& \quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\Bigg]\Bigg]
\end{aligned}$$

$$h_{18}(x,t) := H_0\cdot\mathrm{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}}\right) + h1b(x,t)$$

c. T/S = 500

$S := 0.00005$ dimensionless $\quad T := 0.025\,86400$ m^2/day

$$\omega := \frac{\pi}{60} \qquad r := \omega \qquad \theta := \frac{\pi}{2} \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad m := 100$$

$$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$$

$$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1-\cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$$R1(x,t) := -\sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$$

$$R2(x,t) := \sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$$

$$\begin{aligned}
h1c(x,t) := \frac{1}{2}\cdot H_1\cdot\cos(\omega\cdot t)\cdot\Bigg[&\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ldots \right. \\
&\left. + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t)))\right] \ldots \\
&+\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ldots \right. \\
&\left. + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t)))\right]\Bigg] \ldots \\
+ \frac{1}{2}\cdot H_1\cdot\sin(\omega\cdot t)\cdot\Bigg[&\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t))) \ldots \right. \\
&\left. + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\right] \ldots \\
&+\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t))) \ldots \right. \\
&\left. + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\right]\Bigg]
\end{aligned}$$

$$h_{500}(x,t) := H_0\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}}\right) + h1c(x,t)$$

d. T/S = 1800

$S := 0.00005$ dimensionless $\quad T := 0.09\,86400$ m^2/day

$$\omega := \frac{\pi}{60} \qquad r := \omega \qquad \theta := \frac{\pi}{2} \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad m := 100$$

$$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$$

$$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1-\cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2+4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$$R1(x,t) := -\sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$$

$$R2(x,t) := \sqrt{r\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$$

$H_0 := 5$ meter

$H_1 := 1.5$ meter

$$\begin{aligned} h1d(x,t) := \frac{1}{2}\cdot H_1\cdot\cos(\omega\cdot t)\cdot\Bigg[&\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ldots \atop + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t)))\right] \ldots \\ &+ \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ldots \atop + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t)))\right]\Bigg] \ldots \\ + \frac{1}{2}\cdot H_1\cdot\sin(\omega\cdot t)\cdot\Bigg[&\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R1(x,t),I1(t))) \ldots \atop + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\right] \ldots \\ &+ \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1-F(R2(x,t),I2(t))) \ldots \atop + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\right]\Bigg] \end{aligned}$$

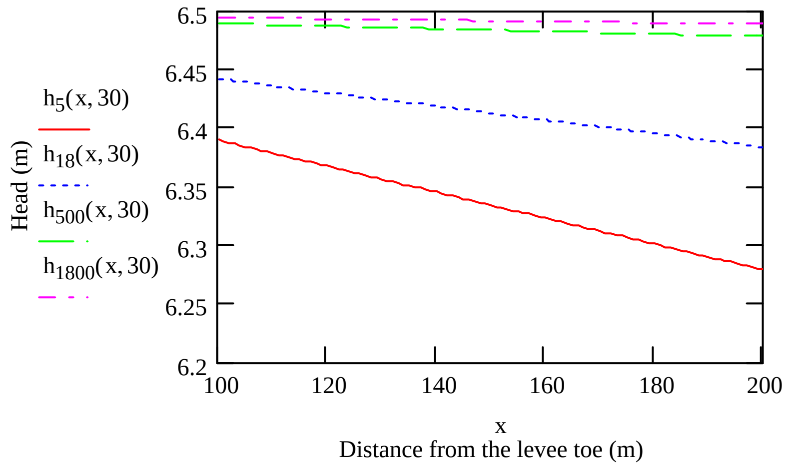
$$h_{1800}(x,t) := H_0\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}}\right) + h1d(x,t)$$

Figure 7.2

Head vs Time for T/S = 5, 18, 500, 1800

$t := 30$ day

$x := 100..200$



$h_5(100,30) = 6.389$ $\quad h_{18}(100,30) = 6.442$ $\quad h_{500}(100,30) = 6.489$ $\quad h_{1800}(100,30) = 6.494$

$h_5(200,30) = 6.279$ $\quad h_{18}(200,30) = 6.383$ $\quad h_{500}(200,30) = 6.478$ $\quad h_{1800}(200,30) = 6.488$

$z := 5$ m

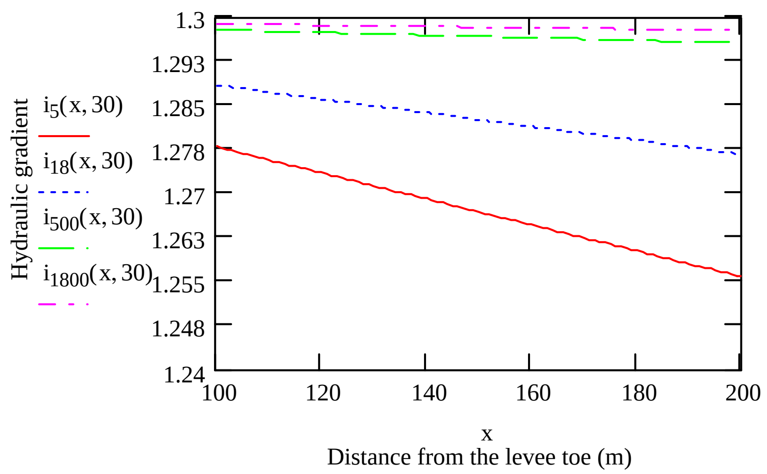
$i_5(x,t) := h_5(x,t)\cdot\frac{1}{z}$ $\qquad i_{500}(x,t) := h_{500}(x,t)\cdot\frac{1}{z}$

$i_{1800}(x,t) := h_{1800}(x,t)\cdot\frac{1}{z}$ $\qquad i_{18}(x,t) := h_{18}(x,t)\cdot\frac{1}{z}$

Figure 7.3

$t := 30$

$x := 100..200$



$i_5(100,30) = 1.278$ $\quad i_{18}(100,30) = 1.288$ $\quad i_{500}(100,30) = 1.298$ $\quad i_{1800}(100,30) = 1.299$

$i_5(200,30) = 1.256$ $\quad i_{18}(200,30) = 1.277$ $\quad i_{500}(200,30) = 1.296$ $\quad i_{1800}(200,30) = 1.298$

Calculation of Substratum Pressures by the Army Corps Method

EM 1110-2-1913: Design and Construstion of Levees details the underseepage analysis. The equations contained in the manual were developed during a study reported in (U.S. Army Engineer Waterways Experiment Station TM 3-424, Appendix A) of piezometric data and seepage mesurements along the Lower Mississippi River and confirmed by model studies. Case 7, which is a semipervious top strata both riverside and landside was selected.

$H := 6.5\text{m}$ head at the riverside $x_1 := 50\text{m}$ $L_2 := 50\text{m}$

$d := 25\text{m}$ assumed thickness of pervious aquifer

$z_b := 5\text{m}$ assumed thickness of top layer

$k_f := 0.1 \cdot 10^{-2} \dfrac{\text{m}}{\text{s}}$ hydraulic conductivity of pervious substratum

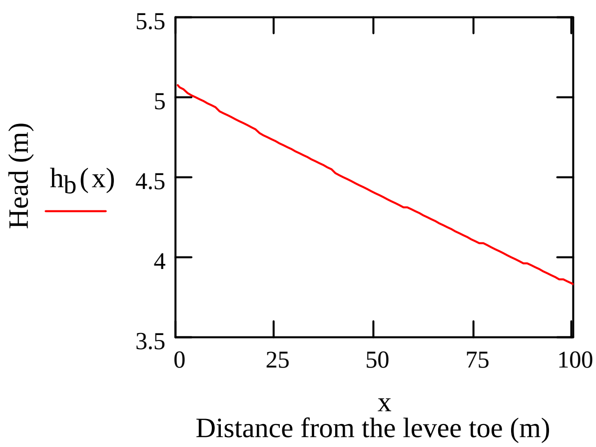
$k_b := 1 \cdot 10^{-6} \dfrac{\text{m}}{\text{s}}$ hydraulic conductivity of top substratum

$c := \sqrt{\dfrac{k_b}{k_f \cdot z_b \cdot d}}$ $x_3 := \dfrac{1}{c}$ $h_0 := \dfrac{H \cdot x_3}{x_1 + L_2 + x_3}$ $h_b(x) := h_0 \cdot e^{-c \cdot x}$

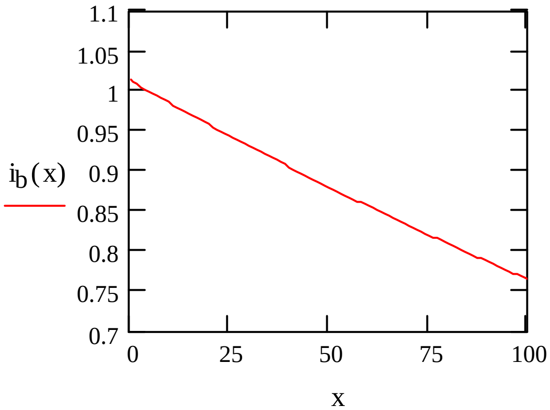
$h_0 = 5.067\text{m}$ head beneath top stratum at landside levee toe

Figure 7.4

$x := 0 .. 100$ distance from landside levee toe



$$i_b(x) := \frac{h_0 \cdot e^{-c \cdot x}}{z_b}$$



$H := 6.5m$ head at the riverside

$x_1 := 50m$ $L_2 := 50m$

$d := 45m$ assumed thickness of pervious aquifer

$z_b := 5m$ assumed thickness of top layer

$k_f := 0.2 \cdot 10^{-2} \dfrac{m}{s}$ hydraulic conductivity of pervious substratum

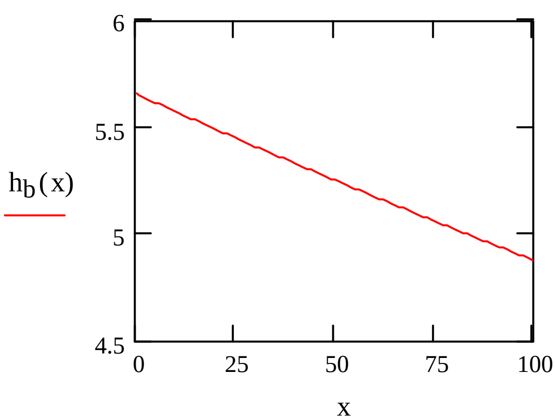
$k_b := 1 \cdot 10^{-6} \dfrac{m}{s}$ hydraulic conductivity of top substratum

$c := \sqrt{\dfrac{k_b}{k_f \cdot z_b \cdot d}}$ $x_3 := \dfrac{1}{c}$ $h_0 := \dfrac{H \cdot x_3}{x_1 + L_2 + x_3}$ $h_b(x) := h_0 \cdot e^{-c \cdot x}$

$h_0 = 5.657m$ head beneath top stratum at landside levee toe

Figure 7.5

$x := 0..100$ distance from landside levee toe



$$i_b(x) := \frac{h_0 \cdot e^{-c \cdot x}}{z_b}$$

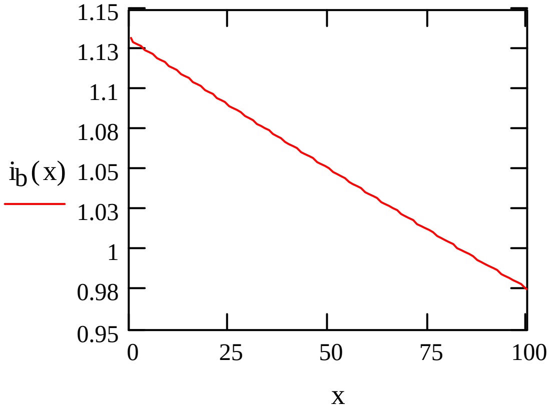
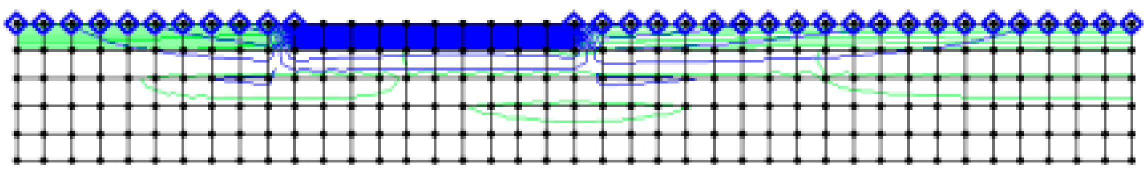


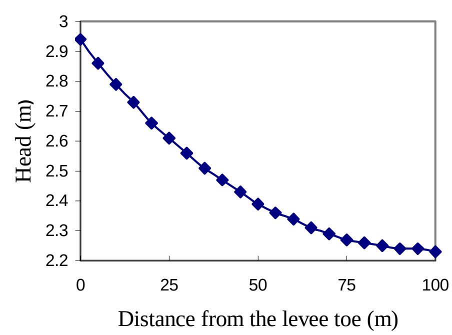
Figure 7.6
SEEP2D Model
A confined aquifer with a depth of 25 m, and hydraulic conductivities of k_h=0.1 cm/sec, k_v=0.0001 cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head was defined at riverside and landside of the levee. The figure of the model is below:

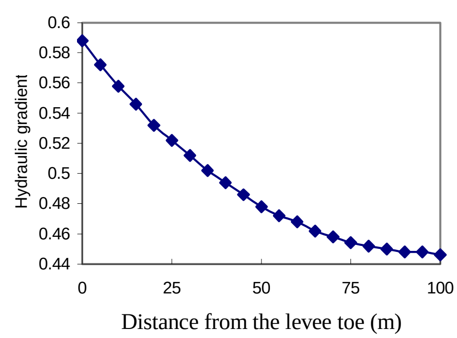


Cumulative analysis purpose
25 m confined aquifer, T=0.025 m^2/sec

Node	Distance (m)	Head (m)	Head-25 (m)	i=h/5
122	0	27.94	2.94	0.588
128	5	27.86	2.86	0.572
134	10	27.79	2.79	0.558
140	15	27.73	2.73	0.546
146	20	27.66	2.66	0.532
152	25	27.61	2.61	0.522
158	30	27.56	2.56	0.512
164	35	27.51	2.51	0.502
170	40	27.47	2.47	0.494
176	45	27.43	2.43	0.486
182	50	27.39	2.39	0.478
188	55	27.36	2.36	0.472
194	60	27.34	2.34	0.468
200	65	27.31	2.31	0.462
206	70	27.29	2.29	0.458
212	75	27.27	2.27	0.454
218	80	27.26	2.26	0.452
224	85	27.25	2.25	0.45
230	90	27.24	2.24	0.448
236	95	27.24	2.24	0.448
242	100	27.23	2.23	0.446

Flow = 21.907





Plane flow problem
25 m confined aquifer, T=0.025 m^2/sec
Number of nodal points------ 246
Number of elements---------- 200
Number of diff. materials--- 1
Elevation of datum---------- 0.000
Unsaturated flow option----- 0
Material Properties

Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.8640E+02	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

Node Point Information

Node	BC	X	Y	Flow-head
1	1	0.00	25.00	31.50
2	0	0.00	20.00	0.00
3	0	0.00	15.00	0.00
4	0	0.00	10.00	0.00
5	0	0.00	5.00	0.00
6	0	0.00	0.00	0.00
7	1	5.00	25.00	31.50
8	0	5.00	20.00	0.00
9	0	5.00	15.00	0.00
10	0	5.00	10.00	0.00
11	0	5.00	5.00	0.00
12	0	5.00	0.00	0.00
13	1	10.00	25.00	31.50
14	0	10.00	20.00	0.00
15	0	10.00	15.00	0.00
16	0	10.00	10.00	0.00
17	0	10.00	5.00	0.00
18	0	10.00	0.00	0.00
19	1	15.00	25.00	31.50
20	0	15.00	20.00	0.00
21	0	15.00	15.00	0.00
22	0	15.00	10.00	0.00
23	0	15.00	5.00	0.00
24	0	15.00	0.00	0.00
25	1	20.00	25.00	31.50
26	0	20.00	20.00	0.00
27	0	20.00	15.00	0.00
28	0	20.00	10.00	0.00
29	0	20.00	5.00	0.00
30	0	20.00	0.00	0.00
31	1	25.00	25.00	31.50
32	0	25.00	20.00	0.00
33	0	25.00	15.00	0.00
34	0	25.00	10.00	0.00
35	0	25.00	5.00	0.00
36	0	25.00	0.00	0.00
37	1	30.00	25.00	31.50
38	0	30.00	20.00	0.00
39	0	30.00	15.00	0.00
40	0	30.00	10.00	0.00
41	0	30.00	5.00	0.00
42	0	30.00	0.00	0.00
43	1	35.00	25.00	31.50
44	0	35.00	20.00	0.00
45	0	35.00	15.00	0.00
46	0	35.00	10.00	0.00
47	0	35.00	5.00	0.00
48	0	35.00	0.00	0.00
49	1	40.00	25.00	31.50
50	0	40.00	20.00	0.00
51	0	40.00	15.00	0.00
52	0	40.00	10.00	0.00
53	0	40.00	5.00	0.00
54	0	40.00	0.00	0.00
55	1	45.00	25.00	31.50
56	0	45.00	20.00	0.00
57	0	45.00	15.00	0.00
58	0	45.00	10.00	0.00
59	0	45.00	5.00	0.00
60	0	45.00	0.00	0.00
61	1	50.00	25.00	31.50
62	0	50.00	20.00	0.00
63	0	50.00	15.00	0.00
64	0	50.00	10.00	0.00
65	0	50.00	5.00	0.00
66	0	50.00	0.00	0.00
67	0	55.00	25.00	0.00
68	0	55.00	20.00	0.00
69	0	55.00	15.00	0.00
70	0	55.00	10.00	0.00
71	0	55.00	5.00	0.00
72	0	55.00	0.00	0.00
73	0	60.00	25.00	0.00
74	0	60.00	20.00	0.00
75	0	60.00	15.00	0.00
76	0	60.00	10.00	0.00
77	0	60.00	5.00	0.00
78	0	60.00	0.00	0.00
79	0	65.00	25.00	0.00
80	0	65.00	20.00	0.00
81	0	65.00	15.00	0.00
82	0	65.00	10.00	0.00
83	0	65.00	5.00	0.00
84	0	65.00	0.00	0.00
85	0	70.00	25.00	0.00
86	0	70.00	20.00	0.00
87	0	70.00	15.00	0.00
88	0	70.00	10.00	0.00
89	0	70.00	5.00	0.00
90	0	70.00	0.00	0.00
91	0	75.00	25.00	0.00
92	0	75.00	20.00	0.00
93	0	75.00	15.00	0.00
94	0	75.00	10.00	0.00
95	0	75.00	5.00	0.00
96	0	75.00	0.00	0.00
97	0	80.00	25.00	0.00
98	0	80.00	20.00	0.00
99	0	80.00	15.00	0.00
100	0	80.00	10.00	0.00
101	0	80.00	5.00	0.00
102	0	80.00	0.00	0.00
103	0	85.00	25.00	0.00
104	0	85.00	20.00	0.00
105	0	85.00	15.00	0.00
106	0	85.00	10.00	0.00
107	0	85.00	5.00	0.00
108	0	85.00	0.00	0.00
109	0	90.00	25.00	0.00
110	0	90.00	20.00	0.00
111	0	90.00	15.00	0.00
112	0	90.00	10.00	0.00
113	0	90.00	5.00	0.00

114	0	90.00	0.00	0.00
115	0	95.00	25.00	0.00
116	0	95.00	20.00	0.00
117	0	95.00	15.00	0.00
118	0	95.00	10.00	0.00
119	0	95.00	5.00	0.00
120	0	95.00	0.00	0.00
121	1	100.00	25.00	25.00
122	0	100.00	20.00	0.00
123	0	100.00	15.00	0.00
124	0	100.00	10.00	0.00
125	0	100.00	5.00	0.00
126	0	100.00	0.00	0.00
127	1	105.00	25.00	25.00
128	0	105.00	20.00	0.00
129	0	105.00	15.00	0.00
130	0	105.00	10.00	0.00
131	0	105.00	5.00	0.00
132	0	105.00	0.00	0.00
133	1	110.00	25.00	25.00
134	0	110.00	20.00	0.00
135	0	110.00	15.00	0.00
136	0	110.00	10.00	0.00
137	0	110.00	5.00	0.00
138	0	110.00	0.00	0.00
139	1	115.00	25.00	25.00
140	0	115.00	20.00	0.00
141	0	115.00	15.00	0.00
142	0	115.00	10.00	0.00
143	0	115.00	5.00	0.00
144	0	115.00	0.00	0.00
145	1	120.00	25.00	25.00
146	0	120.00	20.00	0.00
147	0	120.00	15.00	0.00
148	0	120.00	10.00	0.00
149	0	120.00	5.00	0.00
150	0	120.00	0.00	0.00
151	1	125.00	25.00	25.00
152	0	125.00	20.00	0.00
153	0	125.00	15.00	0.00
154	0	125.00	10.00	0.00
155	0	125.00	5.00	0.00
156	0	125.00	0.00	0.00
157	1	130.00	25.00	25.00
158	0	130.00	20.00	0.00
159	0	130.00	15.00	0.00
160	0	130.00	10.00	0.00
161	0	130.00	5.00	0.00
162	0	130.00	0.00	0.00
163	1	135.00	25.00	25.00
164	0	135.00	20.00	0.00
165	0	135.00	15.00	0.00
166	0	135.00	10.00	0.00
167	0	135.00	5.00	0.00
168	0	135.00	0.00	0.00
169	1	140.00	25.00	25.00
170	0	140.00	20.00	0.00
171	0	140.00	15.00	0.00
172	0	140.00	10.00	0.00
173	0	140.00	5.00	0.00
174	0	140.00	0.00	0.00
175	1	145.00	25.00	25.00
176	0	145.00	20.00	0.00
177	0	145.00	15.00	0.00
178	0	145.00	10.00	0.00
179	0	145.00	5.00	0.00
180	0	145.00	0.00	0.00
181	1	150.00	25.00	25.00
182	0	150.00	20.00	0.00
183	0	150.00	15.00	0.00
184	0	150.00	10.00	0.00
185	0	150.00	5.00	0.00
186	0	150.00	0.00	0.00
187	1	155.00	25.00	25.00
188	0	155.00	20.00	0.00
189	0	155.00	15.00	0.00
190	0	155.00	10.00	0.00
191	0	155.00	5.00	0.00
192	0	155.00	0.00	0.00
193	1	160.00	25.00	25.00
194	0	160.00	20.00	0.00
195	0	160.00	15.00	0.00
196	0	160.00	10.00	0.00
197	0	160.00	5.00	0.00
198	0	160.00	0.00	0.00
199	1	165.00	25.00	25.00
200	0	165.00	20.00	0.00
201	0	165.00	15.00	0.00
202	0	165.00	10.00	0.00
203	0	165.00	5.00	0.00
204	0	165.00	0.00	0.00
205	1	170.00	25.00	25.00
206	0	170.00	20.00	0.00
207	0	170.00	15.00	0.00
208	0	170.00	10.00	0.00
209	0	170.00	5.00	0.00
210	0	170.00	0.00	0.00
211	1	175.00	25.00	25.00
212	0	175.00	20.00	0.00
213	0	175.00	15.00	0.00
214	0	175.00	10.00	0.00
215	0	175.00	5.00	0.00
216	0	175.00	0.00	0.00
217	1	180.00	25.00	25.00
218	0	180.00	20.00	0.00
219	0	180.00	15.00	0.00
220	0	180.00	10.00	0.00
221	0	180.00	5.00	0.00
222	0	180.00	0.00	0.00
223	1	185.00	25.00	25.00
224	0	185.00	20.00	0.00
225	0	185.00	15.00	0.00
226	0	185.00	10.00	0.00
227	0	185.00	5.00	0.00
228	0	185.00	0.00	0.00
229	1	190.00	25.00	25.00
230	0	190.00	20.00	0.00
231	0	190.00	15.00	0.00
232	0	190.00	10.00	0.00
233	0	190.00	5.00	0.00
234	0	190.00	0.00	0.00
235	1	195.00	25.00	25.00
236	0	195.00	20.00	0.00
237	0	195.00	15.00	0.00
238	0	195.00	10.00	0.00
239	0	195.00	5.00	0.00
240	0	195.00	0.00	0.00
241	1	200.00	25.00	25.00
242	0	200.00	20.00	0.00
243	0	200.00	15.00	0.00
244	0	200.00	10.00	0.00
245	0	200.00	5.00	0.00
246	0	200.00	0.00	0.00

Nodal Flows and Heads

Node	Head	Percentage of available head	Flow

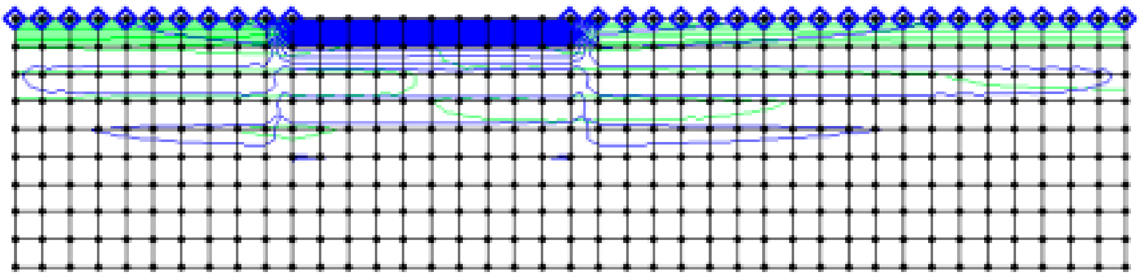
1	0.3150E+02	100.0 %	0.2234E+00	71	0.2744E+02	37.5 %	
2	0.2741E+02	37.0 %		72	0.2743E+02	37.4 %	
3	0.2742E+02	37.2 %		73	0.3015E+02	79.2 %	
4	0.2744E+02	37.5 %		74	0.2727E+02	35.0 %	
5	0.2743E+02	37.4 %		75	0.2747E+02	38.0 %	
6	0.2743E+02	37.4 %		76	0.2742E+02	37.3 %	
7	0.3150E+02	100.0 %	0.4473E+00	77	0.2743E+02	37.4 %	
8	0.2740E+02	37.0 %		78	0.2743E+02	37.4 %	
9	0.2742E+02	37.2 %		79	0.2950E+02	69.2 %	
10	0.2744E+02	37.5 %		80	0.2736E+02	36.3 %	
11	0.2743E+02	37.4 %		81	0.2745E+02	37.7 %	
12	0.2743E+02	37.4 %		82	0.2743E+02	37.3 %	
13	0.3150E+02	100.0 %	0.4488E+00	83	0.2743E+02	37.4 %	
14	0.2739E+02	36.8 %		84	0.2743E+02	37.4 %	
15	0.2742E+02	37.3 %		85	0.2885E+02	59.3 %	
16	0.2744E+02	37.5 %		86	0.2744E+02	37.6 %	
17	0.2743E+02	37.4 %		87	0.2743E+02	37.4 %	
18	0.2743E+02	37.4 %		88	0.2743E+02	37.4 %	
19	0.3150E+02	100.0 %	0.4512E+00	89	0.2743E+02	37.4 %	
20	0.2738E+02	36.6 %		90	0.2743E+02	37.4 %	
21	0.2743E+02	37.3 %		91	0.2821E+02	49.4 %	
22	0.2743E+02	37.5 %		92	0.2752E+02	38.8 %	
23	0.2743E+02	37.4 %		93	0.2742E+02	37.2 %	
24	0.2743E+02	37.4 %		94	0.2743E+02	37.4 %	
25	0.3150E+02	100.0 %	0.4547E+00	95	0.2743E+02	37.4 %	
26	0.2735E+02	36.2 %		96	0.2743E+02	37.4 %	
27	0.2743E+02	37.4 %		97	0.2758E+02	39.7 %	
28	0.2743E+02	37.4 %		98	0.2760E+02	40.0 %	
29	0.2743E+02	37.4 %		99	0.2740E+02	36.9 %	
30	0.2743E+02	37.4 %		100	0.2744E+02	37.5 %	
31	0.3150E+02	100.0 %	0.4592E+00	101	0.2743E+02	37.4 %	
32	0.2732E+02	35.7 %		102	0.2743E+02	37.4 %	
33	0.2744E+02	37.6 %		103	0.2694E+02	29.9 %	
34	0.2743E+02	37.4 %		104	0.2768E+02	41.2 %	
35	0.2743E+02	37.4 %		105	0.2738E+02	36.7 %	
36	0.2743E+02	37.4 %		106	0.2744E+02	37.5 %	
37	0.3150E+02	100.0 %	0.4647E+00	107	0.2743E+02	37.4 %	
38	0.2729E+02	35.2 %		108	0.2743E+02	37.4 %	
39	0.2745E+02	37.7 %		109	0.2630E+02	20.0 %	
40	0.2743E+02	37.4 %		110	0.2776E+02	42.5 %	
41	0.2743E+02	37.4 %		111	0.2737E+02	36.4 %	
42	0.2743E+02	37.4 %		112	0.2744E+02	37.6 %	
43	0.3150E+02	100.0 %	0.4713E+00	113	0.2743E+02	37.4 %	
44	0.2724E+02	34.5 %		114	0.2743E+02	37.4 %	
45	0.2746E+02	37.9 %		115	0.2566E+02	10.1 %	
46	0.2742E+02	37.3 %		116	0.2785E+02	43.8 %	
47	0.2743E+02	37.4 %		117	0.2735E+02	36.1 %	
48	0.2743E+02	37.4 %		118	0.2745E+02	37.7 %	
49	0.3150E+02	100.0 %	0.4790E+00	119	0.2743E+02	37.3 %	
50	0.2719E+02	33.7 %		120	0.2743E+02	37.4 %	
51	0.2748E+02	38.2 %		121	0.2500E+02	0.0 %	-0.1670E+02
52	0.2742E+02	37.2 %		122	0.2794E+02	45.2 %	
53	0.2743E+02	37.4 %		123	0.2732E+02	35.7 %	
54	0.2743E+02	37.4 %		124	0.2746E+02	37.8 %	
55	0.3150E+02	100.0 %	0.4878E+00	125	0.2743E+02	37.3 %	
56	0.2713E+02	32.8 %		126	0.2743E+02	37.4 %	
57	0.2750E+02	38.4 %		127	0.2500E+02	0.0 %	-0.3283E+00
58	0.2742E+02	37.2 %		128	0.2786E+02	44.0 %	
59	0.2744E+02	37.5 %		129	0.2734E+02	36.0 %	
60	0.2743E+02	37.4 %		130	0.2745E+02	37.7 %	
61	0.3150E+02	100.0 %	0.1752E+02	131	0.2743E+02	37.3 %	
62	0.2707E+02	31.8 %		132	0.2743E+02	37.4 %	
63	0.2752E+02	38.7 %		133	0.2500E+02	0.0 %	-0.3177E+00
64	0.2741E+02	37.1 %		134	0.2779E+02	42.9 %	
65	0.2744E+02	37.5 %		135	0.2736E+02	36.3 %	
66	0.2743E+02	37.4 %		136	0.2745E+02	37.6 %	
67	0.3082E+02	89.5 %		137	0.2743E+02	37.4 %	
68	0.2717E+02	33.4 %		138	0.2743E+02	37.4 %	
69	0.2749E+02	38.3 %		139	0.2500E+02	0.0 %	-0.3080E+00
70	0.2742E+02	37.2 %		140	0.2773E+02	41.9 %	

141	0.2738E+02	36.6 %	
142	0.2744E+02	37.6 %	
143	0.2743E+02	37.4 %	
144	0.2743E+02	37.4 %	
145	0.2500E+02	0.0 %	-0.2990E+00
146	0.2766E+02	41.0 %	
147	0.2739E+02	36.8 %	
148	0.2744E+02	37.5 %	
149	0.2743E+02	37.4 %	
150	0.2743E+02	37.4 %	
151	0.2500E+02	0.0 %	-0.2908E+00
152	0.2761E+02	40.1 %	
153	0.2740E+02	37.0 %	
154	0.2744E+02	37.5 %	
155	0.2743E+02	37.4 %	
156	0.2743E+02	37.4 %	
157	0.2500E+02	0.0 %	-0.2833E+00
158	0.2756E+02	39.3 %	
159	0.2741E+02	37.1 %	
160	0.2743E+02	37.4 %	
161	0.2743E+02	37.4 %	
162	0.2743E+02	37.4 %	
163	0.2500E+02	0.0 %	-0.2764E+00
164	0.2751E+02	38.6 %	
165	0.2742E+02	37.3 %	
166	0.2743E+02	37.4 %	
167	0.2743E+02	37.4 %	
168	0.2743E+02	37.4 %	
169	0.2500E+02	0.0 %	-0.2702E+00
170	0.2747E+02	38.0 %	
171	0.2743E+02	37.4 %	
172	0.2743E+02	37.4 %	
173	0.2743E+02	37.4 %	
174	0.2743E+02	37.4 %	
175	0.2500E+02	0.0 %	-0.2646E+00
176	0.2743E+02	37.4 %	
177	0.2744E+02	37.5 %	
178	0.2743E+02	37.4 %	
179	0.2743E+02	37.4 %	
180	0.2743E+02	37.4 %	
181	0.2500E+02	0.0 %	-0.2595E+00
182	0.2739E+02	36.8 %	
183	0.2744E+02	37.6 %	
184	0.2743E+02	37.4 %	
185	0.2743E+02	37.4 %	
186	0.2743E+02	37.4 %	
187	0.2500E+02	0.0 %	-0.2551E+00
188	0.2736E+02	36.4 %	
189	0.2745E+02	37.7 %	
190	0.2743E+02	37.3 %	
191	0.2743E+02	37.4 %	
192	0.2743E+02	37.4 %	
193	0.2500E+02	0.0 %	-0.2511E+00
194	0.2734E+02	35.9 %	
195	0.2745E+02	37.7 %	
196	0.2743E+02	37.3 %	
197	0.2743E+02	37.4 %	
198	0.2743E+02	37.4 %	
199	0.2500E+02	0.0 %	-0.2476E+00
200	0.2731E+02	35.6 %	
201	0.2746E+02	37.8 %	
202	0.2743E+02	37.3 %	
203	0.2743E+02	37.4 %	
204	0.2743E+02	37.4 %	
205	0.2500E+02	0.0 %	-0.2447E+00
206	0.2729E+02	35.2 %	
207	0.2746E+02	37.8 %	
208	0.2743E+02	37.3 %	
209	0.2743E+02	37.4 %	
210	0.2743E+02	37.4 %	
211	0.2500E+02	0.0 %	-0.2422E+00
212	0.2727E+02	35.0 %	
213	0.2746E+02	37.9 %	
214	0.2743E+02	37.3 %	
215	0.2743E+02	37.4 %	
216	0.2743E+02	37.4 %	
217	0.2500E+02	0.0 %	-0.2402E+00
218	0.2726E+02	34.8 %	
219	0.2746E+02	37.9 %	
220	0.2743E+02	37.3 %	
221	0.2743E+02	37.4 %	
222	0.2743E+02	37.4 %	
223	0.2500E+02	0.0 %	-0.2386E+00
224	0.2725E+02	34.6 %	
225	0.2747E+02	37.9 %	
226	0.2743E+02	37.3 %	
227	0.2743E+02	37.4 %	
228	0.2743E+02	37.4 %	
229	0.2500E+02	0.0 %	-0.2375E+00
230	0.2724E+02	34.5 %	
231	0.2747E+02	37.9 %	
232	0.2743E+02	37.3 %	
233	0.2743E+02	37.4 %	
234	0.2743E+02	37.4 %	
235	0.2500E+02	0.0 %	-0.2369E+00
236	0.2724E+02	34.4 %	
237	0.2747E+02	38.0 %	
238	0.2743E+02	37.3 %	
239	0.2743E+02	37.4 %	
240	0.2743E+02	37.4 %	
241	0.2500E+02	0.0 %	-0.1183E+00
242	0.2723E+02	34.4 %	
243	0.2747E+02	38.0 %	
244	0.2743E+02	37.3 %	
245	0.2743E+02	37.4 %	
246	0.2743E+02	37.4 %	

Flow = 2.1907E+01

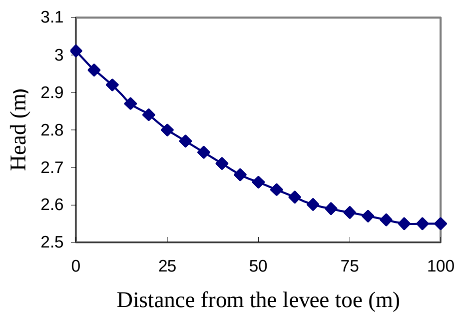
Figure 7.7
SEEP2D Model

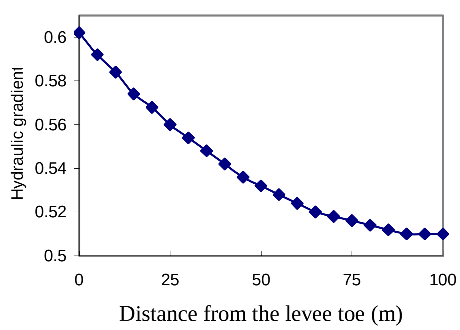
A confined aquifer with a depth of 45 m, and hydraulic conductivities of k_h=0.2 cm/sec, k_v=0.0001 cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head was defined at riverside and landside of the levee. The figure of the model is below:



Cumulative analysis purpose
45 m confined aquifer, T=0.09 m^2/sec

Node	Distance (m)	Head (m)	Head-45 (m)	i=h/5
202	0	48.01	3.01	0.602
212	5	47.96	2.96	0.592
222	10	47.92	2.92	0.584
232	15	47.87	2.87	0.574
242	20	47.84	2.84	0.568
252	25	47.8	2.8	0.56
262	30	47.77	2.77	0.554
272	35	47.74	2.74	0.548
282	40	47.71	2.71	0.542
292	45	47.68	2.68	0.536
302	50	47.66	2.66	0.532
312	55	47.64	2.64	0.528
322	60	47.62	2.62	0.524
332	65	47.6	2.6	0.52
342	70	47.59	2.59	0.518
352	75	47.58	2.58	0.516
362	80	47.57	2.57	0.514
372	85	47.56	2.56	0.512
382	90	47.55	2.55	0.51
392	95	47.55	2.55	0.51
402	100	47.55	2.55	0.51





Model Output

45 m confined aquifer, T=0.09 m^2/sec
Number of nodal points------ 410
Number of elements---------- 360
Number of diff. materials--- 1
Elevation of datum---------- 0.000
Unsaturated flow option----- 0
Material Properties

Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.1728E+03	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

Node Point Information

Node	BC	X	Y	Flow-head
1	1	0.00	45.00	51.50
2	0	0.00	40.00	0.00
3	0	0.00	35.00	0.00
4	0	0.00	30.00	0.00
5	0	0.00	25.00	0.00
6	0	0.00	20.00	0.00
7	0	0.00	15.00	0.00
8	0	0.00	10.00	0.00
9	0	0.00	5.00	0.00
10	0	0.00	0.00	0.00
11	1	5.00	45.00	51.50
12	0	5.00	40.00	0.00
13	0	5.00	35.00	0.00
14	0	5.00	30.00	0.00
15	0	5.00	25.00	0.00
16	0	5.00	20.00	0.00
17	0	5.00	15.00	0.00
18	0	5.00	10.00	0.00
19	0	5.00	5.00	0.00
20	0	5.00	0.00	0.00
21	1	10.00	45.00	51.50
22	0	10.00	40.00	0.00
23	0	10.00	35.00	0.00
24	0	10.00	30.00	0.00
25	0	10.00	25.00	0.00
26	0	10.00	20.00	0.00
27	0	10.00	15.00	0.00
28	0	10.00	10.00	0.00
29	0	10.00	5.00	0.00
30	0	10.00	0.00	0.00
31	1	15.00	45.00	51.50
32	0	15.00	40.00	0.00
33	0	15.00	35.00	0.00
34	0	15.00	30.00	0.00
35	0	15.00	25.00	0.00
36	0	15.00	20.00	0.00
37	0	15.00	15.00	0.00
38	0	15.00	10.00	0.00
39	0	15.00	5.00	0.00
40	0	15.00	0.00	0.00
41	1	20.00	45.00	51.50
42	0	20.00	40.00	0.00
43	0	20.00	35.00	0.00
44	0	20.00	30.00	0.00
45	0	20.00	25.00	0.00
46	0	20.00	20.00	0.00
47	0	20.00	15.00	0.00
48	0	20.00	10.00	0.00
49	0	20.00	5.00	0.00
50	0	20.00	0.00	0.00
51	1	25.00	45.00	51.50
52	0	25.00	40.00	0.00
53	0	25.00	35.00	0.00
54	0	25.00	30.00	0.00
55	0	25.00	25.00	0.00
56	0	25.00	20.00	0.00
57	0	25.00	15.00	0.00
58	0	25.00	10.00	0.00
59	0	25.00	5.00	0.00
60	0	25.00	0.00	0.00
61	1	30.00	45.00	51.50
62	0	30.00	40.00	0.00
63	0	30.00	35.00	0.00
64	0	30.00	30.00	0.00
65	0	30.00	25.00	0.00
66	0	30.00	20.00	0.00
67	0	30.00	15.00	0.00
68	0	30.00	10.00	0.00
69	0	30.00	5.00	0.00
70	0	30.00	0.00	0.00
71	1	35.00	45.00	51.50
72	0	35.00	40.00	0.00
73	0	35.00	35.00	0.00
74	0	35.00	30.00	0.00
75	0	35.00	25.00	0.00
76	0	35.00	20.00	0.00
77	0	35.00	15.00	0.00
78	0	35.00	10.00	0.00
79	0	35.00	5.00	0.00
80	0	35.00	0.00	0.00
81	1	40.00	45.00	51.50
82	0	40.00	40.00	0.00
83	0	40.00	35.00	0.00
84	0	40.00	30.00	0.00
85	0	40.00	25.00	0.00
86	0	40.00	20.00	0.00
87	0	40.00	15.00	0.00
88	0	40.00	10.00	0.00
89	0	40.00	5.00	0.00
90	0	40.00	0.00	0.00
91	1	45.00	45.00	51.50
92	0	45.00	40.00	0.00
93	0	45.00	35.00	0.00
94	0	45.00	30.00	0.00
95	0	45.00	25.00	0.00
96	0	45.00	20.00	0.00
97	0	45.00	15.00	0.00
98	0	45.00	10.00	0.00
99	0	45.00	5.00	0.00
100	0	45.00	0.00	0.00
101	1	50.00	45.00	51.50
102	0	50.00	40.00	0.00
103	0	50.00	35.00	0.00
104	0	50.00	30.00	0.00
105	0	50.00	25.00	0.00
106	0	50.00	20.00	0.00
107	0	50.00	15.00	0.00

108	0	50.00	10.00	0.00
109	0	50.00	5.00	0.00
110	0	50.00	0.00	0.00
111	0	55.00	45.00	0.00
112	0	55.00	40.00	0.00
113	0	55.00	35.00	0.00
114	0	55.00	30.00	0.00
115	0	55.00	25.00	0.00
116	0	55.00	20.00	0.00
117	0	55.00	15.00	0.00
118	0	55.00	10.00	0.00
119	0	55.00	5.00	0.00
120	0	55.00	0.00	0.00
121	0	60.00	45.00	0.00
122	0	60.00	40.00	0.00
123	0	60.00	35.00	0.00
124	0	60.00	30.00	0.00
125	0	60.00	25.00	0.00
126	0	60.00	20.00	0.00
127	0	60.00	15.00	0.00
128	0	60.00	10.00	0.00
129	0	60.00	5.00	0.00
130	0	60.00	0.00	0.00
131	0	65.00	45.00	0.00
132	0	65.00	40.00	0.00
133	0	65.00	35.00	0.00
134	0	65.00	30.00	0.00
135	0	65.00	25.00	0.00
136	0	65.00	20.00	0.00
137	0	65.00	15.00	0.00
138	0	65.00	10.00	0.00
139	0	65.00	5.00	0.00
140	0	65.00	0.00	0.00
141	0	70.00	45.00	0.00
142	0	70.00	40.00	0.00
143	0	70.00	35.00	0.00
144	0	70.00	30.00	0.00
145	0	70.00	25.00	0.00
146	0	70.00	20.00	0.00
147	0	70.00	15.00	0.00
148	0	70.00	10.00	0.00
149	0	70.00	5.00	0.00
150	0	70.00	0.00	0.00
151	0	75.00	45.00	0.00
152	0	75.00	40.00	0.00
153	0	75.00	35.00	0.00
154	0	75.00	30.00	0.00
155	0	75.00	25.00	0.00
156	0	75.00	20.00	0.00
157	0	75.00	15.00	0.00
158	0	75.00	10.00	0.00
159	0	75.00	5.00	0.00
160	0	75.00	0.00	0.00
161	0	80.00	45.00	0.00
162	0	80.00	40.00	0.00
163	0	80.00	35.00	0.00
164	0	80.00	30.00	0.00
165	0	80.00	25.00	0.00
166	0	80.00	20.00	0.00
167	0	80.00	15.00	0.00
168	0	80.00	10.00	0.00
169	0	80.00	5.00	0.00
170	0	80.00	0.00	0.00
171	0	85.00	45.00	0.00
172	0	85.00	40.00	0.00
173	0	85.00	35.00	0.00
174	0	85.00	30.00	0.00
175	0	85.00	25.00	0.00
176	0	85.00	20.00	0.00
177	0	85.00	15.00	0.00
178	0	85.00	10.00	0.00
179	0	85.00	5.00	0.00
180	0	85.00	0.00	0.00
181	0	90.00	45.00	0.00
182	0	90.00	40.00	0.00
183	0	90.00	35.00	0.00
184	0	90.00	30.00	0.00
185	0	90.00	25.00	0.00
186	0	90.00	20.00	0.00
187	0	90.00	15.00	0.00
188	0	90.00	10.00	0.00
189	0	90.00	5.00	0.00
190	0	90.00	0.00	0.00
191	0	95.00	45.00	0.00
192	0	95.00	40.00	0.00
193	0	95.00	35.00	0.00
194	0	95.00	30.00	0.00
195	0	95.00	25.00	0.00
196	0	95.00	20.00	0.00
197	0	95.00	15.00	0.00
198	0	95.00	10.00	0.00
199	0	95.00	5.00	0.00
200	0	95.00	0.00	0.00
201	1	100.00	45.00	45.00
202	0	100.00	40.00	0.00
203	0	100.00	35.00	0.00
204	0	100.00	30.00	0.00
205	0	100.00	25.00	0.00
206	0	100.00	20.00	0.00
207	0	100.00	15.00	0.00
208	0	100.00	10.00	0.00
209	0	100.00	5.00	0.00
210	0	100.00	0.00	0.00
211	1	105.00	45.00	45.00
212	0	105.00	40.00	0.00
213	0	105.00	35.00	0.00
214	0	105.00	30.00	0.00
215	0	105.00	25.00	0.00
216	0	105.00	20.00	0.00
217	0	105.00	15.00	0.00
218	0	105.00	10.00	0.00
219	0	105.00	5.00	0.00
220	0	105.00	0.00	0.00
221	1	110.00	45.00	45.00
222	0	110.00	40.00	0.00
223	0	110.00	35.00	0.00
224	0	110.00	30.00	0.00
225	0	110.00	25.00	0.00
226	0	110.00	20.00	0.00
227	0	110.00	15.00	0.00
228	0	110.00	10.00	0.00
229	0	110.00	5.00	0.00
230	0	110.00	0.00	0.00
231	1	115.00	45.00	45.00
232	0	115.00	40.00	0.00
233	0	115.00	35.00	0.00
234	0	115.00	30.00	0.00
235	0	115.00	25.00	0.00
236	0	115.00	20.00	0.00
237	0	115.00	15.00	0.00
238	0	115.00	10.00	0.00
239	0	115.00	5.00	0.00
240	0	115.00	0.00	0.00
241	1	120.00	45.00	45.00
242	0	120.00	40.00	0.00
243	0	120.00	35.00	0.00
244	0	120.00	30.00	0.00
245	0	120.00	25.00	0.00
246	0	120.00	20.00	0.00
247	0	120.00	15.00	0.00

