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Challenges and Innovations in Tunnelling

Soft Ground Site Investigation & Managing Geotechnical Risks In Tunnelling

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Tunnelling Association of Canada
Association Canadienne Des Tunnels

Section I – Challenges
Geotechnical Investigation

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Outline

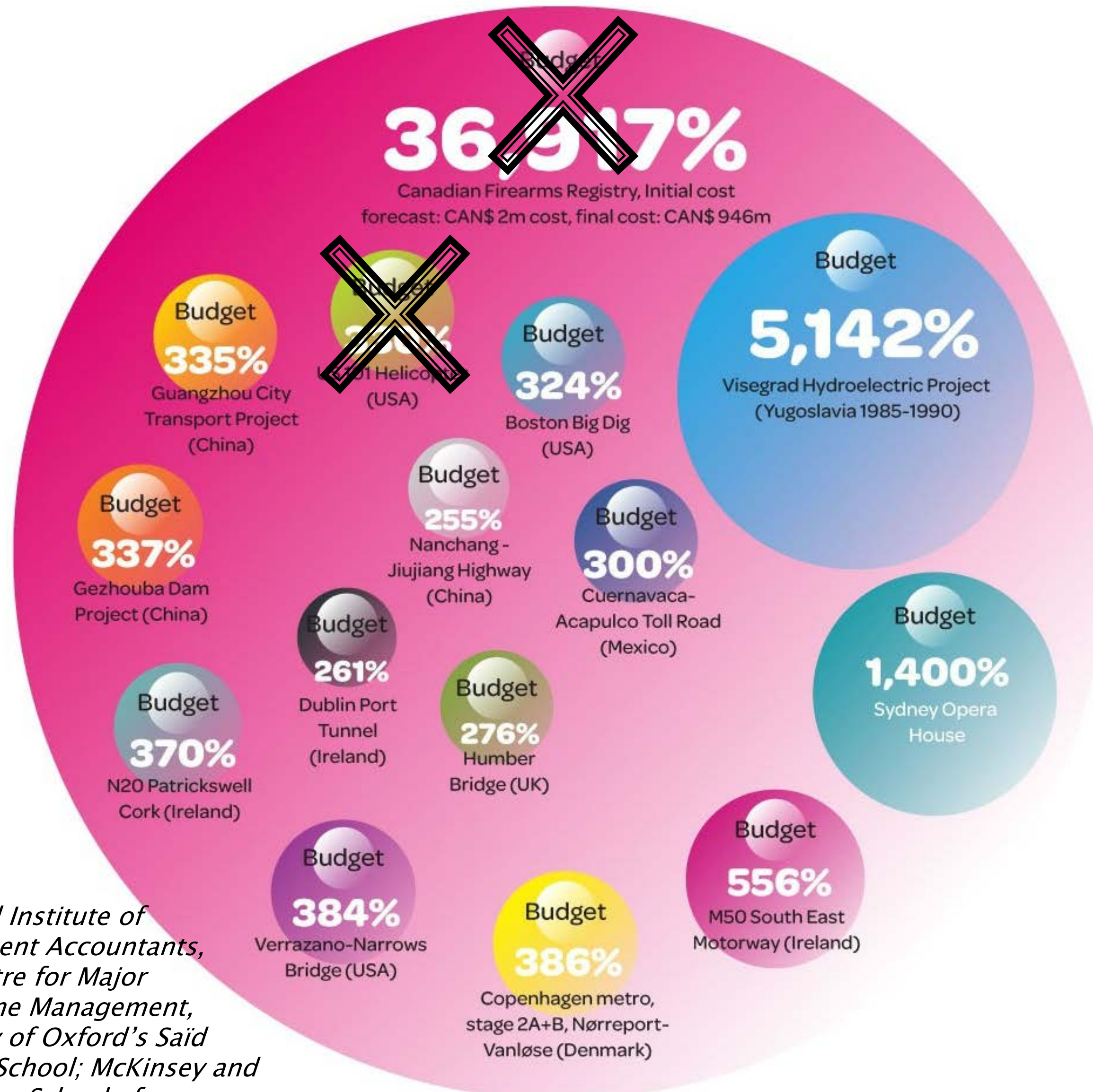
- Introduction
- Geotechnical Risk
- Geotechnical Investigation
  - Scale of Investigation
  - Quality of Investigation
  - Observational Method
- Engineering Assessment
- New Codes and Level of Site Investigation
- Conclusions

Most Important Issues for a Project

- Safety
- Cost
- Schedule

The World's Biggest % Cost Overrun Projects

- 5 out of 13 construction projects are tunnels (3) or involve major excavation (2)

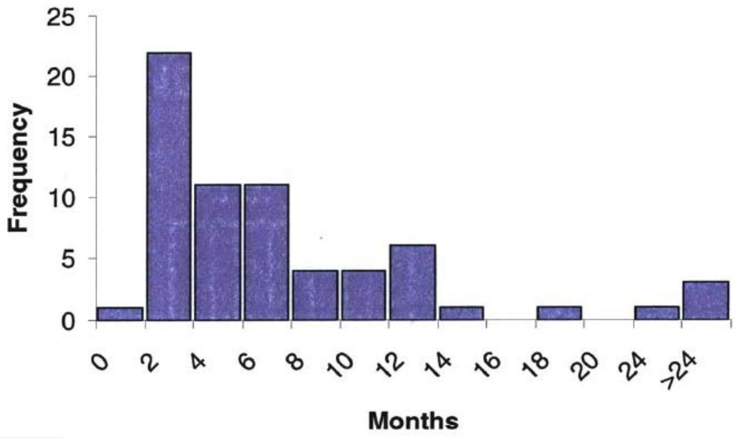


Chartered Institute of Management Accountants, after Centre for Major Programme Management, University of Oxford's Saïd Business School; McKinsey and the London School of Economics – 2013

Schedule Delay

- World Bank Funded Projects with Unexpected Geotechnical Problem

	Year of Construction	Number of Projects	Cost Overrun %		Schedule Delay
			Overall	Civil	
Dam Projects	1966 – 1973	7	12- 130	43 – 174	0 to 44 %
	Average		***61***	***100***	***26 %***
Tunnel Projects	1966 – 1981	16	4 to 120	0 to 134	0 to 4 years
	Average		***42***	***61***	***2.2 years***



R.L.Sousa, 2010 MIT

Tunneling is a Risky Business

Risks to a cost-effective and trouble-free project:

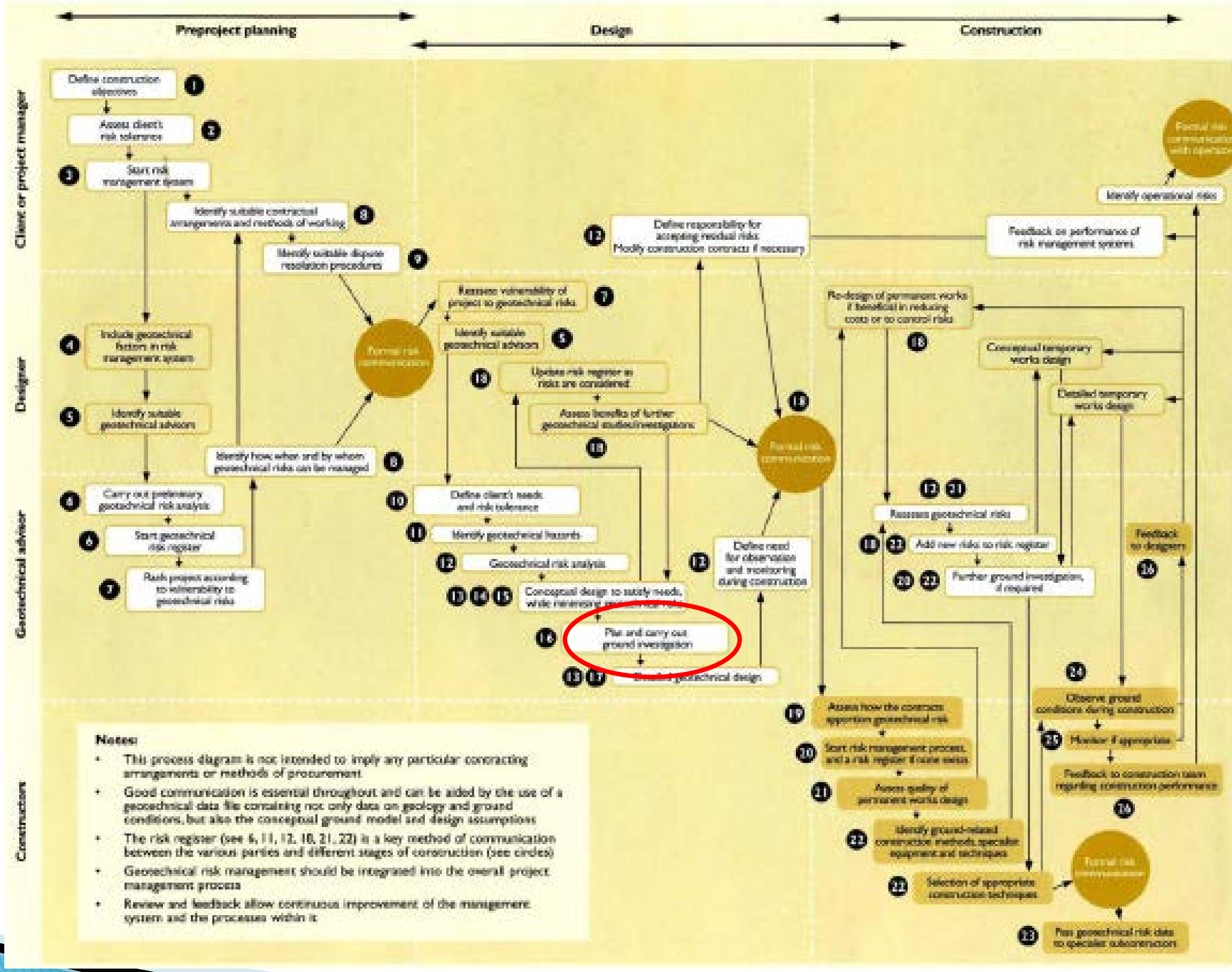
- Geotechnical Risks
- Inadequate design
- Poor planning
- Poor construction practices
- Other subsurface risks

Source of Geotechnical Risk

- Natural complexity and heterogeneity of geological environment
- Testing uncertainty
- Estimation uncertainty
- Engineering models are approximation of physical world