248	0	120.00	10.00	0.00
249	0	120.00	5.00	0.00
250	0	120.00	0.00	0.00
251	1	125.00	45.00	45.00
252	0	125.00	40.00	0.00
253	0	125.00	35.00	0.00
254	0	125.00	30.00	0.00
255	0	125.00	25.00	0.00
256	0	125.00	20.00	0.00
257	0	125.00	15.00	0.00
258	0	125.00	10.00	0.00
259	0	125.00	5.00	0.00
260	0	125.00	0.00	0.00
261	1	130.00	45.00	45.00
262	0	130.00	40.00	0.00
263	0	130.00	35.00	0.00
264	0	130.00	30.00	0.00
265	0	130.00	25.00	0.00
266	0	130.00	20.00	0.00
267	0	130.00	15.00	0.00
268	0	130.00	10.00	0.00
269	0	130.00	5.00	0.00
270	0	130.00	0.00	0.00
271	1	135.00	45.00	45.00
272	0	135.00	40.00	0.00
273	0	135.00	35.00	0.00
274	0	135.00	30.00	0.00
275	0	135.00	25.00	0.00
276	0	135.00	20.00	0.00
277	0	135.00	15.00	0.00
278	0	135.00	10.00	0.00
279	0	135.00	5.00	0.00
280	0	135.00	0.00	0.00
281	1	140.00	45.00	45.00
282	0	140.00	40.00	0.00
283	0	140.00	35.00	0.00
284	0	140.00	30.00	0.00
285	0	140.00	25.00	0.00
286	0	140.00	20.00	0.00
287	0	140.00	15.00	0.00
288	0	140.00	10.00	0.00
289	0	140.00	5.00	0.00
290	0	140.00	0.00	0.00
291	1	145.00	45.00	45.00
292	0	145.00	40.00	0.00
293	0	145.00	35.00	0.00
294	0	145.00	30.00	0.00
295	0	145.00	25.00	0.00
296	0	145.00	20.00	0.00
297	0	145.00	15.00	0.00
298	0	145.00	10.00	0.00
299	0	145.00	5.00	0.00
300	0	145.00	0.00	0.00
301	1	150.00	45.00	45.00
302	0	150.00	40.00	0.00
303	0	150.00	35.00	0.00
304	0	150.00	30.00	0.00
305	0	150.00	25.00	0.00
306	0	150.00	20.00	0.00
307	0	150.00	15.00	0.00
308	0	150.00	10.00	0.00
309	0	150.00	5.00	0.00
310	0	150.00	0.00	0.00
311	1	155.00	45.00	45.00
312	0	155.00	40.00	0.00
313	0	155.00	35.00	0.00
314	0	155.00	30.00	0.00
315	0	155.00	25.00	0.00
316	0	155.00	20.00	0.00
317	0	155.00	15.00	0.00
318	0	155.00	10.00	0.00
319	0	155.00	5.00	0.00
320	0	155.00	0.00	0.00
321	1	160.00	45.00	45.00
322	0	160.00	40.00	0.00
323	0	160.00	35.00	0.00
324	0	160.00	30.00	0.00
325	0	160.00	25.00	0.00
326	0	160.00	20.00	0.00
327	0	160.00	15.00	0.00
328	0	160.00	10.00	0.00
329	0	160.00	5.00	0.00
330	0	160.00	0.00	0.00
331	1	165.00	45.00	45.00
332	0	165.00	40.00	0.00
333	0	165.00	35.00	0.00
334	0	165.00	30.00	0.00
335	0	165.00	25.00	0.00
336	0	165.00	20.00	0.00
337	0	165.00	15.00	0.00
338	0	165.00	10.00	0.00
339	0	165.00	5.00	0.00
340	0	165.00	0.00	0.00
341	1	170.00	45.00	45.00
342	0	170.00	40.00	0.00
343	0	170.00	35.00	0.00
344	0	170.00	30.00	0.00
345	0	170.00	25.00	0.00
346	0	170.00	20.00	0.00
347	0	170.00	15.00	0.00
348	0	170.00	10.00	0.00
349	0	170.00	5.00	0.00
350	0	170.00	0.00	0.00
351	1	175.00	45.00	45.00
352	0	175.00	40.00	0.00
353	0	175.00	35.00	0.00
354	0	175.00	30.00	0.00
355	0	175.00	25.00	0.00
356	0	175.00	20.00	0.00
357	0	175.00	15.00	0.00
358	0	175.00	10.00	0.00
359	0	175.00	5.00	0.00
360	0	175.00	0.00	0.00
361	1	180.00	45.00	45.00
362	0	180.00	40.00	0.00
363	0	180.00	35.00	0.00
364	0	180.00	30.00	0.00
365	0	180.00	25.00	0.00
366	0	180.00	20.00	0.00
367	0	180.00	15.00	0.00
368	0	180.00	10.00	0.00
369	0	180.00	5.00	0.00
370	0	180.00	0.00	0.00
371	1	185.00	45.00	45.00
372	0	185.00	40.00	0.00
373	0	185.00	35.00	0.00
374	0	185.00	30.00	0.00
375	0	185.00	25.00	0.00
376	0	185.00	20.00	0.00
377	0	185.00	15.00	0.00
378	0	185.00	10.00	0.00
379	0	185.00	5.00	0.00
380	0	185.00	0.00	0.00
381	1	190.00	45.00	45.00
382	0	190.00	40.00	0.00
383	0	190.00	35.00	0.00
384	0	190.00	30.00	0.00
385	0	190.00	25.00	0.00
386	0	190.00	20.00	0.00
387	0	190.00	15.00	0.00

388	0	190.00	10.00	0.00
389	0	190.00	5.00	0.00
390	0	190.00	0.00	0.00
391	1	195.00	45.00	45.00
392	0	195.00	40.00	0.00
393	0	195.00	35.00	0.00
394	0	195.00	30.00	0.00
395	0	195.00	25.00	0.00
396	0	195.00	20.00	0.00
397	0	195.00	15.00	0.00
398	0	195.00	10.00	0.00
399	0	195.00	5.00	0.00
400	0	195.00	0.00	0.00
401	1	200.00	45.00	45.00
402	0	200.00	40.00	0.00
403	0	200.00	35.00	0.00
404	0	200.00	30.00	0.00
405	0	200.00	25.00	0.00
406	0	200.00	20.00	0.00
407	0	200.00	15.00	0.00
408	0	200.00	10.00	0.00
409	0	200.00	5.00	0.00
410	0	200.00	0.00	0.00

Nodal Flows and Heads

Node	Head	Percentage of available head	Flow
1	0.5150E+02	100.0 %	0.2526E+00
2	0.4700E+02	30.8 %	
3	0.4748E+02	38.1 %	
4	0.4743E+02	37.4 %	
5	0.4743E+02	37.4 %	
6	0.4743E+02	37.4 %	
7	0.4743E+02	37.4 %	
8	0.4743E+02	37.4 %	
9	0.4743E+02	37.4 %	
10	0.4743E+02	37.4 %	
11	0.5150E+02	100.0 %	0.5055E+00
12	0.4700E+02	30.7 %	
13	0.4748E+02	38.1 %	
14	0.4743E+02	37.4 %	
15	0.4743E+02	37.4 %	
16	0.4743E+02	37.4 %	
17	0.4743E+02	37.4 %	
18	0.4743E+02	37.4 %	
19	0.4743E+02	37.4 %	
20	0.4743E+02	37.4 %	
21	0.5150E+02	100.0 %	0.5064E+00
22	0.4699E+02	30.6 %	
23	0.4748E+02	38.1 %	
24	0.4743E+02	37.4 %	
25	0.4743E+02	37.4 %	
26	0.4743E+02	37.4 %	
27	0.4743E+02	37.4 %	
28	0.4743E+02	37.4 %	
29	0.4743E+02	37.4 %	
30	0.4743E+02	37.4 %	
31	0.5150E+02	100.0 %	0.5080E+00
32	0.4698E+02	30.5 %	
33	0.4748E+02	38.2 %	
34	0.4743E+02	37.4 %	
35	0.4743E+02	37.4 %	
36	0.4743E+02	37.4 %	
37	0.4743E+02	37.4 %	
38	0.4743E+02	37.4 %	
39	0.4743E+02	37.4 %	
40	0.4743E+02	37.4 %	
41	0.5150E+02	100.0 %	0.5102E+00
42	0.4697E+02	30.3 %	
43	0.4749E+02	38.3 %	
44	0.4743E+02	37.3 %	
45	0.4743E+02	37.5 %	
46	0.4743E+02	37.4 %	
47	0.4743E+02	37.4 %	
48	0.4743E+02	37.4 %	
49	0.4743E+02	37.4 %	
50	0.4743E+02	37.4 %	
51	0.5150E+02	100.0 %	0.5130E+00
52	0.4695E+02	30.0 %	
53	0.4750E+02	38.4 %	
54	0.4743E+02	37.3 %	
55	0.4743E+02	37.5 %	
56	0.4743E+02	37.4 %	
57	0.4743E+02	37.4 %	
58	0.4743E+02	37.4 %	
59	0.4743E+02	37.4 %	
60	0.4743E+02	37.4 %	
61	0.5150E+02	100.0 %	0.5166E+00
62	0.4693E+02	29.6 %	
63	0.4750E+02	38.5 %	
64	0.4742E+02	37.3 %	
65	0.4744E+02	37.5 %	
66	0.4743E+02	37.4 %	
67	0.4743E+02	37.4 %	
68	0.4743E+02	37.4 %	
69	0.4743E+02	37.4 %	
70	0.4743E+02	37.4 %	
71	0.5150E+02	100.0 %	0.5207E+00
72	0.4690E+02	29.2 %	
73	0.4751E+02	38.7 %	
74	0.4742E+02	37.2 %	
75	0.4744E+02	37.5 %	
76	0.4743E+02	37.4 %	
77	0.4743E+02	37.4 %	
78	0.4743E+02	37.4 %	
79	0.4743E+02	37.4 %	
80	0.4743E+02	37.4 %	
81	0.5150E+02	100.0 %	0.5256E+00
82	0.4687E+02	28.7 %	
83	0.4753E+02	38.9 %	
84	0.4742E+02	37.2 %	
85	0.4744E+02	37.5 %	
86	0.4743E+02	37.4 %	
87	0.4743E+02	37.4 %	
88	0.4743E+02	37.4 %	
89	0.4743E+02	37.4 %	
90	0.4743E+02	37.4 %	
91	0.5150E+02	100.0 %	0.5311E+00
92	0.4683E+02	28.2 %	
93	0.4754E+02	39.1 %	
94	0.4741E+02	37.1 %	
95	0.4744E+02	37.5 %	
96	0.4743E+02	37.4 %	
97	0.4743E+02	37.4 %	
98	0.4743E+02	37.4 %	
99	0.4743E+02	37.4 %	
100	0.4743E+02	37.4 %	
101	0.5150E+02	100.0 %	0.3388E+02
102	0.4679E+02	27.5 %	
103	0.4756E+02	39.3 %	
104	0.4741E+02	37.0 %	
105	0.4744E+02	37.5 %	
106	0.4743E+02	37.4 %	

107	0.4743E+02	37.4 %	177	0.4743E+02	37.4 %	
108	0.4743E+02	37.4 %	178	0.4743E+02	37.4 %	
109	0.4743E+02	37.4 %	179	0.4743E+02	37.4 %	
110	0.4743E+02	37.4 %	180	0.4743E+02	37.4 %	
111	0.5083E+02	89.7 %	181	0.4630E+02	20.0 %	
112	0.4692E+02	29.6 %	182	0.4776E+02	42.5 %	
113	0.4753E+02	38.9 %	183	0.4735E+02	36.2 %	
114	0.4741E+02	37.1 %	184	0.4745E+02	37.8 %	
115	0.4744E+02	37.5 %	185	0.4743E+02	37.4 %	
116	0.4743E+02	37.4 %	186	0.4743E+02	37.5 %	
117	0.4743E+02	37.4 %	187	0.4743E+02	37.4 %	
118	0.4743E+02	37.4 %	188	0.4743E+02	37.4 %	
119	0.4743E+02	37.4 %	189	0.4743E+02	37.4 %	
120	0.4743E+02	37.4 %	190	0.4743E+02	37.4 %	
121	0.5017E+02	79.6 %	191	0.4565E+02	10.0 %	
122	0.4705E+02	31.6 %	192	0.4788E+02	44.4 %	
123	0.4750E+02	38.4 %	193	0.4732E+02	35.8 %	
124	0.4742E+02	37.2 %	194	0.4746E+02	37.8 %	
125	0.4744E+02	37.5 %	195	0.4743E+02	37.3 %	
126	0.4743E+02	37.4 %	196	0.4744E+02	37.5 %	
127	0.4743E+02	37.4 %	197	0.4743E+02	37.4 %	
128	0.4743E+02	37.4 %	198	0.4743E+02	37.4 %	
129	0.4743E+02	37.4 %	199	0.4743E+02	37.4 %	
130	0.4743E+02	37.4 %	200	0.4743E+02	37.4 %	
131	0.4952E+02	69.5 %	201	0.4500E+02	0.0 %	-0.3288E+02
132	0.4718E+02	33.5 %	202	0.4801E+02	46.3 %	
133	0.4747E+02	38.0 %	203	0.4730E+02	35.3 %	
134	0.4743E+02	37.3 %	204	0.4747E+02	37.9 %	
135	0.4744E+02	37.5 %	205	0.4743E+02	37.3 %	
136	0.4743E+02	37.4 %	206	0.4744E+02	37.5 %	
137	0.4743E+02	37.4 %	207	0.4743E+02	37.4 %	
138	0.4743E+02	37.4 %	208	0.4743E+02	37.4 %	
139	0.4743E+02	37.4 %	209	0.4743E+02	37.4 %	
140	0.4743E+02	37.4 %	210	0.4743E+02	37.4 %	
141	0.4887E+02	59.6 %	211	0.4500E+02	0.0 %	-0.3430E+00
142	0.4730E+02	35.3 %	212	0.4796E+02	45.5 %	
143	0.4745E+02	37.7 %	213	0.4731E+02	35.6 %	
144	0.4743E+02	37.4 %	214	0.4746E+02	37.9 %	
145	0.4743E+02	37.4 %	215	0.4743E+02	37.3 %	
146	0.4743E+02	37.4 %	216	0.4744E+02	37.5 %	
147	0.4743E+02	37.4 %	217	0.4743E+02	37.4 %	
148	0.4743E+02	37.4 %	218	0.4743E+02	37.4 %	
149	0.4743E+02	37.4 %	219	0.4743E+02	37.4 %	
150	0.4743E+02	37.4 %	220	0.4743E+02	37.4 %	
151	0.4823E+02	49.7 %	221	0.4500E+02	0.0 %	-0.3362E+00
152	0.4741E+02	37.1 %	222	0.4792E+02	44.9 %	
153	0.4742E+02	37.3 %	223	0.4733E+02	35.9 %	
154	0.4744E+02	37.5 %	224	0.4746E+02	37.8 %	
155	0.4743E+02	37.4 %	225	0.4743E+02	37.4 %	
156	0.4743E+02	37.4 %	226	0.4743E+02	37.5 %	
157	0.4743E+02	37.4 %	227	0.4743E+02	37.4 %	
158	0.4743E+02	37.4 %	228	0.4743E+02	37.4 %	
159	0.4743E+02	37.4 %	229	0.4743E+02	37.4 %	
160	0.4743E+02	37.4 %	230	0.4743E+02	37.4 %	
161	0.4759E+02	39.8 %	231	0.4500E+02	0.0 %	-0.3298E+00
162	0.4753E+02	38.9 %	232	0.4787E+02	44.2 %	
163	0.4740E+02	36.9 %	233	0.4735E+02	36.1 %	
164	0.4744E+02	37.6 %	234	0.4745E+02	37.7 %	
165	0.4743E+02	37.4 %	235	0.4743E+02	37.4 %	
166	0.4743E+02	37.5 %	236	0.4743E+02	37.5 %	
167	0.4743E+02	37.4 %	237	0.4743E+02	37.4 %	
168	0.4743E+02	37.4 %	238	0.4743E+02	37.4 %	
169	0.4743E+02	37.4 %	239	0.4743E+02	37.4 %	
170	0.4743E+02	37.4 %	240	0.4743E+02	37.4 %	
171	0.4694E+02	29.9 %	241	0.4500E+02	0.0 %	-0.3239E+00
172	0.4765E+02	40.7 %	242	0.4784E+02	43.6 %	
173	0.4738E+02	36.5 %	243	0.4736E+02	36.3 %	
174	0.4745E+02	37.7 %	244	0.4745E+02	37.7 %	
175	0.4743E+02	37.4 %	245	0.4743E+02	37.4 %	
176	0.4743E+02	37.5 %	246	0.4743E+02	37.5 %	

247	0.4743E+02	37.4 %		317	0.4743E+02	37.4 %	
248	0.4743E+02	37.4 %		318	0.4743E+02	37.4 %	
249	0.4743E+02	37.4 %		319	0.4743E+02	37.4 %	
250	0.4743E+02	37.4 %		320	0.4743E+02	37.4 %	
251	0.4500E+02	0.0 %	-0.3184E+00	321	0.4500E+02	0.0 %	-0.2910E+00
252	0.4780E+02	43.1 %		322	0.4762E+02	40.3 %	
253	0.4737E+02	36.5 %		323	0.4743E+02	37.4 %	
254	0.4745E+02	37.6 %		324	0.4743E+02	37.4 %	
255	0.4743E+02	37.4 %		325	0.4744E+02	37.5 %	
256	0.4743E+02	37.4 %		326	0.4743E+02	37.4 %	
257	0.4743E+02	37.4 %		327	0.4743E+02	37.4 %	
258	0.4743E+02	37.4 %		328	0.4743E+02	37.4 %	
259	0.4743E+02	37.4 %		329	0.4743E+02	37.4 %	
260	0.4743E+02	37.4 %		330	0.4743E+02	37.4 %	
261	0.4500E+02	0.0 %	-0.3133E+00	331	0.4500E+02	0.0 %	-0.2886E+00
262	0.4777E+02	42.6 %		332	0.4760E+02	40.0 %	
263	0.4738E+02	36.7 %		333	0.4744E+02	37.5 %	
264	0.4744E+02	37.6 %		334	0.4743E+02	37.4 %	
265	0.4743E+02	37.4 %		335	0.4744E+02	37.5 %	
266	0.4743E+02	37.4 %		336	0.4743E+02	37.4 %	
267	0.4743E+02	37.4 %		337	0.4743E+02	37.4 %	
268	0.4743E+02	37.4 %		338	0.4743E+02	37.4 %	
269	0.4743E+02	37.4 %		339	0.4743E+02	37.4 %	
270	0.4743E+02	37.4 %		340	0.4743E+02	37.4 %	
271	0.4500E+02	0.0 %	-0.3087E+00	341	0.4500E+02	0.0 %	-0.2865E+00
272	0.4774E+02	42.1 %		342	0.4759E+02	39.8 %	
273	0.4739E+02	36.8 %		343	0.4744E+02	37.5 %	
274	0.4744E+02	37.5 %		344	0.4743E+02	37.4 %	
275	0.4743E+02	37.4 %		345	0.4744E+02	37.5 %	
276	0.4743E+02	37.4 %		346	0.4743E+02	37.4 %	
277	0.4743E+02	37.4 %		347	0.4743E+02	37.4 %	
278	0.4743E+02	37.4 %		348	0.4743E+02	37.4 %	
279	0.4743E+02	37.4 %		349	0.4743E+02	37.4 %	
280	0.4743E+02	37.4 %		350	0.4743E+02	37.4 %	
281	0.4500E+02	0.0 %	-0.3044E+00	351	0.4500E+02	0.0 %	-0.2847E+00
282	0.4771E+02	41.6 %		352	0.4758E+02	39.6 %	
283	0.4740E+02	37.0 %		353	0.4744E+02	37.6 %	
284	0.4744E+02	37.5 %		354	0.4743E+02	37.3 %	
285	0.4743E+02	37.4 %		355	0.4744E+02	37.5 %	
286	0.4743E+02	37.4 %		356	0.4743E+02	37.4 %	
287	0.4743E+02	37.4 %		357	0.4743E+02	37.4 %	
288	0.4743E+02	37.4 %		358	0.4743E+02	37.4 %	
289	0.4743E+02	37.4 %		359	0.4743E+02	37.4 %	
290	0.4743E+02	37.4 %		360	0.4743E+02	37.4 %	
291	0.4500E+02	0.0 %	-0.3005E+00	361	0.4500E+02	0.0 %	-0.2832E+00
292	0.4768E+02	41.2 %		362	0.4757E+02	39.5 %	
293	0.4741E+02	37.1 %		363	0.4745E+02	37.6 %	
294	0.4744E+02	37.5 %		364	0.4743E+02	37.3 %	
295	0.4743E+02	37.4 %		365	0.4744E+02	37.5 %	
296	0.4743E+02	37.4 %		366	0.4743E+02	37.4 %	
297	0.4743E+02	37.4 %		367	0.4743E+02	37.4 %	
298	0.4743E+02	37.4 %		368	0.4743E+02	37.4 %	
299	0.4743E+02	37.4 %		369	0.4743E+02	37.4 %	
300	0.4743E+02	37.4 %		370	0.4743E+02	37.4 %	
301	0.4500E+02	0.0 %	-0.2970E+00	371	0.4500E+02	0.0 %	-0.2821E+00
302	0.4766E+02	40.9 %		372	0.4756E+02	39.4 %	
303	0.4742E+02	37.2 %		373	0.4745E+02	37.7 %	
304	0.4743E+02	37.4 %		374	0.4743E+02	37.3 %	
305	0.4743E+02	37.5 %		375	0.4744E+02	37.5 %	
306	0.4743E+02	37.4 %		376	0.4743E+02	37.4 %	
307	0.4743E+02	37.4 %		377	0.4743E+02	37.4 %	
308	0.4743E+02	37.4 %		378	0.4743E+02	37.4 %	
309	0.4743E+02	37.4 %		379	0.4743E+02	37.4 %	
310	0.4743E+02	37.4 %		380	0.4743E+02	37.4 %	
311	0.4500E+02	0.0 %	-0.2938E+00	381	0.4500E+02	0.0 %	-0.2813E+00
312	0.4764E+02	40.6 %		382	0.4755E+02	39.3 %	
313	0.4743E+02	37.3 %		383	0.4745E+02	37.7 %	
314	0.4743E+02	37.4 %		384	0.4743E+02	37.3 %	
315	0.4743E+02	37.5 %		385	0.4744E+02	37.5 %	
316	0.4743E+02	37.4 %		386	0.4743E+02	37.4 %	

387	0.4743E+02	37.4 %	
388	0.4743E+02	37.4 %	
389	0.4743E+02	37.4 %	
390	0.4743E+02	37.4 %	
391	0.4500E+02	0.0 %	-0.2808E+00
392	0.4755E+02	39.2 %	
393	0.4745E+02	37.7 %	
394	0.4743E+02	37.3 %	
395	0.4744E+02	37.5 %	
396	0.4743E+02	37.4 %	
397	0.4743E+02	37.4 %	
398	0.4743E+02	37.4 %	
399	0.4743E+02	37.4 %	
400	0.4743E+02	37.4 %	
401	0.4500E+02	0.0 %	-0.1403E+00
402	0.4755E+02	39.2 %	
403	0.4745E+02	37.7 %	
404	0.4743E+02	37.3 %	
405	0.4744E+02	37.5 %	
406	0.4743E+02	37.4 %	
407	0.4743E+02	37.4 %	
408	0.4743E+02	37.4 %	
409	0.4743E+02	37.4 %	
410	0.4743E+02	37.4 %	

Flow = 3.8768E+01

Transient Analytical Model with Laplace Transform Method with Leakage out of a Confined Aquifer for Cumulative Analysis

a. T/S = 5

$S := 0.005$ dimensionless $\qquad T := 0.025 \cdot 86400$ m^2/day

$L := 0.2 \qquad \omega := \frac{\pi}{60} \qquad \theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \qquad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \qquad m := 100$

$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$

$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$

$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$

$$G(R, I) := \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \sum_{n=1}^{m} \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[\operatorname{erf}(R) + \frac{\exp(-R^2)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I))\right] + \frac{2}{\pi} \cdot \exp(-R^2) \cdot \left(\sum_{n=1}^{m} \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n)\right)$$

$R1(x, t) := -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$

$R2(x, t) := \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$

$h_0 := 5$ meter

$h_1 := 1.5$ meter

$$\begin{aligned}
h_5(x, t) := {} & \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \Bigg[\exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[-\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \\
& + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[-\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \Bigg] \\
& + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \Bigg[\exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \\
& + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \Bigg] \\
& + \frac{1}{2} \cdot h_0 \cdot \left(\exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S} \cdot t}\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S} \cdot t}\right) \right)
\end{aligned}$$

b. T/S = 18

$S := 0.005$ dimensionless $\qquad T := 0.09 \cdot 86400$ m^2/day

$L := 0.2 \qquad \omega := \frac{\pi}{60} \qquad \theta := \operatorname{atan}\left(\frac{S \cdot \omega}{L}\right) \qquad a(x) := \frac{x}{2} \cdot \sqrt{\frac{S}{T}} \qquad m := 100$

$r := \frac{\sqrt{S^2 \omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2 \omega^2 + L^2}}{S}$

$f_n(R, I, n) := 2 \cdot R - 2 \cdot R \cdot \cosh(n \cdot I) \cdot \cos(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \sin(2 \cdot R \cdot I)$

$g_n(R, I, n) := 2 \cdot R \cdot \cosh(n \cdot I) \cdot \sin(2 \cdot R \cdot I) + n \cdot \sinh(n \cdot I) \cdot \cos(2 \cdot R \cdot I)$

$$G(R, I) := \frac{\exp\left(-R^2\right)}{2 \cdot \pi \cdot R} \cdot \sin(2 \cdot R \cdot I) + \frac{2}{\pi} \cdot \exp\left(-R^2\right) \cdot \sum_{n=1}^{m} \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot g_n(R, I, n)$$

$$F(R, I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2 \cdot \pi \cdot R} \cdot (1 - \cos(2 \cdot R \cdot I))\right] + \frac{2}{\pi} \cdot \exp\left(-R^2\right) \cdot \left(\sum_{n=1}^{m} \frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4 \cdot R^2} \cdot f_n(R, I, n)\right)$$

$R1(x, t) := -\sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$

$R2(x, t) := \sqrt{r1 \cdot t} \cdot \cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1 \cdot t} \cdot \sin\left(\frac{\theta}{2}\right)$

$h_0 := 5$ meter

$h_1 := 1.5$ meter

$$\begin{aligned}
h_{18}(x, t) := {} & \frac{1}{2} \cdot h_1 \cdot \cos(\omega \cdot t) \cdot \Bigg[\exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[-\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \ldots \right. \\
& \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \right] \ldots \\
& + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[-\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \ldots \right. \\
& \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \right] \Bigg] \ldots \\
& + \frac{1}{2} \cdot h_1 \cdot \sin(\omega \cdot t) \cdot \Bigg[\exp\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[\cos\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R1(x, t), I1(t))) \ldots \right. \\
& \left. + \sin\left(-x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R1(x, t), I1(t)) \right] \ldots \\
& + \exp\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \cos\left(\frac{\theta}{2}\right)\right) \cdot \left[\cos\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot (1 - F(R2(x, t), I2(t))) \ldots \right. \\
& \left. + \sin\left(x \cdot \sqrt{\frac{S \cdot r}{T}} \cdot \sin\left(\frac{\theta}{2}\right)\right) \cdot G(R2(x, t), I2(t)) \right] \Bigg] \ldots \\
& + \frac{1}{2} \cdot h_0 \cdot \left(\exp\left(-x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} - \sqrt{\frac{L}{S} \cdot t}\right) + \exp\left(x \cdot \sqrt{\frac{L}{T}}\right) \cdot \operatorname{erfc}\left(\frac{x}{2} \cdot \sqrt{\frac{S}{T \cdot t}} + \sqrt{\frac{L}{S} \cdot t}\right) \right)
\end{aligned}$$

c. T/S = 500

$S := 0.00005$ dimensionless $\qquad T := 0.025\,86400$ m^2/day

$L := 0.2 \qquad \omega := \frac{\pi}{60} \qquad \theta := \mathrm{atan}\left(\frac{S\cdot\omega}{L}\right) \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad m := 100$

$r := \frac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2\,\omega^2 + L^2}}{S}$

$f_n(R, I, n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R, I, n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R, I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R, I, n)$$

$$F(R, I) := \left[\mathrm{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1 - \cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R, I, n)\right)$$

$R1(x, t) := -\sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$R2(x, t) := \sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$h_0 := 5$ meter

$h_1 := 1.5$ meter

$$\begin{aligned}
h_{500}(x, t) := {} & \frac{1}{2}\cdot h_1\cdot\cos(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t), I1(t)) \ldots \\
& \quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t), I1(t)))\Bigg] \ldots \\
& \quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t), I2(t)) \ldots \\
& \quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t), I2(t)))\Bigg]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_1\cdot\sin(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t), I1(t))) \ldots \\
& \quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t), I1(t))\Bigg] \ldots \\
& \quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t), I2(t))) \ldots \\
& \quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t), I2(t))\Bigg]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_0\cdot\left(\exp\left(-x\cdot\sqrt{\frac{L}{T}}\right)\cdot\mathrm{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} - \sqrt{\frac{L}{S}\cdot t}\right) + \exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\mathrm{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} + \sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}$$

d. T/S = 1800

$S := 0.00005$ dimensionless $\qquad T := 0.09\cdot 86400$ m^2/day

$L := 0.2 \qquad \omega := \frac{\pi}{60} \qquad \theta := \operatorname{atan}\left(\frac{S\cdot\omega}{L}\right) \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad m := 100$

$r := \frac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2\,\omega^2 + L^2}}{S}$

$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1 - \cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$R2(x,t) := \sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$h_0 := 5$ meter

$h_1 := 1.5$ meter

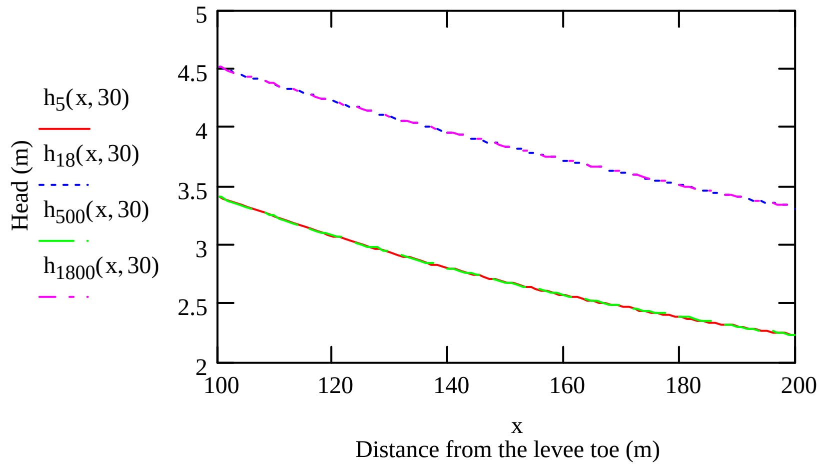
$$\begin{aligned}
h_{1800}(x,t) := {} & \frac{1}{2}\cdot h_1\cdot\cos(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ldots \right. \\
& \left. + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t),I1(t)))\right] \ldots \\
& + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ldots \right. \\
& \left. + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t),I2(t)))\right]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_1\cdot\sin(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t),I1(t))) \ldots \right. \\
& \left. + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\right] \ldots \\
& + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t),I2(t))) \ldots \right. \\
& \left. + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\right]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_0\cdot\left(\exp\left(-x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} - \sqrt{\frac{L}{S}\cdot t}\right) + \exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} + \sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}$$

Head Development with L=0.36 1/d, for different T/S ratios, a,b,c,d=5,18,500,1800

Figure 7.8

$t := 30$ day

$x := 100..200$ m



$h_5(100,30) = 3.408$ $h_{18}(100,30) = 4.51$ $h_{500}(100,30) = 3.41$ $h_{1800}(100,30) = 4.511$

$h_5(200,30) = 2.225$ $h_{18}(200,30) = 3.312$ $h_{500}(200,30) = 2.229$ $h_{1800}(200,30) = 3.313$

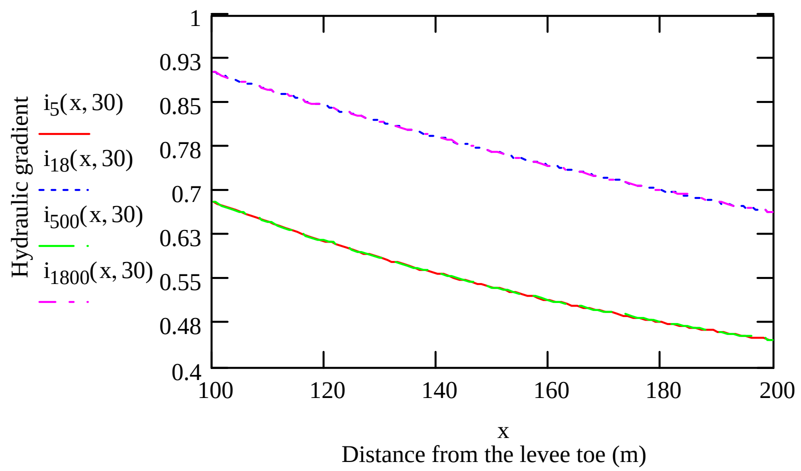
$z := 5$ m

$i_5(x,t) := \frac{1}{z} \cdot h_5(x,t)$ $i_{18}(x,t) := \frac{1}{z} \cdot h_{18}(x,t)$ $i_{500}(x,t) := \frac{1}{z} \cdot h_{500}(x,t)$ $i_{1800}(x,t) := \frac{1}{z} \cdot h_{1800}(x,t)$

Figure 7.9

$t := 30$

$x := 100..200$



$i_5(100,30) = 0.682$ $i_{18}(100,30) = 0.902$ $i_{500}(100,30) = 0.682$ $i_{1800}(100,30) = 0.902$

$i_5(200,30) = 0.445$ $i_{18}(200,30) = 0.662$ $i_{500}(200,30) = 0.446$ $i_{1800}(200,30) = 0.663$

Head Development with L=0.36 1/d, for different T/S ratios, a,b,c,d=5,18,500,1800

a. T/S = 5

$S := 0.005$ dimensionless $\qquad T := 0.025\cdot 86400$ m^2/day

$L := 0.36 \qquad \omega := \frac{\pi}{60} \qquad \theta := \operatorname{atan}\left(\frac{S\cdot\omega}{L}\right) \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad m := 100$

$r := \frac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2\,\omega^2 + L^2}}{S}$

$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1-\cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$R2(x,t) := \sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$h_0 := 5$ meter

$h_1 := 1.5$ meter

$$\begin{aligned}
h_5(x,t) := {} & \frac{1}{2}\cdot h_1\cdot\cos(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ldots \atop + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t),I1(t)))\right] \ldots \\
& + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ldots \atop + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t),I2(t)))\right]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_1\cdot\sin(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t),I1(t))) \ldots \atop + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\right] \ldots \\
& + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t),I2(t))) \ldots \atop + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\right]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_0\cdot\left(\exp\left(-x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} - \sqrt{\frac{L}{S}\cdot t}\right) + \exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} + \sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}$$

b. T/S = 18

$S := 0.005$ dimensionless $\quad T := 0.09 \cdot 86400$ m^2/day

$L := 0.36 \quad \omega := \dfrac{\pi}{60} \quad \theta := \operatorname{atan}\left(\dfrac{S\cdot\omega}{L}\right) \quad a(x) := \dfrac{x}{2}\cdot\sqrt{\dfrac{S}{T}} \quad m := 100$

$r := \dfrac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \dfrac{\sqrt{S^2\,\omega^2 + L^2}}{S}$

$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1 - \cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r1\cdot t}\cdot\cos\left(\dfrac{\theta}{2}\right) + \dfrac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\dfrac{\theta}{2}\right)$

$R2(x,t) := \sqrt{r1\cdot t}\cdot\cos\left(\dfrac{\theta}{2}\right) + \dfrac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\dfrac{\theta}{2}\right)$

$h_0 := 5$ meter

$h_1 := 1.5$ meter

$$\begin{aligned}
h_{18}(x,t) := {}& \frac{1}{2}\cdot h_1\cdot\cos(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ldots \\
&\quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t),I1(t)))\Bigg] \ldots \\
&\quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ldots \\
&\quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t),I2(t)))\Bigg]\Bigg] \ldots \\
&+ \frac{1}{2}\cdot h_1\cdot\sin(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t),I1(t))) \ldots \\
&\quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\Bigg] \ldots \\
&\quad + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t),I2(t))) \ldots \\
&\quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\Bigg]\Bigg] \ldots \\
&+ \frac{1}{2}\cdot h_0\cdot\left(\exp\left(-x\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} - \sqrt{\frac{L}{S}\cdot t}\right) + \exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} + \sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}$$

c. T/S = 500

$S := 0.00005$ dimensionless $\qquad T := 0.025 \cdot 86400$ m^2/day

$L := 0.36 \qquad \omega := \dfrac{\pi}{60} \qquad \theta := \operatorname{atan}\left(\dfrac{S\cdot\omega}{L}\right) \qquad a(x) := \dfrac{x}{2}\cdot\sqrt{\dfrac{S}{T}} \qquad m := 100$

$r := \dfrac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \dfrac{\sqrt{S^2\,\omega^2 + L^2}}{S}$

$f_n(R,I,n) := 2\cdot R - 2\cdot R\cdot\cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R,I,n) := 2\cdot R\cdot\cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R,I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R,I,n)$$

$$F(R,I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1 - \cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R,I,n)\right)$$

$R1(x,t) := -\sqrt{r1\cdot t}\cdot\cos\left(\dfrac{\theta}{2}\right) + \dfrac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\dfrac{\theta}{2}\right)$

$R2(x,t) := \sqrt{r1\cdot t}\cdot\cos\left(\dfrac{\theta}{2}\right) + \dfrac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\dfrac{\theta}{2}\right)$

$h_0 := 5$ meter

$h_1 := 1.5$ meter

$$\begin{aligned}
h_{500}(x,t) := {} & \frac{1}{2}\cdot h_1\cdot\cos(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t)) \ldots \\
& \quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t),I1(t)))\Bigg] \ldots \\
& + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t)) \ldots \\
& \quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t),I2(t)))\Bigg]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_1\cdot\sin(\omega\cdot t)\cdot\Bigg[\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t),I1(t))) \ldots \\
& \quad + \sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t),I1(t))\Bigg] \ldots \\
& + \exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\Bigg[\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t),I2(t))) \ldots \\
& \quad + \sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t),I2(t))\Bigg]\Bigg] \ldots \\
& + \frac{1}{2}\cdot h_0\cdot\left(\exp\left(-x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} - \sqrt{\frac{L}{S}\cdot t}\right) + \exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} + \sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}$$

d. T/S = 1800

$S := 0.00005$ dimensionless $\qquad T := 0.09 \cdot 86400$ m^2/day

$L := 0.36 \qquad \omega := \frac{\pi}{60} \qquad \theta := \operatorname{atan}\left(\frac{S\cdot\omega}{L}\right) \qquad a(x) := \frac{x}{2}\cdot\sqrt{\frac{S}{T}} \qquad m := 100$

$r := \frac{\sqrt{S^2\,\omega^2 + L^2}}{T} \qquad r1 := \frac{\sqrt{S^2\,\omega^2 + L^2}}{S}$

$f_n(R, I, n) := 2\cdot R - 2\cdot R\cdot \cosh(n\cdot I)\cdot\cos(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\sin(2\cdot R\cdot I)$

$g_n(R, I, n) := 2\cdot R\cdot \cosh(n\cdot I)\cdot\sin(2\cdot R\cdot I) + n\cdot\sinh(n\cdot I)\cdot\cos(2\cdot R\cdot I)$

$$G(R, I) := \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot\sin(2\cdot R\cdot I) + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot g_n(R, I, n)$$

$$F(R, I) := \left[\operatorname{erf}(R) + \frac{\exp\left(-R^2\right)}{2\cdot\pi\cdot R}\cdot(1 - \cos(2\cdot R\cdot I))\right] + \frac{2}{\pi}\cdot\exp\left(-R^2\right)\cdot\left(\sum_{n=1}^{m}\frac{\exp\left(-\frac{n^2}{4}\right)}{n^2 + 4\cdot R^2}\cdot f_n(R, I, n)\right)$$

$R1(x, t) := -\sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I1(t) := -\sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$R2(x, t) := \sqrt{r1\cdot t}\cdot\cos\left(\frac{\theta}{2}\right) + \frac{a(x)}{\sqrt{t}} \qquad I2(t) := \sqrt{r1\cdot t}\cdot\sin\left(\frac{\theta}{2}\right)$

$h_0 := 5 \ \text{meter}$

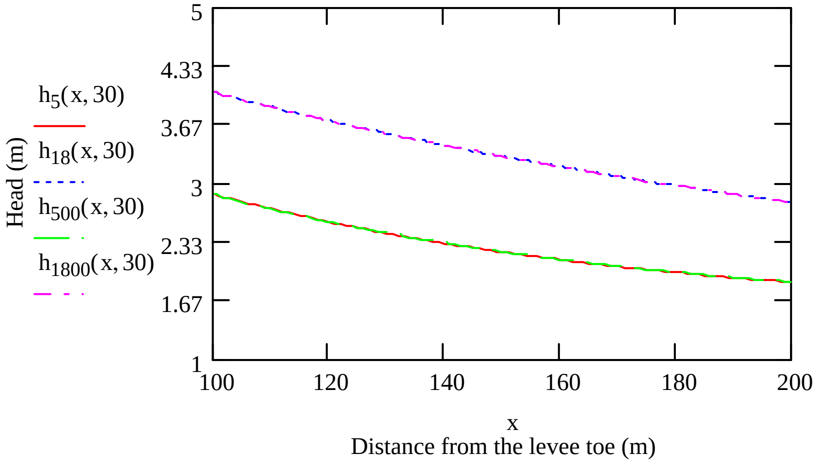
$h_1 := 1.5 \ \text{meter}$

$$\begin{aligned}
h_{1800}(x, t) := {} & \frac{1}{2}\cdot h_1\cdot\cos(\omega\cdot t)\cdot\left[\begin{aligned}&\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{aligned}&-\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t), I1(t)) \ \ldots \\ &+\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t), I1(t)))\end{aligned}\right] \ldots \\ &+\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{aligned}&-\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t), I2(t)) \ \ldots \\ &+\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t), I2(t)))\end{aligned}\right]\end{aligned}\right] \ldots \\
& + \frac{1}{2}\cdot h_1\cdot\sin(\omega\cdot t)\cdot\left[\begin{aligned}&\exp\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{aligned}&\cos\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R1(x,t), I1(t))) \ \ldots \\ &+\sin\left(-x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R1(x,t), I1(t))\end{aligned}\right] \ldots \\ &+\exp\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\cos\left(\frac{\theta}{2}\right)\right)\cdot\left[\begin{aligned}&\cos\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot(1 - F(R2(x,t), I2(t))) \ \ldots \\ &+\sin\left(x\cdot\sqrt{\frac{S\cdot r}{T}}\cdot\sin\left(\frac{\theta}{2}\right)\right)\cdot G(R2(x,t), I2(t))\end{aligned}\right]\end{aligned}\right] \ldots \\
& + \frac{1}{2}\cdot h_0\cdot\left(\exp\left(-x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} - \sqrt{\frac{L}{S}\cdot t}\right) + \exp\left(x\cdot\sqrt{\frac{L}{T}}\right)\cdot\operatorname{erfc}\left(\frac{x}{2}\cdot\sqrt{\frac{S}{T\cdot t}} + \sqrt{\frac{L}{S}\cdot t}\right)\right)
\end{aligned}$$

Figure 7.10

t := 30 day

x := 100.. 200 m



$h_5(100,30) = 2.872$ $h_{18}(100,30) = 4.031$ $h_{500}(100,30) = 2.875$ $h_{1800}(100,30) = 4.032$

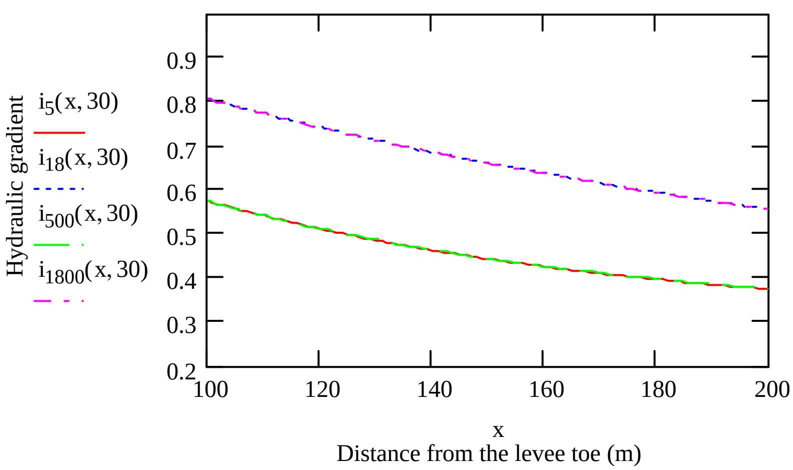
$h_5(200,30) = 1.872$ $h_{18}(200,30) = 2.781$ $h_{500}(200,30) = 1.878$ $h_{1800}(200,30) = 2.782$

z := 5 m

$i_5(x,t) := \frac{1}{z} \cdot h_5(x,t)$ $i_{18}(x,t) := \frac{1}{z} \cdot h_{18}(x,t)$ $i_{500}(x,t) := \frac{1}{z} \cdot h_{500}(x,t)$ $i_{1800}(x,t) := \frac{1}{z} \cdot h_{1800}(x,t)$

Figure 7.11

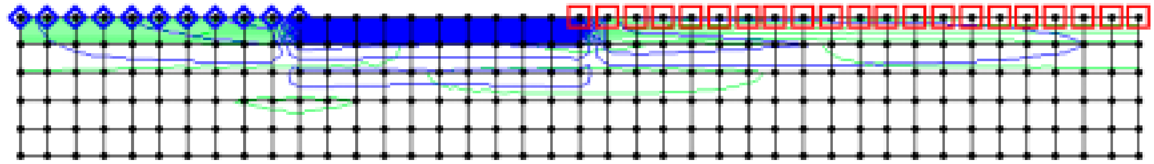
t := 30 x := 100.. 200



$i_5(100,30) = 0.574$ $i_{18}(100,30) = 0.806$ $i_{500}(100,30) = 0.575$ $i_{1800}(100,30) = 0.806$

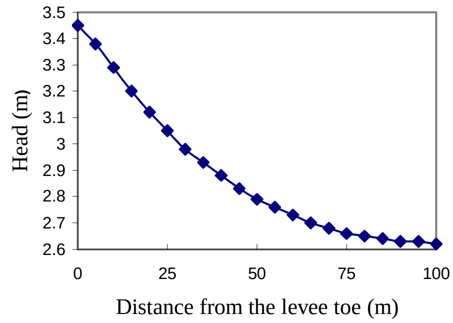
$i_5(200,30) = 0.374$ $i_{18}(200,30) = 0.556$ $i_{500}(200,30) = 0.376$ $i_{1800}(200,30) = 0.556$

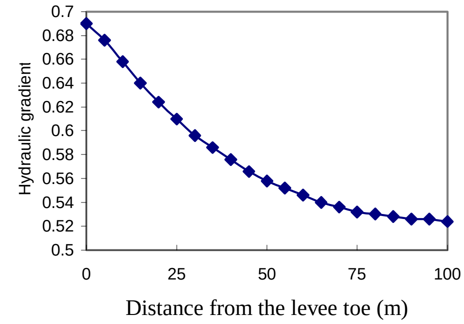
Figure 7.12
SEEP2D Model
An unconfined aquifer with a depth of 25 m, and hydraulic conductivities of k_h=0.1 cm/sec, k_v=0.0001 cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head boundary was defined at riverside and exit face boundary was defined at landside of the levee. The figure of the model is below:



For cumulative analysis
25m exit face, T=0.025 m^2/sec

Node	Distance (m)	Head (m)	Head-25 (m)	i=h/z
122	0	28.45	3.45	0.69
128	5	28.38	3.38	0.676
134	10	28.29	3.29	0.658
140	15	28.2	3.2	0.64
146	20	28.12	3.12	0.624
152	25	28.05	3.05	0.61
158	30	27.98	2.98	0.596
164	35	27.93	2.93	0.586
170	40	27.88	2.88	0.576
176	45	27.83	2.83	0.566
182	50	27.79	2.79	0.558
188	55	27.76	2.76	0.552
194	60	27.73	2.73	0.546
200	65	27.7	2.7	0.54
206	70	27.68	2.68	0.536
212	75	27.66	2.66	0.532
218	80	27.65	2.65	0.53
224	85	27.64	2.64	0.528
230	90	27.63	2.63	0.526
236	95	27.63	2.63	0.526
242	100	27.62	2.62	0.524





Note: Node numbers 122 to 242 are located at 5 m below the landside of the levee.