Geotechnical Risk Management

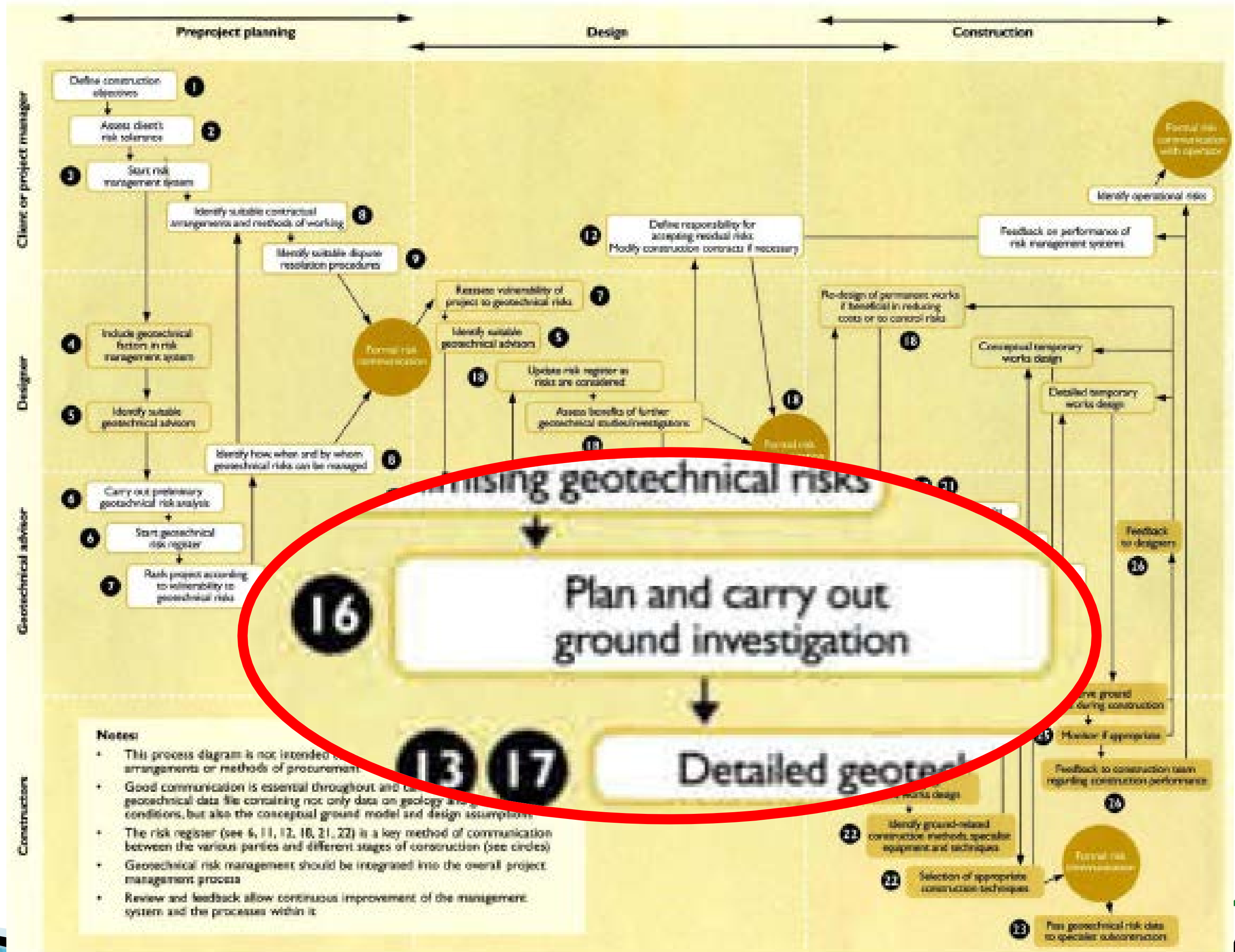
Clayton, 2001



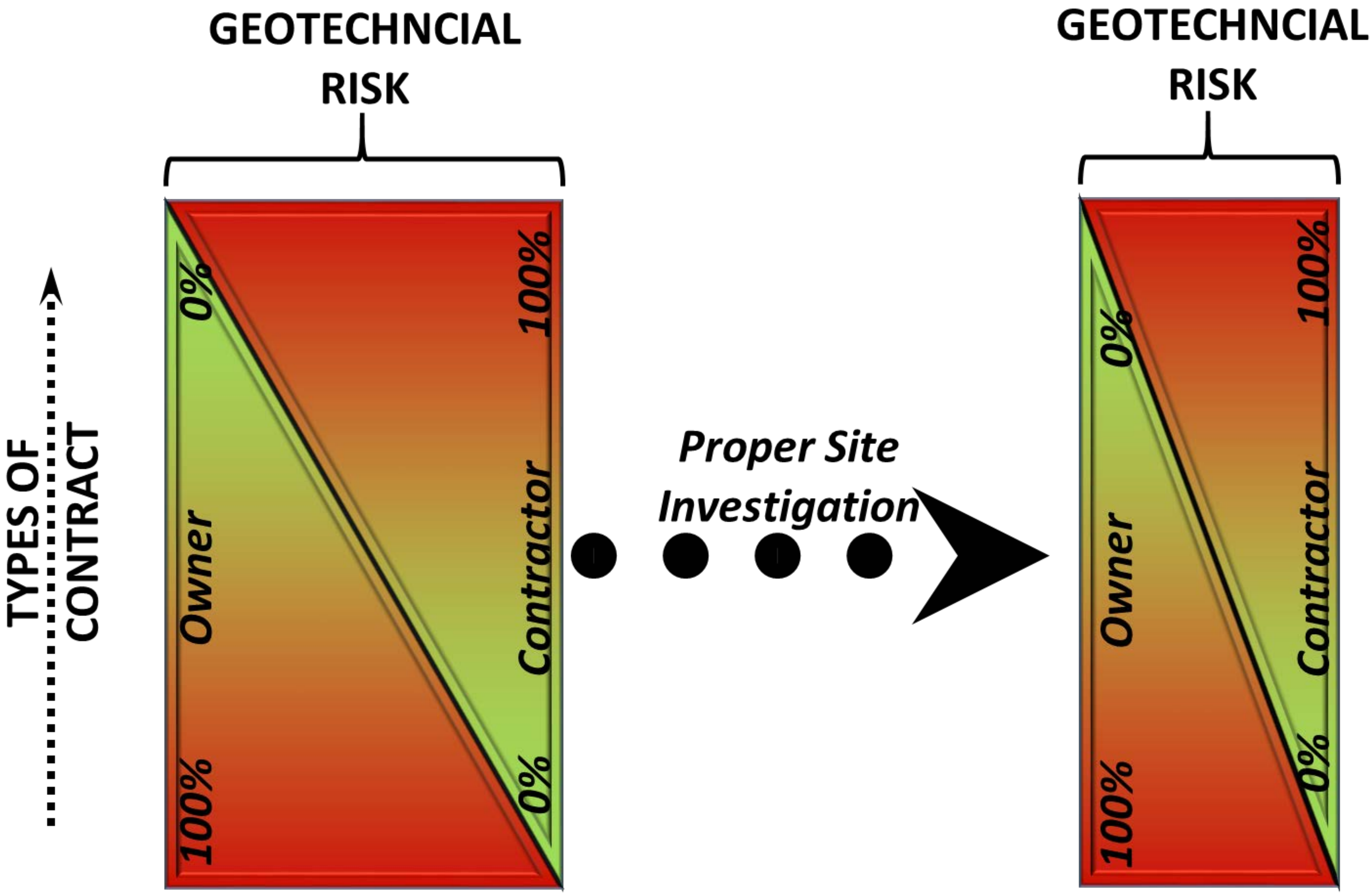
12%

Geotechnical Risk Management

Clayton, 2001



12%


GEOTECHNCIAL RISK
TYPES OF CONTRACT
0%
100%
Owner
Contractor
100%
0%
Proper Site Investigation
GEOTECHNCIAL RISK
0%
100%
Owner
Contractor
100%
0%

13%

Main Objective of Geotechnical Investigation

- Must be an understanding of the **behavior** of the soil to assist:

- Designers: loads, safe and economic design
- Contractors: method, equipment, cost, schedule
- Owners: initial budget, provisional costs, schedule