Model Output

Plane flow problem
25m exit face, T=0.025 m^2/sec
Number of nodal points------ 246
Number of elements---------- 200
Number of diff. materials--- 1
Elevation of datum---------- 0.000
Unsaturated flow option----- 0

Material Properties

Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.8640E+02	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

Node Point Information

Node	BC	X	Y	Flow-head
1	1	0.00	25.00	31.50
2	0	0.00	20.00	0.00
3	0	0.00	15.00	0.00
4	0	0.00	10.00	0.00
5	0	0.00	5.00	0.00
6	0	0.00	0.00	0.00
7	1	5.00	25.00	31.50
8	0	5.00	20.00	0.00
9	0	5.00	15.00	0.00
10	0	5.00	10.00	0.00
11	0	5.00	5.00	0.00
12	0	5.00	0.00	0.00
13	1	10.00	25.00	31.50
14	0	10.00	20.00	0.00
15	0	10.00	15.00	0.00
16	0	10.00	10.00	0.00
17	0	10.00	5.00	0.00
18	0	10.00	0.00	0.00
19	1	15.00	25.00	31.50
20	0	15.00	20.00	0.00
21	0	15.00	15.00	0.00
22	0	15.00	10.00	0.00
23	0	15.00	5.00	0.00
24	0	15.00	0.00	0.00
25	1	20.00	25.00	31.50
26	0	20.00	20.00	0.00
27	0	20.00	15.00	0.00
28	0	20.00	10.00	0.00
29	0	20.00	5.00	0.00
30	0	20.00	0.00	0.00
31	1	25.00	25.00	31.50
32	0	25.00	20.00	0.00
33	0	25.00	15.00	0.00
34	0	25.00	10.00	0.00
35	0	25.00	5.00	0.00
36	0	25.00	0.00	0.00
37	1	30.00	25.00	31.50
38	0	30.00	20.00	0.00
39	0	30.00	15.00	0.00
40	0	30.00	10.00	0.00
41	0	30.00	5.00	0.00
42	0	30.00	0.00	0.00
43	1	35.00	25.00	31.50
44	0	35.00	20.00	0.00
45	0	35.00	15.00	0.00
46	0	35.00	10.00	0.00
47	0	35.00	5.00	0.00
48	0	35.00	0.00	0.00
49	1	40.00	25.00	31.50
50	0	40.00	20.00	0.00
51	0	40.00	15.00	0.00
52	0	40.00	10.00	0.00
53	0	40.00	5.00	0.00
54	0	40.00	0.00	0.00
55	1	45.00	25.00	31.50
56	0	45.00	20.00	0.00
57	0	45.00	15.00	0.00
58	0	45.00	10.00	0.00
59	0	45.00	5.00	0.00
60	0	45.00	0.00	0.00
61	1	50.00	25.00	31.50
62	0	50.00	20.00	0.00
63	0	50.00	15.00	0.00
64	0	50.00	10.00	0.00
65	0	50.00	5.00	0.00
66	0	50.00	0.00	0.00
67	0	55.00	25.00	0.00
68	0	55.00	20.00	0.00
69	0	55.00	15.00	0.00
70	0	55.00	10.00	0.00
71	0	55.00	5.00	0.00
72	0	55.00	0.00	0.00
73	0	60.00	25.00	0.00
74	0	60.00	20.00	0.00
75	0	60.00	15.00	0.00
76	0	60.00	10.00	0.00
77	0	60.00	5.00	0.00
78	0	60.00	0.00	0.00
79	0	65.00	25.00	0.00
80	0	65.00	20.00	0.00
81	0	65.00	15.00	0.00
82	0	65.00	10.00	0.00
83	0	65.00	5.00	0.00
84	0	65.00	0.00	0.00
85	0	70.00	25.00	0.00
86	0	70.00	20.00	0.00
87	0	70.00	15.00	0.00
88	0	70.00	10.00	0.00
89	0	70.00	5.00	0.00
90	0	70.00	0.00	0.00
91	0	75.00	25.00	0.00
92	0	75.00	20.00	0.00
93	0	75.00	15.00	0.00
94	0	75.00	10.00	0.00
95	0	75.00	5.00	0.00
96	0	75.00	0.00	0.00
97	0	80.00	25.00	0.00
98	0	80.00	20.00	0.00
99	0	80.00	15.00	0.00
100	0	80.00	10.00	0.00
101	0	80.00	5.00	0.00
102	0	80.00	0.00	0.00
103	0	85.00	25.00	0.00
104	0	85.00	20.00	0.00
105	0	85.00	15.00	0.00
106	0	85.00	10.00	0.00
107	0	85.00	5.00	0.00
108	0	85.00	0.00	0.00
109	0	90.00	25.00	0.00
110	0	90.00	20.00	0.00
111	0	90.00	15.00	0.00
112	0	90.00	10.00	0.00
113	0	90.00	5.00	0.00
114	0	90.00	0.00	0.00
115	0	95.00	25.00	0.00
116	0	95.00	20.00	0.00
117	0	95.00	15.00	0.00
118	0	95.00	10.00	0.00
119	0	95.00	5.00	0.00
120	0	95.00	0.00	0.00
121	2	100.00	25.00	0.00
122	0	100.00	20.00	0.00
123	0	100.00	15.00	0.00
124	0	100.00	10.00	0.00
125	0	100.00	5.00	0.00
126	0	100.00	0.00	0.00
127	2	105.00	25.00	0.00
128	0	105.00	20.00	0.00
129	0	105.00	15.00	0.00
130	0	105.00	10.00	0.00
131	0	105.00	5.00	0.00
132	0	105.00	0.00	0.00
133	2	110.00	25.00	0.00
134	0	110.00	20.00	0.00
135	0	110.00	15.00	0.00

136	0	110.00	10.00	0.00
137	0	110.00	5.00	0.00
138	0	110.00	0.00	0.00
139	2	115.00	25.00	0.00
140	0	115.00	20.00	0.00
141	0	115.00	15.00	0.00
142	0	115.00	10.00	0.00
143	0	115.00	5.00	0.00
144	0	115.00	0.00	0.00
145	2	120.00	25.00	0.00
146	0	120.00	20.00	0.00
147	0	120.00	15.00	0.00
148	0	120.00	10.00	0.00
149	0	120.00	5.00	0.00
150	0	120.00	0.00	0.00
151	2	125.00	25.00	0.00
152	0	125.00	20.00	0.00
153	0	125.00	15.00	0.00
154	0	125.00	10.00	0.00
155	0	125.00	5.00	0.00
156	0	125.00	0.00	0.00
157	2	130.00	25.00	0.00
158	0	130.00	20.00	0.00
159	0	130.00	15.00	0.00
160	0	130.00	10.00	0.00
161	0	130.00	5.00	0.00
162	0	130.00	0.00	0.00
163	2	135.00	25.00	0.00
164	0	135.00	20.00	0.00
165	0	135.00	15.00	0.00
166	0	135.00	10.00	0.00
167	0	135.00	5.00	0.00
168	0	135.00	0.00	0.00
169	2	140.00	25.00	0.00
170	0	140.00	20.00	0.00
171	0	140.00	15.00	0.00
172	0	140.00	10.00	0.00
173	0	140.00	5.00	0.00
174	0	140.00	0.00	0.00
175	2	145.00	25.00	0.00
176	0	145.00	20.00	0.00
177	0	145.00	15.00	0.00
178	0	145.00	10.00	0.00
179	0	145.00	5.00	0.00
180	0	145.00	0.00	0.00
181	2	150.00	25.00	0.00
182	0	150.00	20.00	0.00
183	0	150.00	15.00	0.00
184	0	150.00	10.00	0.00
185	0	150.00	5.00	0.00
186	0	150.00	0.00	0.00
187	2	155.00	25.00	0.00
188	0	155.00	20.00	0.00
189	0	155.00	15.00	0.00
190	0	155.00	10.00	0.00
191	0	155.00	5.00	0.00
192	0	155.00	0.00	0.00
193	2	160.00	25.00	0.00
194	0	160.00	20.00	0.00
195	0	160.00	15.00	0.00
196	0	160.00	10.00	0.00
197	0	160.00	5.00	0.00
198	0	160.00	0.00	0.00
199	2	165.00	25.00	0.00
200	0	165.00	20.00	0.00
201	0	165.00	15.00	0.00
202	0	165.00	10.00	0.00
203	0	165.00	5.00	0.00
204	0	165.00	0.00	0.00
205	2	170.00	25.00	0.00
206	0	170.00	20.00	0.00
207	0	170.00	15.00	0.00
208	0	170.00	10.00	0.00
209	0	170.00	5.00	0.00
210	0	170.00	0.00	0.00
211	2	175.00	25.00	0.00
212	0	175.00	20.00	0.00
213	0	175.00	15.00	0.00
214	0	175.00	10.00	0.00
215	0	175.00	5.00	0.00
216	0	175.00	0.00	0.00
217	2	180.00	25.00	0.00
218	0	180.00	20.00	0.00
219	0	180.00	15.00	0.00
220	0	180.00	10.00	0.00
221	0	180.00	5.00	0.00
222	0	180.00	0.00	0.00
223	2	185.00	25.00	0.00
224	0	185.00	20.00	0.00
225	0	185.00	15.00	0.00
226	0	185.00	10.00	0.00
227	0	185.00	5.00	0.00
228	0	185.00	0.00	0.00
229	2	190.00	25.00	0.00
230	0	190.00	20.00	0.00
231	0	190.00	15.00	0.00
232	0	190.00	10.00	0.00
233	0	190.00	5.00	0.00
234	0	190.00	0.00	0.00
235	2	195.00	25.00	0.00
236	0	195.00	20.00	0.00
237	0	195.00	15.00	0.00
238	0	195.00	10.00	0.00
239	0	195.00	5.00	0.00
240	0	195.00	0.00	0.00
241	2	200.00	25.00	0.00
242	0	200.00	20.00	0.00
243	0	200.00	15.00	0.00
244	0	200.00	10.00	0.00
245	0	200.00	5.00	0.00
246	0	200.00	0.00	0.00

Nodal Flows and Heads

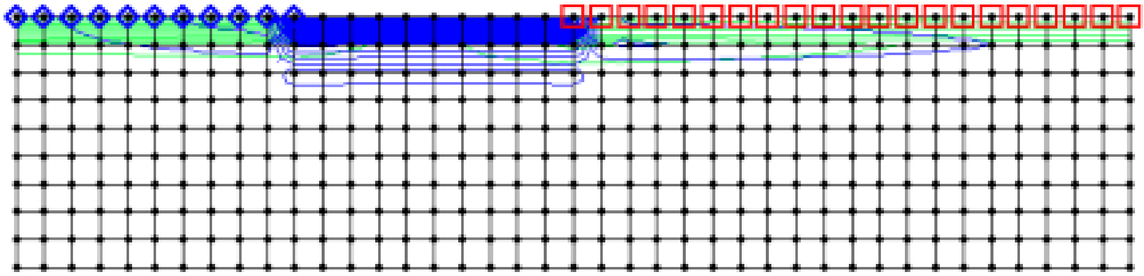
Node	Head	Percentage of available head	Flow
1	0.3150E+02	100.0 %	0.2029E+00
2	0.2779E+02	43.0 %	
3	0.2785E+02	43.8 %	
4	0.2786E+02	44.0 %	
5	0.2785E+02	43.9 %	
6	0.2785E+02	43.9 %	
7	0.3150E+02	100.0 %	0.4062E+00
8	0.2779E+02	42.9 %	
9	0.2785E+02	43.8 %	
10	0.2786E+02	44.0 %	
11	0.2785E+02	43.9 %	
12	0.2785E+02	43.9 %	
13	0.3150E+02	100.0 %	0.4076E+00
14	0.2778E+02	42.8 %	
15	0.2785E+02	43.9 %	
16	0.2786E+02	44.0 %	
17	0.2785E+02	43.9 %	
18	0.2785E+02	43.9 %	
19	0.3150E+02	100.0 %	0.4098E+00
20	0.2777E+02	42.6 %	
21	0.2786E+02	43.9 %	
22	0.2786E+02	43.9 %	
23	0.2785E+02	43.9 %	
24	0.2785E+02	43.9 %	
25	0.3150E+02	100.0 %	0.4130E+00
26	0.2775E+02	42.2 %	
27	0.2786E+02	44.0 %	
28	0.2785E+02	43.9 %	
29	0.2785E+02	43.9 %	
30	0.2785E+02	43.9 %	
31	0.3150E+02	100.0 %	0.4172E+00
32	0.2772E+02	41.8 %	
33	0.2787E+02	44.1 %	
34	0.2785E+02	43.9 %	
35	0.2785E+02	43.9 %	
36	0.2785E+02	43.9 %	
37	0.3150E+02	100.0 %	0.4223E+00
38	0.2768E+02	41.3 %	
39	0.2788E+02	44.3 %	
40	0.2785E+02	43.8 %	
41	0.2785E+02	43.9 %	
42	0.2785E+02	43.9 %	
43	0.3150E+02	100.0 %	0.4284E+00
44	0.2764E+02	40.7 %	
45	0.2789E+02	44.5 %	
46	0.2785E+02	43.8 %	
47	0.2786E+02	43.9 %	
48	0.2785E+02	43.9 %	
49	0.3150E+02	100.0 %	0.4355E+00
50	0.2760E+02	39.9 %	
51	0.2791E+02	44.7 %	
52	0.2784E+02	43.7 %	
53	0.2786E+02	43.9 %	
54	0.2785E+02	43.9 %	
55	0.3150E+02	100.0 %	0.4436E+00
56	0.2754E+02	39.1 %	
57	0.2792E+02	45.0 %	
58	0.2784E+02	43.7 %	
59	0.2786E+02	44.0 %	
60	0.2785E+02	43.9 %	
61	0.3150E+02	100.0 %	0.1727E+02
62	0.2748E+02	38.2 %	
63	0.2794E+02	45.3 %	
64	0.2783E+02	43.6 %	
65	0.2786E+02	44.0 %	
66	0.2785E+02	43.9 %	
67	0.3083E+02	89.6 %	
68	0.2759E+02	39.9 %	
69	0.2792E+02	44.9 %	
70	0.2784E+02	43.7 %	
71	0.2786E+02	44.0 %	
72	0.2785E+02	43.9 %	
73	0.3017E+02	79.5 %	
74	0.2770E+02	41.5 %	
75	0.2789E+02	44.5 %	
76	0.2784E+02	43.7 %	
77	0.2786E+02	43.9 %	
78	0.2785E+02	43.9 %	
79	0.2952E+02	69.5 %	
80	0.2779E+02	42.9 %	
81	0.2787E+02	44.2 %	
82	0.2785E+02	43.8 %	
83	0.2786E+02	43.9 %	
84	0.2785E+02	43.9 %	
85	0.2887E+02	59.6 %	
86	0.2788E+02	44.3 %	
87	0.2785E+02	43.9 %	
88	0.2785E+02	43.9 %	
89	0.2785E+02	43.9 %	
90	0.2785E+02	43.9 %	
91	0.2824E+02	49.8 %	
92	0.2797E+02	45.7 %	
93	0.2784E+02	43.6 %	
94	0.2786E+02	43.9 %	
95	0.2785E+02	43.9 %	
96	0.2785E+02	43.9 %	
97	0.2760E+02	40.0 %	
98	0.2806E+02	47.0 %	
99	0.2782E+02	43.3 %	
100	0.2786E+02	44.0 %	
101	0.2785E+02	43.9 %	
102	0.2785E+02	43.9 %	
103	0.2696E+02	30.2 %	
104	0.2815E+02	48.4 %	
105	0.2780E+02	43.1 %	
106	0.2786E+02	44.1 %	
107	0.2785E+02	43.9 %	
108	0.2785E+02	43.9 %	
109	0.2632E+02	20.3 %	
110	0.2824E+02	49.8 %	
111	0.2778E+02	42.7 %	
112	0.2787E+02	44.1 %	
113	0.2785E+02	43.8 %	
114	0.2785E+02	43.9 %	
115	0.2567E+02	10.2 %	
116	0.2834E+02	51.4 %	
117	0.2775E+02	42.4 %	
118	0.2787E+02	44.2 %	
119	0.2785E+02	43.8 %	
120	0.2786E+02	43.9 %	
121	0.2500E+02	0.0 %	-0.1698E+02
122	0.2845E+02	53.0 %	
123	0.2773E+02	41.9 %	
124	0.2788E+02	44.3 %	
125	0.2785E+02	43.8 %	
126	0.2786E+02	43.9 %	
127	0.2500E+02	0.0 %	-0.4273E+01
128	0.2838E+02	52.1 %	
129	0.2774E+02	42.2 %	
130	0.2788E+02	44.3 %	
131	0.2785E+02	43.8 %	
132	0.2786E+02	43.9 %	
133	0.2516E+02	2.4 %	-0.5684E-13

134	0.2829E+02	50.5 %	
135	0.2777E+02	42.6 %	
136	0.2787E+02	44.2 %	
137	0.2785E+02	43.8 %	
138	0.2786E+02	43.9 %	
139	0.2530E+02	4.6 %	0.1705E-12
140	0.2820E+02	49.2 %	
141	0.2779E+02	42.9 %	
142	0.2787E+02	44.1 %	
143	0.2785E+02	43.9 %	
144	0.2785E+02	43.9 %	
145	0.2543E+02	6.5 %	0.3979E-12
146	0.2812E+02	48.0 %	
147	0.2781E+02	43.2 %	
148	0.2786E+02	44.0 %	
149	0.2785E+02	43.9 %	
150	0.2785E+02	43.9 %	
151	0.2554E+02	8.3 %	-0.5684E-13
152	0.2805E+02	46.9 %	
153	0.2782E+02	43.4 %	
154	0.2786E+02	44.0 %	
155	0.2785E+02	43.9 %	
156	0.2785E+02	43.9 %	
157	0.2565E+02	10.0 %	-0.5684E-13
158	0.2798E+02	45.9 %	
159	0.2784E+02	43.7 %	
160	0.2785E+02	43.9 %	
161	0.2785E+02	43.9 %	
162	0.2785E+02	43.9 %	
163	0.2574E+02	11.4 %	-0.5684E-13
164	0.2793E+02	45.0 %	
165	0.2785E+02	43.8 %	
166	0.2785E+02	43.9 %	
167	0.2785E+02	43.9 %	
168	0.2785E+02	43.9 %	
169	0.2583E+02	12.7 %	0.1137E-12
170	0.2788E+02	44.3 %	
171	0.2786E+02	44.0 %	
172	0.2785E+02	43.9 %	
173	0.2785E+02	43.9 %	
174	0.2785E+02	43.9 %	
175	0.2590E+02	13.9 %	0.4547E-12
176	0.2783E+02	43.6 %	
177	0.2787E+02	44.1 %	
178	0.2785E+02	43.8 %	
179	0.2785E+02	43.9 %	
180	0.2785E+02	43.9 %	
181	0.2597E+02	14.9 %	-0.1137E-12
182	0.2779E+02	43.0 %	
183	0.2787E+02	44.2 %	
184	0.2785E+02	43.8 %	
185	0.2785E+02	43.9 %	
186	0.2785E+02	43.9 %	
187	0.2603E+02	15.8 %	0.5684E-13
188	0.2776E+02	42.4 %	
189	0.2788E+02	44.3 %	
190	0.2785E+02	43.8 %	
191	0.2785E+02	43.9 %	
192	0.2785E+02	43.9 %	
193	0.2608E+02	16.6 %	0.0000E+00
194	0.2773E+02	42.0 %	
195	0.2788E+02	44.3 %	
196	0.2785E+02	43.8 %	
197	0.2785E+02	43.9 %	
198	0.2785E+02	43.9 %	
199	0.2613E+02	17.3 %	0.1705E-12
200	0.2770E+02	41.6 %	
201	0.2788E+02	44.4 %	
202	0.2785E+02	43.8 %	
203	0.2785E+02	43.9 %	
204	0.2785E+02	43.9 %	
205	0.2616E+02	17.9 %	-0.1705E-12
206	0.2768E+02	41.3 %	
207	0.2789E+02	44.4 %	
208	0.2785E+02	43.8 %	
209	0.2785E+02	43.9 %	
210	0.2785E+02	43.9 %	
211	0.2620E+02	18.4 %	0.0000E+00
212	0.2766E+02	41.0 %	
213	0.2789E+02	44.4 %	
214	0.2785E+02	43.8 %	
215	0.2785E+02	43.9 %	
216	0.2785E+02	43.9 %	
217	0.2622E+02	18.8 %	0.1137E-12
218	0.2765E+02	40.8 %	
219	0.2789E+02	44.5 %	
220	0.2785E+02	43.8 %	
221	0.2785E+02	43.9 %	
222	0.2785E+02	43.9 %	
223	0.2624E+02	19.1 %	-0.5684E-13
224	0.2764E+02	40.6 %	
225	0.2789E+02	44.5 %	
226	0.2785E+02	43.8 %	
227	0.2785E+02	43.9 %	
228	0.2785E+02	43.9 %	
229	0.2626E+02	19.3 %	-0.5684E-13
230	0.2763E+02	40.5 %	
231	0.2789E+02	44.5 %	
232	0.2785E+02	43.8 %	
233	0.2785E+02	43.9 %	
234	0.2785E+02	43.9 %	
235	0.2627E+02	19.5 %	0.5116E-12
236	0.2763E+02	40.4 %	
237	0.2789E+02	44.5 %	
238	0.2785E+02	43.8 %	
239	0.2785E+02	43.9 %	
240	0.2785E+02	43.9 %	
241	0.2627E+02	19.5 %	-0.1705E-12
242	0.2762E+02	40.4 %	
243	0.2789E+02	44.5 %	
244	0.2785E+02	43.8 %	
245	0.2785E+02	43.9 %	
246	0.2785E+02	43.9 %	

Flow = 2.1252E+01

Figure 7.13
SEEP2D Model

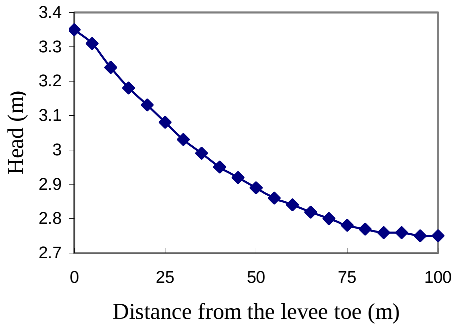
An unconfined aquifer with a depth of 45 m, and hydraulic conductivities of k_h=0.2 cm/sec, k_v=0.0001 cm/sec were defined. The cross-section included 50 m at riverside, 50-m levee base, 100 m at landside. Constant head boundary was defined at riverside and exit face boundary was defined at landside of the levee. The figure is below:

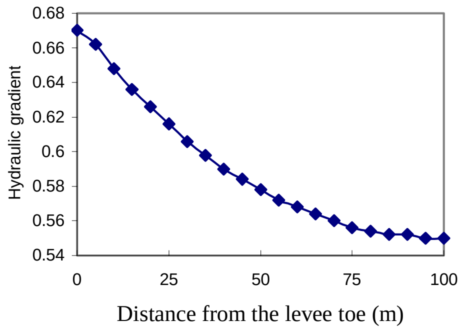


For cumulative analysis
45m exit face, T=0.09 m^2/sec

Node	Distance (m)	Head (m)	Head-45 (m)	i=h/z
202	0	48.35	3.35	0.67
212	5	48.31	3.31	0.662
222	10	48.24	3.24	0.648
232	15	48.18	3.18	0.636
242	20	48.13	3.13	0.626
252	25	48.08	3.08	0.616
262	30	48.03	3.03	0.606
272	35	47.99	2.99	0.598
282	40	47.95	2.95	0.59
292	45	47.92	2.92	0.584
302	50	47.89	2.89	0.578
312	55	47.86	2.86	0.572
322	60	47.84	2.84	0.568
332	65	47.82	2.82	0.564
342	70	47.8	2.8	0.56
352	75	47.78	2.78	0.556
362	80	47.77	2.77	0.554
372	85	47.76	2.76	0.552
382	90	47.76	2.76	0.552
392	95	47.75	2.75	0.55
402	100	47.75	2.75	0.55

Flow = 38.272





Note: Node numbers 202 to 402 are located at 5 m below the landside of the levee.

Model Output

Plane flow problem
45m exit face, T=0.09 m^2/sec
Number of nodal points------ 410
Number of elements---------- 360
Number of diff. materials--- 1
Elevation of datum---------- 0.000
Unsaturated flow option----- 0
Material Properties

Mat	K1	K2	Angle	Uspar1	Uspar2
1	0.1728E+03	0.8600E-01	0.0000E+00	0.1000E-02	0.0000E+00

Node Point Information

Node	BC	X	Y	Flow-head
1	1	0.00	45.00	51.50
2	0	0.00	40.00	0.00
3	0	0.00	35.00	0.00
4	0	0.00	30.00	0.00
5	0	0.00	25.00	0.00
6	0	0.00	20.00	0.00
7	0	0.00	15.00	0.00
8	0	0.00	10.00	0.00
9	0	0.00	5.00	0.00
10	0	0.00	0.00	0.00
11	1	5.00	45.00	51.50
12	0	5.00	40.00	0.00
13	0	5.00	35.00	0.00
14	0	5.00	30.00	0.00
15	0	5.00	25.00	0.00
16	0	5.00	20.00	0.00
17	0	5.00	15.00	0.00
18	0	5.00	10.00	0.00
19	0	5.00	5.00	0.00
20	0	5.00	0.00	0.00
21	1	10.00	45.00	51.50
22	0	10.00	40.00	0.00
23	0	10.00	35.00	0.00
24	0	10.00	30.00	0.00
25	0	10.00	25.00	0.00
26	0	10.00	20.00	0.00
27	0	10.00	15.00	0.00
28	0	10.00	10.00	0.00
29	0	10.00	5.00	0.00
30	0	10.00	0.00	0.00
31	1	15.00	45.00	51.50
32	0	15.00	40.00	0.00
33	0	15.00	35.00	0.00
34	0	15.00	30.00	0.00
35	0	15.00	25.00	0.00
36	0	15.00	20.00	0.00
37	0	15.00	15.00	0.00
38	0	15.00	10.00	0.00
39	0	15.00	5.00	0.00
40	0	15.00	0.00	0.00
41	1	20.00	45.00	51.50
42	0	20.00	40.00	0.00
43	0	20.00	35.00	0.00
44	0	20.00	30.00	0.00
45	0	20.00	25.00	0.00
46	0	20.00	20.00	0.00
47	0	20.00	15.00	0.00
48	0	20.00	10.00	0.00
49	0	20.00	5.00	0.00
50	0	20.00	0.00	0.00
51	1	25.00	45.00	51.50
52	0	25.00	40.00	0.00
53	0	25.00	35.00	0.00
54	0	25.00	30.00	0.00
55	0	25.00	25.00	0.00
56	0	25.00	20.00	0.00
57	0	25.00	15.00	0.00
58	0	25.00	10.00	0.00
59	0	25.00	5.00	0.00
60	0	25.00	0.00	0.00
61	1	30.00	45.00	51.50
62	0	30.00	40.00	0.00
63	0	30.00	35.00	0.00
64	0	30.00	30.00	0.00
65	0	30.00	25.00	0.00
66	0	30.00	20.00	0.00
67	0	30.00	15.00	0.00
68	0	30.00	10.00	0.00
69	0	30.00	5.00	0.00
70	0	30.00	0.00	0.00
71	1	35.00	45.00	51.50
72	0	35.00	40.00	0.00
73	0	35.00	35.00	0.00
74	0	35.00	30.00	0.00
75	0	35.00	25.00	0.00
76	0	35.00	20.00	0.00
77	0	35.00	15.00	0.00
78	0	35.00	10.00	0.00
79	0	35.00	5.00	0.00
80	0	35.00	0.00	0.00
81	1	40.00	45.00	51.50
82	0	40.00	40.00	0.00
83	0	40.00	35.00	0.00
84	0	40.00	30.00	0.00
85	0	40.00	25.00	0.00
86	0	40.00	20.00	0.00
87	0	40.00	15.00	0.00
88	0	40.00	10.00	0.00
89	0	40.00	5.00	0.00
90	0	40.00	0.00	0.00
91	1	45.00	45.00	51.50
92	0	45.00	40.00	0.00
93	0	45.00	35.00	0.00
94	0	45.00	30.00	0.00
95	0	45.00	25.00	0.00
96	0	45.00	20.00	0.00
97	0	45.00	15.00	0.00
98	0	45.00	10.00	0.00
99	0	45.00	5.00	0.00
100	0	45.00	0.00	0.00
101	1	50.00	45.00	51.50
102	0	50.00	40.00	0.00
103	0	50.00	35.00	0.00
104	0	50.00	30.00	0.00
105	0	50.00	25.00	0.00
106	0	50.00	20.00	0.00
107	0	50.00	15.00	0.00
108	0	50.00	10.00	0.00
109	0	50.00	5.00	0.00
110	0	50.00	0.00	0.00
111	0	55.00	45.00	0.00
112	0	55.00	40.00	0.00
113	0	55.00	35.00	0.00
114	0	55.00	30.00	0.00
115	0	55.00	25.00	0.00
116	0	55.00	20.00	0.00
117	0	55.00	15.00	0.00
118	0	55.00	10.00	0.00
119	0	55.00	5.00	0.00
120	0	55.00	0.00	0.00
121	0	60.00	45.00	0.00
122	0	60.00	40.00	0.00
123	0	60.00	35.00	0.00
124	0	60.00	30.00	0.00
125	0	60.00	25.00	0.00
126	0	60.00	20.00	0.00
127	0	60.00	15.00	0.00
128	0	60.00	10.00	0.00
129	0	60.00	5.00	0.00
130	0	60.00	0.00	0.00
131	0	65.00	45.00	0.00
132	0	65.00	40.00	0.00

133	0	65.00	35.00	0.00
134	0	65.00	30.00	0.00
135	0	65.00	25.00	0.00
136	0	65.00	20.00	0.00
137	0	65.00	15.00	0.00
138	0	65.00	10.00	0.00
139	0	65.00	5.00	0.00
140	0	65.00	0.00	0.00
141	0	70.00	45.00	0.00
142	0	70.00	40.00	0.00
143	0	70.00	35.00	0.00
144	0	70.00	30.00	0.00
145	0	70.00	25.00	0.00
146	0	70.00	20.00	0.00
147	0	70.00	15.00	0.00
148	0	70.00	10.00	0.00
149	0	70.00	5.00	0.00
150	0	70.00	0.00	0.00
151	0	75.00	45.00	0.00
152	0	75.00	40.00	0.00
153	0	75.00	35.00	0.00
154	0	75.00	30.00	0.00
155	0	75.00	25.00	0.00
156	0	75.00	20.00	0.00
157	0	75.00	15.00	0.00
158	0	75.00	10.00	0.00
159	0	75.00	5.00	0.00
160	0	75.00	0.00	0.00
161	0	80.00	45.00	0.00
162	0	80.00	40.00	0.00
163	0	80.00	35.00	0.00
164	0	80.00	30.00	0.00
165	0	80.00	25.00	0.00
166	0	80.00	20.00	0.00
167	0	80.00	15.00	0.00
168	0	80.00	10.00	0.00
169	0	80.00	5.00	0.00
170	0	80.00	0.00	0.00
171	0	85.00	45.00	0.00
172	0	85.00	40.00	0.00
173	0	85.00	35.00	0.00
174	0	85.00	30.00	0.00
175	0	85.00	25.00	0.00
176	0	85.00	20.00	0.00
177	0	85.00	15.00	0.00
178	0	85.00	10.00	0.00
179	0	85.00	5.00	0.00
180	0	85.00	0.00	0.00
181	0	90.00	45.00	0.00
182	0	90.00	40.00	0.00
183	0	90.00	35.00	0.00
184	0	90.00	30.00	0.00
185	0	90.00	25.00	0.00
186	0	90.00	20.00	0.00
187	0	90.00	15.00	0.00
188	0	90.00	10.00	0.00
189	0	90.00	5.00	0.00
190	0	90.00	0.00	0.00
191	0	95.00	45.00	0.00
192	0	95.00	40.00	0.00
193	0	95.00	35.00	0.00
194	0	95.00	30.00	0.00
195	0	95.00	25.00	0.00
196	0	95.00	20.00	0.00
197	0	95.00	15.00	0.00
198	0	95.00	10.00	0.00
199	0	95.00	5.00	0.00
200	0	95.00	0.00	0.00
201	2	100.00	45.00	0.00
202	0	100.00	40.00	0.00
203	0	100.00	35.00	0.00
204	0	100.00	30.00	0.00
205	0	100.00	25.00	0.00
206	0	100.00	20.00	0.00
207	0	100.00	15.00	0.00
208	0	100.00	10.00	0.00
209	0	100.00	5.00	0.00
210	0	100.00	0.00	0.00
211	2	105.00	45.00	0.00
212	0	105.00	40.00	0.00
213	0	105.00	35.00	0.00
214	0	105.00	30.00	0.00
215	0	105.00	25.00	0.00
216	0	105.00	20.00	0.00
217	0	105.00	15.00	0.00
218	0	105.00	10.00	0.00
219	0	105.00	5.00	0.00
220	0	105.00	0.00	0.00
221	2	110.00	45.00	0.00
222	0	110.00	40.00	0.00
223	0	110.00	35.00	0.00
224	0	110.00	30.00	0.00
225	0	110.00	25.00	0.00
226	0	110.00	20.00	0.00
227	0	110.00	15.00	0.00
228	0	110.00	10.00	0.00
229	0	110.00	5.00	0.00
230	0	110.00	0.00	0.00
231	2	115.00	45.00	0.00
232	0	115.00	40.00	0.00
233	0	115.00	35.00	0.00
234	0	115.00	30.00	0.00
235	0	115.00	25.00	0.00
236	0	115.00	20.00	0.00
237	0	115.00	15.00	0.00
238	0	115.00	10.00	0.00
239	0	115.00	5.00	0.00
240	0	115.00	0.00	0.00
241	2	120.00	45.00	0.00
242	0	120.00	40.00	0.00
243	0	120.00	35.00	0.00
244	0	120.00	30.00	0.00
245	0	120.00	25.00	0.00
246	0	120.00	20.00	0.00
247	0	120.00	15.00	0.00
248	0	120.00	10.00	0.00
249	0	120.00	5.00	0.00
250	0	120.00	0.00	0.00
251	2	125.00	45.00	0.00
252	0	125.00	40.00	0.00
253	0	125.00	35.00	0.00
254	0	125.00	30.00	0.00
255	0	125.00	25.00	0.00
256	0	125.00	20.00	0.00
257	0	125.00	15.00	0.00
258	0	125.00	10.00	0.00
259	0	125.00	5.00	0.00
260	0	125.00	0.00	0.00
261	2	130.00	45.00	0.00
262	0	130.00	40.00	0.00
263	0	130.00	35.00	0.00
264	0	130.00	30.00	0.00
265	0	130.00	25.00	0.00
266	0	130.00	20.00	0.00
267	0	130.00	15.00	0.00
268	0	130.00	10.00	0.00
269	0	130.00	5.00	0.00
270	0	130.00	0.00	0.00
271	2	135.00	45.00	0.00
272	0	135.00	40.00	0.00

273	0	135.00	35.00	0.00
274	0	135.00	30.00	0.00
275	0	135.00	25.00	0.00
276	0	135.00	20.00	0.00
277	0	135.00	15.00	0.00
278	0	135.00	10.00	0.00
279	0	135.00	5.00	0.00
280	0	135.00	0.00	0.00
281	2	140.00	45.00	0.00
282	0	140.00	40.00	0.00
283	0	140.00	35.00	0.00
284	0	140.00	30.00	0.00
285	0	140.00	25.00	0.00
286	0	140.00	20.00	0.00
287	0	140.00	15.00	0.00
288	0	140.00	10.00	0.00
289	0	140.00	5.00	0.00
290	0	140.00	0.00	0.00
291	2	145.00	45.00	0.00
292	0	145.00	40.00	0.00
293	0	145.00	35.00	0.00
294	0	145.00	30.00	0.00
295	0	145.00	25.00	0.00
296	0	145.00	20.00	0.00
297	0	145.00	15.00	0.00
298	0	145.00	10.00	0.00
299	0	145.00	5.00	0.00
300	0	145.00	0.00	0.00
301	2	150.00	45.00	0.00
302	0	150.00	40.00	0.00
303	0	150.00	35.00	0.00
304	0	150.00	30.00	0.00
305	0	150.00	25.00	0.00
306	0	150.00	20.00	0.00
307	0	150.00	15.00	0.00
308	0	150.00	10.00	0.00
309	0	150.00	5.00	0.00
310	0	150.00	0.00	0.00
311	2	155.00	45.00	0.00
312	0	155.00	40.00	0.00
313	0	155.00	35.00	0.00
314	0	155.00	30.00	0.00
315	0	155.00	25.00	0.00
316	0	155.00	20.00	0.00
317	0	155.00	15.00	0.00
318	0	155.00	10.00	0.00
319	0	155.00	5.00	0.00
320	0	155.00	0.00	0.00
321	2	160.00	45.00	0.00
322	0	160.00	40.00	0.00
323	0	160.00	35.00	0.00
324	0	160.00	30.00	0.00
325	0	160.00	25.00	0.00
326	0	160.00	20.00	0.00
327	0	160.00	15.00	0.00
328	0	160.00	10.00	0.00
329	0	160.00	5.00	0.00
330	0	160.00	0.00	0.00
331	2	165.00	45.00	0.00
332	0	165.00	40.00	0.00
333	0	165.00	35.00	0.00
334	0	165.00	30.00	0.00
335	0	165.00	25.00	0.00
336	0	165.00	20.00	0.00
337	0	165.00	15.00	0.00
338	0	165.00	10.00	0.00
339	0	165.00	5.00	0.00
340	0	165.00	0.00	0.00
341	2	170.00	45.00	0.00
342	0	170.00	40.00	0.00
343	0	170.00	35.00	0.00
344	0	170.00	30.00	0.00
345	0	170.00	25.00	0.00
346	0	170.00	20.00	0.00
347	0	170.00	15.00	0.00
348	0	170.00	10.00	0.00
349	0	170.00	5.00	0.00
350	0	170.00	0.00	0.00
351	2	175.00	45.00	0.00
352	0	175.00	40.00	0.00
353	0	175.00	35.00	0.00
354	0	175.00	30.00	0.00
355	0	175.00	25.00	0.00
356	0	175.00	20.00	0.00
357	0	175.00	15.00	0.00
358	0	175.00	10.00	0.00
359	0	175.00	5.00	0.00
360	0	175.00	0.00	0.00
361	2	180.00	45.00	0.00
362	0	180.00	40.00	0.00
363	0	180.00	35.00	0.00
364	0	180.00	30.00	0.00
365	0	180.00	25.00	0.00
366	0	180.00	20.00	0.00
367	0	180.00	15.00	0.00
368	0	180.00	10.00	0.00
369	0	180.00	5.00	0.00
370	0	180.00	0.00	0.00
371	2	185.00	45.00	0.00
372	0	185.00	40.00	0.00
373	0	185.00	35.00	0.00
374	0	185.00	30.00	0.00
375	0	185.00	25.00	0.00
376	0	185.00	20.00	0.00
377	0	185.00	15.00	0.00
378	0	185.00	10.00	0.00
379	0	185.00	5.00	0.00
380	0	185.00	0.00	0.00
381	2	190.00	45.00	0.00
382	0	190.00	40.00	0.00
383	0	190.00	35.00	0.00
384	0	190.00	30.00	0.00
385	0	190.00	25.00	0.00
386	0	190.00	20.00	0.00
387	0	190.00	15.00	0.00
388	0	190.00	10.00	0.00
389	0	190.00	5.00	0.00
390	0	190.00	0.00	0.00
391	2	195.00	45.00	0.00
392	0	195.00	40.00	0.00
393	0	195.00	35.00	0.00
394	0	195.00	30.00	0.00
395	0	195.00	25.00	0.00
396	0	195.00	20.00	0.00
397	0	195.00	15.00	0.00
398	0	195.00	10.00	0.00
399	0	195.00	5.00	0.00
400	0	195.00	0.00	0.00
401	2	200.00	45.00	0.00
402	0	200.00	40.00	0.00
403	0	200.00	35.00	0.00
404	0	200.00	30.00	0.00
405	0	200.00	25.00	0.00
406	0	200.00	20.00	0.00
407	0	200.00	15.00	0.00
408	0	200.00	10.00	0.00
409	0	200.00	5.00	0.00
410	0	200.00	0.00	0.00

Nodal Flows and Heads

Node	Head	Percentage of available head	Flow
1	0.5150E+02	100.0 %	0.2367E+00
2	0.4729E+02	35.2 %	
3	0.4775E+02	42.4 %	
4	0.4771E+02	41.6 %	
5	0.4771E+02	41.7 %	
6	0.4771E+02	41.7 %	
7	0.4771E+02	41.7 %	
8	0.4771E+02	41.7 %	
9	0.4771E+02	41.7 %	
10	0.4771E+02	41.7 %	
11	0.5150E+02	100.0 %	0.4737E+00
12	0.4729E+02	35.2 %	
13	0.4776E+02	42.4 %	
14	0.4771E+02	41.6 %	
15	0.4771E+02	41.7 %	
16	0.4771E+02	41.7 %	
17	0.4771E+02	41.7 %	
18	0.4771E+02	41.7 %	
19	0.4771E+02	41.7 %	
20	0.4771E+02	41.7 %	
21	0.5150E+02	100.0 %	0.4746E+00
22	0.4728E+02	35.1 %	
23	0.4776E+02	42.4 %	
24	0.4771E+02	41.6 %	
25	0.4771E+02	41.7 %	
26	0.4771E+02	41.7 %	
27	0.4771E+02	41.7 %	
28	0.4771E+02	41.7 %	
29	0.4771E+02	41.7 %	
30	0.4771E+02	41.7 %	
31	0.5150E+02	100.0 %	0.4761E+00
32	0.4727E+02	34.9 %	
33	0.4776E+02	42.5 %	
34	0.4770E+02	41.6 %	
35	0.4771E+02	41.7 %	
36	0.4771E+02	41.7 %	
37	0.4771E+02	41.7 %	
38	0.4771E+02	41.7 %	
39	0.4771E+02	41.7 %	
40	0.4771E+02	41.7 %	
41	0.5150E+02	100.0 %	0.4781E+00
42	0.4726E+02	34.7 %	
43	0.4777E+02	42.6 %	
44	0.4770E+02	41.6 %	
45	0.4771E+02	41.7 %	
46	0.4771E+02	41.7 %	
47	0.4771E+02	41.7 %	
48	0.4771E+02	41.7 %	
49	0.4771E+02	41.7 %	
50	0.4771E+02	41.7 %	
51	0.5150E+02	100.0 %	0.4808E+00
52	0.4724E+02	34.5 %	
53	0.4777E+02	42.7 %	
54	0.4770E+02	41.6 %	
55	0.4771E+02	41.7 %	
56	0.4771E+02	41.7 %	
57	0.4771E+02	41.7 %	
58	0.4771E+02	41.7 %	
59	0.4771E+02	41.7 %	
60	0.4771E+02	41.7 %	
61	0.5150E+02	100.0 %	0.4841E+00
62	0.4722E+02	34.1 %	
63	0.4778E+02	42.8 %	
64	0.4770E+02	41.5 %	
65	0.4771E+02	41.7 %	
66	0.4771E+02	41.7 %	
67	0.4771E+02	41.7 %	
68	0.4771E+02	41.7 %	
69	0.4771E+02	41.7 %	
70	0.4771E+02	41.7 %	
71	0.5150E+02	100.0 %	0.4881E+00
72	0.4719E+02	33.7 %	
73	0.4779E+02	42.9 %	
74	0.4770E+02	41.5 %	
75	0.4771E+02	41.7 %	
76	0.4771E+02	41.7 %	
77	0.4771E+02	41.7 %	
78	0.4771E+02	41.7 %	
79	0.4771E+02	41.7 %	
80	0.4771E+02	41.7 %	
81	0.5150E+02	100.0 %	0.4926E+00
82	0.4716E+02	33.3 %	
83	0.4780E+02	43.1 %	
84	0.4769E+02	41.4 %	
85	0.4771E+02	41.8 %	
86	0.4771E+02	41.7 %	
87	0.4771E+02	41.7 %	
88	0.4771E+02	41.7 %	
89	0.4771E+02	41.7 %	
90	0.4771E+02	41.7 %	
91	0.5150E+02	100.0 %	0.4978E+00
92	0.4713E+02	32.8 %	
93	0.4782E+02	43.3 %	
94	0.4769E+02	41.3 %	
95	0.4772E+02	41.8 %	
96	0.4771E+02	41.7 %	
97	0.4771E+02	41.7 %	
98	0.4771E+02	41.7 %	
99	0.4771E+02	41.7 %	
100	0.4771E+02	41.7 %	
101	0.5150E+02	100.0 %	0.3369E+02
102	0.4709E+02	32.2 %	
103	0.4783E+02	43.6 %	
104	0.4768E+02	41.3 %	
105	0.4772E+02	41.8 %	
106	0.4771E+02	41.7 %	
107	0.4771E+02	41.7 %	
108	0.4771E+02	41.7 %	
109	0.4771E+02	41.7 %	
110	0.4771E+02	41.7 %	
111	0.5083E+02	89.8 %	
112	0.4723E+02	34.3 %	
113	0.4780E+02	43.1 %	
114	0.4769E+02	41.4 %	
115	0.4771E+02	41.8 %	
116	0.4771E+02	41.7 %	
117	0.4771E+02	41.7 %	
118	0.4771E+02	41.7 %	
119	0.4771E+02	41.7 %	
120	0.4771E+02	41.7 %	
121	0.5018E+02	79.6 %	
122	0.4736E+02	36.3 %	
123	0.4777E+02	42.6 %	
124	0.4770E+02	41.5 %	
125	0.4771E+02	41.7 %	
126	0.4771E+02	41.7 %	
127	0.4771E+02	41.7 %	
128	0.4771E+02	41.7 %	
129	0.4771E+02	41.7 %	
130	0.4771E+02	41.7 %	
131	0.4953E+02	69.6 %	
132	0.4748E+02	38.2 %	

133	0.4774E+02	42.2 %	
134	0.4770E+02	41.6 %	
135	0.4771E+02	41.7 %	
136	0.4771E+02	41.7 %	
137	0.4771E+02	41.7 %	
138	0.4771E+02	41.7 %	
139	0.4771E+02	41.7 %	
140	0.4771E+02	41.7 %	
141	0.4888E+02	59.7 %	
142	0.4761E+02	40.1 %	
143	0.4772E+02	41.8 %	
144	0.4771E+02	41.7 %	
145	0.4771E+02	41.7 %	
146	0.4771E+02	41.7 %	
147	0.4771E+02	41.7 %	
148	0.4771E+02	41.7 %	
149	0.4771E+02	41.7 %	
150	0.4771E+02	41.7 %	
151	0.4824E+02	49.8 %	
152	0.4773E+02	42.0 %	
153	0.4769E+02	41.4 %	
154	0.4771E+02	41.8 %	
155	0.4771E+02	41.7 %	
156	0.4771E+02	41.7 %	
157	0.4771E+02	41.7 %	
158	0.4771E+02	41.7 %	
159	0.4771E+02	41.7 %	
160	0.4771E+02	41.7 %	
161	0.4759E+02	39.9 %	
162	0.4785E+02	43.8 %	
163	0.4767E+02	41.0 %	
164	0.4772E+02	41.9 %	
165	0.4771E+02	41.7 %	
166	0.4771E+02	41.7 %	
167	0.4771E+02	41.7 %	
168	0.4771E+02	41.7 %	
169	0.4771E+02	41.7 %	
170	0.4771E+02	41.7 %	
171	0.4695E+02	30.0 %	
172	0.4797E+02	45.7 %	
173	0.4764E+02	40.7 %	
174	0.4773E+02	41.9 %	
175	0.4771E+02	41.6 %	
176	0.4771E+02	41.7 %	
177	0.4771E+02	41.7 %	
178	0.4771E+02	41.7 %	
179	0.4771E+02	41.7 %	
180	0.4771E+02	41.7 %	
181	0.4631E+02	20.1 %	
182	0.4809E+02	47.6 %	
183	0.4762E+02	40.2 %	
184	0.4773E+02	42.0 %	
185	0.4770E+02	41.6 %	
186	0.4771E+02	41.7 %	
187	0.4771E+02	41.7 %	
188	0.4771E+02	41.7 %	
189	0.4771E+02	41.7 %	
190	0.4771E+02	41.7 %	
191	0.4566E+02	10.1 %	
192	0.4822E+02	49.5 %	
193	0.4759E+02	39.8 %	
194	0.4774E+02	42.1 %	
195	0.4770E+02	41.6 %	
196	0.4771E+02	41.7 %	
197	0.4771E+02	41.7 %	
198	0.4771E+02	41.7 %	
199	0.4771E+02	41.7 %	
200	0.4771E+02	41.7 %	
201	0.4500E+02	0.0 %	-0.3308E+02
202	0.4835E+02	51.5 %	
203	0.4756E+02	39.4 %	
204	0.4775E+02	42.3 %	
205	0.4770E+02	41.6 %	
206	0.4771E+02	41.7 %	
207	0.4771E+02	41.7 %	
208	0.4771E+02	41.7 %	
209	0.4771E+02	41.7 %	
210	0.4771E+02	41.7 %	
211	0.4500E+02	0.0 %	-0.5191E+01
212	0.4831E+02	50.9 %	
213	0.4757E+02	39.6 %	
214	0.4774E+02	42.2 %	
215	0.4770E+02	41.6 %	
216	0.4771E+02	41.7 %	
217	0.4771E+02	41.7 %	
218	0.4771E+02	41.7 %	
219	0.4771E+02	41.7 %	
220	0.4771E+02	41.7 %	
221	0.4510E+02	1.5 %	0.0000E+00
222	0.4824E+02	49.9 %	
223	0.4760E+02	39.9 %	
224	0.4774E+02	42.1 %	
225	0.4770E+02	41.6 %	
226	0.4771E+02	41.7 %	
227	0.4771E+02	41.7 %	
228	0.4771E+02	41.7 %	
229	0.4771E+02	41.7 %	
230	0.4771E+02	41.7 %	
231	0.4519E+02	2.9 %	-0.1819E-11
232	0.4818E+02	49.0 %	
233	0.4761E+02	40.2 %	
234	0.4773E+02	42.0 %	
235	0.4771E+02	41.6 %	
236	0.4771E+02	41.7 %	
237	0.4771E+02	41.7 %	
238	0.4771E+02	41.7 %	
239	0.4771E+02	41.7 %	
240	0.4771E+02	41.7 %	
241	0.4527E+02	4.1 %	0.1592E-11
242	0.4813E+02	48.1 %	
243	0.4763E+02	40.5 %	
244	0.4773E+02	41.9 %	
245	0.4771E+02	41.6 %	
246	0.4771E+02	41.7 %	
247	0.4771E+02	41.7 %	
248	0.4771E+02	41.7 %	
249	0.4771E+02	41.7 %	
250	0.4771E+02	41.7 %	
251	0.4534E+02	5.3 %	-0.4547E-12
252	0.4808E+02	47.4 %	
253	0.4765E+02	40.7 %	
254	0.4772E+02	41.9 %	
255	0.4771E+02	41.7 %	
256	0.4771E+02	41.7 %	
257	0.4771E+02	41.7 %	
258	0.4771E+02	41.7 %	
259	0.4771E+02	41.7 %	
260	0.4771E+02	41.7 %	
261	0.4541E+02	6.4 %	0.6821E-12
262	0.4803E+02	46.7 %	
263	0.4766E+02	40.9 %	
264	0.4772E+02	41.8 %	
265	0.4771E+02	41.7 %	
266	0.4771E+02	41.7 %	
267	0.4771E+02	41.7 %	
268	0.4771E+02	41.7 %	
269	0.4771E+02	41.7 %	
270	0.4771E+02	41.7 %	
271	0.4548E+02	7.3 %	-0.1137E-11
272	0.4799E+02	46.0 %	

273	0.4767E+02	41.1 %	
274	0.4772E+02	41.8 %	
275	0.4771E+02	41.7 %	
276	0.4771E+02	41.7 %	
277	0.4771E+02	41.7 %	
278	0.4771E+02	41.7 %	
279	0.4771E+02	41.7 %	
280	0.4771E+02	41.7 %	
281	0.4553E+02	8.2 %	-0.1137E-11
282	0.4795E+02	45.4 %	
283	0.4768E+02	41.3 %	
284	0.4771E+02	41.7 %	
285	0.4771E+02	41.7 %	
286	0.4771E+02	41.7 %	
287	0.4771E+02	41.7 %	
288	0.4771E+02	41.7 %	
289	0.4771E+02	41.7 %	
290	0.4771E+02	41.7 %	
291	0.4559E+02	9.0 %	0.4547E-12
292	0.4792E+02	44.9 %	
293	0.4769E+02	41.4 %	
294	0.4771E+02	41.7 %	
295	0.4771E+02	41.7 %	
296	0.4771E+02	41.7 %	
297	0.4771E+02	41.7 %	
298	0.4771E+02	41.7 %	
299	0.4771E+02	41.7 %	
300	0.4771E+02	41.7 %	
301	0.4563E+02	9.7 %	-0.2274E-12
302	0.4789E+02	44.4 %	
303	0.4770E+02	41.6 %	
304	0.4771E+02	41.7 %	
305	0.4771E+02	41.7 %	
306	0.4771E+02	41.7 %	
307	0.4771E+02	41.7 %	
308	0.4771E+02	41.7 %	
309	0.4771E+02	41.7 %	
310	0.4771E+02	41.7 %	
311	0.4568E+02	10.4 %	-0.2274E-12
312	0.4786E+02	44.0 %	
313	0.4771E+02	41.7 %	
314	0.4771E+02	41.6 %	
315	0.4771E+02	41.7 %	
316	0.4771E+02	41.7 %	
317	0.4771E+02	41.7 %	
318	0.4771E+02	41.7 %	
319	0.4771E+02	41.7 %	
320	0.4771E+02	41.7 %	
321	0.4571E+02	11.0 %	-0.9095E-12
322	0.4784E+02	43.7 %	
323	0.4772E+02	41.8 %	
324	0.4771E+02	41.6 %	
325	0.4771E+02	41.7 %	
326	0.4771E+02	41.7 %	
327	0.4771E+02	41.7 %	
328	0.4771E+02	41.7 %	
329	0.4771E+02	41.7 %	
330	0.4771E+02	41.7 %	
331	0.4575E+02	11.5 %	0.9095E-12
332	0.4782E+02	43.3 %	
333	0.4772E+02	41.9 %	
334	0.4770E+02	41.6 %	
335	0.4771E+02	41.7 %	
336	0.4771E+02	41.7 %	
337	0.4771E+02	41.7 %	
338	0.4771E+02	41.7 %	
339	0.4771E+02	41.7 %	
340	0.4771E+02	41.7 %	
341	0.4577E+02	11.9 %	-0.9095E-12
342	0.4780E+02	43.1 %	
343	0.4773E+02	41.9 %	
344	0.4770E+02	41.6 %	
345	0.4771E+02	41.7 %	
346	0.4771E+02	41.7 %	
347	0.4771E+02	41.7 %	
348	0.4771E+02	41.7 %	
349	0.4771E+02	41.7 %	
350	0.4771E+02	41.7 %	
351	0.4580E+02	12.2 %	0.0000E+00
352	0.4778E+02	42.8 %	
353	0.4773E+02	42.0 %	
354	0.4770E+02	41.6 %	
355	0.4771E+02	41.7 %	
356	0.4771E+02	41.7 %	
357	0.4771E+02	41.7 %	
358	0.4771E+02	41.7 %	
359	0.4771E+02	41.7 %	
360	0.4771E+02	41.7 %	
361	0.4582E+02	12.5 %	0.4547E-12
362	0.4777E+02	42.7 %	
363	0.4773E+02	42.0 %	
364	0.4770E+02	41.6 %	
365	0.4771E+02	41.7 %	
366	0.4771E+02	41.7 %	
367	0.4771E+02	41.7 %	
368	0.4771E+02	41.7 %	
369	0.4771E+02	41.7 %	
370	0.4771E+02	41.7 %	
371	0.4583E+02	12.8 %	-0.4547E-12
372	0.4776E+02	42.5 %	
373	0.4774E+02	42.1 %	
374	0.4770E+02	41.6 %	
375	0.4771E+02	41.7 %	
376	0.4771E+02	41.7 %	
377	0.4771E+02	41.7 %	
378	0.4771E+02	41.7 %	
379	0.4771E+02	41.7 %	
380	0.4771E+02	41.7 %	
381	0.4584E+02	12.9 %	0.2274E-12
382	0.4776E+02	42.4 %	
383	0.4774E+02	42.1 %	
384	0.4770E+02	41.5 %	
385	0.4771E+02	41.7 %	
386	0.4771E+02	41.7 %	
387	0.4771E+02	41.7 %	
388	0.4771E+02	41.7 %	
389	0.4771E+02	41.7 %	
390	0.4771E+02	41.7 %	
391	0.4585E+02	13.0 %	0.4547E-12
392	0.4775E+02	42.3 %	
393	0.4774E+02	42.1 %	
394	0.4770E+02	41.5 %	
395	0.4771E+02	41.7 %	
396	0.4771E+02	41.7 %	
397	0.4771E+02	41.7 %	
398	0.4771E+02	41.7 %	
399	0.4771E+02	41.7 %	
400	0.4771E+02	41.7 %	
401	0.4585E+02	13.1 %	-0.2274E-12
402	0.4775E+02	42.3 %	
403	0.4774E+02	42.1 %	
404	0.4770E+02	41.5 %	
405	0.4771E+02	41.7 %	
406	0.4771E+02	41.7 %	
407	0.4771E+02	41.7 %	
408	0.4771E+02	41.7 %	
409	0.4771E+02	41.7 %	
410	0.4771E+02	41.7 %	

Flow = 3.8272E+01

VITA

Senda Ozkan was born in Adana, Turkey, in 1970. She graduated from Middle East Technical University, Ankara, Turkey, in 1992 with a degree of Bachelor of Science in civil engineering. After graduating, she worked as a Project Engineer with TEMAT AS, Ankara, Turkey. She enrolled in Louisiana State University’s graduate engineering program in the spring of 1995. She graduated in the fall of 1996 with a master’s degree in civil engineering, and continued to her graduate studies at Louisiana State University. She is a registered Professional Engineer and currently works as an Environmental Staff Engineer with Gulf Engineers and Consultants, Inc., Baton Rouge, Louisiana. She is a candidate for a doctoral degree in civil engineering at Louisiana State University.

Enclosure No. 6

RECIRC2819.

US Army Corps of Engineers®
Engineer Research and Development Center

ERDC/GSL TR-02-19

Geotechnical and Structures Laboratory

Performance of Levee Underseepage Controls: A Critical Review

Thomas F. Wolff

September 2002

RECIRC2819.

ERDC/GSL TR-02-19
September 2002

Performance of Levee Underseepage Controls: A Critical Review

by Thomas F. Wolff

Michigan State University
Department of Civil and Environmental Engineering
East Lansing, MI 48824-1226

Final report

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Monitored by Geotechnical and Structures Laboratory
U.S. Army Engineer Research and Development Center
Vicksburg, MS 39180-6199

Contents

List of Figures

Preface

This report was originally prepared for the Rehabilitation, Evaluation, Maintenance and Repair (REMR) Research Program, sponsored by Headquarters, U.S. Army Corps of Engineers (USACE), during the 1980s. This report was completed in 1986 by Dr. Thomas F. Wolff, Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI, under the Intergovernmental Personnel Act of 1970. At the time of writing, computer modeling was new to the engineers' desktop; therefore, some of the recommendations for research development are out of date and some are already in practice. The bulk of this report provides assessment on the performance of levees and the USACE underseepage analysis method. A summary of what has been learned through the observation of floods during the 20-year period of 1966 through 1986 is given, and references are appropriate to the year 1986.

Currently, this report is being published under the Innovative Flood Damage Reduction Research Program (IFDR), sponsored by USACE. Historical information on levee performance was determined a critical research need for the Work Unit "Cumulative Effects of Piping under Levees." Therefore, this report is being published under the more recent IFDR Program. Principal Investigator of the piping work unit is Ms. Eileen Glynn, under the direct supervision of Dr. Joseph Koester, Chief, Geotechnical and Earthquake Engineering Branch (GEEB), Geosciences and Structures Division (GSD), Geotechnical and Structures Laboratory (GSL). Dr. Robert Hall, Chief, GSD, provided general supervision, and Dr. David Pittman was Acting Director, GSL.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
feet per minute	0.5080	centimeters per second
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
square inches	0.00064516	square meters
square inches per foot	19.081	square centimeters per meter

1 Introduction

The Federal Government through the U.S. Army Corps of Engineers (USACE) has a large investment in flood-control levees. Where such levees are built on pervious foundations, seepage beneath the levee (underseepage) during floods can produce pressure and flow conditions capable of initiating subsurface erosion leading to levee failure. Two adverse phenomena may occur; one is sand boils which involves the movement of subsurface sand to the surface by flowing water, and the other is heaving which involves the upward movement of a relatively impervious surface layer resulting from subsurface water pressures in excess of its weight. To prevent such occurrences, the USACE has developed a set of procedures to analyze underseepage conditions on a site-specific basis and a set of procedures to design underseepage control measures. For the most part, these procedures were developed in the 1940s and 1950s. Intensive construction of control measures was accomplished in the 1950s and 1960s. Several moderately large and major floods have provided data from which the validity of the procedures and the security of the constructed system can be inferred. Also, since the 1950s many technical advancements have been made in engineering analysis techniques and construction methods that may merit application to underseepage problems.

The Federal Government's levee system will be expected to provide flood protection for many centuries, regardless of its so-called economic life. It will undoubtedly be subjected to floods equaling and exceeding those already experienced. Conditions along the levees are not static but are subject to periodic natural and man-made changes. Such changes may necessitate review, reanalysis, redesign, reconstruction, and/or modification of the system.

Managers responsible for the rehabilitation, evaluation, maintenance, and/or repair of levees subject to underseepage face the following questions:

a. Are the levee systems safe against underseepage failure during flood?

b. If not, are the methods used to analyze (evaluation) and to design controls (rehabilitation) appropriate and accurate?

c. Do piezometric data obtained during floods provide reliable information applicable to the previous two questions? If so, how should it be interpreted?

d. If controls are necessary, does modern technology offer better and/or more cost-effective designs than those used in the past?

e. If adverse underseepage conditions occur despite all the above, what are the best methods to provide expedient controls?

In response to such concerns, several researchers have prepared voluminous evaluations of the performance of particular levees in particular floods. This report draws on those previous assessments to summarize in one source what has been learned from observations during floods up top 1986. Using that knowledge, the analysis procedures and the performance evaluation procedures are reviewed to identify possible areas of improvement.

2 Historical Perspective

In response to underseepage problems during the 1937 flood, the Mississippi River Commission (MRC), with the approval of the USACE, in 1940 initiated an investigation of the causes of and methods for controlling underseepage and sand boils along Lower Mississippi River Levees. Much of the work was performed by the U.S. Army Engineer Research and Development Center (ERDC)/U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, and involved both analytical and model studies. The work led to an analysis procedure that predicts the quantity of underseepage, the uplift pressure on the base of the top blanket, and the gradient through the top blanket. Where calculated gradients are excessive, controls are provided. Underseepage control measures traditionally employed have been seepage berms and pressure relief wells. To provide hard data regarding underseepage safety and performance of installed control measures, wellpoint piezometers have been installed at numerous locations along the levees. A number of floods have occurred since piezometers and underseepage controls have been installed. In particular, the Mississippi River floods of 1961, 1969, 1973, 1974, 1979, 1982, and 1983 have generated considerable data on levee performance.

Design procedures for berms and wells evolved from work by ERDC, USACE, the U.S. Army Engineer Districts (USAED), St. Louis and Vicksburg, the Lower Mississippi Valley Division (LMVD), and the U.S. Army Engineer Division, Missouri River. Before discussing performance, the evolution of the present analysis and design procedures is briefly summarized in Chapters 3 and 4.

3 Levee Underseepage Analysis Procedures

Bennett (1946) published solutions for steady-state seepage through a two-layer system composed of a semipervious top blanket overlying a pervious substratum. Flow was assumed vertical in the top blanket and horizontal in the substratum. Bennett stated that the substratum must be at least 10 times as permeable as the top blanket for these assumptions to be reasonable. Although Bennett's solution dealt with downward seepage through blankets upstream of dams, it was equally applicable to upward seepage through the top blanket riverside of levees. All later analysis and design equations are based on extensions of Bennett's blanket formulas and make the same assumptions.

Technical Memorandum 3-424 (WES 1956b), documents the analysis of underseepage and design of controls for the Lower Mississippi Valley levees. The focus of the analysis procedure is the prediction of the residual head, h_o, at the levee toe. Dividing the residual head by the thickness of the top blanket, z, yields an exit gradient. Calculating the residual head and the exit gradient requires assigning (estimating or assuming) values for the gross head on the levee, the levee geometry, and the thicknesses and permeabilities of the substratum and the top stratum. If the calculated exit gradient exceeds an allowable value (typically taken as 0.85),[1] underseepage control measures are designed. The analysis procedures extend Bennett's work to include:

a. Transformation of a layered top blanket of thickness, z, with vertical permeabilities, k_1, k_2, ..., to an equivalent uniform top blanket, z_t, with an equivalent vertical permeability, k_b.

b. Calculation of an equivalent horizontal foundation permeability, k_f, for a stratified foundation.

c. Calculation of the distance to effective source of seepage entrance, s, for the special cases of a riverside top blanket of infinite length, a riverside top blanket extending to a river at a finite distance, a riverside blanket extending to a block at a finite distance, and seepage entrance through a

[1] Some Districts have lowered the critical exit gradient to 0.5 since the great flood of 1993.

riverside borrow pit of finite width. Similar cases are treated for the calculation of the distance to the effective seepage exit, x_3.

A significant aspect of the analysis is the selection of a value for the top blanket permeability, k_b. Although laboratory values for clay are typically in the range 10^{-7} to 10^{-9} cm/sec, values on the order of 10^{-3} to 10^{-5} cm/sec must be used in the analysis to provide reasonable results. This is attributed to field permeability being controlled by defects in the top blanket (cracks, root holes, fenceposts, etc.) rather than properties of the intact soil. Designers originally assigned blanket permeability values from tables relating k_b to general material types and ranges of thicknesses (WES 1956a, 1956b). Later the LMVD (USAEDLMV 1976) published curves giving k_b as a function of material type and blanket thickness.

Technical Memorandum 3-424 (WES 1956b) also provided a detailed discussion of the surficial floodplain geology from a three-dimensional (3-D) perspective and its relationship to underseepage and the occurrence of boils. Nevertheless, the recommended mathematical analysis procedures required a two-dimensional (2-D) idealization of conditions with horizontal soil layers of uniform thickness.

Analysis procedures in TM 3-424 (WES 1956b) were summarized in the professional literature by Turnbull and Mansur (1961a). Similar analyses and designs were performed for levees in the USAED, St. Louis, and were documented in TM 3-430 (WES 1956a) and by Mansur and Kaufmann (1957). The TM 3-424 analysis procedures remain intact in the 1978 Engineer Manual 1110-2-1913, “Design and Construction of Levees” (Headquarters, Department of the Army (HQDOA) 1978).

4 Design Methods

Relief Wells

Muskat (1937) published a solution for the potential head along an infinite line of equally spaced fully penetrating wells in a confined aquifer parallel to a line source of seepage. This solution provided the initial approach to well design. To provide compatibility with conditions along levees and construction practices, Muskat's solution was subsequently modified to account for the effects of leakage into and out of the top blanket, the effects of partial penetration, and the effects of a finite-length well line.

Middlebrooks and Jervis (1947) summarized the then-current Corps' design procedures which adjusted Muskat's method to account for partially penetrating wells based on hydraulic model tests by ERDC/WES and electrical-analogy model tests by the USAED, Vicksburg (Jervis 1939). The hydraulic model test results were later published by ERDC/WES (WES 1949) and by Turnbull and Mansur (1954).

Barron (1948) published a solution for the discharge and pressures associated with an infinite line of fully penetrating wells where leakage occurs through the top blanket. As this procedure predicted lower well flows and lower gradients than procedures based on impervious blankets, it allowed greater spacings and more economical designs.

In 1955, the Headquarters, U.S. Army Corps of Engineers, published Civil Works Engineer Bulletin 55-11, which updated design guidance for well design based on the results of more electrical-analogy model studies. The procedure accounted for partially penetrating wells and a leaking top stratum. Solutions were provided for the average and maximum head in the plane of wells as a function of the head on the levee, thickness and permeability of the two idealized foundation layers, well penetration, well spacing, and well diameter. The procedures in TM 3-424 (WES 1956b) are those of Bulletin 55-11, but TM 3-424 provides further detail as to incorporating hydraulic head loss in the well into the analysis. The analysis requires an iterative solution as the head loss in the well, the head between wells, and the well flow are interrelated variables.

In 1963, Engineer Manual 1110-2-1905 (HQDOA 1963) provided extensive tables for design of finite lines of relief wells. The tables were based on additional electrical model studies. To this writer's knowledge, however, these tables have seldom been used in design practice.

Seepage Berms

TM 3-424 (WES 1956b) provided solutions for design of impervious, semipervious, and pervious seepage berms. Most, if not all, subsequent berm designs have been for semipervious berms (berm permeability equal to the blanket permeability). LMVD provided supplemental design criteria to be used with the solutions by letter to its Districts in 1962 (USAEDLMV 1962). Design curves incorporating the criteria were published by LMVD in 1976 (USAEDLMV 1976).

Barron (1980) published detailed derivations of design equations for impervious, semipervious, and pervious berms including special cases of constant and variable safety factors. Barron (1984) later corrected the 1980 work and supplemented it with analysis procedures for short berms where boiling is allowed at some distance from the levee toe. In his conclusions, Barron took note of the deterministic nature of his solutions and their sensitivity to variations in the variables; consequently, he suggested that "a probabilistic approach be used in design."

5 Levee Performance During Floods

Lower Mississippi River

TM 3-424 (WES 1956b) and Turnbull and Mansur (1961a) reported the analysis of piezometer data obtained at 15 piezometer sites during the 1950 high water and selected sites at other times. Conclusions pertinent to this study include the following:

a. *Sand boil occurrence*. The locations of sandboils were highly correlated with local geologic conditions. In point bar areas, most sand boils occurred in ridges adjacent to swales. Sand boils also tended to occur between levees and parallel clay-filled plugs and in landside ditches.

b. *Sand boil gradients*. Where sand boils occurred, measured gradients were in the range 0.5 to 0.8, often about 0.65, and generally lower than the 0.85 value used in the analysis procedure. Two influencing factors were suggested: old boils may be reactivated at relatively low pressures, and the pressure relief resulting from the boil may lower piezometer readings in the area.

c. *Entrance and exit distance*. Both the entrance (s) and exit (x_3) distances varied with river stage. In certain cases, a reduction in the entrance distance with river stage was attributed to scour in riverside borrow pits. It was observed that calculated entrance and exit distances were quite variable, and that a 0.015-m (0.05-ft) reading error in each of two piezometers could result in substantial error in calculating these distances.

d. *Permeability ratios*. Ratios of the substratum horizontal permeability to the landside top stratum vertical permeability, backfigured from the entrance and exit distances, were typically in the range 100 to 2,000.

e. *Permeability.* Apparent top blanket permeability decreased as top blanket thickness increased as a result of the decreased effect of defects, such as root holes and cracks. Also, the permeability of the landside blanket was 2 to 10 times that of the riverside blanket, apparently because of downward flow sealing defects and upward flow opening defects.

Appendix E of TM 3-424 (WES 1956b) reported the analysis of the same sites for the 1961 high water. It was found that residual heads at the levee toe were slightly higher than in 1950. Surprisingly, perhaps, no indications of excessive seepage or sand boils were reported in 1961, which is in considerable contrast to the case in 1950. Effective seepage entrance distances (s) were in the same order of magnitude as in 1950, although large increases and decreases were observed in certain instances. Effective seepage exit distances (x_3) were highly variable, with magnitudes one to two times those measured in 1950. The discrepancies in the entrance and exit distances were variously attributed to unsaturated aquifer conditions, riverside scour, faulty piezometers, and unreliable measurements of the tailwater elevation.

USAE District, St. Louis

Wolff (1974) and the USAED, Saint Louis (1976) reviewed the performance of the Alton-to-Gale (Illinois) levee system along the middle Mississippi River during the record flood of 1973. The review was based on approximately 20,000 piezometer readings obtained from approximately 1,000 piezometers along 384 km (240 miles) of levee. Readings from a significant percentage of the piezometers were extrapolated to design flood stages. To minimize unsteady flow effects, only data obtained during the rising side of the river hydrograph were extrapolated. The 1976 report concluded that the analysis and design procedures generally produced a reliable levee, but identified several sets of special circumstances where existing procedures appear deficient:

a. *Characterization by two soil layers.* Of the reaches found to be apparently still critical with respect to underseepage, many have a thick (6- to 15-m (20- to 50-ft)) layer of sandy silt or silty sand beneath the top blanket and above more pervious sands. In the present analysis and design procedure, this “intermediate” stratum must be mathematically transformed and combined with either the top blanket or substratum. When wells were designed and installed, the intermediate stratum was blanked off as the materials were too fine for the standard filter and screen. During floods, such wells may flow profusely yet piezometers at the base of the top blanket indicate excessive residual heads. This phenomenon occurs because the horizontal permeability of the intermediate stratum is greater than the vertical permeability of the substratum, causing seepage in the intermediate stratum to be more readily conducted landward than toward the well screen (Figure 1). Similar foundation conditions had been tested in the ERDC/WES hydraulic model B (WES 1949), but the wells had not been blanked off.

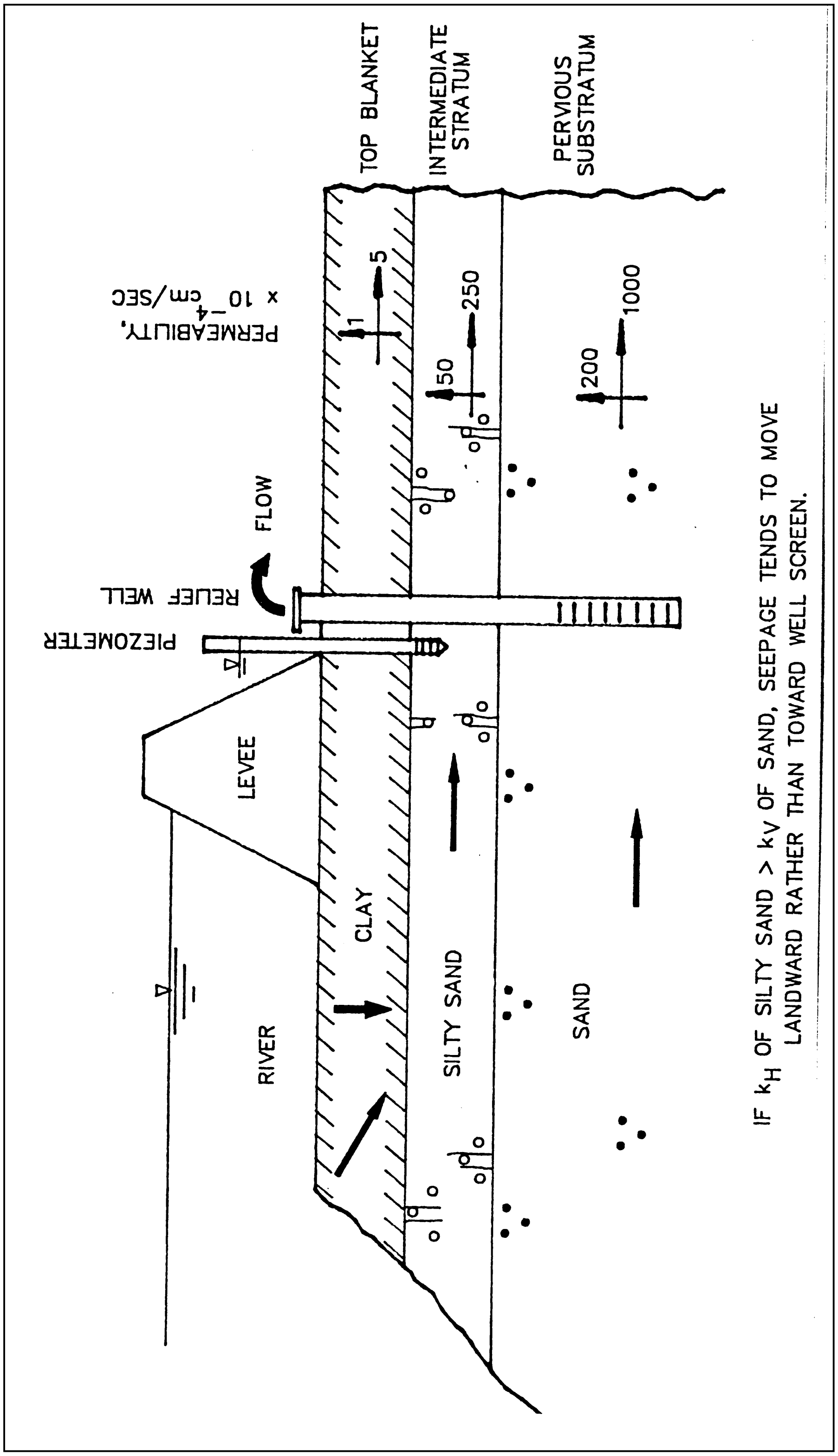


Figure 1. Foundation profile with intermediate stratum

b. *Corners.* Where a levee bends or turns a corner (frequently encountered where a riverfront levee meets a flank levee), the landside toe is subject to seepage from two directions and the measured residual heads may be significantly higher than those predicted from the 2-D analysis.

c. *Back levees and flank levees.* Where levees are built to provide protection from small creeks and streams traversing the main river valley that are not efficiently connected to the pervious substratum, piezometric levels may reflect slowly rising regional groundwater levels rather than being a function of the variables involved in underseepage analysis.

d. *Entrance and exit distances.* Entrance and exit distances calculated at piezometer ranges were frequently found to be shorter than assumed for the original design. Where values of 182 to 305 m (600 to 1,000 ft) were assumed in design, measured values were often 122 m (400 ft) or less.

e. *Permeability ratio.* The ratios k_f/k_b were smaller than assumed for design (400 to 2,000) (WES 1956a) but were reasonably consistent with later design guidance (100 to 800 in Rock Island) (USAED, Rock Island 1960; $k_b = f(z)$, USAEDLMV 1976). It was also noted that data from piezometer ranges in reaches with flowing wells cannot be used to check design assumptions for s and x_3 because of the significant nonlinear effect of the well drawdown on the piezometric surface.

USAE District, Rock Island

Underseepage conditions in the USAED, Rock Island, were assessed by Cunny (1980) and Bawmann (1983) and their assessments were reviewed by Daniel (1985).

Cunny (1980) prepared a comprehensive report involving 29 piezometer ranges and data from as many as nine high water periods; however, for a number of reasons, the amount of reliable data is much smaller than the above figures would suggest. Salient points and conclusions from Cunny's report include the following:

a. *Permeability ratios.* No trend between the ratio k_f/k_{bl} and the blanket thickness z could be identified as was found for the Lower Mississippi Valley levees. However, Cunny (1980) recommended that the value of the permeability ratio be taken as 100 on the landside and 200 on the riverside. These values are lower than previous Rock Island criteria (USAED, Rock Island 1960) and significantly lower than Lower Mississippi Valley criteria.

b. *Residual heads.* Residual piezometric heads at the levee toe were only slightly smaller than calculated using old permeability ratio criteria because of compensating riverside and landside effects. This is further discussed in Table 1.

Table 1
Validity of Assumptions in Underseepage Analysis and Design

Assumptions	Cases Where Inappropriate
Steady-state flow	Rising and falling river, areas with observed timelag in piezometric response
Two-dimensional flow	Corners or bends in levee
	Seepage concentrations adjacent to clay-plugs and clay filled channels
Two-layer foundation	Where an intermediate stratum (usually silty sand) is present
Vertical flow through top stratum	May be inappropriate where an intermediate stratum is modeled as part of top stratum
Horizontal flow through substratum	May be inappropriate where an intermediate stratum is modeled as part of substratum
Continuous and uniform top blanket	Riverside borrow pits
	Landside ditches
	Ridge and swale topography
	Clay-filled channels parallel to levee

c. *Berm design.* Required seepage berm widths based on observed data and conditions are much smaller than those calculated from prevailing criteria. Berm width formulas based on maintaining a factor of safety against uplift may not identify where berms are or are not needed. Berms may not prevent boils, but may only move them away from the levee. It appears that berms (or wells) may not be needed at all where pressures can be uniformly and harmlessly dissipated. Sizing berms using a creep ratio approach may be somewhat better than the uplift approach, but further research is required relative to a rational berm design procedure.

Daniel's (1985) review of the Cunny's report and other Rock Island data yielded the following observations and conclusions:

a. The correlation between measured gradients and the occurrence of sand-boils is weak. Although the analysis suggests initiation of boiling at gradients about 0.85, boils were observed at gradients of 0.54 to 1.02 (avg. 0.68).

b. Calculation of gradients is sensitive to the top stratum thickness, z, an uncertain quantity.

c. There is an inverse correlation between blanket thickness and boil occurrence.

d. Hydraulic conductivity is hard to quantify; values given in Corps criteria are arbitrary.

e. The hydraulic head is not constant along vertical planes as assumed in analysis.

f. The effective exit distance, x_3, is a function of several uncertain parameters and therefore is extremely uncertain.

g. The effective entrance distance landward of the levee toe, x_1, apparently varies with river stage in violation of the design assumptions that it is constant.

h. The critical gradient is based on a homogeneous top blanket with no cohesion and flexural strength.

Daniel's (1985) recommendations include daily reading of piezometers during high water to obtain a better database, further study of the relationship of high water to slope stability, and development of a relatively sophisticated computer program to replace the existing method of analysis.

6 Discussion Regarding Measured Performance

Harr (1977) presented the concept of a design chain (Figure 2). Measurements and performance observations made during floods provide the experience component (fourth link) from which the strength of the preceding links can be gauged. Where performance differs from that predicted, a weakness or anomaly in the chain is indicated. A more detailed analysis chain specific to underseepage analysis is shown in Figure 3. Working backwards through the chain, the following paragraphs discuss the apparently adequate and inadequate aspects of the existing analysis procedures based on measurements and observations made in the Lower Mississippi Valley and the St. Louis and Rock Island Districts.

Occurrence of Sand Boils

Sand boils occur at less-than-predicted gradients. This was noted as early as 1952 (WES 1952) and is well documented in Figure 47 of TM 3-424 (WES 1956b). It was also noted by Daniel (1985) in his analysis of Rock Island performance data. In fact, there is a significant similarity between the TM 3-424 figure and Daniel's figure. Nevertheless, boil occurrence is rare in terms of the many miles of levee subjected to similar gradients. It is apparent that local geologic conditions must have a more significant influence on where boils occur than does the gradient. There is considerable evidence that boil occurrence is often related to concentration of seepage at discontinuities and defects in the top blanket. Such nonuniform blanket geometry is not accounted for in the uniform, 2-D model used for design. Despite the verbage given to geologic conditions in TM 3-424 and the colorful 3-D cross sections illustrating floodplain deposits and their relationship to underseepage, the same analysis and design criteria are applied in the same manner for all types of deposits. The likelihood of boil occurrence at discontinuities is also implied by Cunny (1980) who refers to a long-held concern that berm formulas… are not appropriate for locations where seepage pressures can be uniformly and harmlessly dissipated (emphasis added).

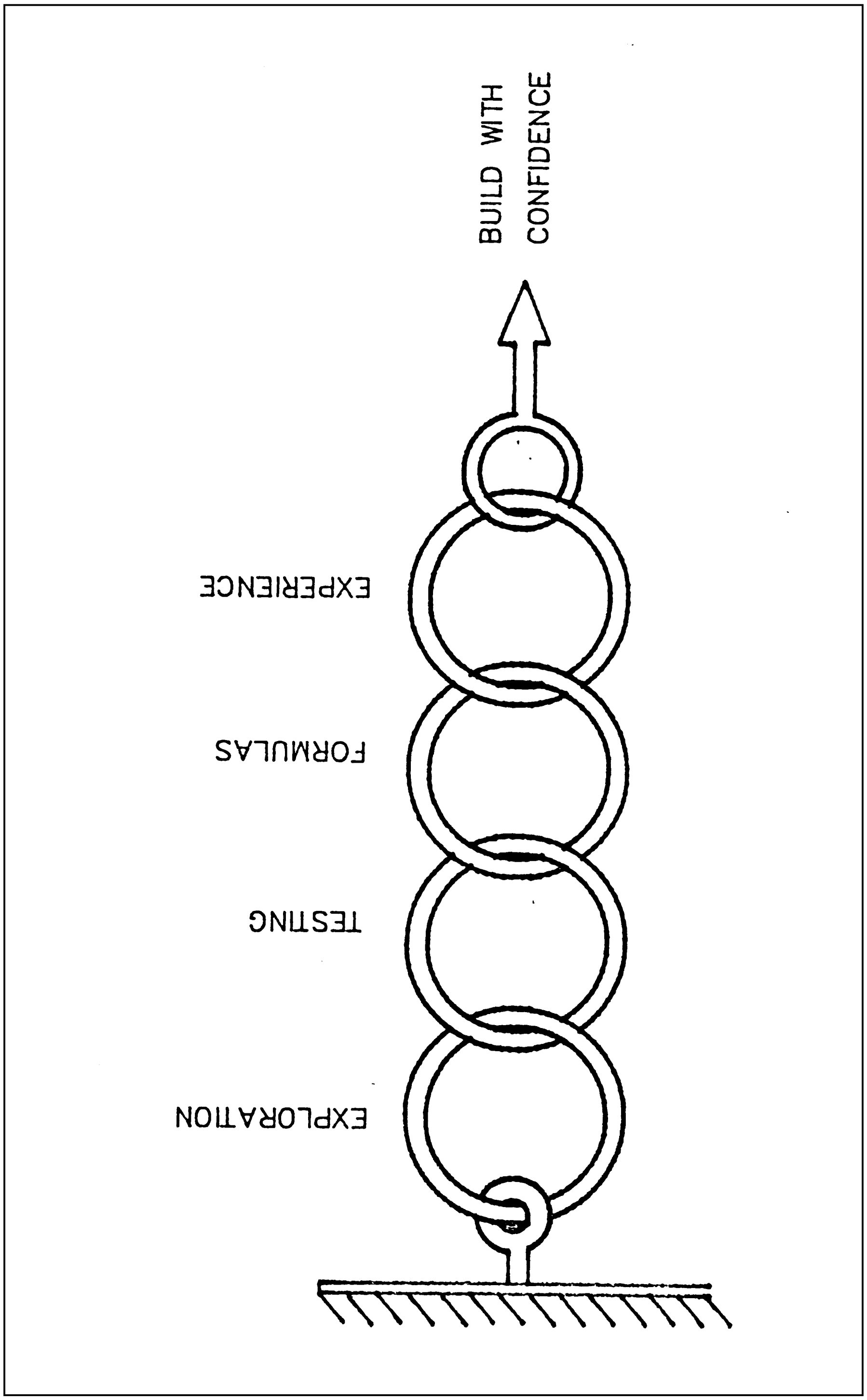


Figure 2. The design chain (after Harr 1977)

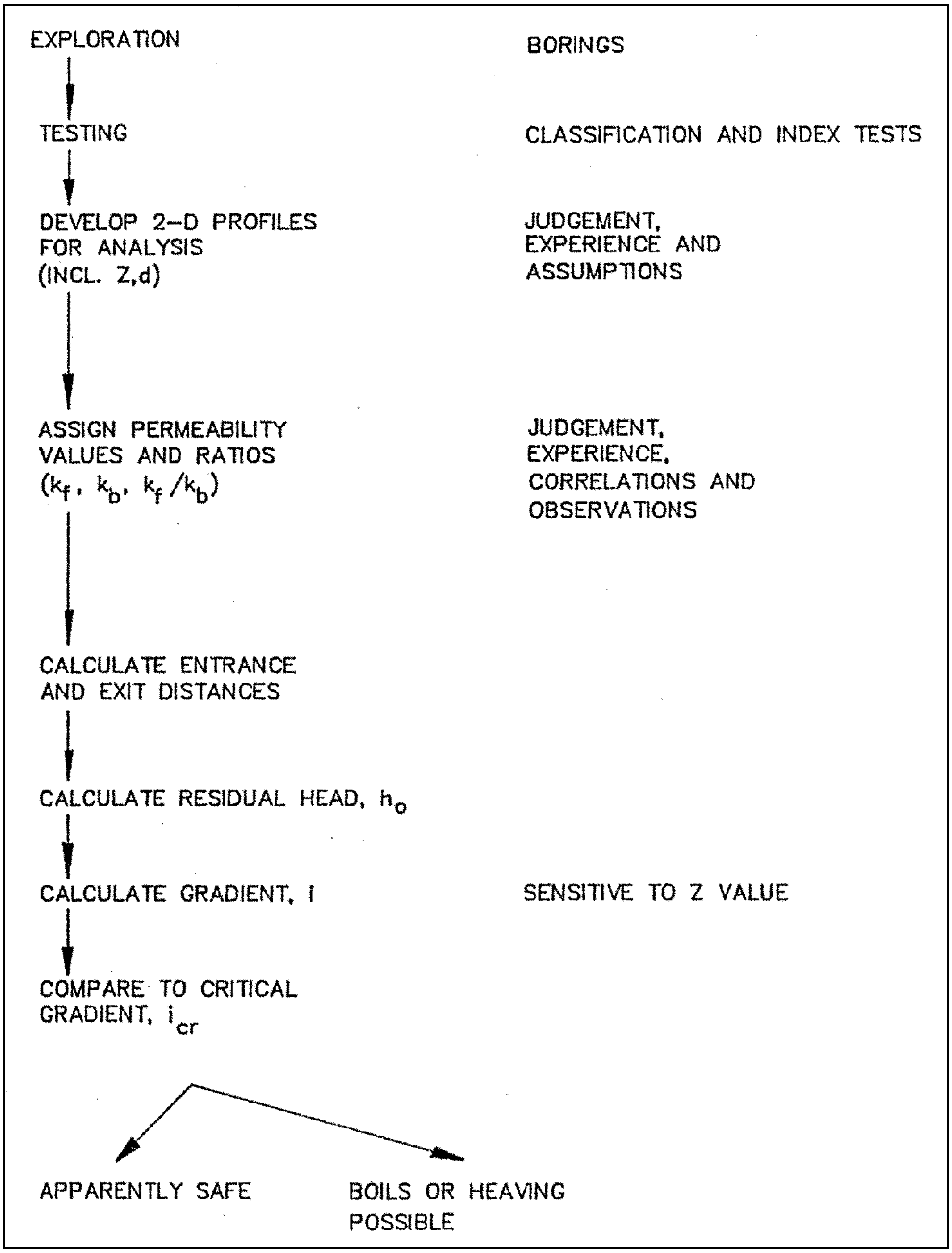


Figure 3. The analysis chain for underseepage

Relationship of Boils to Blanket Thickness

The correlation presented by Daniel (1985) between boil occurrence and top blanket thickness implies that boils are the only concern and overlooks the possibility of rather sudden rupture of thick clay blankets retaining high piezometric pressures (heaving). This was apparently the case of the 1943 floodwall failure at Claryville, MO, described by Middlebrooks and Jervis (1947). Safety, seepage quantities, and pressures are related to both blanket thickness and blanket permeability. These relationships are conceptually illustrated in Figure 4.

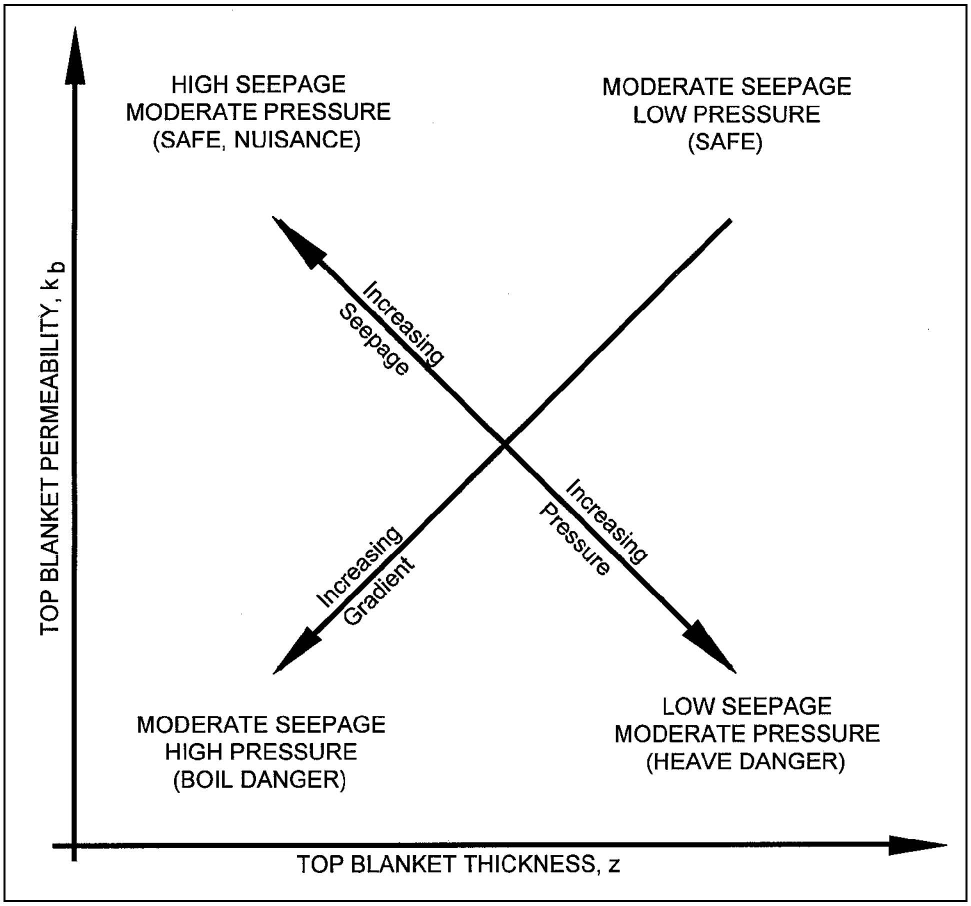


Figure 4. Relationships of seepage and subsurface pressures to blanket properties

Critical Gradient Criteria

Daniel (1985) notes that the calculation of the critical gradient was based on a homogenous top blanket with no cohesion and flexural strength and noted that these assumptions would often be invalid. This was also challenged in a discussion of Turnbull and Mansur's paper (1961b). In this discussion was recommended the use of a factor of safety against uplift defined as the ratio of the saturated weight of the blanket to the piezometric pressure at the base of the blanket. In their reply, Turnbull and Mansur did not argue the concept where the gradient safety factor is greater than the uplift safety factor, but pointed out that it is more conservative to use the gradient safety factor where it is the lower value. Furthermore, they conceded in the case of cohesive clay blankets, particularly in ditch bottoms in which the span is relatively short, the blanket might be sufficiently tough and cohesive to hold a pressure somewhat greater than the critical. However, it does not appear prudent to rely on cohesive strength in most cases for design practice.

Calculation of Gradients

As pointed out by Daniel (1985), the calculation of gradients is an uncertain process because of the difficulty in properly estimating the blanket thickness, z. It becomes very judgmental where a nonhomogeneous blanket must be transformed to an equivalent homogeneous blanket, or where the blanket changes thickness along or beyond the levee toe. In ridge and swale topography, the top blanket may be highly stratified, and development of an idealized design profile by the engineer may seem to be a meaningless process. Estimating blanket thicknesses was a constant problem for the USAED, St. Louis (1976) analysis. Local geology enters the picture again; the equations can predict adverse seepage conditions only to the extent that the section analyzed models the subsurface conditions.

Calculation of Entrance and Exit Distances and Residual Head

Daniel's review suggested that accurate values of the entrance distance, s, and the exit distance, x_3, are almost impossible to obtain. The problems are not as severe in practice as it would appear, even though they are functions of four uncertain parameters. This arises because the prediction of interest is the residual head, h_o, at the levee toe. Working backwards through the analysis equations, h_o is determined by simple proportion involving the entrance and exit distances:

$$h_o = H \frac{x_3}{x_1 + x_2 + x_3} \tag{1}$$

where

x_2 = base width of the levee

$x_1 + x_2$ = entrance distance, s, from the landside toe

It is apparent that h_o can be accurately calculated if the proportion between x_1 and x_3 is reasonably correct, even if their actual values are grossly in error. For a levee reasonably distant from the river,

$$x_{1,3} = \sqrt{\frac{k_f}{k_b} zd} \quad (2)$$

where riverside values of the parameters are used to calculate x_1 and landside values are used to calculate x_3.

As the landside and riverside values are often significantly correlated, the equations yield values for the entrance and exit distances that are generally in correct proportion. Furthermore, the extraction of the square root tends to minimize the effects of error in the parameters, and errors in z and d are just as likely to be compensating as biased. Cunny (1980) implies the same idea; that is, that one can reasonably predict the residual head even with the wrong permeability ratios.

The variation of x_1 and x_3 with river stage noted by Daniel (1985) is discussed in detail in TM 3-424, Appendix E (WES 1956b). Although the analysis procedure requires a constant value, it is inferred that the design value should represent the critical combination of x_1 and x_3 values.

Permeability Values and Ratios

Although hydraulic conductivity (or permeability) is difficult to quantify, the Corps' recommendations are not arbitrary as suggested by Daniel (1985) but are based on considerable experience and piezometric measurements. Residual heads and gradients are dependent only on the ratios of the permeabilities, not their absolute values. As the values used are back-calculated from observed piezometric grade lines and then reused in the same equations to estimate the piezometric grade line for other conditions, it is not surprising that they provide generally good results. The permeability ratios and the blanket formulas form a closed-loop; thus, they tend to work whether they are correct or not.

Nevertheless, data obtained from the 1973 flood in St. Louis indicated lower ratios than those typically recommended for use in the Lower Mississippi Valley, and the Rock Island analysis indicated still lower values. While the reasons for this trend require more study, it is noted that these sites represent significant differences in the geologic environment. The Lower Mississippi is a classic meandering stream in a wide valley. Levees are at relatively great distances from the river, and discontinuities such as clay plugs and oxbows are common. The river carries a high sediment load. At the other extreme, the characteristics of the valley in the Rock Island District are primarily related to glacial melting. The valley is rather narrow and there are relatively few meander deposits. Levees are relatively close to the river. Much of the sediment load enters the river downstream of the Rock Island District. The St. Louis District and the middle Mississippi Valley represent transitional conditions. Concentrations of seepage adjacent to clay plugs or other blanket discontinuities increase residual heads and may result in apparently higher permeability ratios than would be measured under relatively uniform blanket conditions.

Determination of Parameters from Piezometer Data

Estimates of entrance distances, exist distances, and permeability ratios have generally been made only at piezometer ranges because a linear hydraulic grade line can be fitted through a number of points. Too many assumptions appear necessary to estimate these factors from a single piezometer at the levee toe. Nevertheless, all reports of such analyses have mentioned the difficulty in obtaining reasonable values because of the sensitivity of the calculations to minor errors in the differences between piezometer readings. In an effort to assess the relative importance of the variables used in the analysis, a simplified form of the equations yielding the landside residual head was developed (Appendix A). Using this equation and the measured residual head from a single piezometer at the levee toe, and making a few reasonable assumptions, considerable insight can be gained regarding the probable values of x_1, x_3, and the permeability ratio. This item is further discussed in Appendix A.

Assumptions of Vertical and Horizontal Flow

Daniel (1985) points out the weakness of the assumptions of a constant head along vertical planes in the pervious substratum (horizontal seepage). The validity of this assumption increases with increasing permeability ratio; Bennett (1946) warned of the necessary conditions for making this assumption. The error resulting from this assumption was investigated in TM 3-424 (WES 1956b), and data were presented to show that there is generally less than a 0.61-m (2-ft) head difference between piezometers at the base of the blanket and at the midpoint of the aquifer. However, the problems associated with silty sands in an intermediate aquifer noted in the St. Louis analysis and similar problems expressed by U.S. Army Engineer District, New Orleans (personal communication), in silty sands support Daniel's concern.

Deficiencies in Procedures, Summary

Based on the various reviews of performance data, a summary of the assumptions made in underseepage analysis and the special cases in which they may be deficient has been prepared and is given in Table 1. The performance data also indicate that there can be wide variation in the observed values of parameters assumed or calculated in the design. To illustrate this, the ranges of the permeability rates and entrance distances are shown in Figure 5.

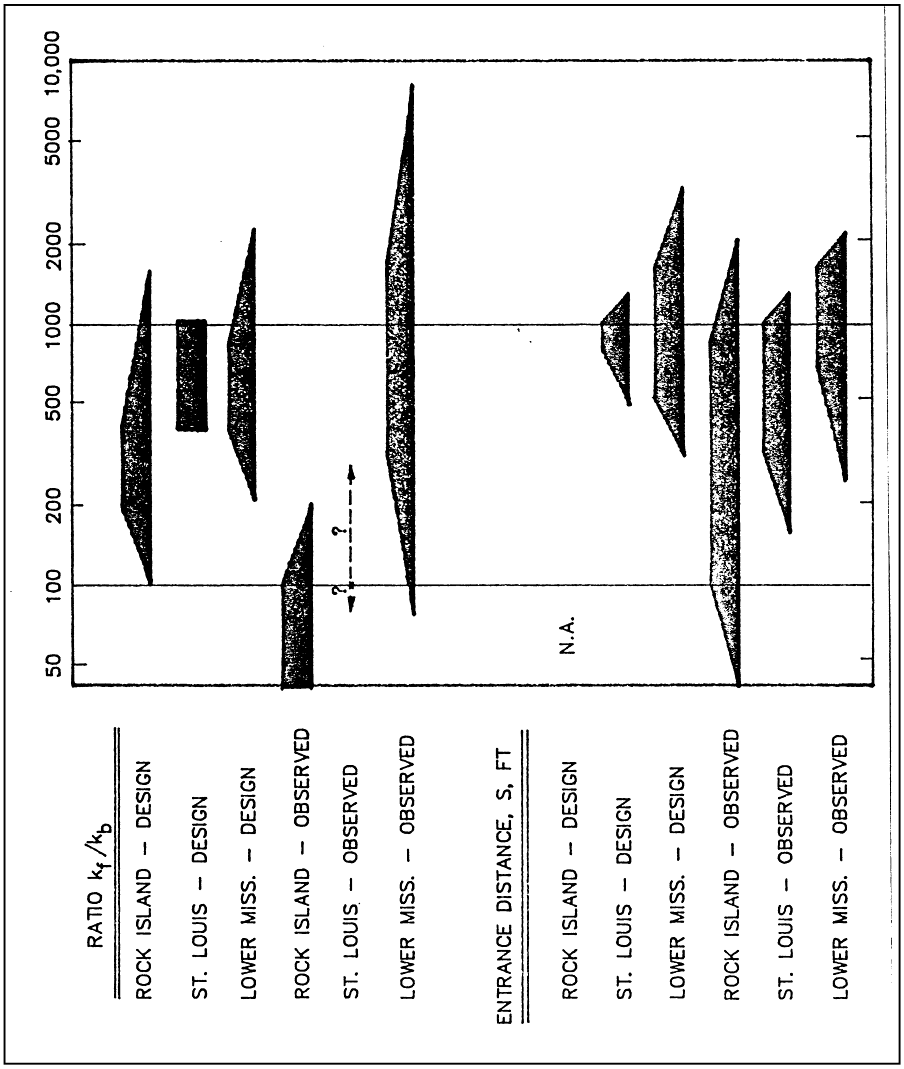


Figure 5. Typical ranges of parameters (k_f/k_b) and s

Possible Improvements to Procedures

Possible improvements to the analysis procedures lie in four areas:

a. Computerized analysis using existing procedures to allow more expedient solutions.

b. Probabilistic adaptation of existing procedures to allow for uncertainty in the parameters.

c. Extension of the existing procedures to more general cases to allow more realistic modeling of actual conditions.

d. Improvements in the exploration process to allow better identifications of the subsurface conditions to be modeled.