IT IS NOT SUFFICIENT TO DESCRIBE STRATIGRAPHY & GROUNDWATER TABLE

14%

Effectiveness of Site Investigation

- Depends on:
  - Scale
  - Quality
  - Engineering Assessment

- Geotechnical unknowns usually exist in reverse correlation to the above

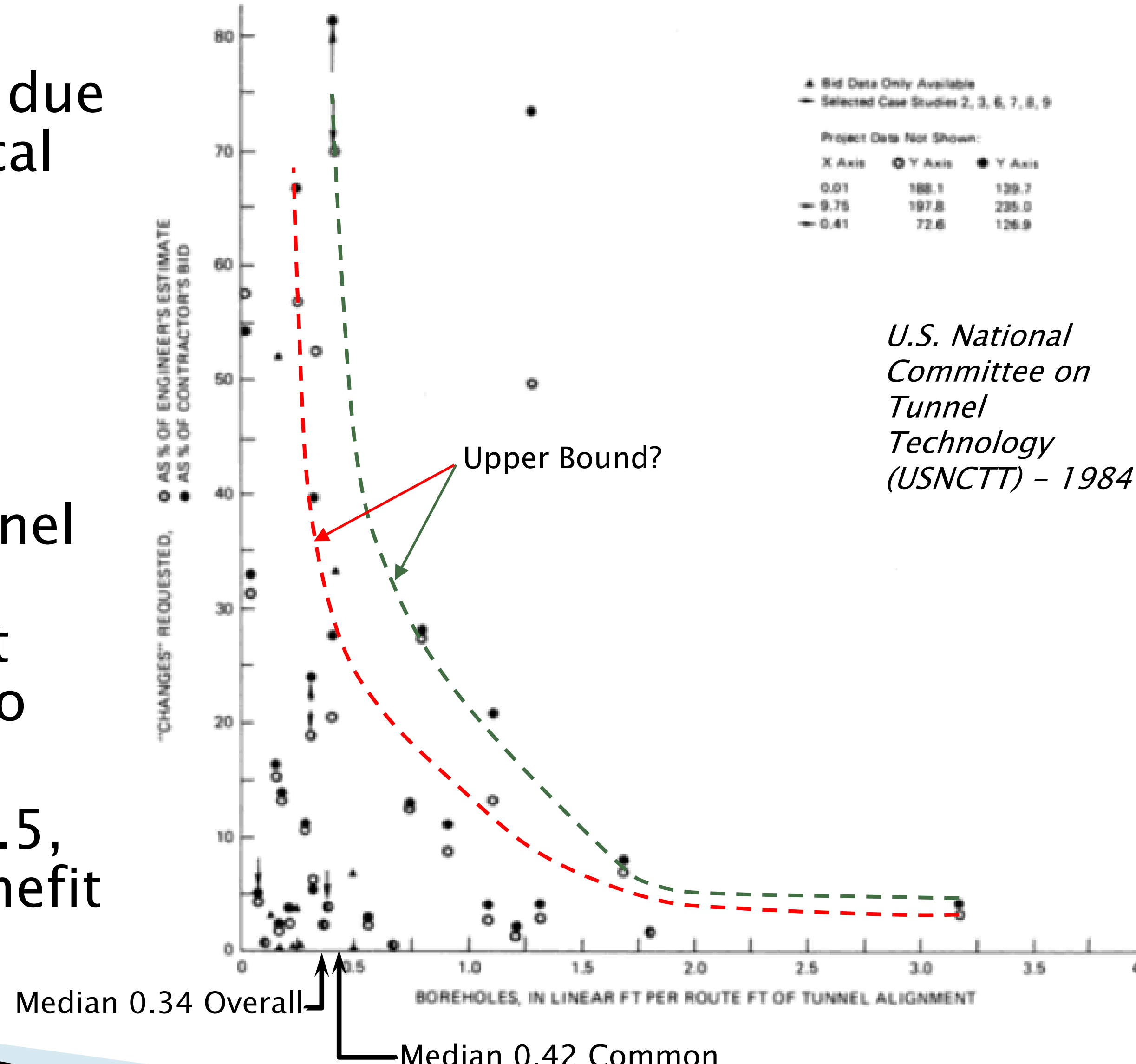
15%

Questions

- Is there a universal correlation between <u>scale</u> of investigation and <u>risk</u>?
  - NO
- Different geological regions → Different variability of soil deposits and property → Impossible to have a universal correlation
- Project risk is also dependent on construction method (e.g., EPB TBM vs. NATM/SEM)
- Apparently, it is possible to come up with upper bound

Cost Overrun vs. Scale of Investigation

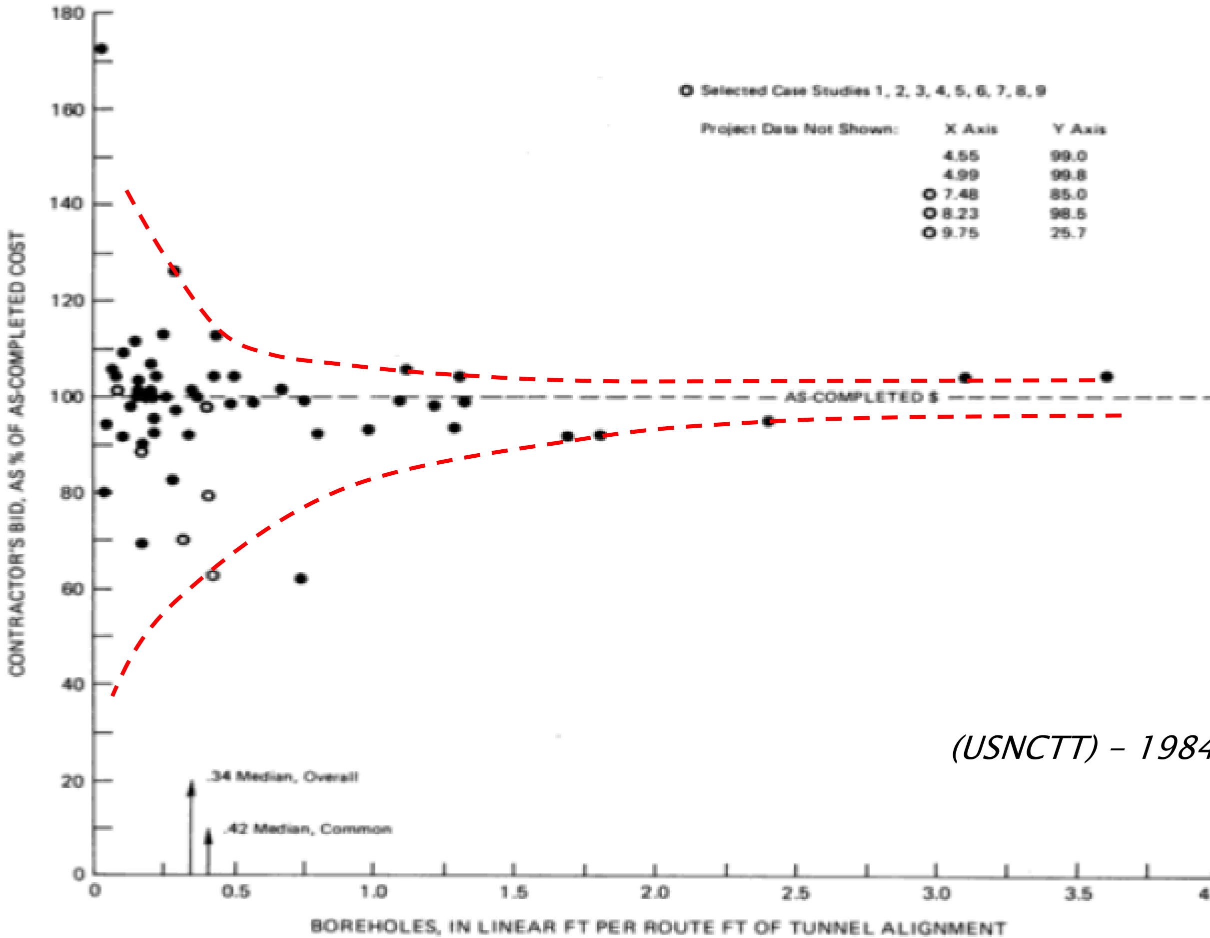
- Cost overrun due to geotechnical issues
- 84 projects, including 10 Canadian projects
- Borehole/tunnel ratio of 0.5: potential cost overrun, up to 60%
- B/T ratio > 1.5, not much benefit



Contractor Bid vs. Scale of Investigation

The more information a contractor has about subsurface geotechnical conditions, the more informed and competitive will be his bid

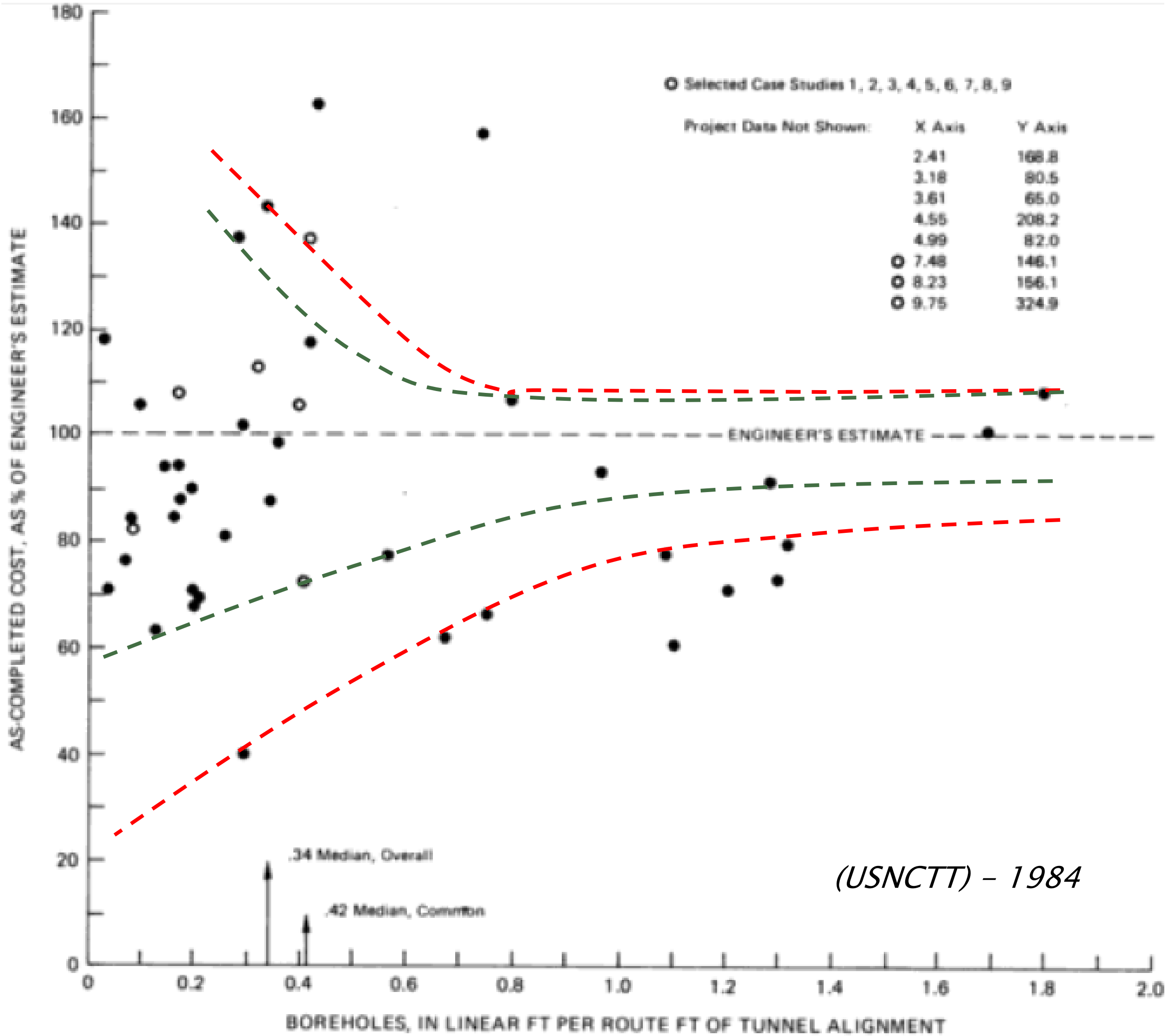
source: American Council of Engineering Companies and the Associated General Contractors of America