The equations for seepage analysis as well as for design of seepage berms and relief wells have been adapted to computer programs by several parties, including Mr. Patrick Conroy of the St. Louis District and one implemented by Jaycor, Inc., for the ERDC. Daniel's (1985) recommendation of a relatively sophisticated computer program is vague. As he notes what he believes are significant deficiencies in the present analytical technique, it is not what should be computerized.

Barron (1984) suggested that the uncertainty of the variables was the problem rather than the analytical techniques and suggested development of a probabilistic approach.

However, Table 1 has identified several cases where the uniform, 2-D idealized profile used in analysis is incompatible with the actual subsurface conditions. Suggested areas of improvement in this regard (items *c* and *d* above) are noted in Chapter 9 of this report.

7 Problems with Underseepage Monitoring and Controls

Maintenance of Piezometers

In all regions studied, there have been numerous occasions of piezometers being damaged by tractors and other vehicles, and piezometers malfunctioning because of siltation and blockage by foreign substances. All of the major performance review reports cite problems with faulty piezometers. A rotating maintenance program is employed by the St. Louis District that provides for inspection and repair of every piezometer over a 3- to 5-year cycle.

Piezometer Reading During Flood

Review of the various performance reports indicates that methods for determining which piezometers to read and when to read them varies considerably from District to District and from time to time. Several reports recommend daily piezometer readings during flood. Such frequency was nearly accomplished by the St. Louis District during the 1973 flood; however, emphasis on quantity of readings can cause engineers to be inundated with data with the attendant risk of a failure occurring while the data are waiting to be analyzed.

Piezometer reading during flood has two somewhat contrary objectives real-time safety assessment and the evaluation of design procedures using performance data. In the first case, the emphasis should be on wide-scale coverage and visual assessment of the levee system by trained geotechnical engineers. In this case, the engineers read piezometers only to the extent necessary to assess safety, and piezometers are selected based on such concerns as high apparent pressures (flowing piezometers), known problem areas based on previous performance, and areas with new levees and no previous experience. In the second case, procedure assessment, the emphasis should be on obtaining complete information, but only in carefully selected areas where the subsurface conditions are sufficiently well-defined to permit detailed analysis. Experienced technicians may be used for acquiring data as the analysis may be done at a later date. Equally important to both cases is the measurement of river levels and landside impoundment levels as well as piezometric levels; these measurements have been often cited as being overlooked in the performance review reports.

Premature Relief Well Flow

A significant operational problem with relief wells has been that they begin to flow at overbank, but noncritical, river stages. Where collection and disposal measures are not provided for well effluent, such as along certain agricultural levees in the St. Louis District, crop damage may occur during normal spring high water. Consequently, farmers have obstructed well outlets with lumber, sandbags, and other devices, posing a potential threat to underseepage control. Beginning with the record 1973 flood, local interests have been cooperative in removing obstructions as significant river stages occur and when advised by field engineers. The only solution employed to date has consisted of providing the wells with a removable plastic standpipe that prevents premature flow but reduces the factor of safety. There has been considerable discussion over the years, but little research and development, on providing a positive but foolproof valving system that would open when needed.

Deterioration of Relief Wells

Historically, there has been concern with the use of relief wells for underseepage control because of possible reduction of efficiency over time resulting from screen incrustation. A detailed discussion of the problem is beyond the scope of this report. To evaluate possible reduction in efficiency, pumping tests have been periodically performed on wells in the Lower Mississippi Valley (WES 1952) and in the St. Louis District (Montgomery 1972; USAED, St. Louis 1976). The earlier reports document a reduction in well efficiency (sometimes substantial) with time but at a decreasing rate. The later report and subsequent unpublished studies in the St. Louis District indicate that prolonged well flow and changes in groundwater chemistry during flood may lead to recovery of lost efficiency at the time the wells are most needed.

8 European Practice

Peter (1982) provides a thorough review of underseepage analysis techniques employed in Europe, with particular emphasis on the Danube Valley. The differential equations for landward propagation of seepage pressures through layered anisotropic foundation soils are presented and numerical solution is suggested. Also, a discussion is presented regarding the prediction of sandboil occurrence using the critical gradient versus the critical velocity approach. In the critical velocity approach, soil properties (grain and/or pore diametric porosity, grain size distribution) and water velocity are considered in addition to unit weight.

It is apparent that European engineers have continued theoretical and laboratory research beyond the 1950's methods used by the USACE. However, the available presentations are highly theoretical and not amenable to practice in their present form; also the fourth link (experience) of the design chain is not present for American levees and soils. Any new research and development in underseepage analysis and control should include a careful review of European research and practice.

9 Conclusions and Recommendations

Conclusions

To prevent sandboils and heaving of the top blanket, the USACE has devised a system of underseepage analysis procedures and control measure design procedures. The analysis procedures seek to find reaches where the exit gradient at design flood would exceed a critical value (typically 0.85),[1] based on foundation properties and geometry and the assumptions described in Table 1. In the reaches found, the USACE designs and constructs control measures (seepage berms or relief wells) that are costly and have associated operational problems.

Based on data from St. Louis, Rock Island, and the Lower Mississippi, it can be fairly stated that boils occur in locations that are primarily governed by minor geologic details and discontinuities. Where they do occur, they are associated with apparent gradients of 0.5 to 0.9, often on the order of 0.7.

Although the local geology is identified as being of great importance in the development of underseepage problems, in practice it is incorporated into the analysis procedure only in a very indirect and judgmental manner and may often be overshadowed by the number-crunching aspects of the design. The uniform, 2-D cross section used in analysis is incapable of predicting seepage conditions in nonuniform or discontinuous profiles.

In the writer's opinion, the present procedures in practice probably identify most of the reaches where underseepage may be critical and probably misidentify many more reaches. On the other hand, they probably miss a few critical reaches which then require remedial treatment during flood. To hazard an educated guess, the reader is referred to Table 2, which is based entirely on the writer's experience and opinion, and is intended to illustrate defects in the analysis chain more than to present defensible numbers.

A critical weak point in the entire analysis and design process is the characterization of the top blanket. No reasonable and consistent method is available that will lead two designers with the same boring log to necessarily

[1] Districts have lowered the critical exit gradient to 0.5 since the great flood of 1993.

Table 2
Estimated Adequacy of Seepage Analysis Procedures[1]

Identified	Actually Critical	Actually Noncritical	Total
Critical	19%	21%	40%
Noncritical	1%	59%	60%
Total	20%	80%	100%

[1] Figures are estimated percentages of levee length.

similar values of z and k_b, yet the calculation process is driven by these variables. The blanket profile is often developed by borings 152 m (500 ft) apart, sampled on 0.9- to 1.5-m (3- to 5-ft) increments. Continuity of lenses and layers in the top blanket is usually uncertain. Division of the levee profile into design reaches is an undocumented "art." Much of the success of present designs might be attributable to the fact that much of the design was accomplished by a relatively small group of engineers also involved in the development of the equations and criteria.

Parameters such as the permeability ratio between the foundation and the top blanket seem to exhibit significant variations going from the Upper Mississippi River to the Lower Mississippi River and there is reason to hypothesize that such differences result from the depositional environment of the materials. More detailed research in this regard may yield a more rational approach to estimating such parameters.

Development of supplemental analytical techniques would be useful for certain situations listed in Table 1. If the present procedures are to be revised with a view toward reduction of the number of reaches requiring controls, the emphasis should be on the geometry, characteristics, and continuity of the top blanket.

Recommendations[1]

To update underseepage analysis and control techniques for their second 50 years, research recommendations are offered in the three areas of analysis, design and construction, and expedient control during floods.

Analysis

Apparent research needs include the following:

a. Development of a 2-D analysis procedure incorporating three foundation layers, each with anisotropic permeability conditions (Figure 6).

[1] Some recommendations are out of date, because this report was written in 1989 and published 2002.

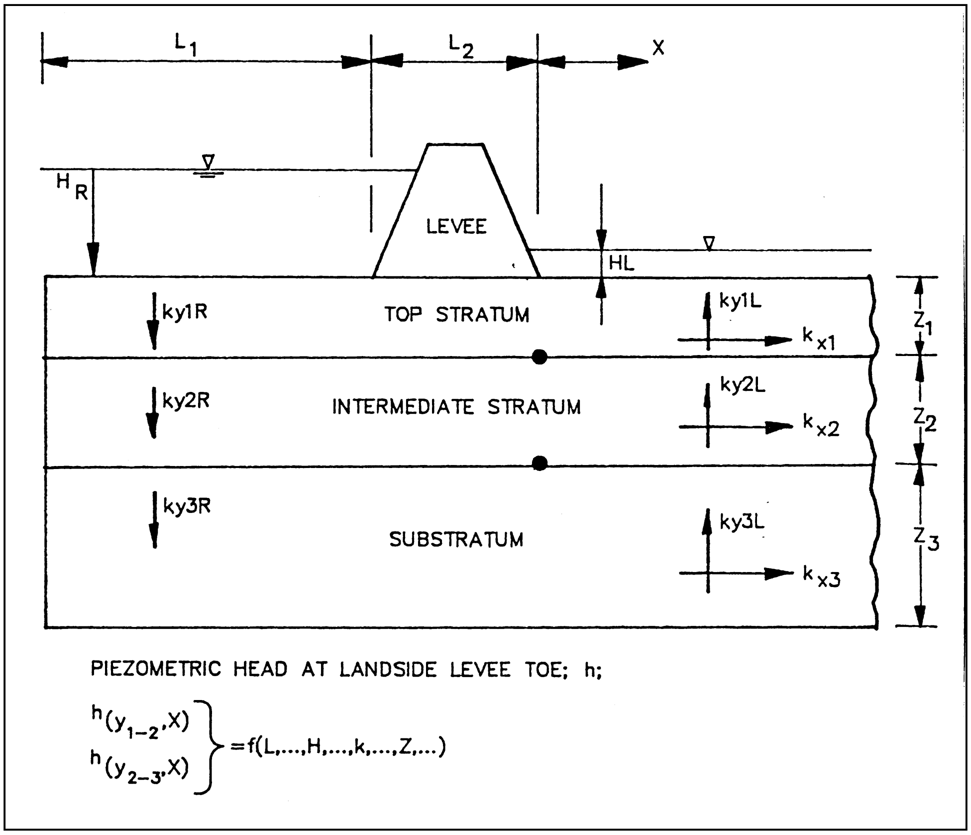


Figure 6. Analysis model for three-layer foundation

b. Development of a 2-D analysis procedure for nonuniform foundation conditions such as borrow pits, ditches, and clay plugs parallel to the levee (Figure 7).

c. Development of an analysis procedure for levee corners (Figure 8).

d. Development of a general, 3-D analysis procedure (Figure 9).

e. Development of an analysis procedure accounting for time effects.

f. Development of probabilistic analysis procedures that consider uncertainty in the variables.

g. Research into better techniques to characterize the top blanket and subdivide reaches. The cone penetrometer and shallow geophysical techniques offer the capability to significantly increase the level of information normally obtained by conventional borings.

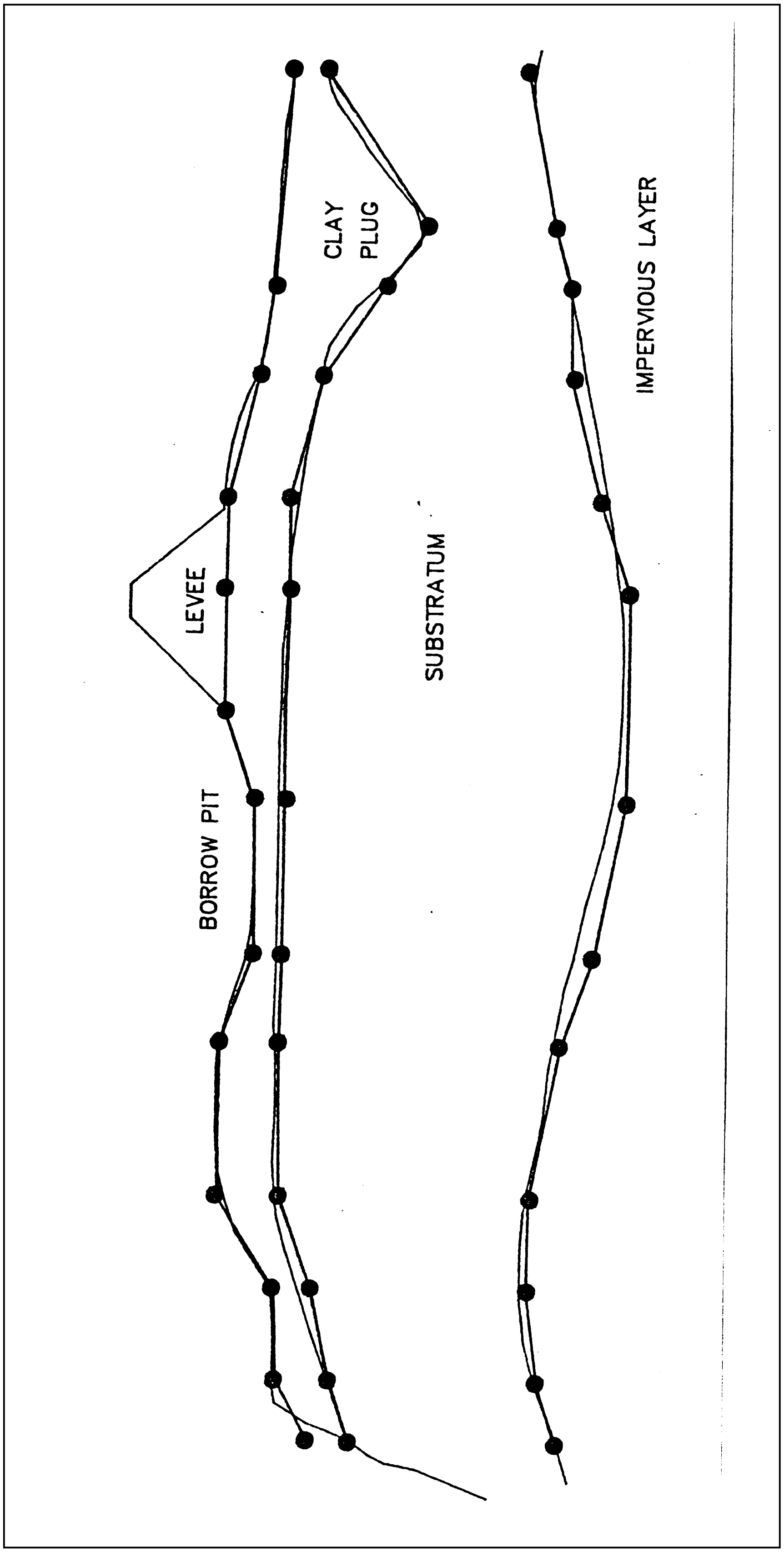


Figure 7. Analysis model for nonuniform foundation materials

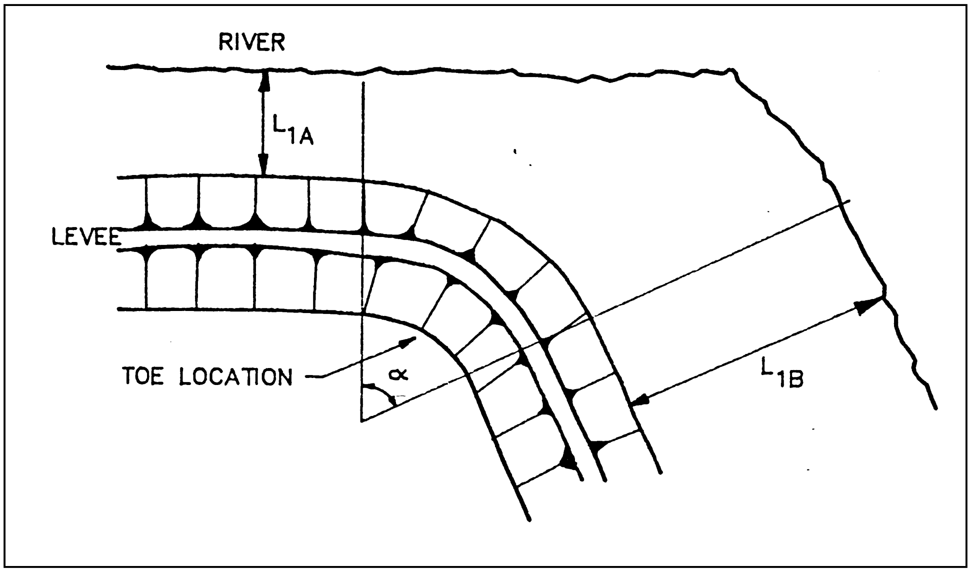


Figure 8. Analysis model for levee corners

Design and construction

Apparent research activities include the following:

a. Entrance losses for modern well screens. Designers still use curves for wooden well screens with a 572-sq cm per meter (30-sq in.) open area per foot. Modern wire-wound well screens provide open areas in excess of 1,908 sq cm per meter (100 sq in. per foot). This higher efficiency is not incorporated in design because reliable head loss data are not available.

b. Design and construction of shallow jetted wells. It may be cost-effective to construct lines of partially penetrating wells installed by jetting similar to the techniques used for installing suction wells for dewatering. Although more wells would be required, the savings in drilling and filter placement may likely result in a net savings.

c. Use of continuous prefabricated vertical drains (similar to prefabricated wall drains) along the levee toe.

Expedient control during floods

Traditional sand bag ringing of sandboils is labor-intensive, time-consuming, and hazardous to personnel. Many other techniques for boil control could be conceived and evaluated. These might include:

a. Weighted geotextile blankets.

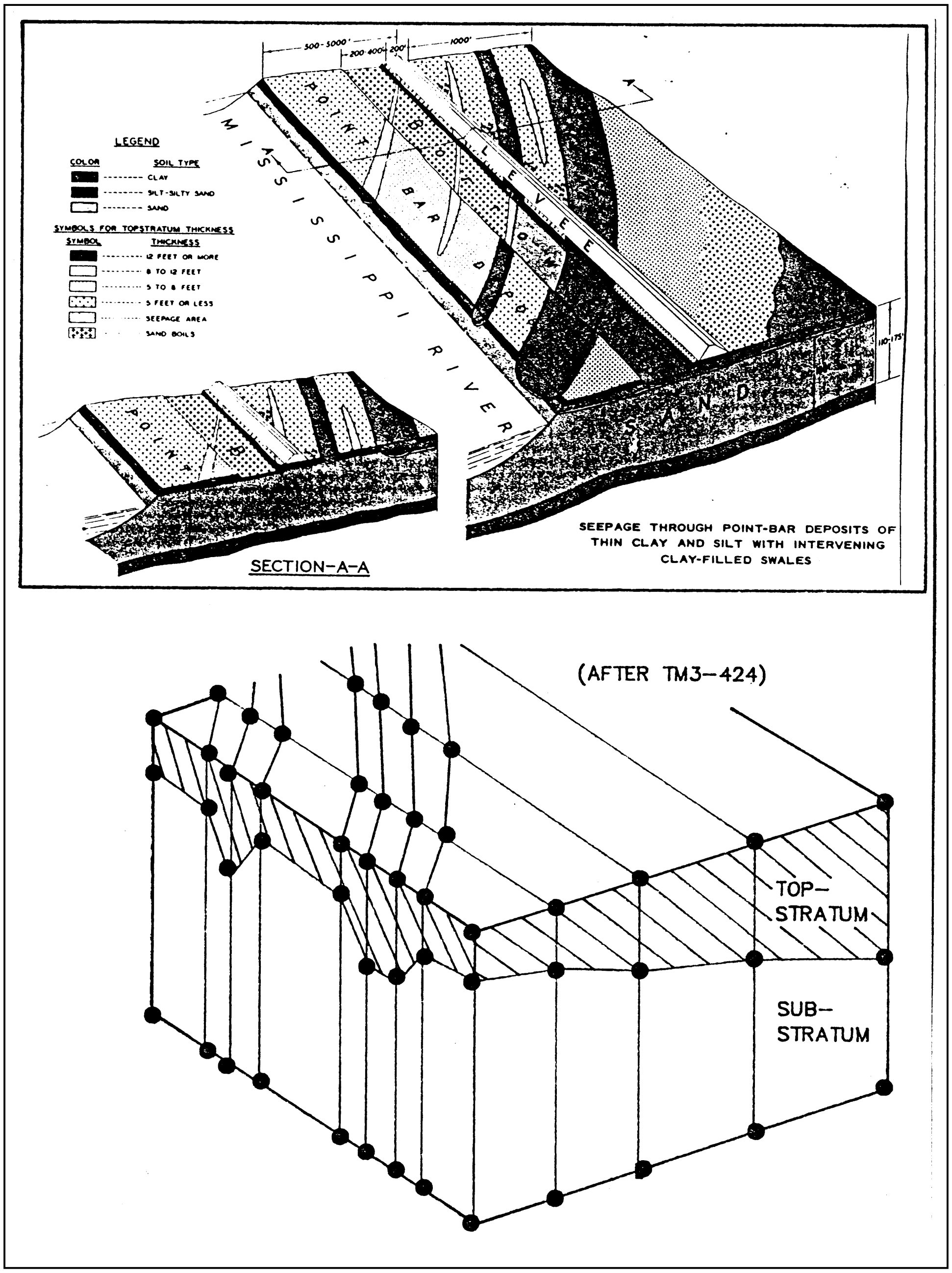


Figure 9. Analysis model for 3-D geometry

b. Dropping or driving a well screen into the boil.

c. Additional perforation of the top blanket.

References

Barron, R. A. (1948). "The effect of a slightly pervious top blanket on the performance of relief wells," *Proceedings, 2nd International Conference on Soil Mechanics*, Rotterdam, Vol IV, p 324.

______ . (1980). "Mathematical analysis of landside seepage berms," Miscellaneous Paper GL-80-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

______ . (1984). "Mathematical analysis of landside seepage berms," Technical Report REMR-GT-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Bawmann, D. H. (1983). "Inspection of instrumentation during high water, Mississippi River flood control projects, river mile 342 to river mile 287," Memorandum to ED-G Files, U.S. Army Engineer District, Rock Island, IL.

Bennett, P. T. (1946). "The effect of blankets on the seepage through pervious foundations," *Transactions, American Society of Civil Engineers*, Vol 111, p 215.

Cunny, R. W. (1980). "Documentation and analysis of Rock Island underseepage data," Technical Report GL-80-3, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Daniel, D. E. (1985). "Review of piezometric data for various ranges in the Rock Island District," U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Harr, M. E. (1977). *Mechanics of particulate media*. McGraw-Hill, New York.

Headquarters, Department of the Army. (1955). Civil Works Engineer Bulletin 55-11, Washington, DC.

______ . (1963). "Design of finite relief well systems," Engineer Manual EM 1110-2-1905, Washington, DC.

______ . (1978). "Design and construction of levees," Engineer Manual 1110-2-1913, Washington, DC.

Jervis, W. H. (1939). "Mississippi River levees, seepage; results of studies at Black Bayou, Mississippi, Station 3140-3240," U.S. Army Engineer District, Vicksburg, MS.

Mansur, C. I., and Kaufman, R. I. (1957). "Underseepage, Mississippi River levees, St. Louis District," *Transactions, American Society of Civil Engineers*, Vol 122.

Middlebrooks, T. A., and Jervis, W. H. (1947). "Relief well systems for dams and levees," *Transactions, American Society of Civil Engineers*, Vol 112, p 1321.

Montgomery, R. L. (1972). "Investigation of relief wells, Alton to Gale, Illinois," Miscellaneous Paper S-72-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Muskat, M. (1937). *The flow of homogeneous fluids through pervious media.* McGraw-Hill, New York.

Peter, P. (1982). *Canal and river levees.* Elsevier Publishing Co., Amsterdam.

Turnbull, W. J., and Mansur, C. I. (1954). "Relief well systems for dams and levees," *Transactions, American Society of Civil Engineers*, Vol 119, pp 842-878.

______ . (1961a). "Investigation of underseepage - Mississippi River levees," *Transactions, American Society of Civil Engineers*, Vol 126, pp 1429-1485.

______ . (1961b). "Design of control measures for dams and levees," *Transactions, American Society of Civil Engineers*, Vol 126, pp 1486-1539.

U.S. Army Engineer District, Rock Island. (1960). "Report of conference on underseepage for agricultural levees," Internal Memorandum.

U.S. Army Engineer District, St. Louis. (1976). "Re-evaluation of underseepage controls, Mississippi River levees, Alton to Gale, Illinois; 1976 Relief Well Pumping Test," report to Lower Mississippi Valley Division.

U.S. Army Engineer Division, Lower Mississippi Valley. (1962). "Procedures for design of landside seepage berms for Mississippi River levees," letter to Districts in LMVD.

______ . (1976). "Engineering and design: Soil mechanics design data," DIVR 1110-1-400, Sec 8, Part 6, Item 1, Vicksburg, MS.

U.S. Army Engineer Waterways Experiment Station. (1949). "Relief well systems for dams and levees on pervious foundations; model investigations," Technical Memorandum 3-304, Vicksburg, MS.

U.S. Army Engineer Waterways Experiment Station. (1952). "Control of underseepage by relief wells, Trotters, Mississippi," Technical Memorandum 3-341, Vicksburg, MS.

______ . (1956a). "Investigation of underseepage, Mississippi River levees, Alton to Gale, Illinois," Technical Memorandum No. 3-430, Vicksburg, MS.

______ . (1956b). "Investigation of underseepage and its control, lower Mississippi River levees," Technical Memorandum No. 3-424, Vicksburg, MS.

Wolff, T. F. (1974). "Performance of underseepage control measures during the 1973 Mississippi River flood, Columbia Levee District, Illinois," Master's Thesis, Oklahoma State University.

Bibliography

Barron, R. A. (1952). "The efficacy of landside toe drains in controlling foundation seepage and uplift," Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA.

Bligh, W. P. (1910). "Dams, barrages, and weirs on porous foundations," *Engineering news*, p 708.

Casagrande, A. (1940). "Survey of levee conditions," Letter to the President, Mississippi River Commission, Vicksburg, MS.

Chapman, T. G. (1957). "Two-dimensional groundwater flow through a bank with vertical faces," *Geotechnique*, 7, 35-40.

Cedergren, H. R. (1968). *Seepage, drainage, and flow nets.* Wiley, New York.

De Berard, W. W. (1922). "Fighting floods on the Mississippi River above Vicksburg," *Engineering news-record* 88, 814.

De Wit, J. M., Sellmeijer, J. B., and Penning, A. (1981). "Laboratory testing on piping." *Proceedings, 10th International Conference on Soil Mechanics and Foundation Engineering.* Stockholm, 1, 517.

Desai, C. S. (1970). "Seepage in Mississippi River banks; analysis of transient seepage using viscous flow model and numerical methods," Miscellaneous Paper S-70-3, Report 1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Fisk, H. N. (1944). "Geological investigation of the Alluvial Valley of the Lower Mississippi River," Mississippi River Commission, Vicksburg, MS.

"Flood water conditions on the Lower Mississippi." (1922). *Engineering news-record* 88(21), 868.

Ground water and wells. (1966). Johnson Co., St. Paul, MN.

Harza, L. F. (1936). "The best means for preventing piping," *Transactions, 2nd International Congress on Large Dams* 5, 139-150.

Lane, E. W. (1935). "Security from underseepage - masonry dams on earth foundations," *Transactions, American Society of Civil Engineers* 100, 1257.

Mansur, C. I. (1958). "Laboratory and in-site permeability of sand," *Transactions, American Society of Civil Engineers* 123, 868.

Mansur, C. I., and Kaufman, R. I. (1962). "Dewatering." *Foundation Engineering.* G. A. Leonards, ed., McGraw-Hill, New York, 241-350.

Miltronovas, F. (1968). "Laboratory tests of relief well filters: Wells along Mississippi River levees, Alton to Gale, Illinois," Miscellaneous Paper S-68-4, U.S. Army Engineer Waterways Experiment Stations, Vicksburg, MS.

Nakajima, Y. (1968). "Study of failure of piping in polder dikes for land reclamation," *Soils and Foundations* VIII(4), 30-47.

Peter, P. (1974). "Piping problem in the Danube Valley in Czechoslovakia," *Proceedings, 4th Danube European Conference on Soil Mechanics and Foundation Engineering.* Bled, 35-40.

Tracy, F. T. (1973). "A plane and axisymmetric finite element program for steady-state and transient seepage problems," Miscellaneous Paper K-73-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Turnbull, W. J., Krinitzsky, E. L., and Johnson, S. J. (1950). "Sedimentary geology of the lower Mississippi River and its influence on foundation problems," *Applied sedimentation.* Wiley, New York.

Turnbull, W. J., and Mansur, C. I. (1961). "Construction and maintenance of control measures," *Transactions, American Society of Civil Engineers* 126, 1540-1568.

U.S. Army Engineer District, St. Louis. (1960). "Performance of seepage control measures, St. Louis District," unpublished file report.

______ . (1976). "Re-evaluation of underseepage controls, Mississippi River levees, Alton to Gale, Illinois, phase I: Performance of underseepage controls during the 1973 flood."

U.S. Army Engineer Waterways Experiment Station. (1936). "Report of experiments and investigations to determine efficacy of sublevees and berms in the control of underseepage," Technical Memorandum 101-1, Vicksburg, MS.

______ . (1939). "The efficacy of systems of drainage wells for the relief of subsurface hydrostatic pressures," Technical Memorandum 151-1, Vicksburg, MS.

______ . (1942). "Field and laboratory investigation of design criteria for drainage wells," Technical Memorandum 195-1, Vicksburg, MS.

U.S. Army Engineer Waterways Experiment Station. (1948). "Underseepage and crevasse data, lower Mississippi River levees, Lower Mississippi Valley Division, Cairo, Illinois, to New Orleans, Louisiana," Vicksburg, MS.

______ . (1949). "Efficacy of partial cutoffs for controlling underseepage beneath levees," Technical Memorandum 3-267, Vicksburg, MS.

______ . (1950). "Investigation of underseepage and its control by relief wells, Commerce and Trotters, Mississippi," Technical Memorandum No. 3-319, Vicksburg, MS.

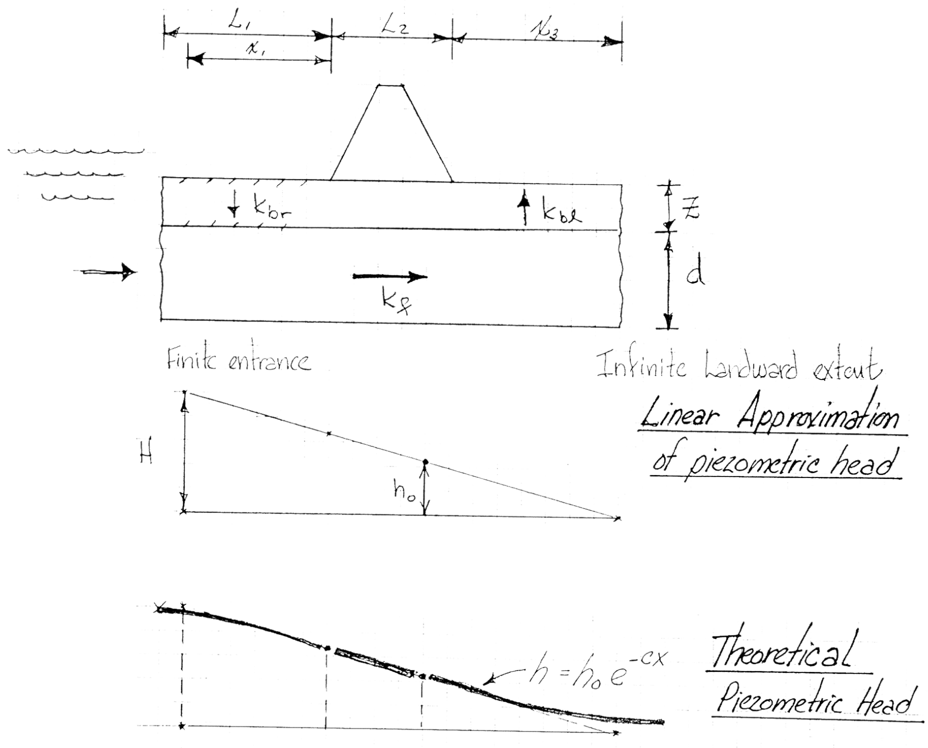
______ . (1952). "Memorandum: Basis of design, pressure relief wells for levees in the St. Louis District," unpublished memorandum, Vicksburg, MS.

Warriner, J. B., and Banks, D. C. (1977). "Numerical analysis of partially penetrating random well arrays," Technical Report S-77-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Van Zyl, D., and Harr, M. E. (1981). "Seepage erosion analysis of structures," *Proceedings, 10th International Conference on Soil Mechanics and Foundation Engineering*, Stockholm, Vol 1, p 503.

Appendix A
Derivation of Alternate Equation for Residual Head

EQUATION FOR HEAD AT LANDSIDE TOE



<u>EQUATION FOR h_O:</u>

$$\left(\frac{h_o}{H}\right) = \left[\tanh\,(\beta\, C_\ell L_1) + C_\ell L_2 + 1\right]^{-1}$$

where $C_\ell = \sqrt{\dfrac{k_{b\ell}}{k_f \cdot z \cdot d}}$ a "resistance" factor

and $B = \sqrt{\left(\dfrac{k_{br}}{k_{b\ell}}\right)\left(\dfrac{z_\ell}{z_r}\right)} \approx \sqrt{\left(\dfrac{k_{br}}{k_{b\ell}}\right)}$ a "blanket factor"

DERIVATION OF RESIDUAL HEAD EQUATION

$$h_O = \frac{H\ x_3}{S + x_3}$$

$$\left(\frac{h_o}{H}\right) = \left(\frac{x_3}{S + x_3}\right) = \frac{x_3}{x_1 + L_2 + x_3}$$

$$C_\ell = \left(\frac{1}{x_3}\right) = \sqrt{\frac{k_{b\ell}}{k_f \cdot z_{t\ell} \cdot d}} \qquad C_r = \sqrt{\frac{k_{br}}{k_f \cdot z_{tr} \cdot d}}$$

$$\frac{C_r}{C_\ell} = \left(\frac{k_{br}}{k_f \cdot z_{tr} \cdot d}\right)^{1/2} \left(\frac{k_{b\ell}}{k_f \cdot z_{t\ell} \cdot d}\right)^{-1/2}$$

$$\frac{C_r}{C_\ell} = \sqrt{\left(\frac{k_{br}}{k_{b\ell}}\right)\left(\frac{z_{t\ell}}{z_{tr}}\right)} = \beta, \text{ the BLANKET FACTOR}$$

$\therefore\ C_r = \beta\ C_\ell$

$$\left(\frac{h_o}{H}\right) = \frac{x_3}{x_1 + L_2 + x_3}$$

$$\left(\frac{h_o}{H}\right) = (x_3)(x_1 + L_2 + x_3)^{-1}$$

$$\left(\frac{h_o}{H}\right) = \left(\frac{1}{C_\ell}\right)\left(\frac{\tanh\ (C_r L_1)}{C_r} + L_2 + \frac{1}{C_\ell}\right)^{-1}$$

$$\left(\frac{h_O}{H}\right) = \left(\frac{1}{C_\ell}\right) \left(\frac{\tanh\ \ (BC_\ell L_1)}{C_\ell} + \frac{C_\ell L_2}{C_\ell} + \frac{1}{C_\ell}\right)^{-1}$$

$$\left(\frac{h_o}{H}\right) = \left[\tanh\ (\beta\ C_\ell L_1) + C_\ell L_2 + 1\right]^{-1}$$

<u>Example to assess proper design parameters</u>,

Measure $\left(\dfrac{h_o}{H}\right), L_1, L_2$

Find (β, C_ℓ values that satisfy solution, use β = 0.1, 0.2, 0.4, 0.7, 1.0)

Then, knowing d and z, estimate

$$\left(\frac{k_f}{k_{b\ell}}\right), \left(\frac{k_{br}}{k_{b\ell}}\right) \mathit{for}\ z_{t\ell} = z_{cr}, \beta = \sqrt{\frac{k_{br}}{k_{b\ell}}}$$

Example: Rock Island, Sky Island, Range B:

Piezometer B3,

On May '65, $\dfrac{h_o}{H} = \dfrac{2.7}{466.8 - 458.2} = 0.314$

$L_1 \approx 200'$, $L_2 \approx 200'$

$0.314 = [\tanh(\beta\, C_\ell\, 200) + C_\ell(200) + 1\,]^{-1}$

$\tanh(200\,\beta\, C_\ell) + 200\, C_\ell + 1 = 3.1852$

$\tanh(200\,\beta\, C_\ell) + 200\, C_\ell = 2.1852$

Assume β = 0.1 ($k_{b\ell} = 100\, k_{br}$)

$\tanh(20\, C_\ell) + 200\, C_\ell = 2.1852$

Solve by iteration:

Try $C_\ell = 0.0010$

tanh (0.02) + (200)(0.001) = 0.0200 + 0.200 = 0.2200

Try $C_\ell = 0.0100$

tanh (0.2) + 2 = (0.1974) + (2) = 2.1974

Try

$C_\ell = 0.0090$

tanh (0.18) + 1.80 = 0.17808 + 1.800 = 1.9781

Try $C_\ell = 0.0099$

$\tanh(0.198) + 1.98 = 0.1964 + 1.98 = 2.1764$

Use $C_\ell = 0.0099$ for $\beta = 0.1$

$$0.0099 = \sqrt{\frac{1}{\left(\frac{k_f}{k_o}\right) \cdot z \cdot d}} \qquad z = 7.4', \; d = 34'$$

$$\left(\frac{k_f}{k_b}\right) = 41$$

Assume $\beta = 0.7071$ ($k_{b\ell} = 2\ k_{br}$)

$\tanh((200)(0.7071)\ C_\ell) + 200\ C_\ell + 1 = 3.1852$

$\tanh(141.4\ C_\ell) + 200\ C_\ell = 2.1852$

Try $C_\ell = 0.0099$

$\tanh(1.3999) + 1.98 = 0.8853 + 1.9800 = 2.8653$

Try $C_\ell = 0.0090$

$\tanh(141.4 \times 0.009) + (200)(0.009) =$

$\tanh(1.2726) + 1.8000$

$0.854 + 1.8000 = 2.654$

Try $C_\ell = 0.0050$

$\tanh(141.4 \times 0.005) + (200)(0.005) =$

$0.608 + 1.000 = 1.608$

Try $C_\ell = 0.0070$

$\tanh(141.4 \times 0.007) + (200)(0.007) =$

$0.756 + 1.400 = 2.156$ *

Try $C_\ell = 0.0065$

$\tanh(141.4 \times 0.0065) + (200)(0.0065) =$

$0.720 + 1.300 = 2.0200$

Try $C_\ell = 0.0067$

tanh (141.4 × 0.0067) + (200)(0.0067) =

0.739 + 1.34 = 2.079

$$0.0070 = \sqrt{\frac{1}{\left(\frac{k_f}{k_b}\right) \cdot 7.4 \cdot 34}}$$

$$\left(\frac{k_f}{k_b}\right) = 81$$

For the range of assumptions on β, we find:

$k_{b\ell} = 100\ k_{br}$ $\beta = 0.1$ $\left(\frac{k_f}{k_{b\ell}}\right) = 41$

$k_{b\ell} = 2\ k_{br}$ $\beta = 0.707$ $\left(\frac{k_f}{k_{b\ell}}\right) = 81$

Cunny (1980)[1] (p. 101) finds $\left(\frac{k_f}{k_{b\ell}}\right) = 54$

* The ratio $\left(\frac{k_f}{k_{b\ell}}\right)$ can be bounded knowing L_1, L_2, $z_{b\ell}$, d, $\left(\frac{h_o}{H}\right)$

  * Need data from one piezometer to get $\left(\frac{h_o}{H}\right)$

  * Assume $0.1 < \beta < 0.707$

[1] References are listed on page 32 of main text of this report.

RECIRC2819.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
September 2002

2. REPORT TYPE
Final report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Performance of Levee Underseepage Controls: A Critical Review

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Thomas F. Wolff

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Michigan State University
Department of Civil and Environmental Engineering
East Lansing, MI 48824-1226

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Corps of Engineers, Washington, DC 20314-1000;
U.S. Army Engineer Research and Development Center
Geotechnical and Structures Laboratory
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
ERDC/GSL TR-02-19

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Federal Government through the U.S. Army Corps of Engineers (USACE) has a large investment in flood-control levees. Where such levees are built on pervious foundations, seepage beneath the levee (underseepage) during floods can produce pressure and flow conditions capable of initiating subsurface erosion leading to levee failure. Two adverse phenomena may occur; one is sand boils which involves the movement of subsurface sand to the surface by flowing water, and the other is heaving which involves the upward movement of a relatively impervious surface layer resulting from subsurface water pressures in excess of its weight. To prevent such occurrences, the USACE has developed a set of procedures to analyze underseepage conditions on a site-specific basis and a set of procedures to design underseepage control measures. For the most part, these procedures were developed in the 1940s and 1950s. Intensive construction of control measures was accomplished in the 1950s and 1960s. Several moderately large and major floods have provided data from which the validity of the procedures and the security of the constructed system can be inferred. Also, since the 1950s many technical advancements have been made in engineering analysis techniques and construction methods that may merit application to underseepage problems.

(Continued)

15. SUBJECT TERMS

Critical gradient	Internal erosion	Permeability	Relief well	Underseepage
Flood-control levee	Levee design	Piezometer	Sand boils	
	Mississippi River	Piping	Seepage berms	

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		50	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

14. (Concluded).

The Federal Government's levee system will be expected to provide flood protection for many centuries, regardless of its so-called economic life. It will undoubtedly be subjected to floods equaling and exceeding those already experienced. Conditions along the levees are not static but are subject to periodic natural and man-made changes. Such changes may necessitate review, reanalysis, redesign, reconstruction, and/or modification of the system.

Several researchers have prepared voluminous evaluations of the performance of particular levees in particular floods. This report draws on those previous assessments to summarize in one source what has been learned from observations during floods up to 1986. Using that knowledge, the analysis procedures and the performance evaluation procedures are reviewed to identify possible areas of improvement.

Enclosure No. 7

RECIRC2819.

State of California
Natural Resources Agency
DEPARTMENT OF WATER RESOURCES
Division of Integrated Regional Water Management

Site Characterization and Groundwater Monitoring Data Analysis Summary Prospect Island Tidal Habitat Restoration Project Solano County, California

North Central Region Office

Eric Hong, P.E.……………………………………………………………..Office Chief
Juan Escobar, P.E.…………………………………………………………Chief, Water Management Branch

This report was prepared by:

Christopher L. Bonds, C.HG………………………………………………….Senior Engineering Geologist
Mark C. Souverville, P.G..……………………………………………………Engineering Geologist
Steven T. Springhorn, P.G..…………………………………………………..Engineering Geologist

Memorandum Report
January 2014

GEOLOGIC AND GEOMORPHIC SETTING

- The majority of the Ryer Island land surface is well below (approximately 5 feet) the average water surface elevation of Miner Slough. This creates seepage pressure from Miner slough toward Ryer Island.
- The RD 501 drainage system artificially lowers groundwater levels (typically 2-3 feet below ground surface). The artificial lowering of groundwater levels further increases the seepage pressure from Miner Slough toward Ryer Island.
- The island interiors have been impacted by agricultural practices, such as aeration, decomposition, compaction, burning, and erosion. Extensive draining of the organic and peaty deposits for agriculture has altered much of the original surficial geologic and geomorphic character and resulted in subsidence on Prospect and Ryer Islands. Subsidence increases the hydraulic gradient from the surrounding sloughs to Prospect and Ryer Islands.
- A levee underseepage evaluation was performed as part of a larger regional levee investigation and the following key finding was made; approximately 90% of recorded underseepage-related performance problems in the Sacramento Valley and Delta occur along levees designated as having high and very high underseepage susceptibility. Of the 15 miles of levee evaluated within this study area, 14.3 miles (96%) had high to very high underseepage susceptibility.

SITE CHARACTERIZATION AND DEVELOPMENT OF HYDROGEOLOGIC CONCEPTUAL MODEL

- Four hydrogeologic units (HU) were defined based on the 3D lithologic model; Levee, Upper Clay, Main Sand, Lower Clay.
- The Upper Clay HU on average is thinner under Ryer Island and thicker under Prospect Island (16 feet - Ryer, 25 feet - Prospect). There appears to be a correlation between the RD 501 reported seepage areas with locations of thin clay (less than 15 feet). Also, the presence of surface drainage ditches further reduce the thickness of the clay in these areas. It was concluded in the Delta Risk Management Study that clay blanket thicknesses of 15 feet or less have the largest impacts on underseepage and the presence of drainage ditches excavated into thin clay blankets significantly increases underseepage.
- Based on the 3D lithologic model, bathymetry, and bed sediment sample data, the channel bottoms of Miner Slough and Sacramento River Deep Water Ship Channel (DWSC) are physically connected to the Main Sand HU throughout the study area.

the land surface inside the levees on Prospect Island is near sea level to slightly below sea level and nearly all the land on Ryer Island is below sea level. As documented in GEI (1999), “most of Ryer Island is below water surface elevations in the surrounding rivers, creeks, and sloughs…and…groundwater levels are controlled by a network of dewatering ditches which flow to a low point at the southern end of the island where the water is removed by pumping.” The Ryer Island drainage system, that is excavated into the surface layer of organic clay and silt, is used to artificially lower groundwater levels enough (typically 2 to 3 feet below ground surface (bgs) to create an aerobic root zone in order to grow crops. The artificial lowering of groundwater levels increases the hydraulic gradient from Miner Slough toward Ryer Island.

The geomorphic setting of the study area consists of islands separated by fluvial channels and tidal sloughs that, prior to construction of artificial levees and dredge cuts, were directly connected with fluvial and estuarine hydrology and sediment fluxes. The islands are saucer-shaped in cross section, and possess elevated natural levees consisting of silt and loam from overflow of the directly-adjacent channels and sloughs. Prior to reclamation, the central part of the islands were covered by organic silts and clays with varying amounts of peat originally formed from decaying vegetation. The island interiors have been impacted by agricultural practices, such as aeration, decomposition, compaction, burning, and erosion. Extensive draining of the organic and peaty deposits for agriculture has altered much of the original surficial geologic and geomorphic character and resulted in subsidence on Prospect and Ryer Islands. Subsidence increases the hydraulic gradient from the surrounding sloughs to Prospect and Ryer Islands.

Surficial deposits on Prospect and Ryer Island are late Holocene, unconsolidated and fine-grained muck (organic-rich silt and clay) with lesser amounts of peat (Atwater, 1982; USACE, 2001a). The percentage of organic material (peat) is highest near the center of the Delta, and decreases in the direction of higher elevations of the delta edge (Atwater, 1982). A quantitative analysis of the distribution of organic material in the Delta, completed by Deverel and Leighton (2010), indicates the majority of the study area has between 0-6% organic material with the southern portion of the DWR-owned Prospect Island having between 6-11% organic material. This matches well with surface and subsurface data within the study area.

Geomorphic assessment and surficial geologic mapping of Prospect and Ryer Islands were completed as part of the current study. These materials were prepared as an addendum to the Geomorphic Assessment and Surficial Mapping of the West Delta Study Area Technical Memorandum (Fugro William Lettis & Associates (FWLA), 2010) (**Appendix A**).

Enclosure No. 8

TECHNICAL SCIENCES
Abbrev.: Techn. Sc., No 14(2), Y 2011

MODELLING EVENTS OCCURRING IN THE CORE OF A FLOOD BANK AND INITIATED BY CHANGES IN THE GROUNDWATER LEVEL, INCLUDING THE EFFECT OF SEEPAGE

***Jarosława Kaczmarek*[1], *Danuta Leśniewska*[2]**

[1] Chair of Civil Engineering and Building Constructions
University of Warmia and Mazury in Olsztyn
[2] Division of Geotechnics
University of Technology in Koszalin

Key words: flood banks, changes in groundwater levels, water seepage, FEM modelling.

Abstract

The paper presents results of numerical modelling of the response of a flood bank to the rising or lowering water table. The modelling was performed with the finite element method (FEM) in two variants: excluding the effect of groundwater seepage through the flood bank (PLAXIS v. 8) and including groundwater seepage during intervals between increments in the height of the groundwater table (PLAXIS 2D 2010 with a FLOW model).

MODELOWANIE ZJAWISK ZACHODZĄCYCH W KORPUSIE WAŁU PRZECIWPOWODZIOWEGO POD WPŁYWEM ZMIAN POZIOMU WÓD GRUNTOWYCH Z UWZGLĘDNIENIEM FILTRACJI

***Jarosława Kaczmarek*[1], *Danuta Leśniewska*[2]**

[1] Katedra Budownictwa i Konstrukcji Budowlanych
Uniwersytet Warmińsko-Mazurski w Olsztynie
[2] Katedra Geotechniki
Politechnika Koszalińska

Słowa kluczowe: wały przeciwpowodziowe, zmiany poziomu wód gruntowych, przepływ wody w gruncie, modelowanie MES.

Abstrakt

W pracy przedstawiono wyniki modelowania numerycznego zachowania się wału przeciwpowodziowego w trakcie podnoszenia i obniżania zwierciadła wody. Modelowanie przeprowadzono metodą elementów skończonych (MES) w dwóch wariantach: bez uwzględnienia przepływu wody w gruncie (PLAXIS wersja 8) oraz z uwzględnieniem przepływu wód gruntowych w okresach między przyrostami wysokości zwierciadła wody (PLAXIS 2D 2010 z modułem FLOW).

Introduction

Understanding and modelling events which occur in the core of a flood bank caused by fluctuations in the groundwater level is the first step towards predicting changes inside flood banks due to different hydrometeorological conditions. In 2008, under the framework of the Scientific Network called *Transport of sediments and contaminants and degradation of environment in rivers, river mouths and marine coastal areas* (TROIAnet) and in collaboration with the Institute of Hydroengineering of the Polish Academy of Sciences in Gdańsk, experimental tests on a physical model of the riverward slope of a levee were carried out, including studies on changes in the core of the flood bank caused by rising and lowering the groundwater table level (KACZMAREK, LEŚNIEWSKA 2010, LEŚNIEWSKA, KACZMAREK 2010). These studies were a continuation of some earlier research, completed under the EU 6th Framework Research Project FLOODsite, carried out in 2006–2009 (LEŚNIEWSKA et al. 2007, KACZMAREK et al. 2009), which demonstrated that changes in the groundwater table level could lead to alterations in the structure of a levee, which in extreme cases – alongside other modifications due to such external events as atmospheric precipitation, changing water levels in rivers and water reservoirs protected by flood embankments, might cause levee failure or damage. The current physical experiments on a model of a flood bank are carried out at the Institute of Hydroengineering in Gdańsk under the research project NN 506317039 called *Studies on changes in the microstructure of ground and its influence on processes of water flow and contamination transport in flood banks*.

The preliminary results of the numerical modelling of deformations in a flood embankment under the effect of changing groundwater levels have been presented in the papers by KACZMAREK, LEŚNIEWSKA (2010) and LEŚNIEWSKA, KACZMAREK (2010).

The analysed case

The numerical analysis was carried out for the conditions transferred from one of the experimental tests, in which an incremental rise and fall in the groundwater level were investigated. A change in the groundwater level was constant and equalled ±20 cm. This case was discussed in some earlier articles, e.g. KACZMAREK, LEŚNIEWSKA 2010, LEŚNIEWSKA, KACZMAREK 2010, except that the previous numerical modelling executed with the software package PLAXIS (version 8) could not take into account the fact that as the water table outside the flood bank rises, it begins to flow through the ground (seepage). This flow

Enclosure No. 9

STATEMENT OF CHRISTOPHER H. NEUDECK, R.C.E.

in re

DRAFT SUPPLEMENTAL
Mitigated Negative Declaration
and
Draft Initial Study

Engineering Geotechnical Studies for the
Bay Delta Conservation Plan and/or
Preliminary Engineering Studies for the
Delta Habitat Conservation and Conveyance Program

I am Christopher H. Neudeck, with Kjeldsen, Sinnock & Neudeck, Inc., P.O. Box 844, Stockton, California 95201. I am a Registered Civil Engineer in the State of California and have worked with the Delta Islands including flood control, drainage and irrigation for the past twenty-eight (28) years. I am the District Engineer for numerous reclamation districts in the Sacramento-San Joaquin Delta (Delta). (A statement of my qualifications is attached hereto as "Exhibit A.")

The California Department of Water Resources (DWR) has recently released a "DRAFT SUPPLEMENTAL Mitigated Negative Declaration and Draft Initial Study, Engineering Geotechnical Studies for the Bay Delta Conservation Plan and/or Preliminary Engineering Studies for the Delta Habitat Conservation and Conveyance Program," (hereinafter "MND/IS"). The Project Description for the MND/IS states that DWR is planning to conduct various geotechnical activities within the Delta including the following:

> **Landside Test Pits:** "The geotechnical investigation program on land will consist of . . . approximately 30 shallow test pit excavations (typically 4 feet wide x 12 feet long x 12 feet deep) in soils to measure soil load-bearing capacity, physical properties of the sediments, location of the groundwater table, and other typical geologic and geotechnical parameters." (MND/IS, p. 5.)

> **Landside Borings:** "The geotechnical investigation program on land will consist of approximately 220 to 240 exploration locations . . . , including drilling boreholes and performing cone penetration tests (CPT); . . . . [¶] Depths of test holes will generally vary from about 5 to 225 feet. At three selected locations, drilling may extend to a depth of approximately 500 feet . . . ." (MND/IS, p. 6) [¶] "[A]t approximately 20 boring locations . . . a depth of 300 feet (rather than 225 feet) is required . . . ." (*Ibid.*)

> **Overwater Borings:** "[A]pproximately 80 overwater geotechnical borings in the Delta waterways between 2010 and 2012. . . . The depths of borings are planned to range between 100 and 200 feet below the mud line (i.e., river bottom). (MND/IS, p. 2.)

DWR concludes in its MND/IS that "[w]ith [the] implementation of [various] mitigation and conservation measures, the proposed project as modified would have no significant effect on the environment." (MND/IS, p. i.) I am generally familiar with the California Environmental Quality Act (CEQA) and with CEQA Guidelines section 15382 which provides:

> "Significant effect on the environment" means a substantial, or potentially substantial, adverse change in any of the physical conditions within the area affected by the project including land, air, water, minerals, flora, fauna, ambient noise, and objects of historic or aesthetic significance. . . .

It is my opinion, for the reasons set forth herein, that DWR is incorrect and that its proposed project as modified *may indeed* result in a potentially substantial, adverse change to the environment. In particular, it is my opinion that there is a reasonable possibility that the proposed project as modified will substantially undermine the integrity of the levee systems which protect the Delta lands from flooding and substantially impair flood fighting capabilities, and, as a result, there is a reasonable possibility that the proposed project as modified will create substantial levee damage and cause potential levee failure. Additional mitigation measures are needed and should be adopted to minimize such undermining, impairment, damage and failure.

At the outset, DWR should consult with and obtain the permission from all affected reclamation districts prior to conducting any of the foregoing or other geotechnical activities on or near the reclamation districts' levees, drainage facilities or other reclamation works. As the engineer for numerous reclamation districts I am familiar with reclamation districts' authority under the law which includes the following:

> Water Code section 50652: "Control over works and affairs of district. The board [of trustees of the reclamation district] shall exercise general supervision and complete control over the construction, maintenance and operation of the reclamation works, and generally over the affairs of the district."

> Water Code section 50013: "Reclamation works. 'Reclamation works' means such public works and equipment as are necessary for the unwatering, watering, or irrigation of district lands and other district operations."

The various reclamation districts are most familiar with their levee systems and a mitigation measure should be imposed to require DWR to consult with the affected reclamation districts and obtain their careful review and permission before any geotechnical activities take place on or near their reclamation works.

As it stands, DWR's proposed project suffers from an overall lack of any meaningful detail in terms of when and where such geotechnical activities will take place and, hence, what specific reclamation works DWR will be impacting during the performance of such activities, i.e., during the hauling of equipment to and from the sites, the stationing and operation of equipment at the sites, etc.

Among other restrictions, it is my opinion that restrictions are needed in terms of the location and timing of the geotechnical activities to minimize the reasonable possibility that such activities will substantially undermine the integrity of the levee systems and substantially impair flood fighting capabilities.

1. The Location of <u>Landside Test Pits</u> Should be Restricted.

With regard to the location of the landside test pits, while the MND/IS states that the "[t]est pits will not be dug on any levees . . ." (MND/IS, p. 6), is not clear how close to the levees they will be dug. For example, they can presumably be dug at the base of the levee, i.e. immediately adjacent to the landside levee toe.

It is my opinion that digging such test pits near levees creates the reasonable possibility that the integrity of the levee will be substantially undermined. To minimize that possibility, the test pits should be setback an adequate distance from the landside toe of the levee and that distance must be evaluated by taking into consideration all of the specific geologic and other conditions at the particular site.

While DWR does not limit the size of the test pits and, instead, simply states that they will "typically" be "4 feet wide x 12 feet long x 12 feet deep," even that typical size is tremendously significant if it is dug within the vicinity of a levee.

One of the major reasons an open deep test pit is a substantial concern on or near a levee that is subject to "seepage" (discussed more fully below) is because the test pit will create a preferential path for the seepage flow and accelerate the rate of seepage to the point where the seepage flow starts to erode the interior core of the levee and carry out foundation material of the levee thereby undermining the integrity of the levee and potentially causing levee failure. Having an open deep test pit on or near the levee at a point that is well below sea level during any time and, in particular, during high water times presents a reasonable possibility of substantial levee damage and potential levee failure due to a gross levee foundation failure.

With regard to the *timing* of the test pits, while the MND/IS states that the test pits will be backfilled on the same day as they are dug (MND/IS, p. 6), the MND/IS places no restrictions on *when* they can be dug. Accordingly, they can be dug any time of the year, even during extreme high water and storm events when reclamation districts are actively patrolling their levees and/or flood fighting and when their levees are highly saturated and already under extreme stress from high water pressure, high winds and heavy rains. Digging such pits near the levees during such times exponentially increases the possibility that the digging will substantially undermine the integrity of the levee.

Accordingly, to minimize the reasonable possibility that the integrity of the levees will be substantially undermined by the test pits, a mitigation measure should be imposed to ensure that the test pits are located a sufficient distance landward of the landside levee toes, and that the determination of that sufficient distance should be determined by taking into consideration all of the specific geologic and other conditions at each particular site and should be subject to the review and approval of the affected reclamation district (and/or other entity responsible for the operation and maintenance of the particular levee at issue).

2. The Location and Timing of <u>Landside Borings</u> Should be Restricted.

With regard to the location of the approximately 220 to 240 landside borings, presumably any number of those borings can take place directly on the levees (i.e., directly on the waterside or landside slopes, or crowns of the levees) as well as immediately adjacent to the landside levee toes. Conducting the borings on or near the levees creates the reasonable possibility that such activities will substantially undermine the integrity of the levee systems as well as substantially impair flood fighting capabilities.

a. Substantial Impairment of Flood Fighting Capabilities.

With regard to the impairment of flood fighting capabilities, DWR places no restrictions on *when* the drilling can take place. Accordingly, as with the test pits, the borings can be dug any time of the year, even during high water and storm events when reclamation districts and/or other entities are actively patrolling the levees and/or flood fighting. During such events the levees are highly saturated and already under extreme stress from high water pressure, high winds and heavy rains.

During such events it is imperative that the reclamation district's visibility of its levees is not obstructed by vehicles or equipment such as the drilling vehicles/equipment. It is also imperative that the reclamation district's own vehicle and equipment access along its levee crowns for patrolling or flood fighting is not obstructed or impaired by the presence of DWR's vehicles/equipment. In addition, during such events the reclamation district needs to be able to timely respond to any potential levee problems, such as sloughing or cracking of its levee slopes, levee boils from increased seepage flowing through or under the levees, etc. Any equipment, such as the drilling vehicles/equipment than cannot be quickly and easily moved out of the way creates the reasonable possibility of substantial impairment of the ability to address levee problems in the immediate vicinity of such vehicles/equipment before they escalate out of control.

According to the MND/IS, the time frame of the drilling varies according to how deep the boring is:

Drilling time required for each [landside] drill hole is approximately 3 work days for drill holes less than 100 feet deep, approximately 5 work days for drill holes to 225 feet deep [approximately 10 days for drill holes up to 300 feet deep], and up to 3 weeks or more for deeper drill holes up to 500 feet deep.

(MND/IS, p. 6.)

For the reasons discussed above, the mere presence of the drilling equipment for up to 21+ days on or near the levees creates the reasonable possibility that levee patrol and flood fighting capabilities will be substantially impaired in terms of impairment to visibility and impairment to access by levee patrol and flood fighting vehicles/equipment.

Moreover, during an emergency, when a levee is beginning to fail, every second counts. The MND/IS fails to discuss how quickly the drilling vehicles/equipment, especially the ones that are already in the middle of boring several hundred feet, can be relocated and moved out of the way. But even if they could be "quickly" moved out of the way, as noted above, their mere presence on or near the levee obstructs visibility of levee problems that are occurring in the immediate vicinity of the vehicles/equipment and, hence, substantially impairs the ability to detect levee problems at their initial stages before they escalate out of control. And when seconds count, to the extent the equipment can be moved within a couple of hours, that is not quick enough.

Accordingly, to minimize the possibility of substantial impairment of flood fighting capabilities, at a minimum, a mitigation measure should be imposed to prohibit any such borings on or within a specified distance from any levee during any high water events or during times of anticipated high water events (i.e., events where the water levels are at, or anticipated to be, at the high end of, or beyond, their typical ranges a result of high tides, high river runoff, low atmospheric pressure, etc. or any combination of such factors). That specified distance should be determined by taking into consideration all of the specific geologic and other conditions at each particular site and should be subject to the review and approval of the affected reclamation district (and/or other entity responsible for the operation and maintenance of the particular levee at issue).

b. Substantial Undermining of Levee Integrity.

The location of the landside borings on or near levees and any time of the year, even during high water and storm events, also creates the reasonable possibility that such activities will substantially undermine the integrity of the levees. To minimize that possibility, at a minimum, none of the borings should take place on or near any levee during any high water events or during times of anticipated high water events. Those are times when levee systems are already under increased stress from the high water pressures, which is also typically accompanied by high winds and heavy rains.

To understand one of the reasons why conducting borings on or near levees during high water events creates the potential for substantial levee damage or failure, one must understand "seepage," a phenomenon I have over 28 years of experience in dealing with. In general, seepage is the flow of river water under and through levees, and it is common knowledge that seepage flows under and through nearly all levees with the Delta, and, hence, within the areas of DWR's proposed borings. (Exceptions include where an artificial slurry wall or other "cut-off" type wall is constructed to physically block the flow of seepage under or through levees, which is very expensive and not common within the Delta.)

In general, seepage occurs as a result of the river waters being higher in elevation than the lands on the other side of the levee that is holding back those waters, together with the fact that levees are made of soil materials that are permeable. This discrepancy in elevation exists continuously in the vast majority of the Delta. In the outer perimeter of the Delta, where the lands are higher in elevation, it may occur only during high water events where there are large amounts of water flowing down the rivers from the upper watersheds which cause the water elevation in the rivers to rise.[1]

In light of my familiarity with the hydrology in the Delta, it is my opinion that all of the areas where proposed borings will be located involve levees that hold back river water that is at times higher than the lands on the other side of those levees and, hence, all experience seepage flowing under and/or through their levees in various degrees and at various times throughout the year, with many areas towards the center of the Delta experiencing constant seepage, 24 hours a day, 365 days a year.

When the water elevation in the rivers is abnormally high, the flow of seepage under and through the levees is also abnormally high. Those are the times when DWR's proposed boring of holes on or near levees is the most dangerous and has the highest possibility of resulting in substantial levee impairment or failure, and, hence, are times when such boring should be avoided.

DWR's proposed borings involve borings up to 8 inches in diameter and up to 500 feet in depth. DWR proposes to "seal" the borings *after the boring is complete* by "using cement-bentonite grout in accordance with California regulations and industry standards (Water Well Standards, DWR 74-81 and 74-90)." (MND/IS, pp. 5 & 6.) However, while DWR fails to demonstrate that the borings can truly be "sealed," especially where very lose, permeable soil is involved such as "peat soil" which is widespread throughout the delta (see "Exhibit B"), there will be a period of time during and after the drilling of the bores that the bores will *not* be sealed. That time period varies according to how deep the boring is and, as discussed above, can be up to 21+ days. (MND/IS, p. 6.)

Thus, the bore holes will remain unsealed for up to 21+ days. The reason an unsealed bore is a major concern on or near a levee that is subject to seepage, and especially when it is

---

[1] See excerpts from DWR's Delta Atlas attached hereto as "Exhibit B," which describe the low elevations of the lands within the Delta, the various river flood elevations, etc.

subject to abnormally high levels of seepage, is because that unsealed bore hole can create a preferential path for the seepage flow and accelerate the rate of seepage to the point where the seepage flow starts to erode the interior core of the levee and carry out foundation material of the levee thereby undermining the integrity of the levee and potentially causing levee failure. Having an unsealed bore hole on or near the levee for up to 21+ days during high water times presents a reasonable possibility of substantial levee damage and potential levee failure.

Understanding that the unsealed bore hole will have drilling fluid/mud within it during drilling and *may* have drilling fluid/mud left within it during non-drilling periods, it is unlikely that the weight of the drilling fluid/mud is heavy enough to counter the pressure that would be caused by the seepage beneath and through the levee. General practice for geotechnical explorations is not to leave any unsealed holes at the toe of the levee unattended. The MND/IS makes no provision for any such attendance notwithstanding the fact that it confirms that there will indeed be significant non-drilling periods. (See e.g., MND/IS, p. 13 [the drilling activities "will [only] take place between sunrise and sunset"].)

To minimize the possibility of substantial levee damage and potential levee failure, at a minimum, a mitigation measure should be imposed to prohibit any such borings on or within a specified distance from any levee during any high water events or during times of anticipated high water events. That specified distance should, again, be determined by taking into consideration all of the specific geologic and other conditions at each particular site and should be subject to the review and approval of the affected reclamation district (and/or other entity responsible for the operation and maintenance of the particular levee at issue).

In addition, at all times, regardless of whether there is, or there is anticipated to be, a high water event, a mitigation measure should be imposed to require all unsealed bores located at the toe of the levee, or at other elevations along the levee slopes or landward of the levee slopes, that are below the river water elevations, to be attended during all non-drilling periods and monitored for any seepage flow through, or in the vicinity of, the bore. A procedure, along with suitable equipment and materials, should be on site to promptly address and (attempt to) control any such flow. Said procedure, and the proximity to the levee where this mitigation measure should be imposed, should be subject to the review and approval of the affected reclamation district (and/or other entity responsible for the operation and maintenance of the particular levee at issue).

3. The Location and Timing of <u>Overwater Borings</u> Should be Restricted.

With regard to the overwater borings, since 50 of the approximately 80 borings are for "intake structures" and 5 to 10 of those borings are for "docking facilities," it appears such borings can be located very near, if not on, the waterside slopes of various levees. With regard to the timing, the MND/IS restricts the overwater borings to August 1 through October 31st. (MND/IS, p. 2.)

While DWR once again proposes to "seal" the bores with bentonite-cement grout, that "sealing" will once again not take place *until the boring is complete*. (MND/IS, p. 4.) Since the bores can be drilled up to 200 feet below the bottom of the slough or river (*ibid.*), presumably the bores may remain unsealed for 5 or more days. (MND/IS, p. 6.)

The drilling of unsealed overwater borings creates the reasonable possibility of creating a preferential pathway to allow river water to more freely push or flow into the underlying groundwater table thereby increasing the hydraulic head on the groundwater underlying the river which, in turn, exerts increased hydraulic pressure on the nearby levees as the groundwater tries to equalize with the lower groundwater table below and on the landside of the levees. This increased pressure can lead to increased seepage under or through the nearby levees which not only increases the drainage burdens of the reclamation districts but also impairs the integrity of the levee and can, if the increased seepage is unnoticed or cannot be timely controlled, result in the ultimate failure of the levee and the entire host of devastating environmental and human impacts associated therewith.

While the overwater borings cannot be conducted outside August 1 to October 31, high water events can still occur within that time frame. Accordingly, to minimize the possibility of substantial levee damage and potential levee failure, at a minimum, a mitigation measure should be imposed to prohibit any such borings during any high water events or during the time of anticipated high water events. Such a mitigation measure would at least ensure that any increased seepage and the problems associated therewith will not be at a time when the levee is already being subjected to abnormally high seepage pressure and flow. Such a mitigation measure would also help minimize the possibility that the mere presence of the drilling equipment near or on the waterside slopes of levees during such times will not substantially interfere with emergency levee work or other flood fighting activities.

Christopher H. Neudeck — 8/2/10

Christopher H. Neudeck, R.C.E. — (Date)
CA Lic 43473 exp. 6/30/12

REGISTERED PROFESSIONAL ENGINEER
CHRISTOPHER H. NEUDECK
NO. 43478
EXP. 06/30/12
CIVIL
STATE OF CALIFORNIA
8/2/10

Exhibit A

to Statement of Christopher H. Neudeck, R.C.E.

KJELDSEN SINNOCK NEUDECK INC. Civil Engineers and Land Surveyors

Resume

Christopher H. Neudeck

PRINCIPAL ENGINEER

REGISTRATION

Civil Engineer No. 43473, California

EDUCATION

B.S., Civil Engineering, 1982
University of Santa Clara, California

SUMMARY

Mr. Neudeck has 28 years experience in the field of civil engineering. His emphasis has been in the area of planning, design, and construction of a wide variety of water resource and public works related projects. As a principal in the firm of Kjeldsen, Sinnock & Neudeck, Inc., Mr. Neudeck is responsible for planning, designing, estimating, contracting, and managing projects undertaken by the firm. Mr. Neudeck's background provides him the expertise and capability of handling all phases of project development, from the initial planning stages through the operation of the completed project.

EXPERIENCE

Mr. Neudeck currently serves as the Engineer and Local Agency Representative for numerous Reclamation Districts in the Sacramento - San Joaquin Delta. In addition Mr. Neudeck has served as the Principal Engineer/Project Engineer for KSN on many flood control projects including, most recently the project to restore 100 year flood protection for the City of Stockton and San Joaquin County. Mr. Neudeck's experience includes the management of large scale mapping projects used to form the background for planning, right of way, and the design of projects. Mr. Neudeck has also been recognized by the State of California for the synergistic combination of habitat restoration with conventional flood control techniques.

The following is a representative sample of recent surveying, mapping and right of way assignments managed by Mr. Neudeck:

<u>San Joaquin Area Flood Control Agency (SJAFCA) Flood Protection Restoration Project</u> – SJAFCA undertook an extremely aggressive project to improve, in a period of only 3 years, over 52 mile of levees providing flood protection to the City of Stockton. KSN, under Mr. Neudeck's direction, provided surveying, mapping, right of way acquisition documents and civil design and specifications for flood control improvements throughout the 52 levee miles of the project. This very impressive project required close coordination with other consultants whose dedication and commitment to schedule prevented a large portion of the City of Stockton from being mapped within the flood plain. If those maps had been issued, property owners would have been required to obtain flood insurance, and stricter, more expensive building standards would have been imposed in the flood-prone areas. SJAFCA officials were able to convince FEMA representatives to delay issuing the maps while KSN and the SJAFCA team of consultants constructed the flood control improvements consisting of flood wall and levee improvements along 40 miles of existing channel levees, 12 miles of new levees, widening of existing floodway with set-back levees and set-back benching, modifications to 24 bridges and the addition of two major detention basins

Christopher H. Neudeck
PRINCIPAL ENGINEER

KJELDSEN SINNOCK NEUDECK INC. Civil Engineers and Land Surveyors

Tuolumne River Restoration Project for Turlock Irrigation District (TID) – TID undertook an expansive river restoration project intended to improve river channel, riparian and fisheries conditions within a 27-mile stretch of the Tuolumne River corridor below LaGrange Dam. The work was designed to correct the negative effects of intensive land and water resource development going back to the Gold Rush. KSN, under Mr. Neudeck's direct supervision, provided a full spectrum of surveying and mapping services for the project. KSN provided static GPS control, aerial Photogrammetry, digital orthophoto backgrounds, bathymetric surveys, and right-of-way mapping. KSN crews were faced with challenging field and hydraulic conditions but were always able to complete their tasks and maintain survey grade accuracies. KSN worked closely with TID and its design consultants from the initial stages of the conceptual design and preliminary right-of-way through construction as-builts.

Spooner Summit Export Pipeline Survey & Mapping Project for Incline Village General Improvement District. (IVGID) – Around 1970 the 22-mile Incline Village Effluent Export Pipeline (EEP) was built to serve the rapidly growing, 22-sq mi Nevada resort town, situated at the northeast corner of Lake Tahoe. By 2002 the Incline Village General Improvement District (IVGID) had been forced to make emergency repairs following a number of leaks in the pipeline. Rather than continuing to conduct emergency repairs at a high cost, IVGID concluded that a condition assessment was needed to determine if the pipeline would have to be temporarily rehabilitated or, in the worst-case scenario, replaced immediately. IVGID retained the engineering firm HDR to conduct a condition assessment and develop a rehabilitation project who in turn then hired KSN to assist them in the surveying and mapping of the existing as well as proposed pipeline alignments. KSN, under the direct supervision of Mr. Neudeck, undertook the surveying project which involved establishing a complex primary survey control network in mountainous terrain together with a secondary network of over 70 horizontal and vertical photo control targets. The mapping was completed utilizing aerotriangulation techniques to bridge the models in rough terrain and to minimize the need for costly ground surveys. KSN proudly received a 2005 Engineering Excellence Merit Award from the Consulting Engineers and Land Surveyors for our performance on this project.

LEVEE AND FLOOD CONTROL PROJECTS

- San Joaquin County Channel Hydraulic Studies
- Discovery Bay Slope Failure Investigation and Remedial Repair Project
- Rehabilitation and restoration of several flooded islands including Jones Tract 2004 within the Sacramento/San Joaquin Delta.
- Habitat Mitigation/Enhancement Plan for Channel Island Berm Restoration
- Mapping and delineation of riparian boundaries for the West Lathrop/River Islands Development
- Development of water habitat in conjunction with the design and construction of flood control improvements for the State of California Department of Water Resources.
- Mapping, Right of Way, and design of improvement for over 52 miles of levee for San Joaquin Area Flood Control Agency
- Mapping for USACOE IDIQ Design Engineering for Water Resources Project Sacramento District

KJELDSEN SINNOCK NEUDECK INC. Civil Engineers and Land Surveyors

LEVEE AND FLOOD CONTROL PROJECTS (CONTINUED)

- Bishop Tract, Reclamation District 2042, Design and Construction of 100 Year Flood Control Improvements
- Atlas Tract, Reclamation District 2126, Design and Construction of 100 Year Flood Control Improvements.
- Hotchkiss Tract, Reclamation District No. 799, Design and Construction of 100 Year Flood Control Improvements.
- Byron Tract, Reclamation District No. 800, Design and Construction of 100 Year Flood Control Improvements.
- Shima Tract, Reclamation District No, 2115, Design and Construction of 100 Year Flood Control Improvements.

SURVEYING AND MAPPING PROJECTS AND RIGHT-OF-WAY ACQUITIONS PROJECTS

- SJAFCA Flood Restoration Project
- Merced River Habitat Restoration, Snelling
- IVGID Pipeline, Incline Village, Nevada
- TID Habitat Restoration, Tuolumne River, Waterford
- Sunrise-Douglas Pipeline, Sacramento County
- SSJID Geographic Boundary Description
- SSJID Mapping Facilities Mapping

PROFESSIONAL SOCIETIES

Mr. Neudeck is a current member of the following professional organizations:

American Society of Civil Engineers (ASCE) (Past President)
National Society of Professional Engineers (NSPE)
Consulting Engineers and Land Surveyors of California (CELSOC)

BOARDS OR COMMITTEES

Mr. Neudeck is a current member of the following Boards or Committees:

Habitat Advisory Committee to State of CA Delta Levee Subventions Program
CALFED Levees & Channels Technical Advisory Committee
CALFED Levees & Channels Seismic Sub-Team
California Central Valley Flood Control Association
California Delta Resource Conservation & Development Council

Mr. Neudeck is a recognized authority on flood control in the Sacramento-San Joaquin Delta and often is called upon to testify before the State Legislature and has also testified before Congress on flood control related matters.

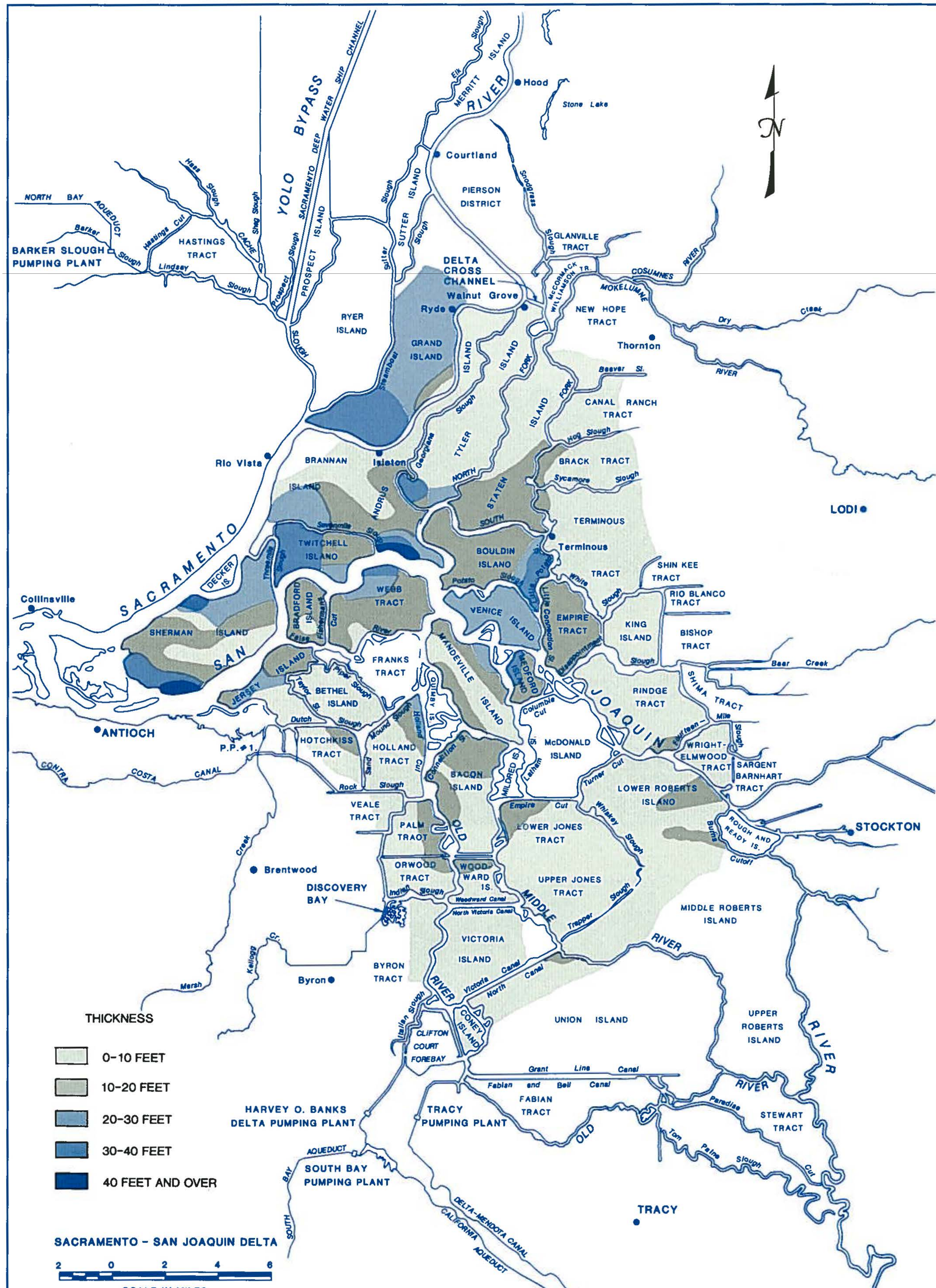
Exhibit B

to Statement of Christopher H. Neudeck, R.C.E.

RECIRC2819.

SACRAMENTO DELTA SAN JOAQUIN ATLAS

California Department of Water Resources
1993

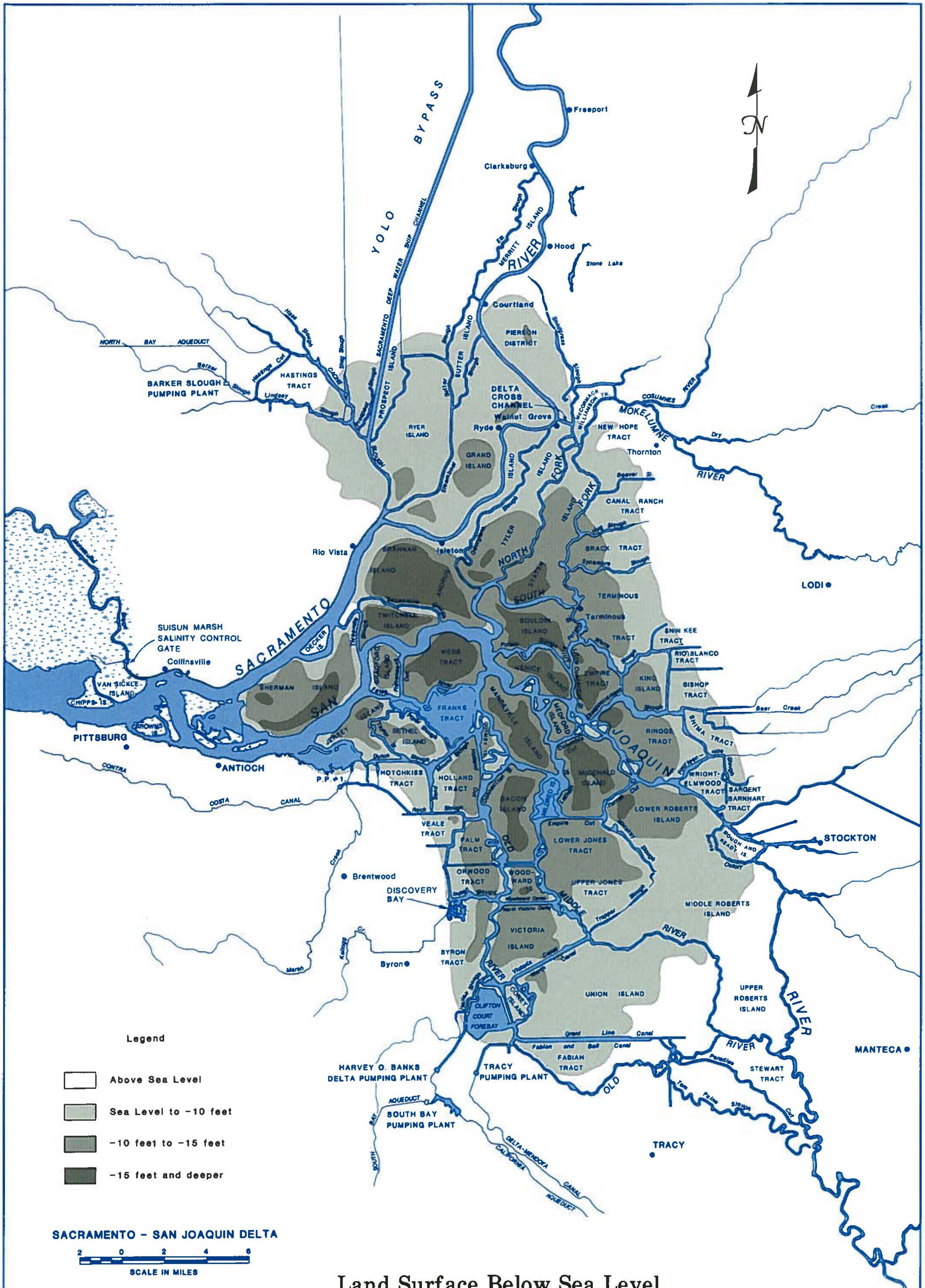


Thickness of Organic Materials

Thickness of Organic Materials

For millions of years, river flows and tidal action deposited sediment in the Delta, the low point of the Central Valley. Thick organic soil, commonly referred to as peat, was formed as tules and other plants were covered by this sediment throughout the years. These organic soils, up to 60 feet deep in some areas, were first farmed in the mid-1800s. Although highly productive for agriculture, peat is also very prone to subsidence (see the following section).

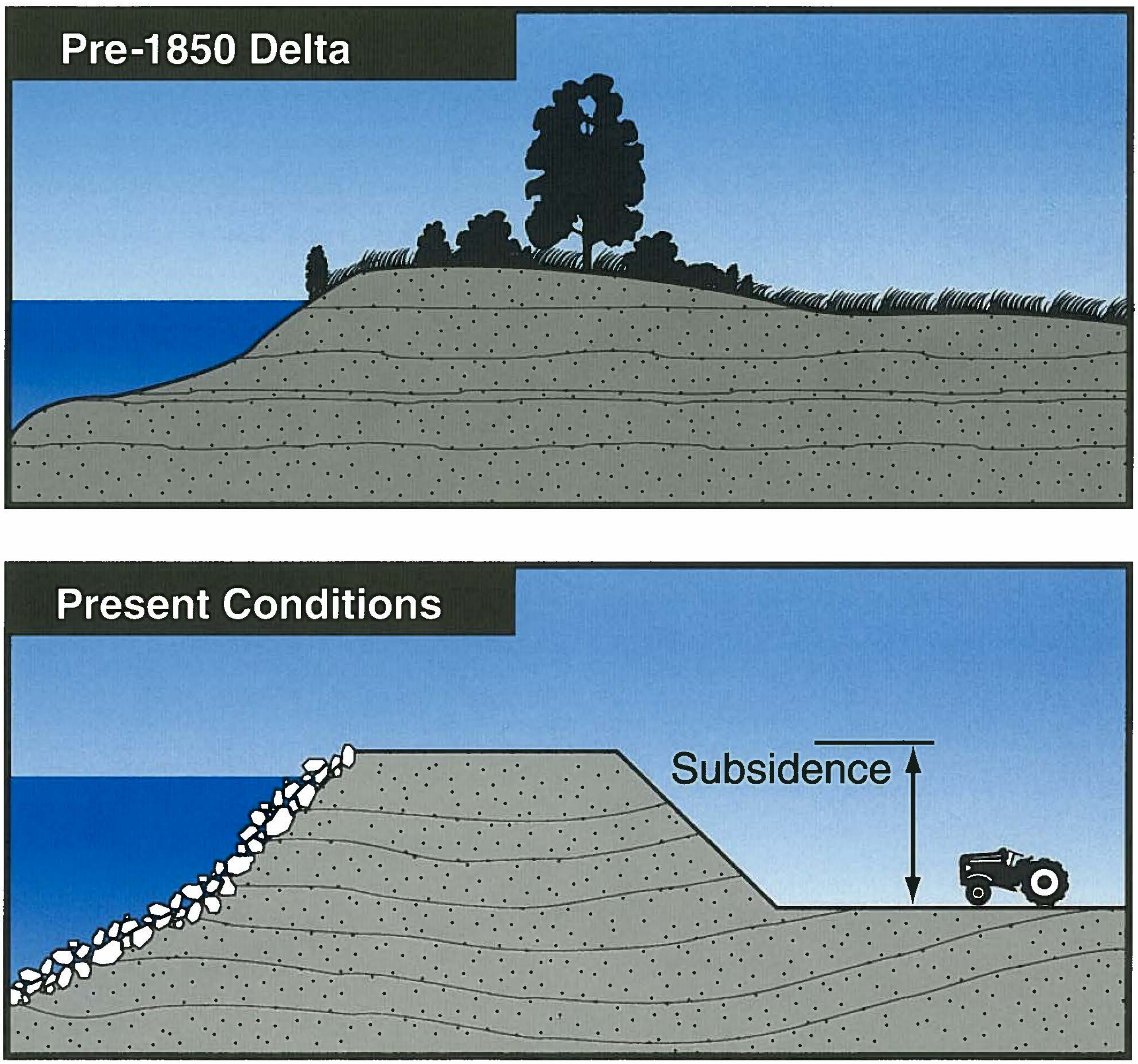
Farming on Sherman Island. Delta crops average a gross value of over $500 million per year.

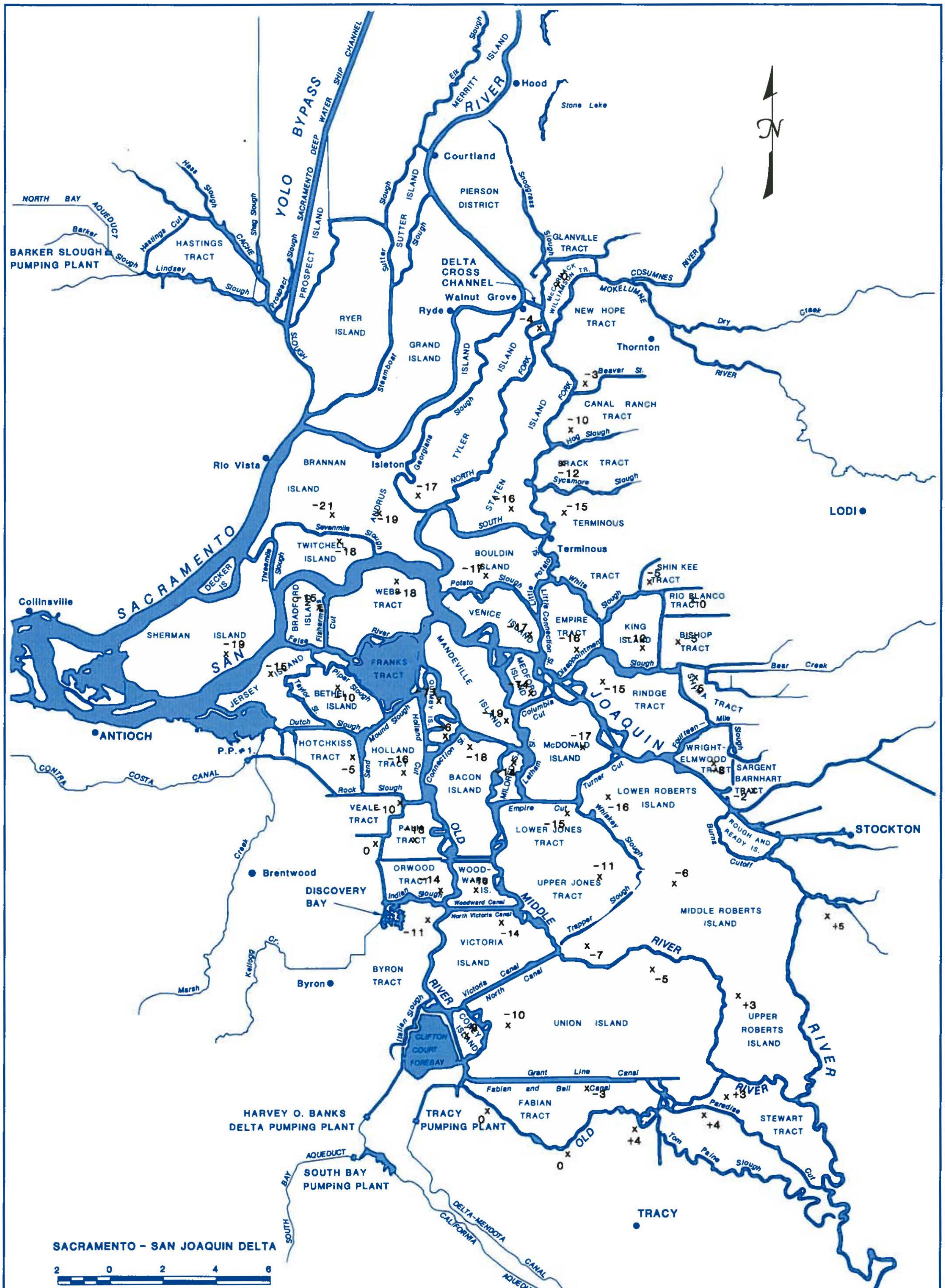


Land Surface Below Sea Level

Land Surface Below Sea Level

As shown in the figure to the left, some land in the central and western Delta is more than 15 feet below sea level. This situation is caused by land subsidence which is primarily the result of the loss of organic soil (peat). The loss is caused by exposure of peat to oxygen, which converts organic carbon solids to carbon dioxide and aqueous carbon. Subsidence is a major concern in the Delta because it increases the water pressure on levees and, therefore, the probability of levee failure and flooding.





Lowest Surface Elevations

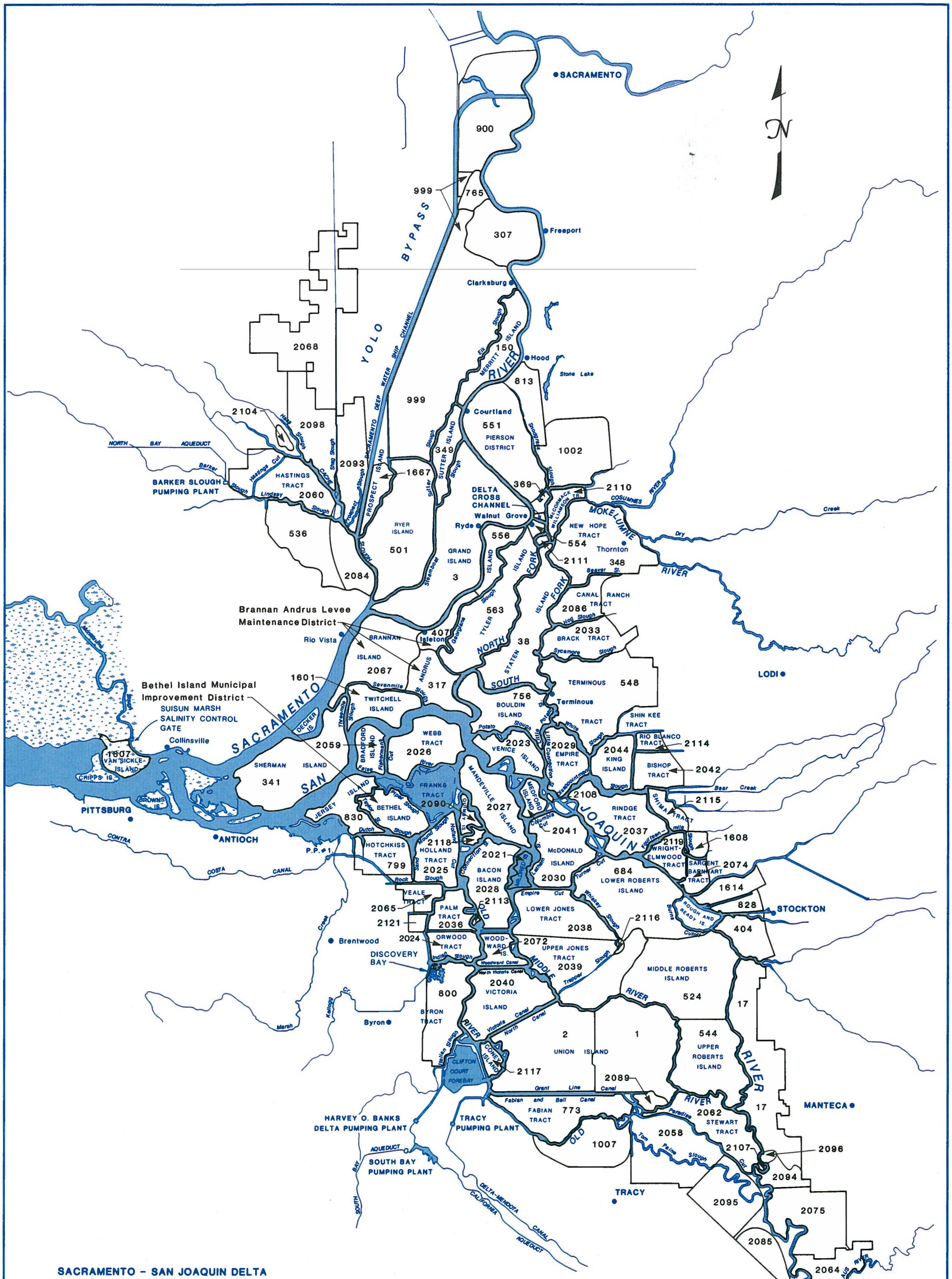
Lowest Surface Elevations

Today, in low-lying areas of the Delta, hundreds of miles of levees are needed to keep the land from being flooded by the surrounding water. The water surface can be over 20 feet higher than the land surface. As a result of this condition, a levee failure could result in flooding during the summer as well as the winter.

At least four levee failures have occurred during the summer or early fall — Webb Tract, June 1950; Andrus-Brannan Island, June 1972; Jones Tract, September-October 1980; and MacDonald Island, August 1982.

Cracks occurring on the levees of a low-lying island.

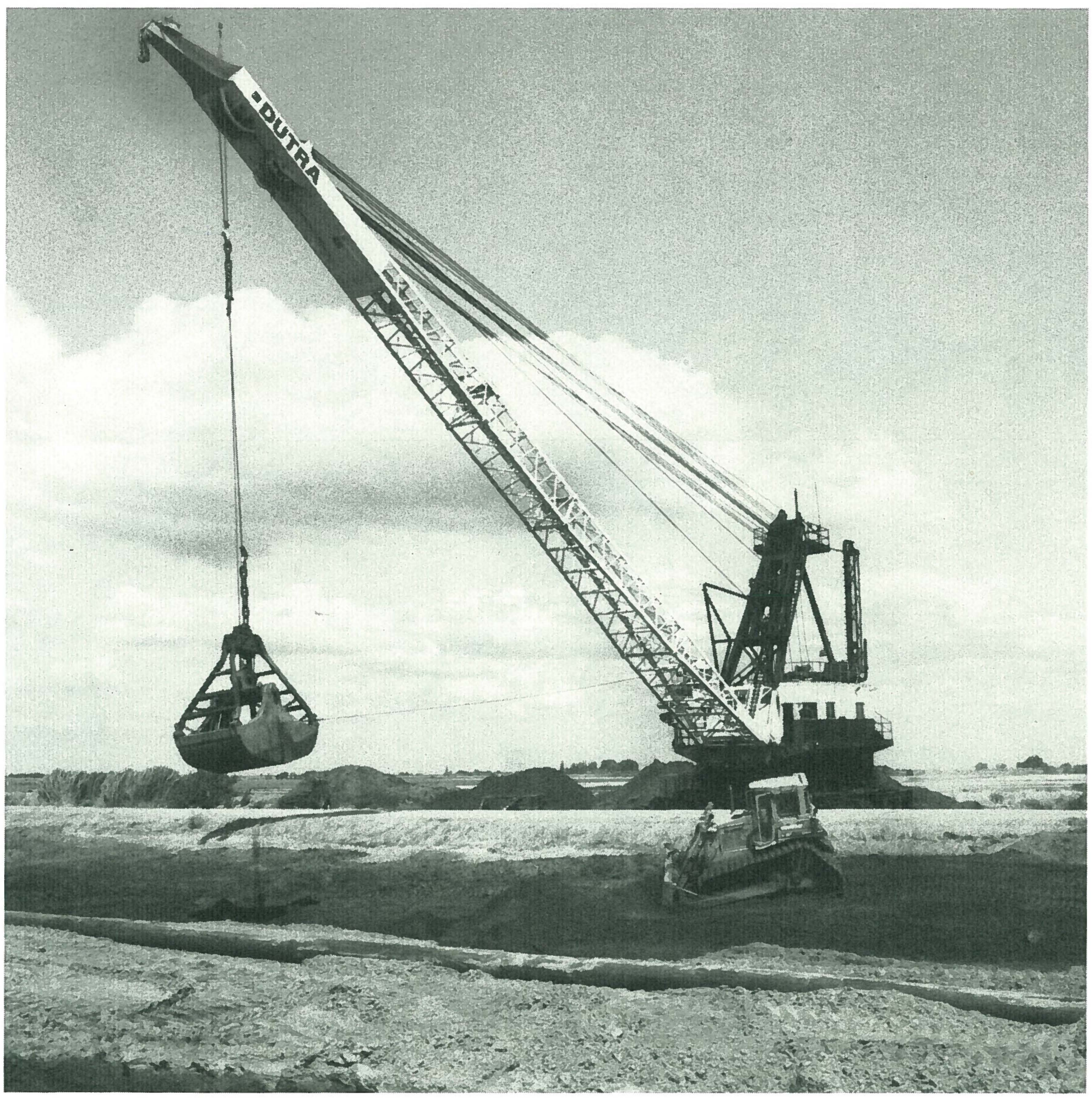
Land subsidence on Orwood Tract is exposing piles supporting the East Bay Municipal Utility District Aqueduct. These piles extend deep into the ground to assure continued stability.