(USNCTT) – 1984

19%

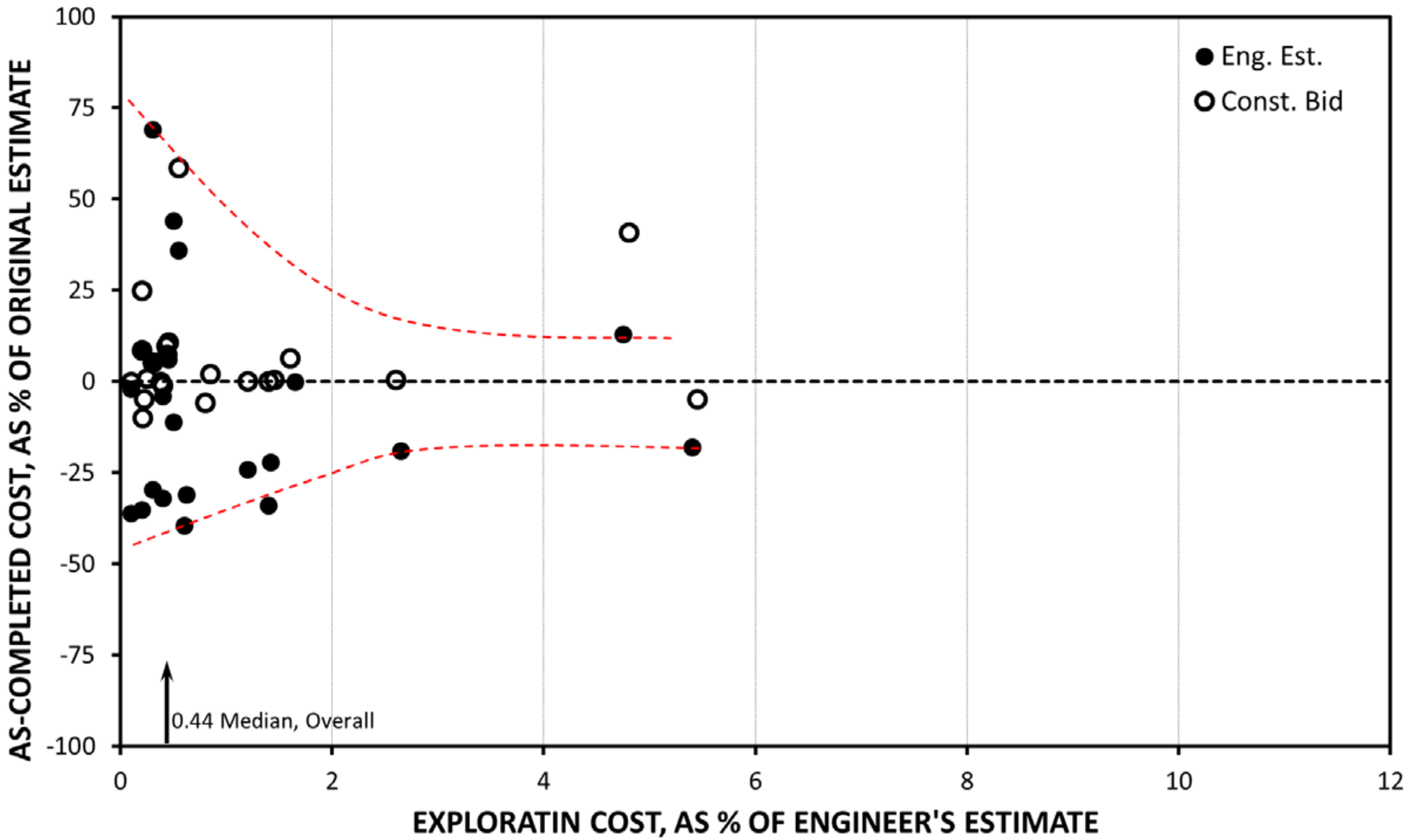
Designer Estimate vs. Scale of Investigation



(USNCTT) – 1984

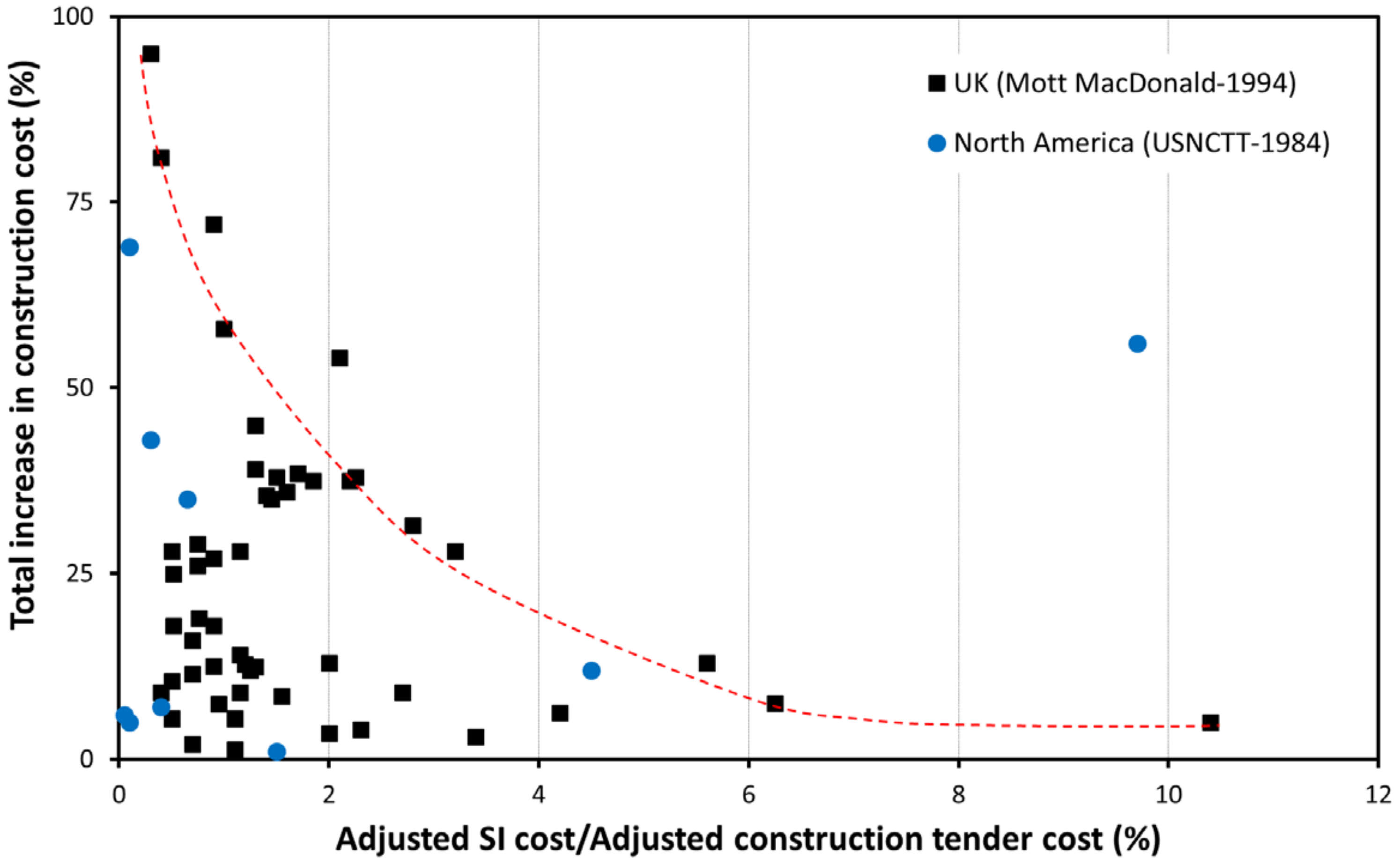
20%

Original Estimate vs. Cost of Investigation



(USNCTT) – 1984

Cost Overrun Due to Geotechnical Issues vs. Cost of Investigation



22%

Scale/Cost of Site Investigation is not Everything

- Cost is not always a valid indication of effectiveness
- Site investigation cost may be reduced, without increasing the risk, by appropriate choice of investigation methods
  - Prior tunneling knowledge in project area
  - Existing geotechnical information for the area
  - Sensitivity of the construction method to the soil behaviour
  - Quality of the investigation
  - Adopting observational method
  - Engineering Assessment

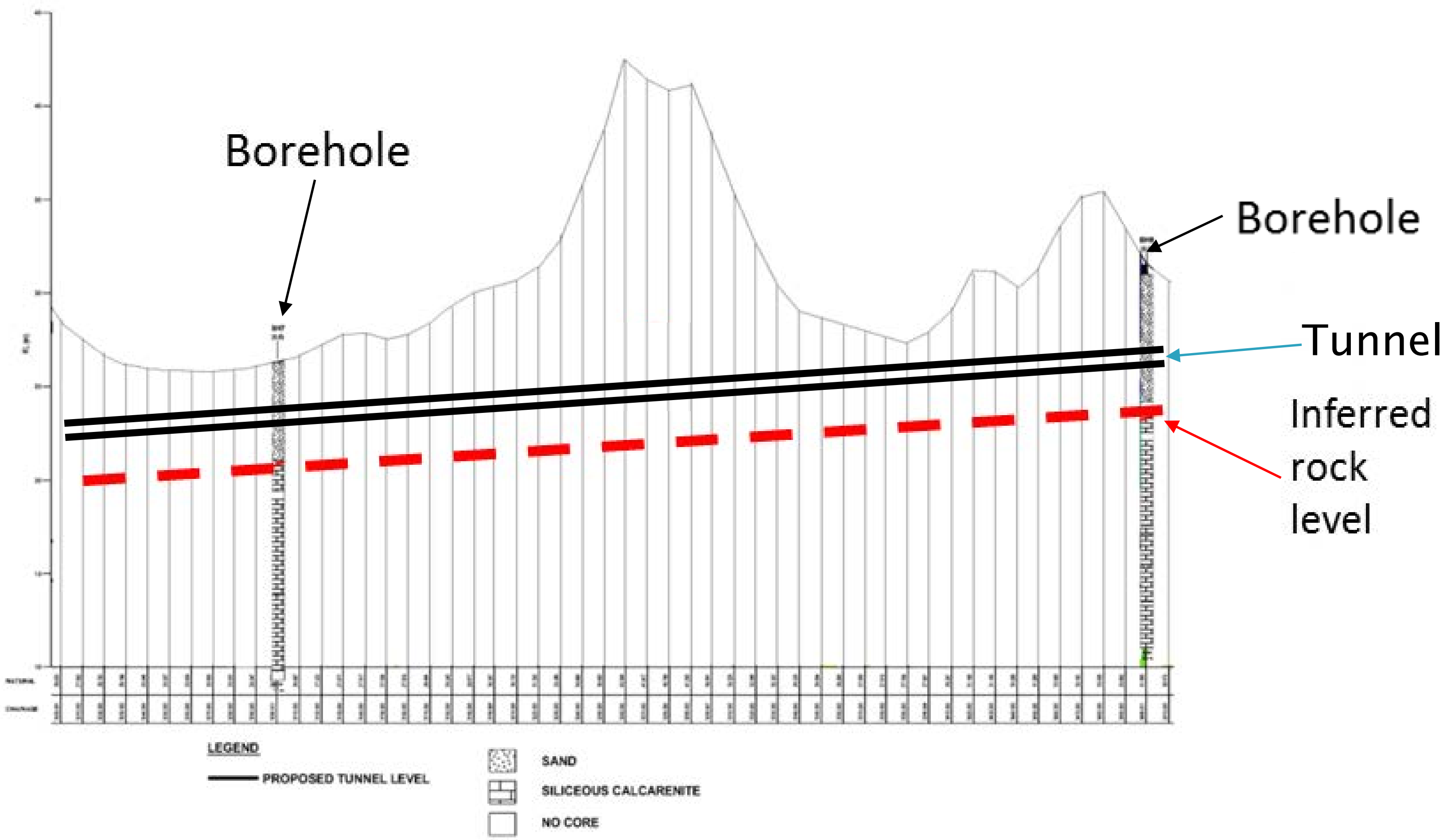
24%

Geophysics Survey

- Geophysics is a form of non-destructive in situ testing (NDT) whose objective is to provide supplementary subsurface information in a cost-effective manner
- It is not a substitute to boreholes.
- Helps to maintain geotechnical risk while keeping the number of boreholes reasonable

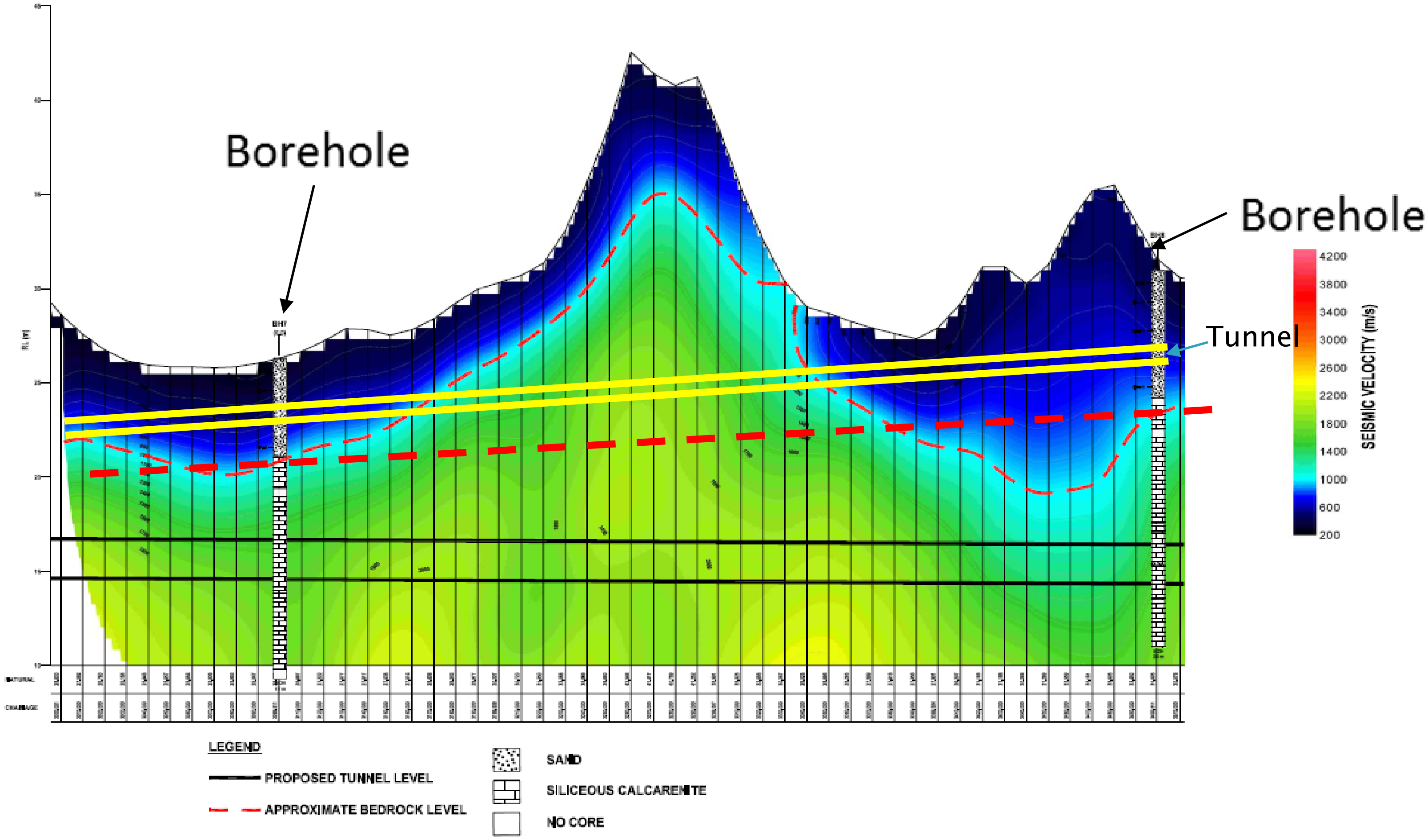
25%

Seismic Survey



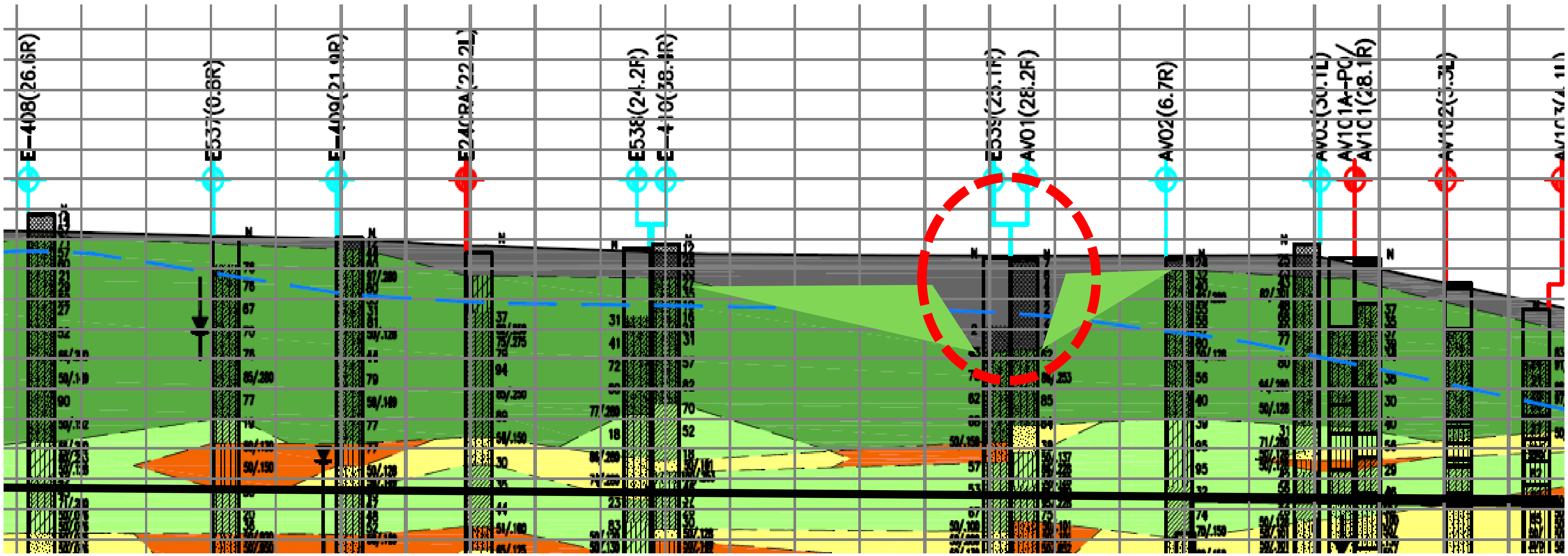
26%

Seismic Survey (Refraction, MASW, TISAR)