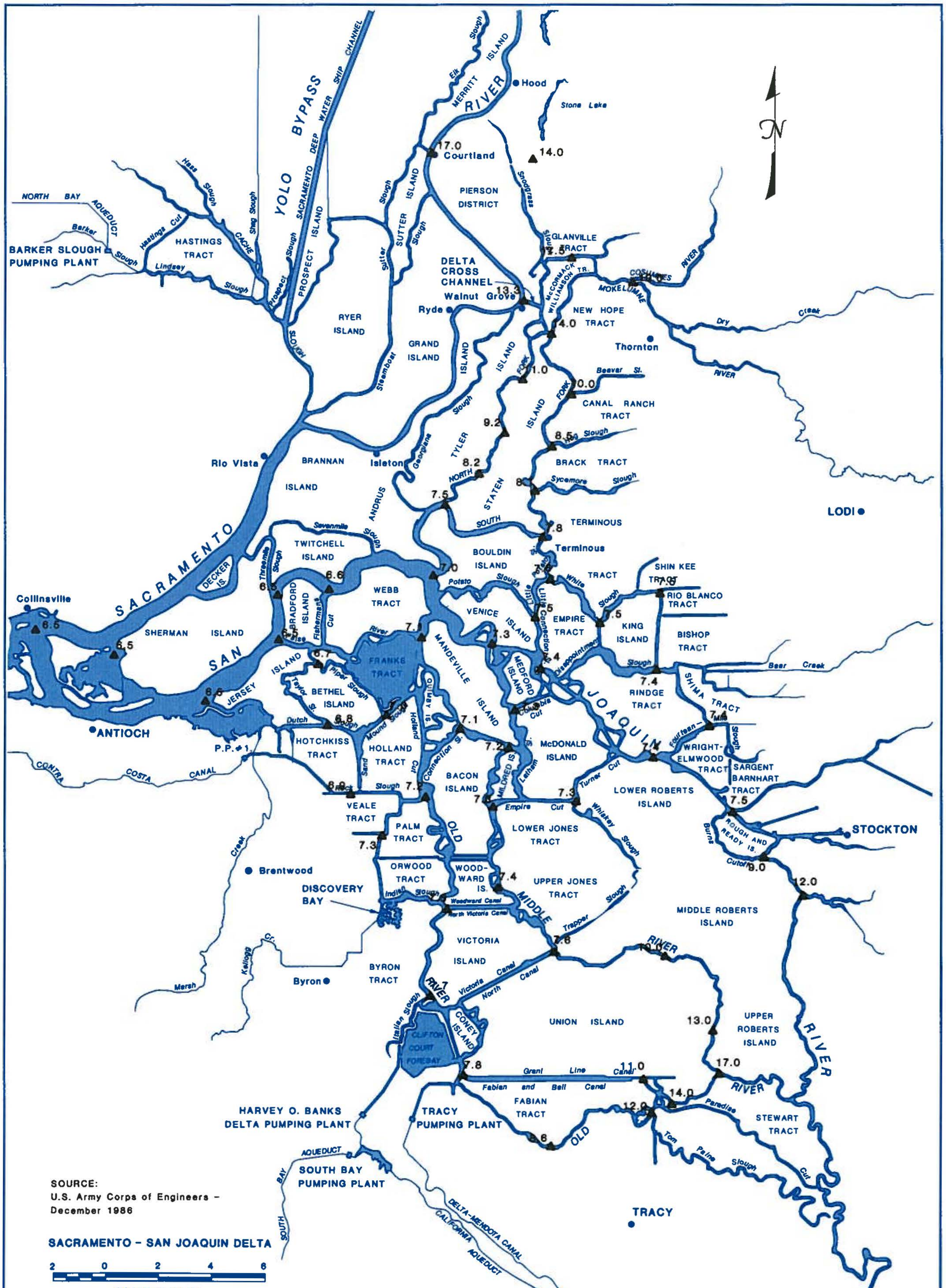
Reclamation and Levee Maintenance Districts

Reclamation and Levee Maintenance Districts

In 1855, California passed the Reclamation District Act providing for sale of swamp and overflow lands at $1 per acre with payments over 5 years, and a 320-acre limit. Today, these lands in the Delta are ringed with levees and have their own districts for maintaining the levees. Some islands belong to more than one district. A more populated island, Bethel, has an organization with broader responsibilities which is known as the Bethel Island Municipal Improvement District. Information on expenditures for levee emergency work and annual maintenance for these districts is contained in Tables 1 and 2 (pages 81 - 84) along with values for acreage and miles of levee.



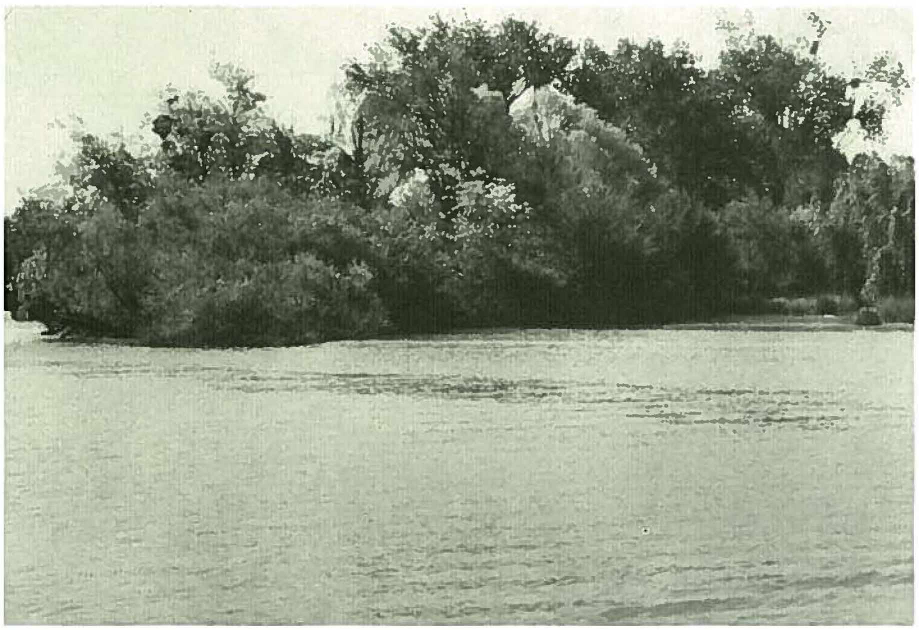
Levee rehabilitation on Twitchell Island.



Flood Stage Elevations

Flood Stage Elevations

Rivers and channels surrounding the central and western Delta have a limited ability for carrying flood flows. For example, a flood causing water levels in the north Delta to increase by 10 feet may only cause a 1-foot increase in water levels in the central and western Delta. Sedimentation, which limits the flood-carrying capacity of the channels, has occurred in various places throughout the Delta, particularly along the South Fork of the Mokelumne River. In 1986, the U. S. Army Corps of Engineers estimated the 100-year flood stages to be as shown on the map at left.



Sedimentation in the Mokelumne River encourages vegetative growth which limits flood-carrying capacity.

A combination of high tides, winter floodflows, and poor levees can result in flooded islands.

Enclosure No. 10

RECIRC2819.

CM-010

ATTORNEY OR PARTY WITHOUT ATTORNEY *(Name, State Bar number, and address)*:

James C. Phillips, SBN 121848; John M. Feser, Jr., SBN 209736
Office of the Attorney General
1300 I Street, P.O. Box 944255, Sacramento, CA 94244-2550
TELEPHONE NO.: 916-322-5473 FAX NO.: 916-322-8288
ATTORNEY FOR *(Name)*: Petitioner State of California, Dept. of Water Resources

FOR COURT USE ONLY

FILED
SUPERIOR COURT - STOCKTON
09 FEB 26 AM 9:57
ROSA JUNQUEIRO, CLERK
MOUCHIA FORD
BY DEPUTY

SUPERIOR COURT OF CALIFORNIA, COUNTY OF San Joaquin
STREET ADDRESS: 222 East Weber Avenue, Room 303
MAILING ADDRESS:
CITY AND ZIP CODE: Stockton, CA 95202
BRANCH NAME:

CASE NAME:
State, Dept. of Water Resources v. Reclamation District No. 548, et al.

CIVIL CASE COVER SHEET

☐ **Unlimited** (Amount demanded exceeds $25,000)
☑ **Limited** (Amount demanded is $25,000 or less)

Complex Case Designation

☐ **Counter** ☐ **Joinder**

Filed with first appearance by defendant (Cal. Rules of Court, rule 3.402)

CASE NUMBER: 39-2009-00204887-CU-EI-STK

JUDGE:

DEPT:

Items 1–6 below must be completed (see instructions on page 2).

1. Check **one** box below for the case type that best describes this case:

Auto Tort
☐ Auto (22)
☐ Uninsured motorist (46)

Other PI/PD/WD (Personal Injury/Property Damage/Wrongful Death) Tort
☐ Asbestos (04)
☐ Product liability (24)
☐ Medical malpractice (45)
☐ Other PI/PD/WD (23)

Non-PI/PD/WD (Other) Tort
☐ Business tort/unfair business practice (07)
☐ Civil rights (08)
☐ Defamation (13)
☐ Fraud (16)
☐ Intellectual property (19)
☐ Professional negligence (25)
☐ Other non-PI/PD/WD tort (35)

Employment
☐ Wrongful termination (36)
☐ Other employment (15)

Contract
☐ Breach of contract/warranty (06)
☐ Rule 3.740 collections (09)
☐ Other collections (09)
☐ Insurance coverage (18)
☐ Other contract (37)

Real Property
☑ Eminent domain/Inverse condemnation (14)
☐ Wrongful eviction (33)
☐ Other real property (26)

Unlawful Detainer
☐ Commercial (31)
☐ Residential (32)
☐ Drugs (38)

Judicial Review
☐ Asset forfeiture (05)
☐ Petition re: arbitration award (11)
☐ Writ of mandate (02)
☐ Other judicial review (39)

Provisionally Complex Civil Litigation (Cal. Rules of Court, rules 3.400–3.403)
☐ Antitrust/Trade regulation (03)
☐ Construction defect (10)
☐ Mass tort (40)
☐ Securities litigation (28)
☐ Environmental/Toxic tort (30)
☐ Insurance coverage claims arising from the above listed provisionally complex case types (41)

Enforcement of Judgment
☐ Enforcement of judgment (20)

Miscellaneous Civil Complaint
☐ RICO (27)
☐ Other complaint *(not specified above)* (42)

Miscellaneous Civil Petition
☐ Partnership and corporate governance (21)
☐ Other petition *(not specified above)* (43)

2. This case ☐ is ☑ is not complex under rule 3.400 of the California Rules of Court. If the case is complex, mark the factors requiring exceptional judicial management:
   a. ☐ Large number of separately represented parties
   b. ☐ Extensive motion practice raising difficult or novel issues that will be time-consuming to resolve
   c. ☐ Substantial amount of documentary evidence
   d. ☐ Large number of witnesses
   e. ☐ Coordination with related actions pending in one or more courts in other counties, states, or countries, or in a federal court
   f. ☐ Substantial postjudgment judicial supervision
3. Remedies sought *(check all that apply)*: a. ☐ monetary b. ☑ nonmonetary; declaratory or injunctive relief c. ☐ punitive
4. Number of causes of action *(specify)*:
5. This case ☐ is ☑ is not a class action suit.
6. If there are any known related cases, file and serve a notice of related case. *(You may use form CM-015.)*

Date: February 24, 2009
James C. Phillips/John M. Feser, Jr.
(TYPE OR PRINT NAME)

[signature] for James C. Phillips
(SIGNATURE OF PARTY OR ATTORNEY FOR PARTY)

NOTICE

- Plaintiff must file this cover sheet with the first paper filed in the action or proceeding (except small claims cases or cases filed under the Probate Code, Family Code, or Welfare and Institutions Code). (Cal. Rules of Court, rule 3.220.) Failure to file may result in sanctions.
- File this cover sheet in addition to any cover sheet required by local court rule.
- If this case is complex under rule 3.400 et seq. of the California Rules of Court, you must serve a copy of this cover sheet on **all** other parties to the action or proceeding.
- Unless this is a collections case under rule 3.740 or a complex case, this cover sheet will be used for statistical purposes only.

Form Adopted for Mandatory Use
Judicial Council of California
CM-010 [Rev. July 1, 2007]

CIVIL CASE COVER SHEET

Cal. Rules of Court, rules 2.30, 3.220, 3.400–3.403, 3.740;
Cal. Standards of Judicial Administration, std. 3.10
www.courtinfo.ca.gov

INSTRUCTIONS ON HOW TO COMPLETE THE COVER SHEET

To Plaintiffs and Others Filing First Papers. If you are filing a first paper (for example, a complaint) in a civil case, you **must** complete and file, along with your first paper, the *Civil Case Cover Sheet* contained on page 1. This information will be used to compile statistics about the types and numbers of cases filed. You must complete items 1 through 6 on the sheet. In item 1, you must check **one** box for the case type that best describes the case. If the case fits both a general and a more specific type of case listed in item 1, check the more specific one. If the case has multiple causes of action, check the box that best indicates the **primary** cause of action. To assist you in completing the sheet, examples of the cases that belong under each case type in item 1 are provided below. A cover sheet must be filed only with your initial paper. Failure to file a cover sheet with the first paper filed in a civil case may subject a party, its counsel, or both to sanctions under rules 2.30 and 3.220 of the California Rules of Court.

To Parties in Rule 3.740 Collections Cases. A "collections case" under rule 3.740 is defined as an action for recovery of money owed in a sum stated to be certain that is not more than $25,000, exclusive of interest and attorney's fees, arising from a transaction in which property, services, or money was acquired on credit. A collections case does not include an action seeking the following: (1) tort damages, (2) punitive damages, (3) recovery of real property, (4) recovery of personal property, or (5) a prejudgment writ of attachment. The identification of a case as a rule 3.740 collections case on this form means that it will be exempt from the general time-for-service requirements and case management rules, unless a defendant files a responsive pleading. A rule 3.740 collections case will be subject to the requirements for service and obtaining a judgment in rule 3.740.

To Parties in Complex Cases. In complex cases only, parties must also use the *Civil Case Cover Sheet* to designate whether the case is complex. If a plaintiff believes the case is complex under rule 3.400 of the California Rules of Court, this must be indicated by completing the appropriate boxes in items 1 and 2. If a plaintiff designates a case as complex, the cover sheet must be served with the complaint on all parties to the action. A defendant may file and serve no later than the time of its first appearance a joinder in the plaintiff's designation, a counter-designation that the case is not complex, or, if the plaintiff has made no designation, a designation that the case is complex.

CASE TYPES AND EXAMPLES

Auto Tort
- Auto (22)–Personal Injury/Property Damage/Wrongful Death
- Uninsured Motorist (46) *(if the case involves an uninsured motorist claim subject to arbitration, check this item instead of Auto)*

Other PI/PD/WD (Personal Injury/ Property Damage/Wrongful Death) Tort
- Asbestos (04)
  - Asbestos Property Damage
  - Asbestos Personal Injury/ Wrongful Death
- Product Liability *(not asbestos or toxic/environmental)* (24)
- Medical Malpractice (45)
  - Medical Malpractice– Physicians & Surgeons
  - Other Professional Health Care Malpractice
- Other PI/PD/WD (23)
  - Premises Liability (e.g., slip and fall)
  - Intentional Bodily Injury/PD/WD (e.g., assault, vandalism)
  - Intentional Infliction of Emotional Distress
  - Negligent Infliction of Emotional Distress
  - Other PI/PD/WD

Non-PI/PD/WD (Other) Tort
- Business Tort/Unfair Business Practice (07)
- Civil Rights (e.g., discrimination, false arrest) *(not civil harassment)* (08)
- Defamation (e.g., slander, libel) (13)
- Fraud (16)
- Intellectual Property (19)
- Professional Negligence (25)
  - Legal Malpractice
  - Other Professional Malpractice *(not medical or legal)*
- Other Non-PI/PD/WD Tort (35)

Employment
- Wrongful Termination (36)
- Other Employment (15)

Contract
- Breach of Contract/Warranty (06)
  - Breach of Rental/Lease
    - Contract *(not unlawful detainer or wrongful eviction)*
  - Contract/Warranty Breach–Seller Plaintiff *(not fraud or negligence)*
  - Negligent Breach of Contract/ Warranty
  - Other Breach of Contract/Warranty
- Collections (e.g., money owed, open book accounts) (09)
  - Collection Case–Seller Plaintiff
  - Other Promissory Note/Collections Case
- Insurance Coverage *(not provisionally complex)* (18)
  - Auto Subrogation
  - Other Coverage
- Other Contract (37)
  - Contractual Fraud
  - Other Contract Dispute

Real Property
- Eminent Domain/Inverse Condemnation (14)
- Wrongful Eviction (33)
- Other Real Property (e.g., quiet title) (26)
  - Writ of Possession of Real Property
  - Mortgage Foreclosure
  - Quiet Title
  - Other Real Property *(not eminent domain, landlord/tenant, or foreclosure)*

Unlawful Detainer
- Commercial (31)
- Residential (32)
- Drugs (38) *(if the case involves illegal drugs, check this item; otherwise, report as Commercial or Residential)*

Judicial Review
- Asset Forfeiture (05)
- Petition Re: Arbitration Award (11)
- Writ of Mandate (02)
  - Writ–Administrative Mandamus
  - Writ–Mandamus on Limited Court Case Matter
  - Writ–Other Limited Court Case Review
- Other Judicial Review (39)
  - Review of Health Officer Order
  - Notice of Appeal–Labor Commissioner Appeals

Provisionally Complex Civil Litigation (Cal. Rules of Court Rules 3.400–3.403)
- Antitrust/Trade Regulation (03)
- Construction Defect (10)
- Claims Involving Mass Tort (40)
- Securities Litigation (28)
- Environmental/Toxic Tort (30)
- Insurance Coverage Claims *(arising from provisionally complex case type listed above)* (41)

Enforcement of Judgment
- Enforcement of Judgment (20)
  - Abstract of Judgment (Out of County)
  - Confession of Judgment *(non-domestic relations)*
  - Sister State Judgment
  - Administrative Agency Award *(not unpaid taxes)*
  - Petition/Certification of Entry of Judgment on Unpaid Taxes
  - Other Enforcement of Judgment Case

Miscellaneous Civil Complaint
- RICO (27)
- Other Complaint *(not specified above)* (42)
  - Declaratory Relief Only
  - Injunctive Relief Only *(non-harassment)*
  - Mechanics Lien
  - Other Commercial Complaint Case *(non-tort/non-complex)*
  - Other Civil Complaint *(non-tort/non-complex)*

Miscellaneous Civil Petition
- Partnership and Corporate Governance (21)
- Other Petition *(not specified above)* (43)
  - Civil Harassment
  - Workplace Violence
  - Elder/Dependent Adult Abuse
  - Election Contest
  - Petition for Name Change
  - Petition for Relief From Late Claim
  - Other Civil Petition

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

FILED
SUPERIOR COURT - STOCKTON
09 FEB 26 AM 10:00
ROSA JUNQUEIRO, CLERK
MOUCHIA FORDE
BY ______
DEPUTY

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: 39-2009-00204887-CU-EI-STK PETITIONER'S NOTICE OF HEARING RE PETITION FOR ORDER PERMITTING ENTRY AND INVESTIGATION OF REAL PROPERTY [CODE OF CIVIL PROCEDURE, § 1245.030] APN: 025-020-13 APN: 025-100-14

PLEASE TAKE NOTICE that on July 6, 2009, at ~~8:30~~ 10:00 a.m. or as soon thereafter as the Petition may be heard, in Department 41 of the above-entitled Court, located at 222 E Weber Ave, California, is appointed as the date, time and place for the hearing on the heretofore filed Petition of Petitioner State of California, acting by and through the California Department of Water Resources, for an Order of this Court Permitting Entry and Investigation upon the real property described in the Petition for the activities set forth in the Petition.

Notice of hearing is given to Respondents by personal service of a copy of this Notice, the Petition, and the [Proposed] Order for Entry and Investigation of Real Property. All opposing and reply papers shall be governed by Code of Civil Procedure section 1005, subdivision (c).

Pursuant to Local Rule 3.113D, the Court will make a tentative ruling on the merits of this matter by 1:30 p.m. the Court day before the hearing. To receive the tentative ruling, call (209) 468-2868 or access the Internet at www.stocktoncourt.org. If you do not call the Court at (209) 468-2867, and the opposing party by 4:00 p.m., the Court day before the hearing, no hearing will be held.

Dated: Feb 17, 2009.

Respectfully submitted,

EDMUND G. BROWN JR, Attorney General
of the State of California

By: ____________________
JAMES C. PHILLIPS,
Deputy Attorney General
JOHN M. FESER, JR.,
Deputy Attorney General

Attorneys for Petitioner State of California by and through the Department of Water Resources

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

Attorneys for Petitioner STATE OF CALIFORNIA, by and through THE DEPARTMENT OF WATER RESOURCES

FILED
SUPERIOR COURT - STOCKTON
09 FEB 26 AM 10:00
ROSA JUNQUEIRO, CLERK
MOLICHIA FORDE
DEPUTY

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through THE DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: 39-2009-00204887-CU-EI-STK PETITIONER'S PETITION FOR ORDER PERMITTING ENTRY AND INVESTIGATION OF REAL PROPERTY; EXHIBITS; DECLARATIONS IN SUPPORT [CODE OF CIVIL PROCEDURE, § 1245.030] APN: 025-020-13 APN: 025-100-14

1. Petitioner is the State of California, acting by and through the Department of Water Resources (DWR). Petitioner is authorized to acquire property for public purposes pursuant to authorization contained in the Property Acquisition Act (Part 11, Division 3, Title 2 of the Government Code), and Code of Civil Procedure section 1230.010 et seq. The public purpose herein is the Bay Delta Conservation Plan (BDCP). The DWR is currently working on a study for the BDCP and will study near-term and long-term approaches to meet the objectives of providing for the conservation of covered species and their habitats, addressing the requirements

of the federal and State Endangered Species laws, water supply reliability, seismic and flood durability, ecosystem health and resilience, water quality, schedule, cost and options. Delays in completing studies for the BDCP may result in continued degradation of habitat for fisheries and may reduce the reliability of water deliveries in the State of California. Studies are to determine the best alternatives for future conveyances to ensure reliable water supplies for fisheries, habitat and other water users. The studies are scheduled to be completed in the year 2011.

2. Respondent(s) is/are the owner(s) of real property in San Joaquin County, as set forth herein: APN(s): 025-020-13 and 025-100-14.

3. In accordance with the provisions of Code of Civil Procedure section 1245.010, et seq., petitioner, as a potential condemnor, is entitled to an order to enter property to make photographs, studies, surveys, examinations, tests, soundings, borings, samplings, appraisals, archeological, environmental, botanical, biological, geological, and engineering examinations, or to engage in similar activities reasonably related to acquisition or use of that property to determine the suitability of the property for a potential public use. Petitioner needs this information to design the project using sound engineering and environmental practices.

4. Petitioner seeks to enter the real property delineated on the map attached hereto and incorporated herein, to determine its suitability for environmental studies for the BDCP.

5. The identity of the owner(s) of the real property described in Paragraphs 2 and 4 of this petition is as follows: Reclamation District No. 548.

6. The true names and capacities, whether individual, corporate, or otherwise, of each of the respondents named herein as Does One to Ten, inclusive, are unknown to petitioner, who, therefore, seeks jurisdiction over respondents by such names, and will, upon ascertaining the true names and capacities of any of the respondents, amend this petition to show their true names and capacities; that the fictitiously named respondents, and each of them, have or claim to have an interest in the real property heretofore described, but that the nature, character and extent of such interest are unknown to the petitioner.

7. Petitioner seeks entry to the real property described in Paragraph 2 and 4 by teams of experts and technicians, for the purposes of conducting those activities set forth in Paragraph 3

above. Details of the biological, botanical, archaeological, environmental, topographical and geological studies contemplated are set forth with particularity in the attached declarations of staff of the DWR (Teresa Engstrom, Derrick Adachi, Frank Glick, Donald C. Guy, Janis K. Offerman, Louis Vonderscheer, Reza Tajeran, and Allan T. Davis.), and are incorporated herein by reference. Petitioner seeks an immediate order permitting entry for a period of time up to and including December 31, 2011, in order to conduct the required studies.

8. Code of Civil Procedure section 1245.060 governs compensation for actual damage to or substantial interference with the possession or use of the subject property. The nature and scope of activities described in Paragraph 3 above, and as set forth with particularity in the attached Declarations of staff of DWR, may result in actual damage to Assessor Parcel Number(s) 025-100-13 and 025-100-14 and interference with its possession and use in the probable amount of $1,000.00 (One Thousand Dollars). The Declaration of Allan T. Davis, Supervising Land Agent overseeing the Real Estate activities of DWR, attached hereto and incorporated herein by reference, sets forth the basis for the proffered opinion of the probable amount of just compensation.

9. Petitioner requests, pursuant to Code of Civil Procedure section 1245.030, this court set a time and place for a hearing on petitioner's request for an Order Permitting Entry and Investigation of Real Property, and fixing the probable amount of compensation to be deposited for the benefit of the owner of the property for possible damage to the property and interference with its possession and use. Petitioner shall give notice by personal service of a "Notice of Hearing Re Petition for Order Permitting Entry and Investigation of Real Property", this filed Petition, and [Proposed] Order For Entry and Investigation of Real Property.

WHEREFORE, petitioner prays for an immediate Order of this court permitting entry upon the real property for the activities hereinbefore described for a period of time up to and including December 31, 2011, from the effective date of the Order permitting entry; for the

/////

fixing of the probable amount of compensation to be deposited for the owners of the property for the possible damage to the property and substantial interference with its possession and use.

Dated: Feb 19, 2009.

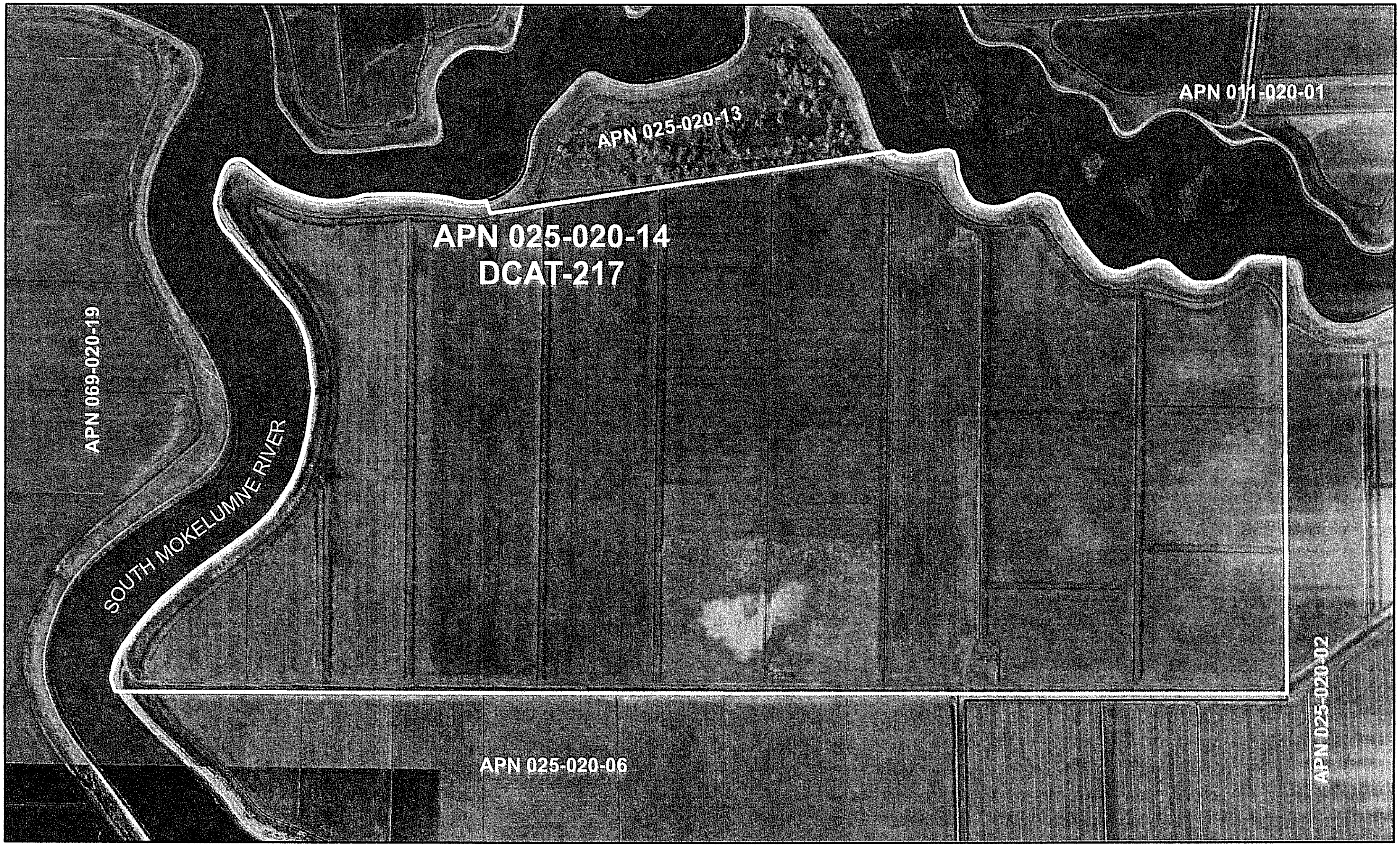
Respectfully submitted,

EDMUND G. BROWN JR, Attorney General
of the State of California

By: ____________________
JAMES C. PHILLIPS,
Deputy Attorney General
JOHN M. FESER, JR.
Deputy Attorney General

Attorneys for Petitioner STATE OF CALIFORNIA, by and through THE DEPARTMENT OF WATER RESOURCES

RECIRC2819.



SAN JOAQUIN COUNTY

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
DIVISION OF ENGINEERING - GEODETIC BRANCH

N.T.S. This exhibit does not represent a Survey and is for informational purposes only

DELTA HABITAT CONSERVATION AND CONVEYANCE PROGRAM PARCEL EXHIBIT - THROUGH

RECIRC2819.

SAN JOAQUIN COUNTY

STATE OF CALIFORNIA
THE RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES
DIVISION OF ENGINEERING - GEODETIC BRANCH

N.T.S. This exhibit does not represent a Survey and is for informational purposes only

DELTA HABITAT CONSERVATION AND CONVEYANCE PROGRAM
PARCEL EXHIBIT - THROUGH

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	**Case No.:** APN: 025-020-13 APN: 025-100-14 **[PROPOSED] ORDER AFTER HEARING PERMITTING ENTRY AND INVESTIGATION OF REAL PROPERTY, NOTICE OF SCHEDULED CONFERENCE**

The petition of STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES, filed with this court on ______________2009, for entry upon and investigation of Respondents Reclamation District No. 548 real property is granted, subject to the particular and specific orders as follows:

I. GEOLOGIC STUDIES

Respondents must grant entry to Petitioner's employees, agents and contractors for the purpose of studying and determining foundation and geologic conditions existing on portions of the Respondent's real property.

a. Access will be granted for this work for a period of ten days for four persons on each day.

b. Access will be during the period of 8 a.m. to 5 p.m. on Mondays through Fridays.

c. Such periods of access need not be continuous.

d. Petitioner will give Respondents 48 hour notice of the intended entry date, the tests to be performed, the number of persons who will enter and the vehicles and equipment they will bring with them.

Respondents will immediately after receipt of this order designate a person to receive such notice, giving that person's name, telephone number and fax number and mailing address. Notice will be by means of telephone call and contemporaneous fax of information, followed by the faxed message mailed to the designated person.

e. Petitioner may do geologic testing on Respondent's property as described in the Declaration of Frank Glick attached to the petition in this matter.

f. Petitioner may dig test pits as needed, utilizing a back hoe or other machinery as needed. Petitioner may drill soil sample holes as needed, utilizing whatever drilling equipment is needed. The test pits and soil sample holes will be restored to their original condition as nearly as is possible after such testing is concluded.

g. Petitioner may conduct electrical resistivity surveys utilizing whatever equipment is necessary. All equipment utilized will be removed immediately after testing.

h. Petitioner will insure that Respondents or any of Respondent's tenants do not suffer any interruptions in utility services due to such geologic testing and investigation.

II. <u>ENVIRONMENTAL STUDIES</u>

a. Respondents must grant access to the Petitioner's employees, agents, and contractors for the purpose of studying and investigation of the flora and fauna on Respondent's real property.

b. Such access will include the following:

    1. A one or two person team may have five eight-hour periods to walk over the entire surface of the real property and access must be granted into every building which could contain the storage of hazardous materials. Such person or persons may be accompanied by Respondent's personnel for security purposes. Such

persons may take photographs of all areas of the property with the express exception of the facility now leased to a contractor for the Homeland Security Agency.

2. A one or two person team may utilize the same day, or another day, to walk over the surface of the real property, without the entry into any building, for documentation and recordation of their observations. Such persons may utilize a vehicle for entry onto the property. Such persons may take unlimited photographs.
3. A one or two person team may have access for two days (in addition to the days listed above) to take soil samples utilizing a 3" hand auger. Respondents will be notified of the proposed sampling locations prior to sampling. No pavement or concrete will be augured without the express order of this court upon ex parte application as explained below. As usual, Respondent's personnel may accompany Petitioner's investigators. Auger holes will be restored to their original condition as nearly as possible after cores are removed.
4. Access must be granted to Petitioner's personnel during the night for fauna observations and trapping. Access will be granted for the entire property for the period of 10 nighttime periods for two persons each period, as needed. Respondent's personnel may accompany Petitioner's personnel if Respondents desires. Such investigators may enter the property with a vehicle to transport equipment.
5. Access must be granted for 4 other day time periods for 3 to 4 persons on each visit, and for eight additional days for a two person team as needed.

c. Any and all environmental studies will have access to the entire property with the exclusion of building interiors (except as specified in paragraph II, b. 1., above). None of Petitioner's personnel will be allowed to smoke while on Respondent's real property.

III. <u>ARCHEOLOGICAL STUDIES</u>

a. Access will be granted to one to two persons for four days in the entire area of the real property. Such persons may take photographs of all areas, including the exterior of buildings.

b. Notice of the time and nature of the entries will be provided as ordered in paragraph I.d., above.

IV. RESTRICTIONS APPLYING TO ALL ENTRIES

a. The period of access granted by this order is to June 30, 2011.

b. Any of Respondent's personnel who may accompany Petitioner's personnel will obey the directions of Petitioner's personnel as to the distance they must maintain from Petitioner's personnel and any safety equipment they must wear.

c. Should Respondents desire it, Petitioner's personnel will wear identification badges while on Respondent's real property. Such badges will be provided as needed by Respondents.

d. None of Petitioner's personnel will be allowed to smoke while on the Respondent's real property.

V. PROCEDURE FOR MODIFICATION OR CLARIFICATION OF THIS ORDER

In the event a party desires clarification of this order, or modification of this order, such party will schedule an ex parte hearing, upon 48 hour, telephone and fax notice to counsel of the other party, and approval of the court, for such modification and/or clarification. No such hearing may be scheduled on Monday or Tuesday, but only on Wednesday, Thursday, or Friday, so as to guard against weekend notice.

VI. NOTICE OF SCHEDULING CONFERENCE

A scheduling conference will be conducted in Department _______ at 8:30 a.m., on ________2009, to schedule a hearing on the proper amount of probable compensation.

Dated this _____day of ________, 2009.

____

Honorable Judge of the Superior Court

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

FILED
SUPERIOR COURT - STOCKTON
09 FEB 26 AM 10: 00
ROSA JUNQUEIRO, CLERK
MOUCHIA FORDE
DEPUTY

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: APN: 025-020-13 APN: 025-100-14 DECLARATION OF TERESA ENGSTROM IN SUPPORT OF PETITIONER'S PETITION FOR RIGHT OF ENTRY

I, TERESA ENGSTROM, make this declaration in support of the STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES' (DWR's) Bay Delta Conservation Plan (BDCP). I have personal knowledge of the following, and if called as a witness, I would and could testify competently thereto.

1. I have been employed by the DWR for more than twenty years as an engineer, and I am currently a Principal Engineer for DWR. I make this declaration in support of this Petition by the DWR for an Order Permitting Entry and Investigation of properties in the Counties of Sacramento, San Joaquin, Contra Costa, Solano and Yolo. I am the Project

Coordinator for the BDCP and am therefore, responsible for the budgeting, scheduling, and overall control of the work.

2. The DWR is currently working on a study for the BDCP and will study near-term and long-term approaches to meet the objectives of providing for the conservation of covered species and their habitats, addressing the requirements of the federal and State Endangered Species laws, water supply reliability, seismic and flood durability, ecosystem health and resilience, water quality, schedule, cost and options. Delays in completing studies for the BDCP may result in continued degradation of habitat for fisheries and may reduce the reliability of water deliveries in the State of California. Studies are to determine the best alternatives for future conveyances to ensure reliable water supplies for fisheries, habitat and other water users. The studies are scheduled to begin upon entry and are to be completed in the year 2011.

3. Access is needed onto the properties to complete studies in order to conduct necessary environmental surveys and geologic explorations up through and including December 31, 2011. As many of the environmental studies are dependent on the time of year and weather, time is of the essence in obtaining access to these properties at the earliest possible time.

4. The environmental work shall consist of the following: DWR and/or its consultants will conduct professional and technical evaluations, studies, and surveys, necessary and/or required to plan, design, develop, and possibly construct components of the BDCP. Field studies and surveys include, but are not limited to, aesthetics, agricultural, archeological, biological, historical and cultural, anthropologic, paleontologic, hydrologic, and recreation resources and conditions to establish baseline conditions, ascertain and characterize resources, and report on resources as appropriate and necessary for Project development and permitting. The particulars of each study are set forth in the attached Declaration of DWR staff technical experts, which are incorporated by reference. Photographs and measurements will be taken, as needed.

5. Environmental studies, geologic exploration, Phase 1 site assessments, cultural resources inventories, surveying and mapping, and probable damage estimates are required of properties throughout the delta. The particulars of these studies, explorations, assessments

mapping, and estimates, and are set forth in the attached declarations of Derrik Adachi, Frank Glick, Donald C. Guy, Janis K. Offerman, Louis Vanderscheer, Reza Tajeran, and Allan T. Davis.

6. The study area consists of properties located in the Sacramento, San Joaquin, Contra Costa, Solano and Yolo Counties, and traverse generally south of the City of Sacramento, north of Clifton Court Forebay, and from the eastern to the western boundary of the legal delta.

7. DWR has repeatedly attempted to obtain voluntary access to the properties, but consent for entry has not been obtained. Attached as Exhibit "A" is a true and correct copy of the documents sent to all the respondent landowners and the proposed temporary entry permit.

8. The access will be for engineers, environmental scientists, technician, geologists, and other study participants either employed by the DWR or under contract with DWR.

I declare under penalty of perjury that the foregoing is true and correct. Executed at Sacramento, California, this day 12 of December 2008.

Teresa Engstrom

Teresa Engstrom, Declarant

Date

name
address
city, state ZIP

Dear

The Department of Water Resources (DWR) is requesting a temporary entry permit from _____________ for the property identified as Assessor's Parcel No(s). _________ in _______________ County, as shown on the enclosed map.

The purpose of this permit is to allow DWR's officers, employees, agents, and persons under contract to enter with all necessary equipment to conduct studies for the Delta Habitat Conservation and Conveyance Program (DHCCP) to include environmental, cultural, geologic, geodetic, Phase 1 Environmental Assessment, and for such other incidental purposes as may be required.

If you agree to the terms, conditions, and provisions of the enclosed permit, please sign and date two copies, provide a telephone number, and return them to me in the enclosed prepaid envelope. The third copy is for your records. A fully executed permit will be mailed to you.

If you need additional information or would like to discuss this further, you may contact me at (916) ____________, or toll free at (866) 688-3227.

Sincerely,

Enclosures

OWNER: Landowner Name

Project:	Bay Delta Conservation Plan (BDCP) Study Area:
DWR Parcel No(s).:	«DWR_PARCEL»
County:	«COUNTY»
APN(s):	«APN_1», «APN_2», «APN_3», «APN_4»

TEMPORARY ENTRY PERMIT

OWNER gives permission to the Department of Water Resources of the State of California (DWR) and its officers, employees, agents and contractors, to enter with all necessary equipment onto OWNER's land in the county of «COUNTY», State of California, described as that portion of Assessor's Parcel No(s). «APN_1», «APN_2», «APN_3», and «APN_4» marked on the attached map (Property). This permission is granted for the purpose of conducting the activities described in Exhibit A of this Permit, including ground and aerial surveys, engineering, biological, geological, archaeological, floral and faunal studies, Phase 1 Environmental Site Assessments, and for other incidental purposes as may be required. This permission is subject to the following conditions:

1. DWR will exercise reasonable precautions to avoid damages and to protect persons and property. DWR's survey and investigation team members shall read and heed all signs posted as notification of potentially hazardous chemical substances used on the property.

DWR agrees not to unreasonably interfere with operations on the property. DWR shall limit vehicular and pedestrian access to those routes reasonably identified by OWNER or his/her representative. If access is by dirt roads, every effort will be made by DWR to avoid producing excess dust and to avoid access by vehicles where muddy conditions could cause damage to the roads.

DWR acknowledges that the property may include, without limitation, the use of pesticides, herbicides, fertilizer or other chemical substances (collectively "Substances"). DWR hereby agrees to accept and assume any and all risks of injury or damage arising from or relating to entry upon or use of the property including, without limitation, injury or damage from exposure to Substances, except for such risks caused by the gross negligence or intentional tortious conduct of OWNER.

2. DWR understands and agrees that any information gathered on OWNER's property in accordance with activities described in Exhibit A of this Permit and for other incidental purposes as may be required is highly sensitive and strictly confidential, and shall be maintained by DWR with the utmost confidence. DWR agrees that such information about the landowners's property, operations, practices, the land's environmental data, etc. obtained by the implementing agency or any of its employees, officers agents, contractors and/or representatives shall remain strictly confidential and shall not be disclosed or revealed to outside sources or used for any manner inconsistent with this Permit agreement or as required by law.

Subject to conditions listed in Civil Code Section 1798.24, DWR shall establish and implement appropriate and reasonable administrative, technical, and physical safeguards to ensure the security and confidentiality of records.

[Continued on Page 2]

OWNER's Name, Address, and Phone No.

____

____

Phone No.____________________

▶____________________
Signature

▶____________________
Signature

Date: ____________________

Recommended for Acceptance:

▶____________________
, Land Agent Date

ACCEPTED:

Department of Water Resources of the State of California

▶____________________
Allan T. Davis,
Supervising Land Agent

Date: ____________________

CONSENT OF TENANT(S)

We, the Tenants of the Property described in this Temporary Entry Permit, are under lease with OWNER, hereby consent to the execution of this Temporary Entry Permit. We also agree that all damages payable will be paid to OWNER as described above.

____
Signature

Date: ____________________

____
(Mailing Address of Tenant if different than above)

Phone No: ____________________

Exhibit A

PROJECT STUDIES AND SCOPING

For purposes of the Temporary Access Permit, all survey-related activities will be conducted by qualified and trained DWR personnel and/or authorized representatives (contractors/consultants) under the direction of a DWR Project Manager. DWR may conduct the following checked activities:

☐ I. GEODETIC MAPPING

Geodetic mapping involves measuring the shape and area of the property by using the exact position of geographical points as a reference. The geodetic mapping activities will require the installation of targets on the property and then using a small aircraft to take photographs while flying over the property. All flights will occur during daylight hours and two (2) flights will be required. Those flights will be spaced several weeks apart. Mapping will require from one (1) to three (3) site visits. Site visits may last up to eight (8) hours in duration and will require two (2) persons on the first site visit and one (1) person on any subsequent site visits.

In addition to the small aircraft, equipment used to complete the mapping activity will include standard survey trucks and, if the property is muddy, all terrain vehicles for property access. A tripod, a hand-held receiver, antenna and data collector unit will also be used. The targets will by set by using a sledgehammer to drive iron pipe flush with the ground surface. The iron pipes will be placed at the center of an aerial ground target. GPS surveying equipment will then be used to determine the exact location of the target. If livestock is present, chicken wire (or a similar type of fence fabric) will be installed around the target marker by using a hand-held staple gun and hammer. Staff will return with GPS equipment to resurvey, check, clean, and repair the target when necessary. After the second aerial flight has been completed, staff will return to remove target material from the ground surface. Property owners may elect to retain the iron pipes installed on the property for future use.

Field surveying will occur to study possible future project alignments. Surveying activities will use two (2) by two (2) inch wood lath-stakes with flagging attached to the stakes and they will be placed in the ground following a lineal progression that may traverse the property. Survey crews consisting of three (3) to five (5) individuals will be on site during daylight hours. Site visits may occur on non-consecutive days and may take from six (6) to sixteen (16) hours to complete. Survey crews will use of vehicle and hand-held field surveying equipment to complete field surveys.

Geodetic, mapping, and surveying activities in the study area may have a significant impact on any future design, scheduling and/or cost of a preferred alignment for a future project.

☐ II. ENGINEERING GEOLOGY

Geologic activities will include field surveying, mapping and geotechnical exploration. The geotechnical exploration will include auger and/or mud rotary drilling, soils sampling using a Standard Penetometer Test (SPT) barrel and Shelby tubes, Cone Penetometer Testing (CPT), resistivity surveys, and the installation and monitoring of groundwater monitoring wells. The excavation of test pits is possible. Prior to exploration activities, several site inspections will be needed to evaluate access, potential environmental restrictions, potential cultural and archaeological resources, the locations of underground utilities, etc. *Engineering Geology Activities;* Site exploration will be performed in phases. Those phases are to measure electrical resistivity, drill exploration and installation of test pets. Activities for each phase can last from a few hours to a few days and are described as follows:

1. Electrical resistivity measurements will be taken that require personnel to set up equipment and perform tests. Electrical resistivity equipment consists of hand-held and suit case-size equipment. Four (4) one-half inch diameter steel probes are temporarily hammered about twelve inches deep into the ground and are connected together with wires. Measurements of voltage and current are taken between pairs of electrodes. Test measurements take approximately thirty (30) minutes to complete. At completion probes and equipment are removed. Measurements may require up to four (4) vehicles and up to six (6) staff on site at any one time.

2. Geologic test pits will be necessary to determine the depths of ground water. Geologic test pits are approximately twenty (20) feet long by four (4) feet wide, and will be excavated to a depth of approximately twelve (12) feet using a standard size backhoe, equivalent in size to a John Deer, Model 580. Installation of test pits may require from two (2) to four (4) persons. Once test pits have been installed, it is estimated from one (1) to two (2) persons and one (1) vehicle will return to the site for monitoring purposes. Site visits and may last up to thirty minutes in duration and will occur on non-consecutive days.

3. Drill exploration will generally be performed using an eight-inch diameter auger which is usually trucked-mounted and

powered by and industrial engine with 200 to 300 cubic inches of displacement, equipped with a muffler and spark arrester. The only dust hazard associated with this equipment is dust resulting from driving to and from drill sites. Prior to drilling or digging, USA (Underground Service Alert) will be contracted to mark all known utility lines. Soil samples will be obtained for testing. The depth of test holes will vary from about five (5) feet to one-hundred feet. Test holes will be spaced approximately every one-thousand feet apart. An associated truck or small loader with a "Baker Tank" will be on site to dispose of drilling mud and cutting from rotary drilling. Additional vehicles may be present at short time intervals to deliver supplies. The drilling time required for each drill hole is normally less than two (two) work days.

Geologic, surveying, and mapping activities in the study area may have a significant impact on any future design, scheduling and/or cost of a preferred alignment for a future project.

☐ III. UTILITIES

Inventory of existing utilities will consist of a review of public records and a walking survey of the property. Records review and walking survey are completed in compliance with best practices as outlined by the California Public Utilities Commission. Site reconnaissance consists of ground surveys with minimal ground disturbance which may require shallow scraping of surface soils, one to three inches deep, in small localized areas.

☐ IV. CULTURAL RESOURCES

Cultural resources studies include both archaeological surveys and architectural and historic resource evaluations. Archaeological surveys involve walking through the property and recording any archaeological resources that are observed on the ground surface. If the ground surface is not visible due to vegetation, surveyors may use a hand trowel to perform minimally invasive clearance of vegetation. Photographs and Global Positioning System (GPS) location readings will be taken to record archaeological resources. Architectural and historic resource evaluations will involve noting the structures present on the property (houses, barns, sheds, etc.) and historic features (e.g., levees) within the study area. Photographs and GPS location readings will also be taken.

A site visit will be conducted in order to perform a Phase 1 Cultural Resources inventory in compliance with the California Environmental Quality Act and the National Historic Preservation Act implementing regulations. Site reconnaissance will consist of ground surveys with minimal ground disturbance and may require shallow scraping of surface soils, at a depth of one (1) to three (3) inches, in small, localized areas.

The presence of cultural resources within the study area that are eligible for listing in either the California Register, Historical Resources Register, or the National Register of Historic Places may have a significant impact on any future design, scheduling and/or cost of a preferred alignment for a future project.

☐ V. ENVIRONMENTAL STUDIES

The environmental surveys involve a variety of specialties and primarily consist of observations made by environmental specialists. Minor ground disturbances with a shovel or hand trowel may be required. Any holes will be filled and compacted immediately. Regardless of the surveys to be conducted, DWR will restore the property, as near as possible, to its original condition.

A. Botanical Surveys: Surveys will include walking and photographing the property, recording plant species, collecting unknown plant species, making wetland delineations (when applicable) and examining the soil. The property will be accessed by small vehicle and/or a small boat. Hand-held GPS receivers, cameras, and hand-held shovels will be used to complete the surveys. Holes will be dug approximately two (2) feet wide by two (2) feet deep in order to study soils. Any disturbance of property soils will be minor and will be returned to the original condition to the best extent possible. All botanical surveys and delineations will be conducted during daylight hours during the months of February through October. It is anticipated that botanical surveys will take from one (1) to four (4) days to complete and that from one (1) to six (6) persons may be on the property at a time. Should wetlands be found, an additional one (1) to four (4) days may be needed to complete delineations.