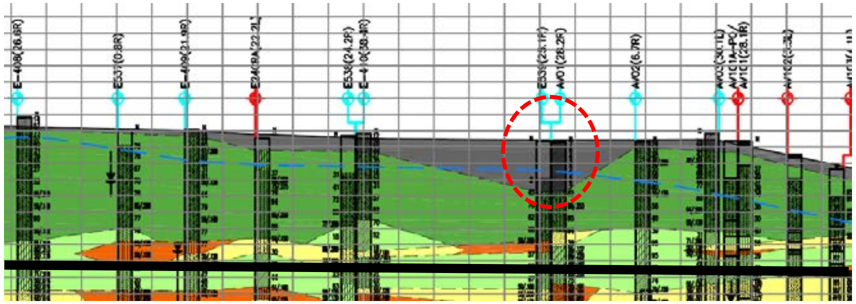


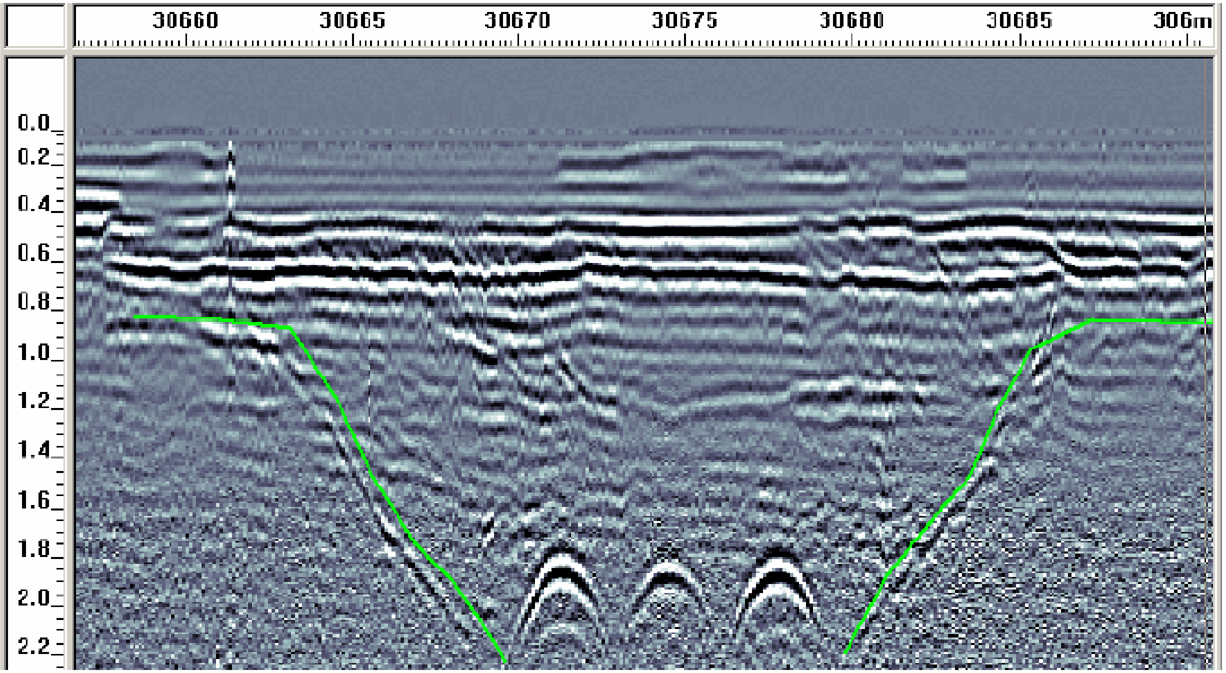
27%

GPR



GPR

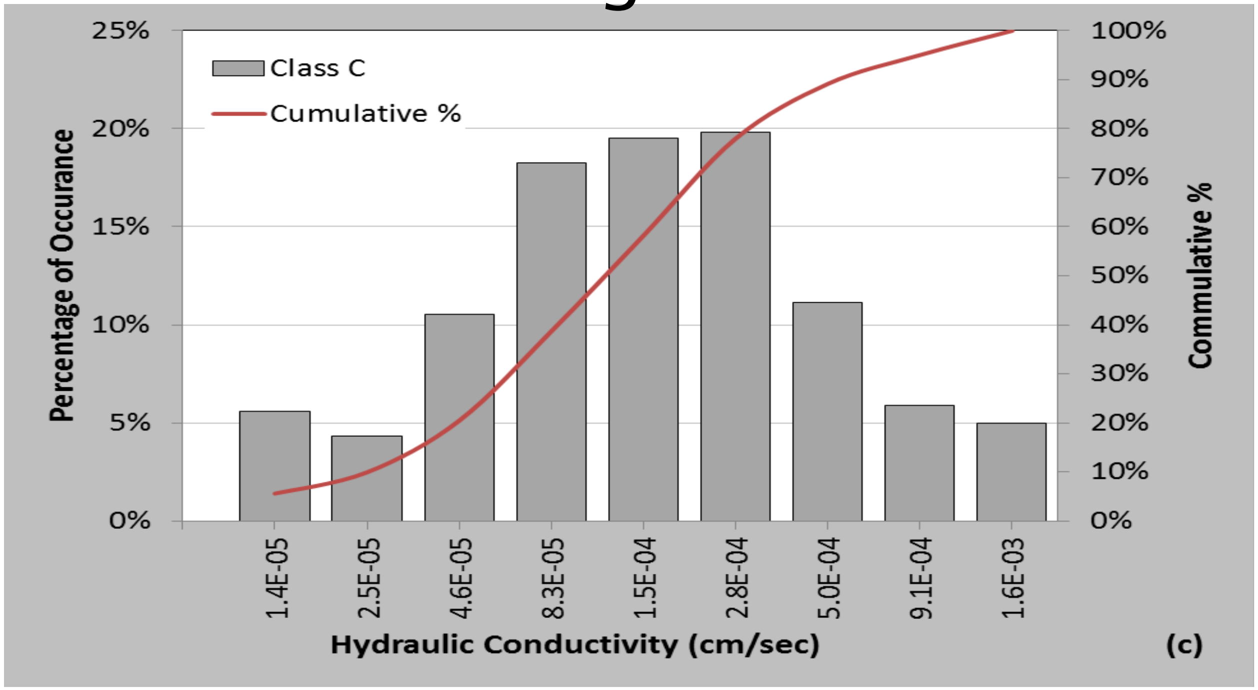



30660
30665
30670
30675
30680
30685
306m
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2

29%

Groundwater

- Hydraulic conductivity of the soil ranges by a few orders of magnitude

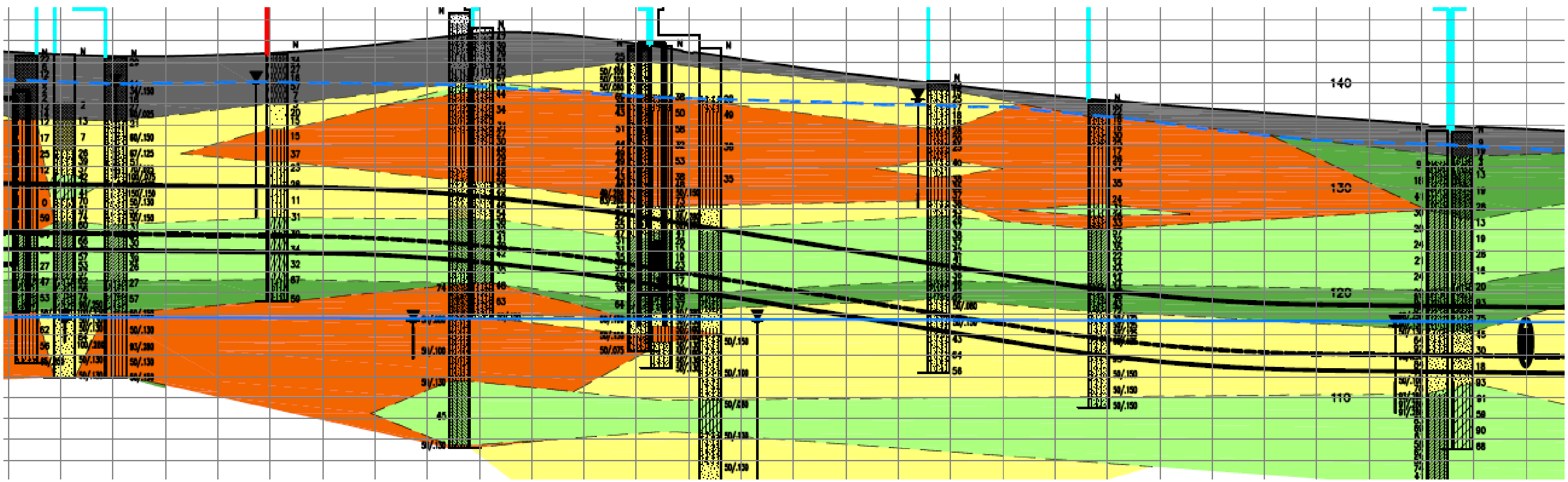


(Manzari & Galaa 2013)

31%

Groundwater

- Hydraulic conductivity of the soil ranges by a few orders of magnitude
- Tunnel projects may extended through more than one groundwater regime



Groundwater

- Hydraulic conductivity of the soil ranges by a few orders of magnitude
- Tunnel projects may extended through more than one groundwater regime
- Groundwater and its effects on the subsurface materials require greater attention during investigation programs
- Long-term pump tests are critical tool

31%

Sonic Drilling

- Large drill rig that vibrates a large-diameter core barrel into the ground recovering soil samples

Sonic Drilling

- 12% of delays in mechanized urban tunneling projects is the boulder problem –USNCTT 1984
- Sonic method most successful method for assessment of boulder (Frank & Chapman-2001& Del Nero-2012)
- Great for documenting engineering geology
- Very useful for groundwater study