B. Fisheries Studies: Habitat evaluations for various sensitive fish species may include evaluation of water depth, flow velocities, water quality, riparian vegetation, and channel substrate. Fish sampling in adjacent sloughs may require vehicle access for transport of nets and other sampling equipment. Fisheries Studies fall into three generalized survey categories and are described as follows:

1. Recreation Surveys will include identification and observation of any existing recreation use on the property as well as adjacent waterways. Identification and observations will require: documentation of the types of current activities on the

property and equipment used; the estimation of number of people who use the property; interviews to gain information about visitor origin, residence, and habits; determining the season(s) of use (if any); and scoping the potential for future recreational use. Studies will require from one (1) to two (2) persons each site visit. Equipment used for the surveys will include hand-held cameras, binoculars, and clipboards. Personnel will use a vehicle while on site. Site visits will occur between 7:00 a.m. and 7:00 p.m. A typical site visit takes less than one hour to complete; however, in some instances to obtain meaningful interviews with recreationists, some site visits may take up to four (4) hours to complete. Depending on the type of recreation being observed, personnel may visit the site once a day, or up to five times per day. Recreational activities tend to be seasonal and will be observed on non-consecutive days between the months of March and November. During those months personnel may be on the property for up to thirty non-consecutive (30) site visits.

2. Fisheries Surveys will include surveying all rivers and streams on the property that may be within a sensitive fish species distribution range, and will include the visual evaluation of habitat including upland and riparian vegetation. Activities to conduct water quality sampling of temperature and dissolved oxygen content, water depth and flow-velocities will include the use of a vehicle, a small boat or kayak, binoculars, buckets, seines and nets, fish measuring boards and microscopes. The days and hours required to complete surveys will occur two (2) weeks a month, for three (3) days each week, and may last up to eight (8) hours each day in order to complete the surveys. It is anticipated that the months of surveys will occur will be between September and May.

3. Hydrologic Surveys will include identification and characterization of drainage, streams, creeks and wetland delineations, storm water drains, and storm water flow patterns that may impact water quality. Equipment required to conduct hydrologic surveys will include a vehicle and a small boat. All hydrologic surveys will occur during daylight hours and will take from two (2) to four (4) persons to complete the survey. Surveys may require from one (1) to six (6) site visits to complete and will occur on non-consecutive days during the wet and dry seasons.

C. Wildlife Surveys: Habitat evaluations will be completed for all sensitive species of reptiles and amphibians that could occur in the study area (giant garter snake, western pond turtle, California red-legged frog, and California tiger salamander) with the potential for surveys to determine whether the species are present as well as their distribution on the Property. Surveys of wildlife fall into three generalized categories and are described as follows:

1. Vernal Pool Surveys: Aerial photograph interpretation with soil characterizations for likelihood of vernal pool presence will be completed. Location of vernal pools based on vegetation, soil characteristics, ponding, and the presence of invertebrates may occur. If fairy shrimp/tadpole shrimp are present on the property, then protocol level surveys must be performed on non-consecutive days, occurring intermittently over a period of two years to determine the presence or absence of fairy shrimp/tadpole shrimp. Once it is determined that a vernal pool has a listed species, the pool will no longer need to be surveyed. The required time on site will be determined by the pools' ability to hold water for at least two weeks to begin a survey, invertebrate fauna, and rainfall. Surveys will require the use of a vehicle, binoculars, digital camera, handheld Global Positioning System (GPS) unit, a dip net, and other collection equipment. All activities will occur during daylight hours. The anticipated months of performing surveys are between the months of November and May. Dependent upon the number of pools found (if any), four (4) surveys occurring on non-consecutive days per during the wet season, for two consecutive wet seasons, may be required.

2. Reptilian and Amphibian Surveys: Evaluations of aquatic and upland habitats for sensitive species of reptiles and amphibians will occur on the property and will include visual walking surveys of the property. A variety of methods will be used to complete surveys and may include trapping of species using floating aquatic traps. Equipment used will include vehicles, kayaks, shovels, thermometers, wind meters, tap measures, scales, dip-nets, seines, cast nets, minnow traps, dift-fences and pit-fall traps approximately one (1) foot in diameter dug in the ground. Any disturbance of property soils will be minor and will be returned to normal to the best extent possible. Surveys will require a crew of from one (1) to six (6) persons. Site visits to the property will occur depending upon the habitat and species surveyed and can occur both during day and night hours. It is estimated that no more than five (5) night visits to the property will be required. Sites visits will occur on non-consecutive days and will occur during wet and dry seasons. During rainy periods site visits may occur up to seven days per week.

3. Avian Surveys: Evaluation of habitat for sensitive bird species will include observations from vehicles or walking surveys of the property. Equipment used will include vehicles, binoculars/spotting scopes, cameras, GPS units and laptop computers. Surveys may be up to two (2) days for a maximum of eight hours in duration. It is anticipated surveys will occur from March through September and also in the month of December. Two surveys per year may be required and surveys will be conducted for multiple years.

4. Mammal Surveys: Surveys will be completed for Riparian Brush Rabbit, Riparian Woodrat, and Bat species. Surveys for Riparian Brush Rabbit and Riparian Woodrat will be via species-specific trapping in riparian scrub and riparian forest habitat. Habitat evaluation surveys for various sensitive bat species will be conducted, and in a very few instances, habitat may be surveyed for the bat species themselves, via netting and vocalization surveys. A two person crew will be involved for each survey. The type of equipment utilized includes All-terrain vehicles (ATVs), maps, GPS units, Rabbit and Woodrat traps, flagging, track plates, auto-photography units, computer equipment, and kayaks/canoes in very rare instances, bat-nets,

anabat equipment, photography equipment, and computer equipment. The Rabbit and Woodrat surveys may take as many as ten days per year, eight hours in duration and may occur in the early morning, evening, or night hours. The bat surveys may take as many as ten days per year, six hours in duration occurring during evening and night hours. The anticipated survey months are February through November. Surveys will be for the durations previously described and will occur on two consecutive years. Survey requirements and entry on the properties are subject to change depending on the result of the first year's surveys.

☐ D. **After-Survey Monitoring** In addition to the surveys described above, information concerning the occurrence of threatened or endangered species at sites containing potential habitat for the species, or sites designated as critical for the species, must be obtained through properly conducted surveys carried out by a permitted biologist.

Environmental surveying and monitoring activities in the study area may have a significant impact on any future design, scheduling and/or cost of a preferred alignment for a future project.

☐ VI. PHASE 1 ENVIRONMENTAL SITE ASSESSMENT

The purpose of the Phase 1 Environmental Site Assessment is to evaluate the study area for potential environmental hazards or degradation caused by the release of hazardous materials. The study area can consist of all parcels and adjacent properties within and outside the study area, including access roads and staging areas. This investigation will include the review of historic land use and land title records; federal and State regulatory agency environmental databases; consultation with local environmental health officials, communication with the current land owners or operators.

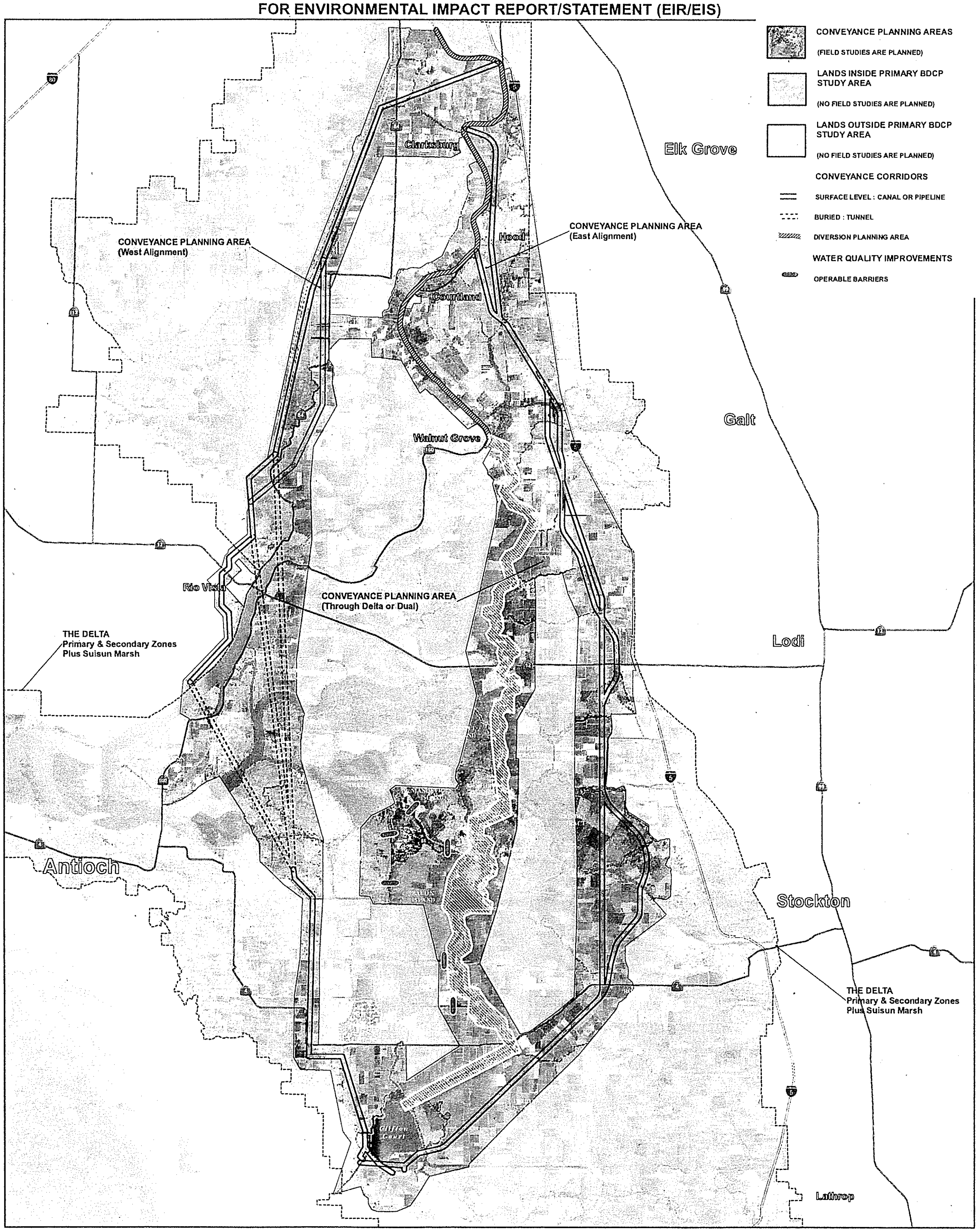
Phase 1 Environmental Site Assessment will include entering the property to perform site reconnaissance in accordance with the American Society of Testing materials (ASTM), Standard Practice for Environmental Site Assessment; Phase 1 Environmental Site Assessment Process Designation 1527-05 and newly adopted federal regulations pursuant to 40 code of Federal Regulation, Part 312 – Standards and Practices for all Appropriate Inquires. Site assessment will include the use of a 3/4 ton pickup or a kayak or canoe where appropriate, and will include walking the property, making visual observations, and documenting visual observations and recording locations of "recognized environmental conditions" using GPS, digital photography, and tape measures. Should it be determined that the collection of samples are necessary, a hand-auger, three (3) inches in diameter will be used to auger to a maximum soil depth of fifteen (15) feet. A shovel will be used for surface work and replacement of soil extracted from the collection of samples. Any disturbance of property soils will be minor and will be returned to pre-survey conditions to the best extent possible. Whenever possible, a predetermined sampling location will be identified prior to taking samples. Best efforts will be used to avoid breaking through pavement or concrete.

Site visits will occur only during daylight hours, most likely between the hours of 8:00 a.m. to 7:00 p.m. and will require from one (1) to three (3) staff persons on site. Visits may last up to a day and a half in duration. If the property is large in size, multiple visits may be required, but no more than five (5) site visits will be required for Phase 1 Environmental Site Assessment activities.

The presence of recognized environmental conditions within the study area may have a significant impact on any future design, scheduling and/or cost of a preferred alignment for a future project.

RECIRC2819.

BAY DELTA CONSERVATION PLAN (BDCP)
CONCEPT-LEVEL CONVEYANCE PLANNING AREAS
FOR ENVIRONMENTAL IMPACT REPORT/STATEMENT (EIR/EIS)



DEPARTMENT OF WATER RESOURCES
DIVISION OF ENGINEERING

0 1 2 4 6 8 10 Miles

PRELIMINARY
SUBJECT TO REVISION

Aerial Photography: NAIP 2005

rev. 8/26/2008 17:32

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

FILED
SUPERIOR COURT - STOCKTON
09 FEB 26 AM 10: 00
ROSA JUNQUEIRO, CLERK
BY MOLICHIA FORDE
DEPUTY

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: APN: 025-020-13 APN: 025-100-14 DECLARATION OF DERRICK ADACHI IN SUPPORT OF PETITIONER'S PETITION FOR RIGHT OF ENTRY

I, Derrick Adachi, make this declaration in support of the STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES' (DWR's) Bay Delta Conservation Plan (BDCP). I have personal knowledge of the following, and if called as a witness, I would and could testify competently thereto.

1. I have a Bachelor of Arts degree in Environmental Studies with a concentration in Biological Science from the University of California at Berkeley. I have worked in excess of

twenty-seven years in the field of environmental protection and compliance, twenty-six of those years working for the State of California.

2. Of those twenty-six years, I worked eight years for the California Environmental Protection Agency (Cal/EPA), Department of Pesticide Regulation (formerly part of the California Department of Food and Agriculture) and nearly five years for the Department of Toxic Substances Control. For the past thirteen years I have been working for DWR.

3. I am currently an Environmental Program Manager I and Chief of the Environmental Compliance and Evaluation Branch, Division of Environmental Services for DWR. I oversee the environmental surveys for the BDCP and am responsible for the completion of environmental reconnaissance studies and field work needed for preparation of environmental documents required by the California Environmental Quality Act (CEQA) and the National Environmental Policy Act (NEPA), Project conformance with requirements of the California Endangered Species Act (CESA) and the federal Endangered Species Act (ESA), and the federal Clean Water Act and Porter-Cologne Water Quality Control Act as applicable to the BDCP.

4. Environmental studies, evaluations, and assessments described herein are required to gather information to assess project feasibility, complete the project design, prepare the appropriate environmental documents, acquire required permits, and define the appropriate mitigation for project impacts. Entry onto the requested properties is necessary to define the current environmental setting and to perform general environmental reconnaissance of the area, as well as biological, archaeological, and hydrological assessments. Assessments are surveys that are carried out within the study area of proposed project footprints and alignments that include alternative routes and projected feature sites associated with the alignments being studied. In addition, assessments are carried out within the permanent rights of way of proposed alignments, up to five-hundred (500) feet on either side of the center-lines of alignments studied, and within and along proposed temporary right-of-ways, access roads and construction lay-down areas studied for future project alignments. The following environmental assessments and evaluations will not cause significant physical disturbance to the property and all observations

are acquired by walking the properties and taking digital pictures and Global Positioning Satellite Stationing (GPS) waypoints.

5. A general environmental reconnaissance survey of the area will: characterize the current use and condition of the property and note existing improvements and near-by land uses; characterize existing scenic views, visual corridors, recreational resources, public services, utilities, and service systems; note nearby sensitive receptors with respect to noise and air quality impacts; and note obvious and existing hazards.

6. To complete Recreational surveys, activities will include the identification and observation of existing recreation use on all parcels and adjacent waterways (if any); contact (interviews) with recreationists as necessary to document types of activities and equipment used, the estimation of number of people employing recreational use of the properties, interviews to gain information about visitor origin/residence and habits, generalization of seasons(s) of use (if any), and scoping of potential for future recreation use. From one to two staff persons will be required for each day the properties are surveyed. The surveys will consist primarily of visual observations of recreationists and their activities. A subset of those observed will be contacted in the field for the purpose of conducting interviews. Some interviewees may be provided with follow-up survey materials to be mailed back to DWR. Equipment necessary to conduct surveys includes an automobile, binoculars, camera, and survey data forms. DWR staff (or consultants) will visit the site one to five times per survey day. It is anticipated that staff may visit the site up to thirty times during the recreation season between March and November. Visits will occur between the hours of 7 a.m. and 7 p.m. Depending on the activity observed, surveys may consist of walking surveys or stationary surveys. The walking survey of the site will typically take less than one hour to complete. During the stationary survey, DWR staff (and/or consultants) may be posted in one general location and may perform continuous observation of recreationists for up to a four-hour duration. In some cases, the stationary observation may occur twice in the same day, for a total duration of eight hours for the survey.

7. A biological survey of the property will: identify existing plants and characterize the vegetation community; evaluate existing vegetation for its suitability as habitat for special

status species; visually characterize the soil and the existing substrate; and will identify observed wildlife and look for signs of certain special status species. Activities necessary to complete Botanical surveys for sensitive plant species and wetland delineations will include walking the site to assess the habitat and determine the presence or absence of sensitive plant species, collecting samples of vegetation, recording locations using handheld GPS equipment, photographing landscape and vegetation, and digging holes approximately two feet wide and two feet deep to examine soil. Watersides of larger sloughs and rivers and in-stream islands may require surveys by small boat. All surveys and delineations will be conducted during daylight hours during the months of February through October. It is anticipated between two and six people will require one to four days to survey each parcel. The number of personnel and time necessary to complete Botanical surveys will depend on the size of the property, the variability of the vegetation, and the number of wetland areas at each site. Agricultural lands (row crops, orchards, and vineyards) with no ditches and no adjacent habitat will require the least amount of surveying while areas with wetlands or dense riparian habitat will require the most. If wetlands are found during the initial site assessment, an additional one to four days may be needed to complete delineations.

8. Archaeological surveys will be restricted to surface examination for artifacts and evidence of prior occupation. No artifacts will be collected. Sites of artifacts and evidence of other historic indicators will be flagged and recorded. The results of the surveys will provide information to guide decisions concerning any future project alignments being considered in the study area.

9. Hydrologic surveys include: identification and characterization of drainage, streams, and creeks and delineation of wetlands; notation of observed conditions that may impact water quality; and location of storm water drains and notation of storm water flow patterns. Many of the surveys must be conducted at a specific time of year when target species are expected to be present. In addition to the visual evaluations and assessments described above, information concerning the occurrence of threatened or endangered species at sites containing potential habitat for the species or sites designated as critical habitat for the species must be

obtained through properly conducted surveys carried out by a permitted biologist. These additional surveys are prerequisite to obtaining future project permits associated with an identified future project alignment and must be obtained from the U.S. Fish and Wildlife Service ("USFWS") and the California Department of Fish and Game for project compliance with the CESA and ESA. The U.S. Fish and Wildlife Service has identified and designated land in Sacramento, San Joaquin, Contra Costa, Yolo and Solano Counties as critical habitat for endangered species. All or a portion of the properties studied are included in the critical habitat for various listed species. Therefore, translocation surveys will be carried out to determine the presences or absence of species within critical habitat traversed by the future proposed alignments that are being studied.

10. Activities to complete surveys of vernal pools will include aerial photograph interpretation with soil characterizations and field surveys. During field surveys, vernal pools may be located based on vegetation, ponding, and invertebrate occupancy. If the presence of listed Brachiopods (shrimp) is possible within a given Pool(s), based on aerial and on ground interpretations, and if a presence determination is necessary, then the USFWS protocol level surveys will be conducted for up to two years to determine the presence or absence of shrimp. Pools with confirmed identification of listed species will no longer need to be surveyed. At least one month's notice must be given to USFWS prior to any protocol level or activity involving species captured for identification. The number of personnel necessary to conduct vernal pools, and listed Branchiopod surveys will be from two to three people. The equipment used to complete vernal pool and listed Branchiopod surveys will include: ArcView-Global Imaging Systems, GPS, camera, binoculars, aquatic nets, holding trays, glass vials, dissecting microscope, and species identification books. This equipment is small enough to transport easily in a medium sized field vehicle. When combined, the total size of equipment used to conduct the vernal pool, Fairy Shrimp, and Tadpole Shrimp surveys, excluding vehicles and nets, is approximately the size of a large backpack. The net used for surveying is approximately 3.5 feet in length and 8 inches in width. The days/hours necessary to complete the vernal pool and listed Branchiopod surveys are dependent upon the aerial interpretation and the number of pools found or deemed

present. Dependent upon the level of surveys required according to protocol, then four surveys per year, during the wet season, for two consecutive years may be required. The anticipated months of performing surveys will begin when pools hold water for approximately three weeks, most likely occurring between November and May, and are dependent upon rain quantities.

11. DWR will also conduct habitat evaluations for the following sensitive species of reptiles and amphibians that could be present on the properties: giant garter snake ("GGS"), western pond turtle ("WPT"), California red-legged frog ("CRF"), and California tiger salamander ("CTS"). These species utilize aquatic and upland habitat, so the habitat evaluation will consist of characterizing the species-specific suitability of aquatic habitat (e.g., irrigation ditches, stock ponds, vernal pools, emergent marsh, sloughs, creeks, rivers) and adjacent uplands (up to 1.2 miles away from certain aquatic habitats). Species presence surveys, when necessary, involve using a variety of methods to either observe or capture species. Surveys for GGS will be "visual encounter surveys" using binoculars and the trapping of GGS using floating aquatic traps in appropriate habitat. Surveys for WPT will require incidental observations. Surveys for CRF will entail visual surveys using binoculars and potential larval sampling using dipnets or seines in appropriate habitat. Surveys for CTS will require aquatic larval sampling using dipnets, seines, cast nets, and/or minnow traps and upland habitat surveys using drift fences and pitfall traps in appropriate habitat. The number of DWR personnel and/or its contractors involved in habitat surveys will be one to four people to complete. Species presence surveys will require at least two people but may require up to eight people on the properties at one time should surveys be completed simultaneously in multiple areas in the study area. The type of equipment utilized by survey crews will include one vehicle per crew, binoculars, camera, field notebook and/or micro-recorder, GPS, floating aquatic minnow traps which are approximately two feet by one foot in size, kayaks, thermometers, wind meter, coolers, tape measure, digital calipers, scale for weighing species, canvas snake bags for (retaining/transporting) species, flashlights, headlights, dipnets, drift fences, and pit-fall traps which are approximately one foot in diameter, dug and placed in the ground. The duration of time to complete evaluation and species presence surveys varies according to the amount of habitat that needs to be evaluated or surveyed as well as the

ease of access conditions to walk/drive to the habitat being studied. All habitat evaluations will be conducted during daylight hours and will likely take no more than eight days per parcel, per year to complete. However, if species presence surveys are required for the CRF, night-time work will also be necessary. The anticipated months of duration to complete species presence surveys varies dependent upon the habitat and species surveyed. Surveys for GGS and WPT will occur from May through September; CTS and CRF from October through May; with daily checking of traps, seven days a week. Additional surveys for CRF will occur from January through February and will consist of two-day surveys conducted for four nights during breeding season and one day and one night survey from March through December during non-breeding season. Surveys for CTS will occur between March and May, once a month for two years and during the rainy season, November through February will occur daily survey CTS for seven days a week during the rainy period.

12. Activities to identify the habitats of sensitive fish species that may be altered should the location of a preferred project alignment be identified include surveying all rivers and streams on the properties within each species' distribution range for the identification of potential habitat. Fish may have crucial habitat requirements that will need to be surveyed. These habitat surveys include water quality sampling of temperature and dissolved oxygen content, water depth and flow velocities. Visual evaluation for quality upland and riparian vegetation for stabilizing soil and provide shade; clean gravel for spawning and egg rearing; large woody debris providing resting and hiding places, and varied channel forms. The number of personnel necessary to conduct habitat surveys will consist of four person crews. Equipment necessary to conduct the habitat evaluations includes a vehicle, camera, field notebook, GPS, flow meter and YSI that measures water temperature, electric conductivity, and dissolved oxygen. Other field equipment needed may be motor boats or kayaks, binoculars, buckets, seines and plankton nets, fish measuring boards and dissection microscopes. The days/hours necessary to complete surveys are two weeks a month, three days each week, and eight hours each day. Anticipated months of survey activities are October through April.

13. Surveys will be completed for Riparian Brush Rabbit, Riparian Woodrat, and Bat species. Surveys for Riparian Brush Rabbit and Riparian Woodrat will be via species-specific trapping in riparian scrub and riparian forest habitat. Habitat evaluation surveys for various sensitive bat species will be conducted, and in a very few instances, habitat may be surveyed for the bat species themselves, via netting and vocalization surveys. A two person crew will be involved for each survey. The type of equipment utilized includes All-terrain vehicles (ATVs), maps, GPS units, Rabbit and Woodrat traps, flagging, track plates, auto-photography units, computer equipment, and kayaks/canoes in very rare instances, bat-nets, anabat equipment, photography equipment, and computer equipment. The Rabbit and Woodrat surveys may take as many as ten days per year, eight hours in duration and may occur in the early morning, evening, or night hours. The bat surveys may take as many as ten days per year, six hours in duration occurring during evening and night hours. The anticipated survey months are February through November. Surveys will be for the durations previously described and will occur on two consecutive years. Survey requirements and entry on the properties are subject to change depending on the result of the first year's surveys.

14. General surveys for sensitive bird species, and/or species habitat components required by sensitive species will be conducted. Surveys will primarily be by vehicle, although in some instances, surveyors may walk the properties to reach habitats. A two-person crew will be used for each survey. The type of equipment to be utilized will include; vehicles, binoculars/spotting scopes, photography equipment, maps, GPS units, and laptop computers. The days/hours required to complete the surveys will primarily be two days with a maximum of eight hours per day. Some properties in the study area may require as many as ten days per year, up two hours per day to complete the surveys. Surveys will be conducted for multiple years. Surveys are anticipated to be conducted from March through September, and in the month of December. Survey requirements and entry onto the properties are subject to change in future years depending on results of the first year's surveys.

15. Failure to complete environmental studies and surveys at this time will result in increased costs for future project alignments being considered to help stem the continued

degradation of habitat for fisheries and the continued reliability of water deliveries in the State of California.

16. The study area consists of properties located in the Sacramento, San Joaquin, Contra Costa, Solano and Yolo Counties, and traverses generally south of the City of Sacramento, north of Clifton Court Forebay, and from the eastern to the western boundary of the legal delta. The subject property is located in San Joaquin County.

I declare under the penalty of perjury under the laws of the State of California that the foregoing is true and correct. Executed at Sacramento, California, this 21 day of November, 2008.

Derrick Adachi, Declarant

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

FILED
SUPERIOR COURT - STOCKTON
09 FEB 26 AM 10: 00
ROSA JUNQUEIRO CLERK
BY MOUCHIA FORDE
DEPUTY

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: APN: 025-020-13 APN: 025-100-14 DECLARATION OF FRANK L. GLICK IN SUPPORT OF PETITIONER'S PETITION FOR RIGHT OF ENTRY

I, FRANK L. GLICK make this declaration in support of the STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES' (DWR's) Bay Delta Conservation Plan (BDCP). I have personal knowledge of the geologic setting of the study area, and if called to serve as a witness, I would and could testify to the following.

1. I am Chief of the Project Geology Section of the DWR and I am in charge of the geologic investigations relating to the BDCP. I am a Registered Geologist and have worked for the Department for thirty-one (31) years.

2. Entry onto the property is needed to permit geologists, surveyors, engineers, a drilling rig, other testing vehicles, equipment, and supplies and crews to perform geologic studies to determine soil types and conditions and to determine foundation and geologic conditions that

are pertinent to the design and construction of the BDCP. Geologic activities will include field mapping and geotechnical exploration. These studies are necessary to determine the best physical and economically appropriate design.

3. The study area consists of properties located in the Sacramento, San Joaquin, Contra Costa, Yolo and Solano Counties, and traverses generally south of the City of Sacramento, north of Clifton Court Forebay, and from the eastern to the western boundary of the legal delta. The subject property is located in San Joaquin County.

4. Access to properties is needed through June 30, 2011. Site exploration will be performed in approximately three (3) phases, with each phase lasting from a few hours to a few days. Prior to drilling or digging, USA (Underground Service Alert) will be contracted to mark all known utility lines.

5. Geologic exploration will consist of auger and/or mud rotary drilling, soils sampling using a Standard Penetometer test ("SPT") barrel and Shelby tubes, cone Penetrometer testing ("CPT"), electrical resistivity and other geophysical surveys, test pits, and the installation and monitoring of groundwater monitoring wells to obtain soil samples and to determine the depth to groundwater.

6. The electrical resistivity surveys consists of driving four (4) one-half inch diameter steel probes about twelve (12) inches into the ground and measuring the voltage and current between different pairs of electrodes. The process takes about thirty (30) minutes, and at the completion, the probes and equipment are all removed.

7. Drill exploration will generally be performed using an eight-inch diameter auger or 94mm (3.7-inch) diameter mud rotary drill rig. Soil samples will be obtained for testing. Upon completion of drilling, holes will be sealed using cement-bentonite grout. Depths of test-holes will vary from about five (5) to two-hundred (200) feet. Drilling time required for each drill hole is normally less than two (2) work days.

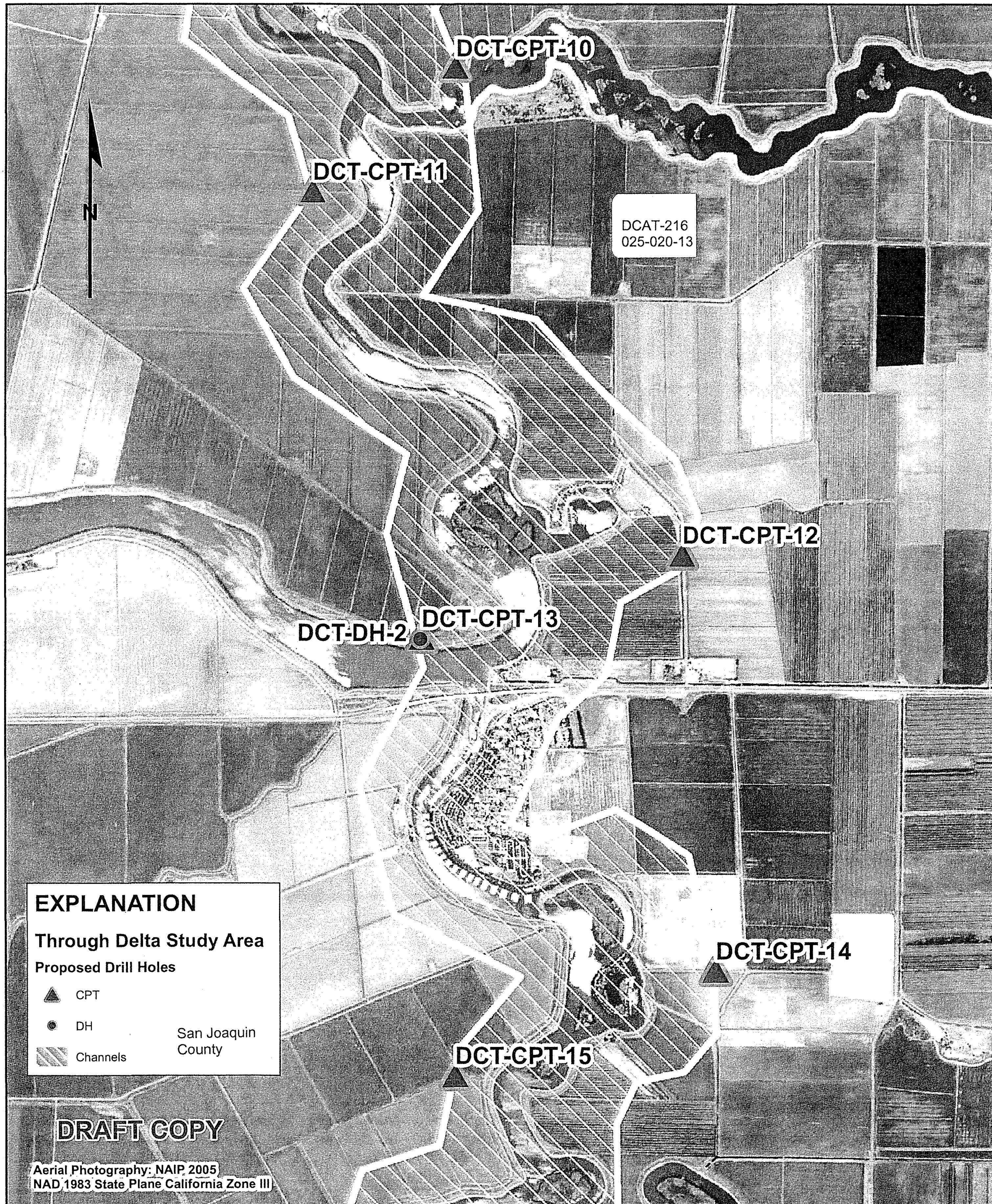
8. The exploration drills are usually truck-mounted and powered by an industrial engine with 200 to 300 cubic inches of displacement and equipped with a muffler and spark arrester. Noise level of this equipment is comparable to the noise produced by a diesel truck.

The only dust hazard associated with this equipment is road dust resulting from driving to and from the drill sites.

9. The dimensions of geologic test pits will be approximately twenty (20) feet long by about four (4) feet wide, and will be excavated to a depth of about twelve (12) feet using a standard size backhoe, equivalent in size to a John Deere, Model 580. After test pits are completed, the pits will be backfilled with native soils and the areas will be returned to their pre-excavation condition.

I declare under the penalty of perjury under the laws of the State of California that the foregoing is true and correct. Executed at Sacramento, California, this 2 day of December 2008.

Frank L. Glick, Declarant



DRAWING SCALES	GEOLOGY REPORT No.	STATE OF CALIFORNIA THE RESOURCES AGENCY DEPARTMENT OF WATER RESOURCES DIVISION OF ENGINEERING PROJECT GEOLOGY SECTION STATE WATER FACILITIES	DELTA HABITAT CONSERVATION & CONVEYANCE PROGRAM THROUGH DELTA STUDY AREA PROPOSED EXPLORTION LOCATION MAP	RELEASE DATE.
0 800 1,600 2,400 3,200 4,000 Feet	CNSTRUCTION SPEC. No.			SHEET No. 3 of 9
	GEOLOGY DRAWING No.			FIGURE 2

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

FILED
SUPERIOR COURT - STOCKTON
09 FEB 26 AM 10: 00
ROSA JUNQUEIRO CLERK
BY MOUCHIA FORDE
DEPUTY

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: APN: 025-020-13 APN: 025-100-14 DECLARATION OF DONALD C. GUY IN SUPPORT OF PETITIONER'S PETITION FOR RIGHT OF ENTRY

I, DONALD C. GUY, make this declaration in support of the STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES' (DWR's) Bay Delta Conservation Plan (BDCP). I have personal knowledge of the following, and if called as a witness, I would and could testify competently thereto.

1. I am an Environmental Scientist with DWR's Division of Environmental Services, Environmental Compliance and Evaluation Branch, Environmental Site Assessment Section and have been serving in this capacity for six (6) years. I possess a degree in biology

from California State University, Sacramento and have worked for DWR for a total of seven (7) years.

2. A Phase 1 Environmental Site Assessment (ESA) described herein is a process to determine if real property and improvements are subject to recognized environmental conditions, which include the presence or release of any hazardous substances or petroleum products. At a minimum, a Phase 1 ESA consists of a records review (includes historical and government environmental records); site reconnaissance or site visit; interviews (with past/current owners, operators and/or occupants of the property as well as contacts with federal/State/local government officials); and a written report.

3. The study area consists of properties located in the Sacramento, San Joaquin, Contra Costa, Solano and Yolo Counties, and traverses generally south of the City of Sacramento, north of Clifton Court Forebay, and from the eastern to the western boundary of the legal delta. The subject property is located in San Joaquin County.

4. Entry onto the subject properties is necessary to perform the site reconnaissance component of a Phase I ESA in accordance with American Society of Testing materials (ASTM), Standard Practice for Environmental Site Assessment: Phase I Environmental Site Assessment Process Designation 1527-05 and newly adopted federal regulations pursuant to 40 code of Federal Regulations, Part 312 – Standards and Practices for All Appropriate Inquiries. The presence of recognized environmental conditions (REC) may have a significant impact on the design, scheduling and costs of the proposed project.

5. As a part of the site inspection and investigation, I would like to interview a knowledgeable owner or manager of the subject property so I may complete a site reconnaissance checklist, which includes, among other things, descriptions of the general site setting, exterior observations, building interior and exterior observations, and observations regarding the interior condition.

6. If collection of samples is determined to be necessary, a hand auger, three (3) inches in diameter will be used to a maximum soil depth of fifteen (15) feet. A shovel will be used for surface work and replacement of soil. Any disturbance property soils will be minor and

will be returned to normal to the best extent possible. If possible, a predetermined sampling location will be identified, as opposed to a random sampling location. Best efforts will be used to avoid breaking through pavement or concrete.

I declare under the penalty of perjury under the laws of the State of California that the foregoing is true and correct. Executed at Sacramento, California, this 20 day November of 2008.

Donald C. Guy

Donald C. Guy, Declarant

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

FILED
SUPERIOR COURT - STOCKTON
09 FEB 26 AM 9:59
ROSA JUNQUEIRO, CLERK
BY MOUCHIA FORDE
DEPUTY

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: APN: 025-020-13 APN: 025-100-14 DECLARATION OF JANIS K. OFFERMANN IN SUPPORT OF PETITIONER'S PETITION FOR RIGHT OF ENTRY

I, JANIS K. OFFERMANN, make this declaration in support of the STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES' (DWR's) Bay Delta Conservation Plan (BDCP). I have personal knowledge of the following, and if called as a witness, I would and could testify competently thereto.

1. I am a Senior Environmental Planner with DWR's Division of Environmental Services, Environmental Compliance and Evaluation Branch, Cultural, Recreation & Environmental Planning Section and have been serving in this capacity for seven years. I possess a Masters Degree in Anthropology from the University of California, Davis, and have

worked for DWR for seven years. I have worked for the State of California as an archaeologist and cultural resources manager for twenty-four years.

2. A Phase 1 Cultural Resources Inventory is necessary for the subject properties. The Phase 1 process will determine whether the study area contains any previously known cultural resources (archaeological sites, historic buildings, and sacred sites) and may identify the presence of any new resources. At a minimum, a Phase 1 Cultural Resources Inventory consists of a records review (information obtained from the California Historical Resources Information System, the California Native American Heritage Commission, knowledgeable local Native American and local historical societies); site reconnaissance or site visit; and written report. A Phase 1 Cultural Resources Inventory is completed prior to acquisition to protect the prospective buyer from future environmental liability. Entry onto the subject property is necessary to perform the site reconnaissance component of a Phase 1 Cultural Resources Inventory in compliance with California Environmental Quality Act Sections 21083.2 and 15064.5, and Public Resources Code 5024, and Section 106 of the National Historic Preservation Act and implementing regulations under 36 Code of Federal Regulations 800, as amended. The presence of cultural resources that are eligible for listing in either the California Register of Historical Resources or the National Register of Historic Places within the study area may have a significant impact on the design, scheduling, and costs for any future proposed project alignment. The site reconnaissance will consist of ground surveys with minimal ground disturbance and may require possible shallow scraping of surface soils, one to three inches, in small, localized areas.

///

3. The study area consists of properties located in the Sacramento, San Joaquin, Contra Costa, Yolo and Solano Counties, and traverses generally south of the City of Sacramento, north of Clifton Court Forebay, and from the eastern to the western boundary of the legal delta. The subject property is located in San Joaquin County.

I declare under the penalty of perjury under the laws of the State of California that the foregoing is true and correct. Executed at Sacramento, California, this 21 day of November, 2008.

Janis K. Offermann

Janis K. Offermann, Declarant

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

FILED
SUPERIOR COURT - STOCKTON
09 FEB 26 AM 9:59
ROSA JUNQUEIRO CLERK
BY MOLICHIA FORDE
DEPUTY

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: APN: 025-020-13 APN: 025-100-14 DECLARATION OF LOUIS VONDERSCHEER IN SUPPORT OF PETITIONER'S PETITION FOR RIGHT OF ENTRY

I, LOUIS VONDERSCHEER, make this declaration in support of the STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES' (DWR's) Bay Delta Conservation Plan (BDCP). I have personal knowledge of the following, and if called as a witness, I would and could testify competently thereto.

1. I am a licensed surveyor and have been employed by the DWR for more than eight (8) years, and I am currently a Senior Land Surveyor for the Department. I make this declaration in support of this Petition by the DWR for an Order permitting Entry and Investigation of properties located in the BDCP study area.

2. Entry onto properties is needed to afford surveyors the ability to set wood-lath stakes for surveying purposes, placed approximately every 100 feet on the property in the areas being studied for proposed future alignments, and for the placement of iron pipe flush with ground surfaces to form the centers of aerial ground targets that will be installed by DWR staff to complete photogrammetric surveying. Should livestock be present on the property, chicken wire (or similar type fence fabric) will be installed around the target. Global Positioning Satellite Stationing ("GPS") surveying equipment will be used to determine the location of the target. A small fixed wing aircraft will be used to photograph the iron pipe and targets. If necessary, DWR staff will return to the property after the initial placement of the target to clean and repair targets. After a second flight, DWR staff will remove the target materials, leaving the iron pipe in place to be utilized in the future. Referenced trips can occur any time within a two (2) month span. Site visits are not dependent on season, however, the best months for aerial photography necessary to complete photogrammetric mapping occurs in the late winter and early spring, from February through March, when area trees have not yet "leafed". Bare tree branches provide the optimum conditions to complete aerial photography.

3. The study area consists of properties located in the Sacramento, San Joaquin, Contra Costa, Solano and Yolo Counties, and traverses generally south of the City of Sacramento, north of Clifton Court Forebay, and from the eastern to the western boundary of the legal delta. The subject property is located in San Joaquin County.

I declare under penalty of perjury that the foregoing is true and correct. Executed at Sacramento, California, this 2nd day Dec of 2008.

Louis Vonderscheer, Declarant

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: APN: 025-020-13 APN: 025-100-14 DECLARATION OF REZA TAJERAN IN SUPPORT OF PETITIONER'S PETITION FOR RIGHT OF ENTRY

I, REZA TAJERAN, make this declaration in support of the STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES' (DWR's) Bay Delta Conservation Plan (BDCP). I have personal knowledge of the following, and if called as a witness, I would and could testify competently thereto.

1. I am an Electrical Engineer with DWR's Division of Engineering and have been serving in this capacity for nearly eleven years. I am a licensed Engineer and have worked for DWR for almost twenty-eight years. I have worked for the State of California as an Electrical Engineer manager for sixteen years.

2. Engineering studies are necessary to inventory all existing utilities found on the subject properties in the study area. The inventory process will determine whether the study area contains any previously known utilities, including but not limited to above and below ground electrical, gas, water, sewer, telecommunication and fibre optic lines. At a minimum, the inventory of existing utilities will consists of a records review; site reconnaissance or site visit; and a written report. An inventory of existing utilities is completed prior identifying preferred alignments of proposed future projects. Entry onto the subject properties is necessary to perform the site reconnaissance component of to inventory existing utilities in compliance with best practices as outlined by the California Public Utilities Commission, and the implementation of regulations under General Order 95, Overhead Electric Line Construction, as amended. The presence of utilities area may have a significant impact on the design, scheduling, and costs for an identified preferred alignment for any future project. The site reconnaissance will consist of ground surveys with minimal ground disturbance and may require possible shallow scraping of surface soils, one to three inches deep, in small, localized areas.

3. The study area consists of properties located in the Sacramento, San Joaquin, Contra Costa, Yolo and Solano Counties, and traverses generally south of the City of Sacramento, and from the eastern to the western boundary of the legal delta. The subject property is located in San Joaquin County.

I declare under the penalty of perjury under the laws of the State of California that the foregoing is true and correct. Executed at Sacramento, California, this 24 day of November 2008.

Reza Tajeran, Declarant

EDMUND G. BROWN JR.
Attorney General of the State of California
ALBERTO L. GONZÁLEZ, SBN 117605
Supervising Deputy Attorney General
JAMES C. PHILLIPS, SBN 121848
Deputy Attorney General
Telephone: (916) 322-5473
JOHN M. FESER, JR., SBN 209736
Deputy Attorney General
Telephone: (916) 324-5118
1300 I Street
P.O. Box 944255
Sacramento, CA 94244-2550
Facsimile: (916) 322-8288

Attorneys for Petitioner STATE OF CALIFORNIA,
by and through the DEPARTMENT OF WATER RESOURCES

SUPERIOR COURT OF CALIFORNIA

FOR THE COUNTY OF SAN JOAQUIN

STATE OF CALIFORNIA, by and through the DEPARTMENT OF WATER RESOURCES Petitioner, vs. Reclamation District No. 548, DOES 1 TO 10, inclusive, Respondents.	Case No.: APN: 025-020-13 APN: 025-100-14 DECLARATION OF ALLAN T. DAVIS IN SUPPORT OF PETITIONER'S PETITION FOR ENTRY

I, ALLAN T. DAVIS, make this declaration in support of the STATE OF CALIFORNIA, DEPARTMENT OF WATER RESOURCES' (DWR's) Bay Delta Conservation Program (BDCP). I have personal knowledge of the following, and if called as a witness, I would and could testify competently thereto.

1. I have been employed by the State of California, Department of Transportation and Department of Water Resources, for twenty-four years. Currently, I am the Supervising Land Agent overseeing the Real Estate Services activities for the Department of Water Resources. Prior to my current assignment I was a Senior Land Agent for 16 years. During that

time I served as the Supervisor over the Appraisal Unit from August 1992 to October 1999 and appraised numerous agricultural, commercial/industrial, residential and vacant properties. My experience includes appraising properties throughout the State including in Sacramento, San Joaquin, Contra Costa, Yolo and Solano Counties. Beginning in 1991, I have presented Declarations to the Superior Courts. As part of DWR's BDCP, I have given opinions on the probable compensation to be deposited in support of the Department's Petitions for Orders for Entry and Investigation of Real Property on various parcels in Sacramento, San Joaquin, Contra Costa, Solano and Yolo Counties. On behalf of DWR I have also provided past court testimony regarding appraisals. I have personal knowledge of the following, and if called as a witness, I would and could testify competently thereto.

2. DWR is in charge of investigating the property of the respondent in San Joaquin County, as described to this Petition, in order to conduct necessary mapping of surficial geologic features in the study area, geological investigations, topographical surveys and environmental studies. I have read every Declaration prepared by DWR staff in support of this Petition for an Order Permitting Entry and Investigation of Real Property and know the contents thereof.

3. It is necessary and essential that permission to enter onto the property described above be obtained for the time period beginning with the issuance of a court order and terminating December 31, 2011.

4. I am familiar with and have personally viewed the respondent's property from aerial photos and public roadways in order to determine the probable amount of compensation for actual damage to, or substantial interference with, the respondent's possession and use by reason of the petitioner's entry and activities. I am informed and believe the subject property is used for Truck Crops. I do not know the nature and extent of the actual operations or activities conducted on the property. My opinion is for the purpose of setting the probable amount of compensation pursuant to Code of Civil Procedure 1245.030.

5. I am familiar with the proposed entry for environmental studies, geologic surveys and mapping, and Phase 1 Site assessments necessary for the BDCP. The reconnaissance is required to gather information on the occurrence of sensitive, rare, threatened and endangered

species and to locate and identify plant and wildlife habitat to complete the studies for the BDCP.

6. I am familiar with the proposed archaeological reconnaissance which will determine the presence or absence of previously recorded or unrecorded cultural resources in the subject area. This reconnaissance consists of ground surveys within the 1,000-foot right of way corridor.

7. The property would be accessed by use of existing county roads and private roads and will include DWR vehicles, equipment and staff physically on the property to conduct the required studies and mapping activities.

8. I am familiar with the proposed entry for environmental surveys, cultural resources inventory, geological testing and Phase 1 Site Assessments which will consist of environmentalists, biologists, geologists, surveyors, engineers, a drilling rig and crews to perform environmental and geologic studies to determine foundation and construction conditions. Geologic activities will consist of geologic mapping, making electric resistivity measurements, performing seismic refraction surveys, and drilling exploration borings. Drill holes will be performed using an eight-inch diameter auger or 94mm (3.7-inch) diameter mud rotary drill. All instruments and testing devices will be removed upon completion of the studies. All holes will be backfilled and sealed.

9. I am familiar with the proposed hydrologic surveys that will include identification and characterization of drainages, streams and creeks, and delineation of wetlands; notation of observed conditions that may impact water quality, and location of storm water drains and notation of storm water flow patterns.

10. The map attached to the Declaration of Frank Glick, Chief of the Project Geology, identified as "Bay Delta Conservation Plan (BDCP) Concept-Level Conveyance Planning Areas", shows the location of proposed drill holes, the proposed Resistivity Lines on the subject property, as well as the scope of the geologic exploration. The resistivity measurements will be made at about 500-foot intervals in the study area. Seismic refraction surveys will be made in the study areas along proposed conveyance alignment corridors.

11. DWR needs to obtain the right of entry through December 31, 2011 because many of the surveys must be conducted at a specific time of year when targeted species are expected to be present. Presence of sensitive species or habitat may have a significant impact on the design, scheduling, and costs of the project.

12. By use of accepted real property appraisal methods for Truck Crops, where less intrusive studies will be performed, Assessor's Parcel No(s). 025-100-13 and 025-100-14, it is my opinion that $1,000 represents the maximum probable amount of compensation for DWR's entry onto the property at issue for the time period requested. I assessed minor impacts to the subject parcels. It is my opinion that $500 represents the maximum probable amount of compensation for the types of studies and surveys to be performed by DWR staff and its contractors.

I declare under the penalty of perjury under the laws of the State of California that the foregoing is true and correct. Executed at Sacramento, California, this 15th day of December 2008.

Allan T. Davis, Declarant

From: Dante Nomellini, Jr. <dantejr@pacbell.net>
Sent: Friday, October 30, 2015 2:57 PM
To: BDCPcomments
Cc: Dante Nomellini, Jr.
Subject: CDWA SUPPLEMENTAL comments on the Partially Recirculated BDCP EIR_EIS
Attachments: CDWA SUPPLEMENTAL comments on the Partially Recirculated BDCP EIR_EIS.pdf

Attached hereto please find the following document:

"CDWA SUPPLEMENTAL comments on the Partially Recirculated BDCP EIR_EIS" (approx. 13 MB; 453 pages)

Please reply to this email acknowledging receipt of that document.

Thank you,
Dan Jr.
Attorney for the Central Delta Water Agency

Dante J. Nomellini, Jr. ("Dan Jr.")
Attorney at Law
Nomellini, Grilli & McDaniel
Professional Law Corporations
235 East Weber Avenue
Stockton, CA 95202
Mailing address:
P.O. Box 1461
Stockton, CA 95201-1461
Telephone: (209) 465-5883
Facsimile: (209) 465-3956
Email: dantejr@pacbell.net