33%

Geotechnical Investigation and Observational Method

- Investigation must be planned based on a model

GEOLOGICAL MODEL

↓

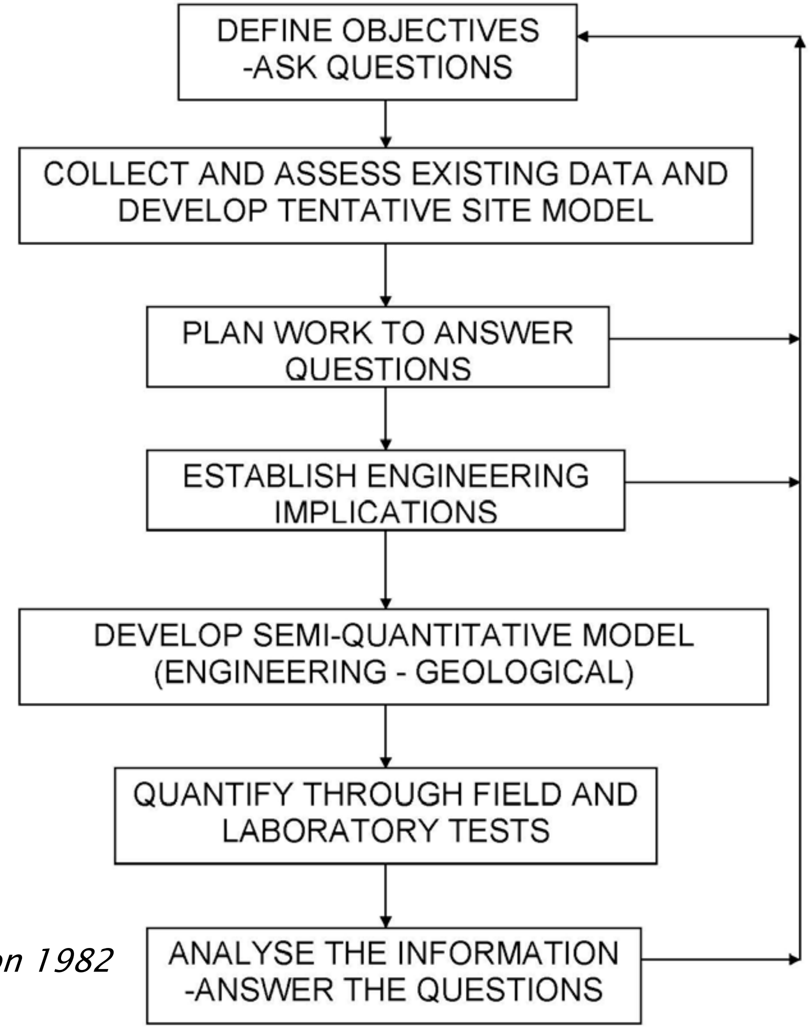
GEOTECHNICAL MODEL

↓

ANALYTICAL MODEL

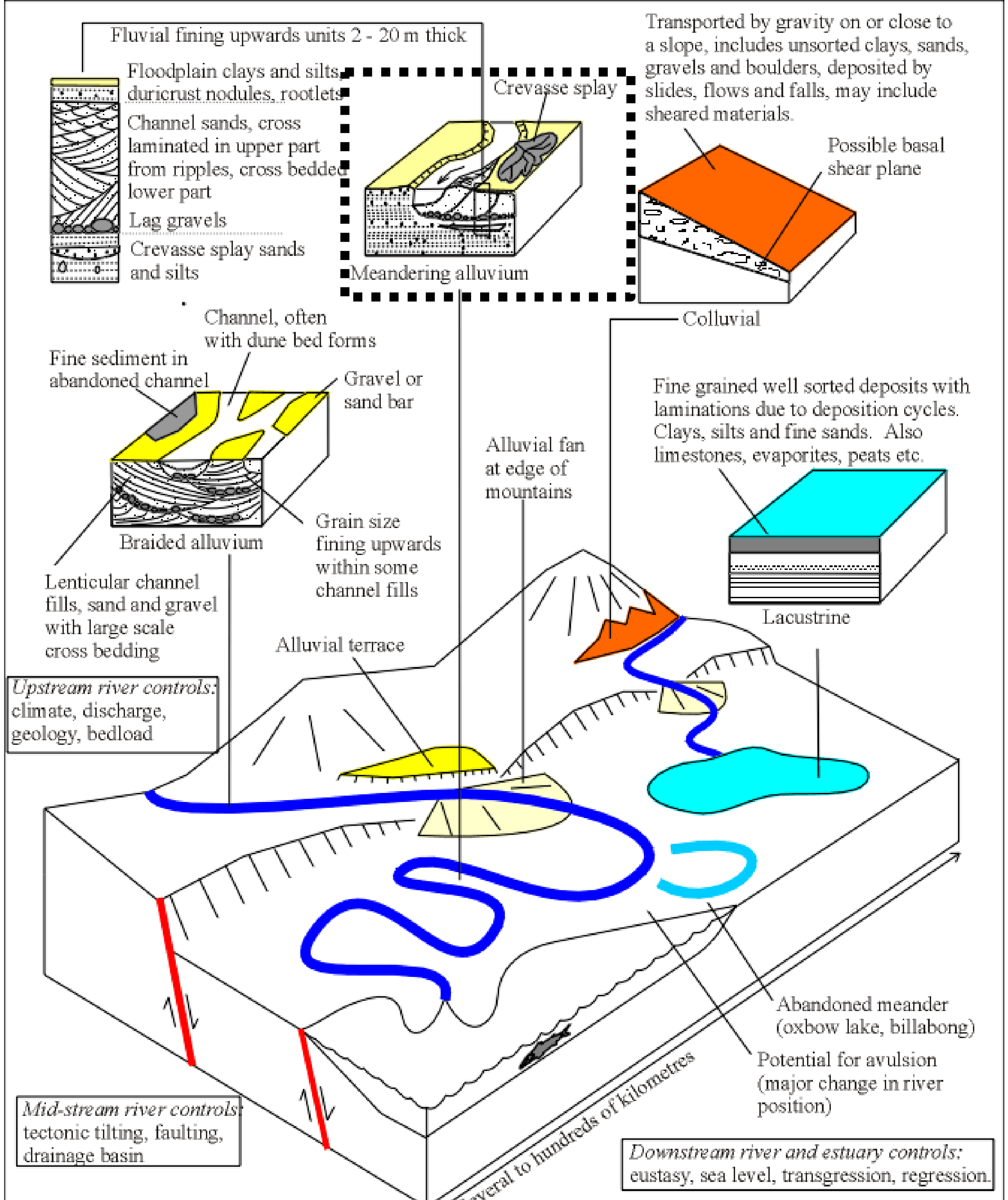
Geotechnical Investigation and Observational Method

- Investigation must be planned based on a model



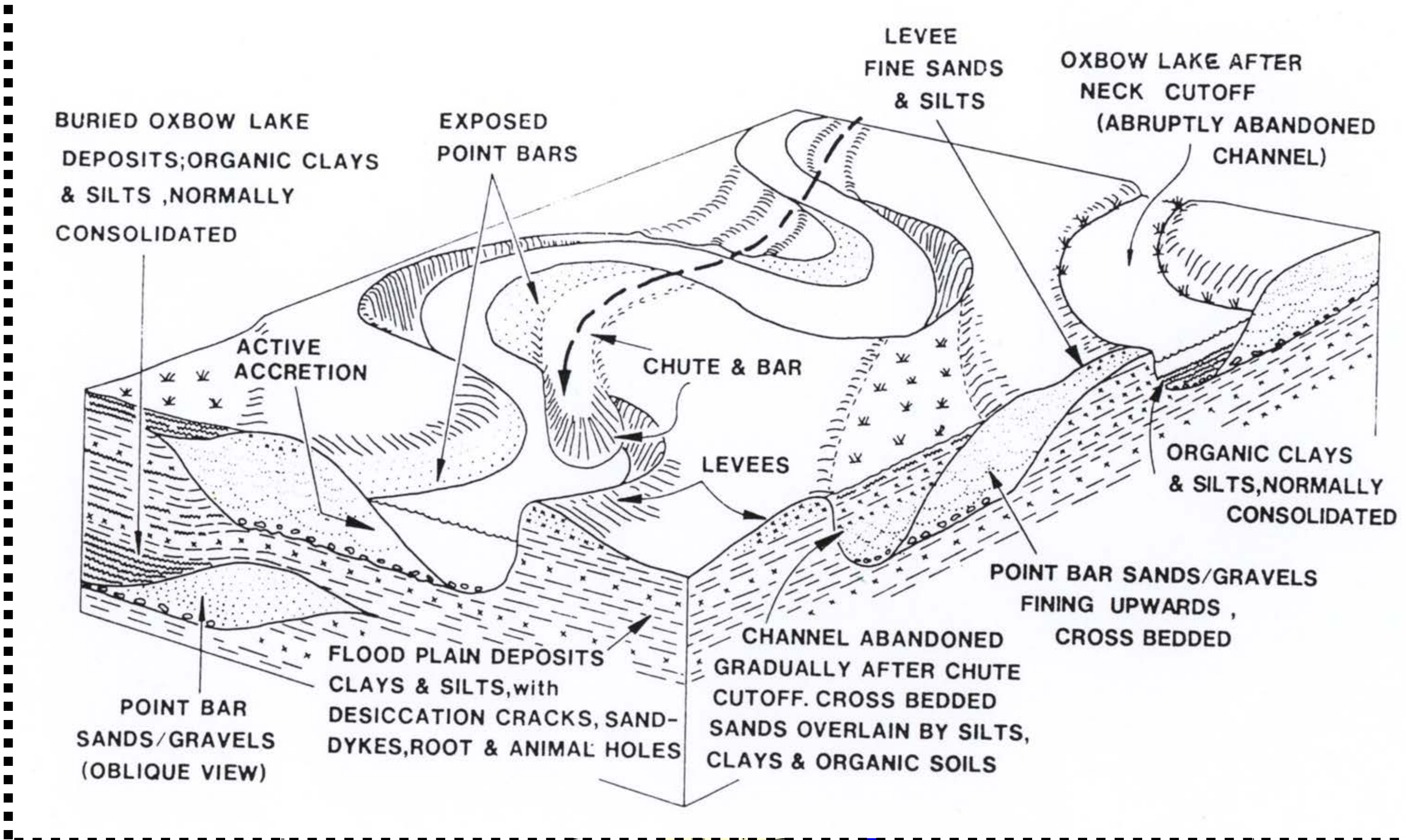
Stapledon 1982

35%

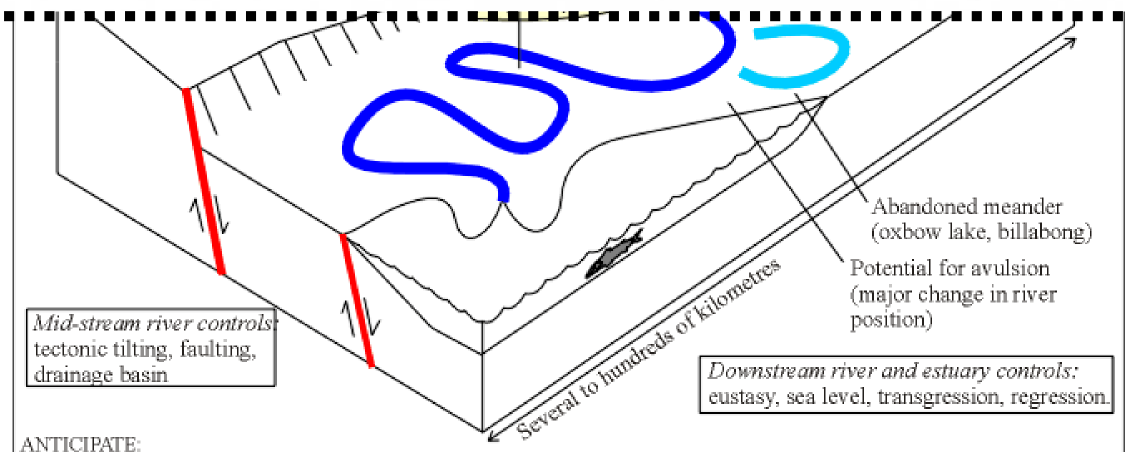


ANTICIPATE:

36%



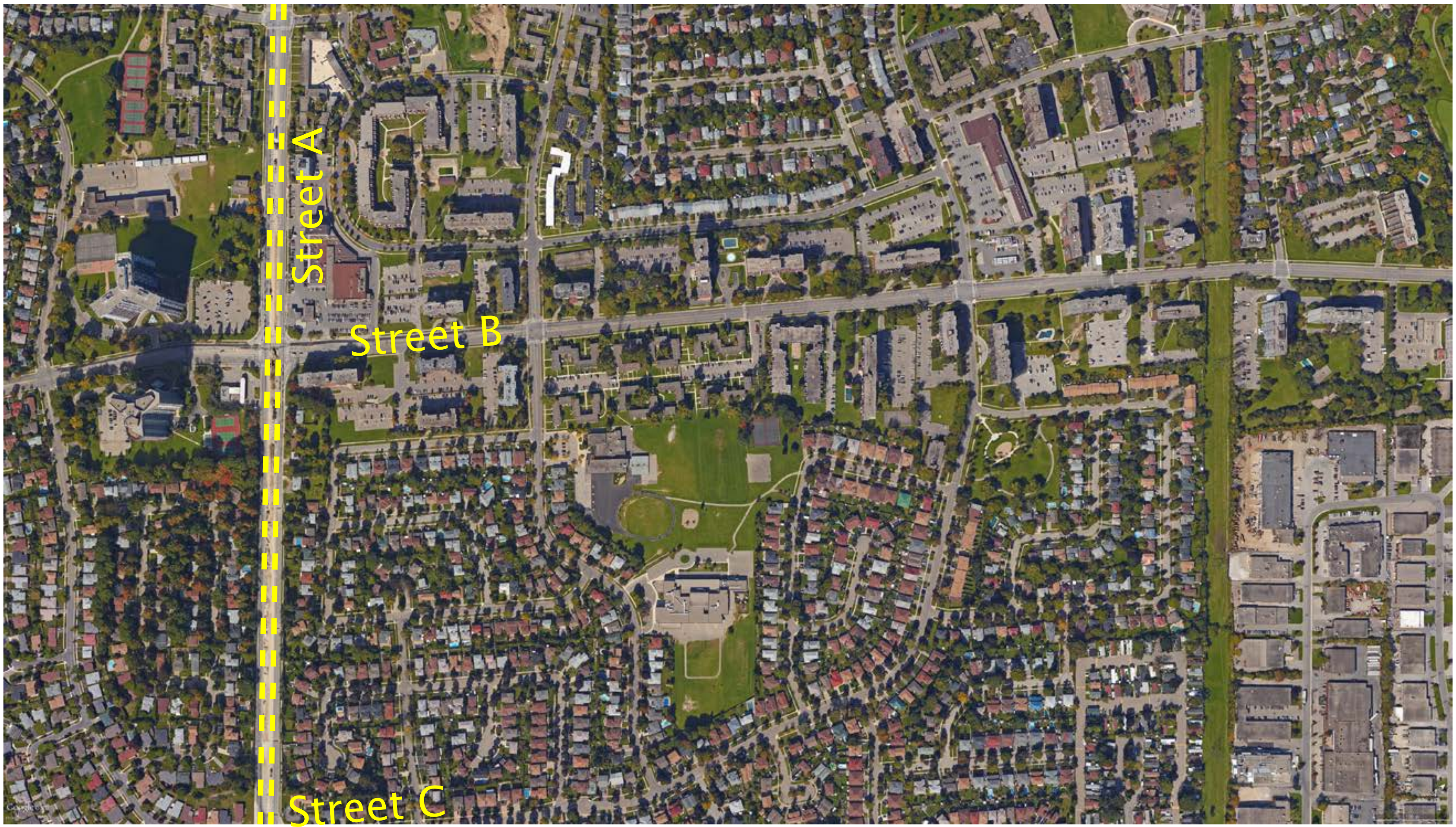
LEVEE
FINE SANDS
& SILTS
OXBOW LAKE AFTER
NECK CUTOFF
(ABRUPTLY ABANDONED
CHANNEL)
BURIED OXBOW LAKE
DEPOSITS;ORGANIC CLAYS
& SILTS ,NORMALLY
CONSOLIDATED
EXPOSED
POINT BARS
ACTIVE
ACCRETION
CHUTE & BAR
LEVEES
ORGANIC CLAYS
& SILTS,NORMALLY
CONSOLIDATED
POINT BAR SANDS/GRAVELS
FINING UPWARDS ,
CROSS BEDDED
CHANNEL ABANDONED
GRADUALLY AFTER CHUTE
CUTOFF. CROSS BEDDED
SANDS OVERLAIN BY SILTS,
CLAYS & ORGANIC SOILS
FLOOD PLAIN DEPOSITS
CLAYS & SILTS,with
DESICCATION CRACKS, SAND-
DYKES,ROOT & ANIMAL HOLES
POINT BAR
SANDS/GRAVELS
(OBLIQUE VIEW)



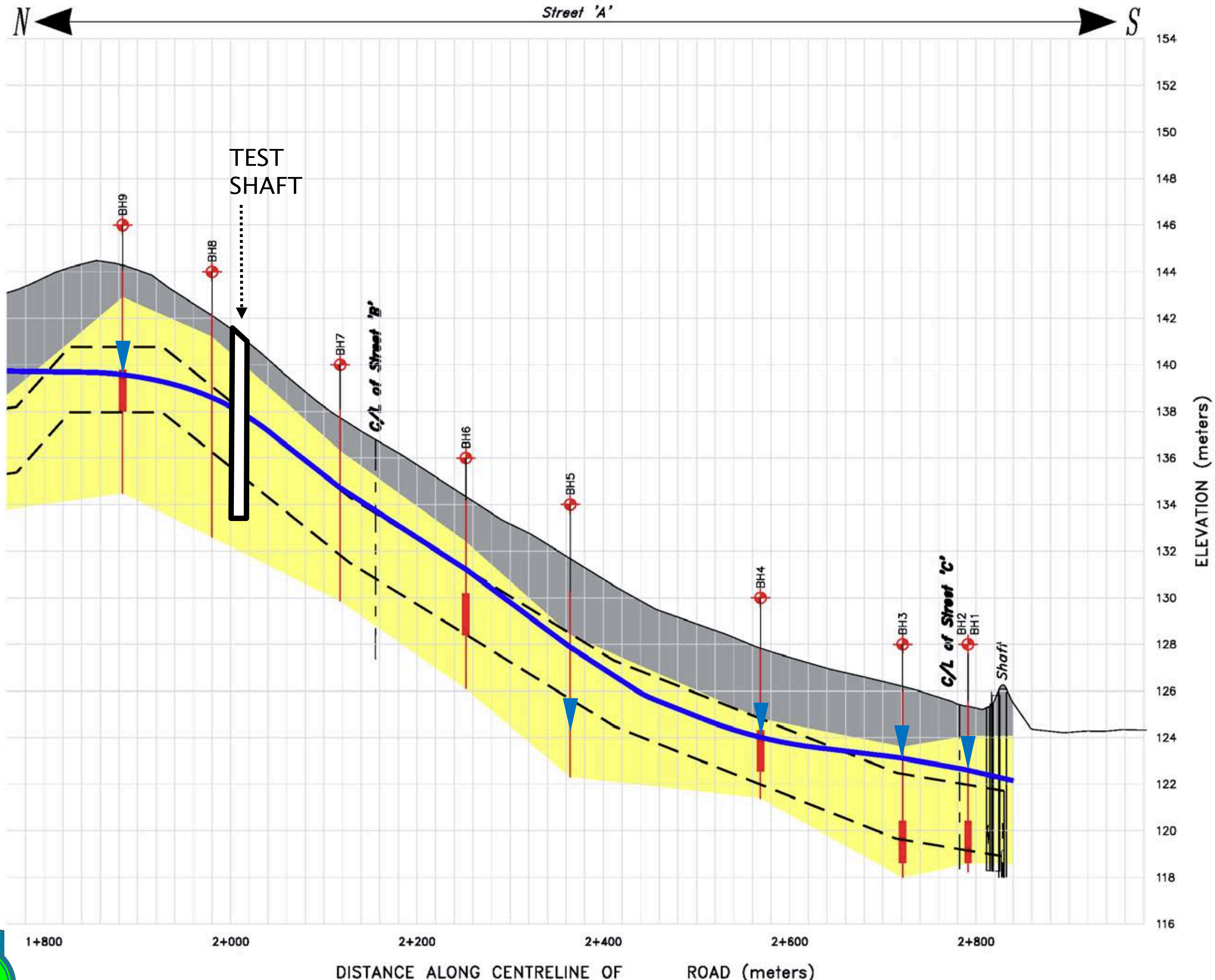
Abandoned meander
(oxbow lake, billabong)
Potential for avulsion
(major change in river
position)
Several to hundreds of kilometres
Mid-stream river controls:
tectonic tilting, faulting,
drainage basin
Downstream river and estuary controls:
eustasy, sea level, transgression, regression.
ANTICIPATE:

36%

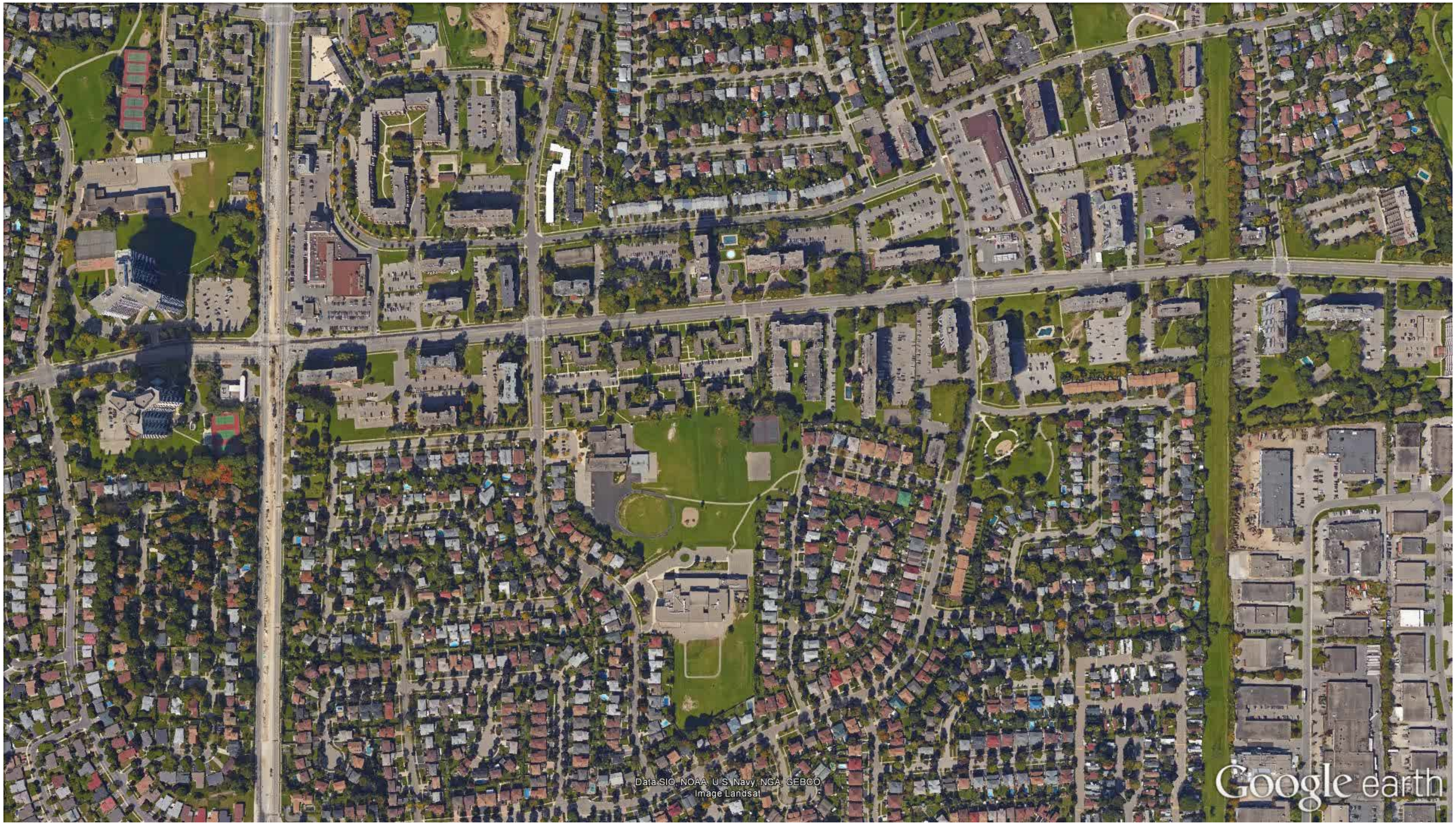
Example 1



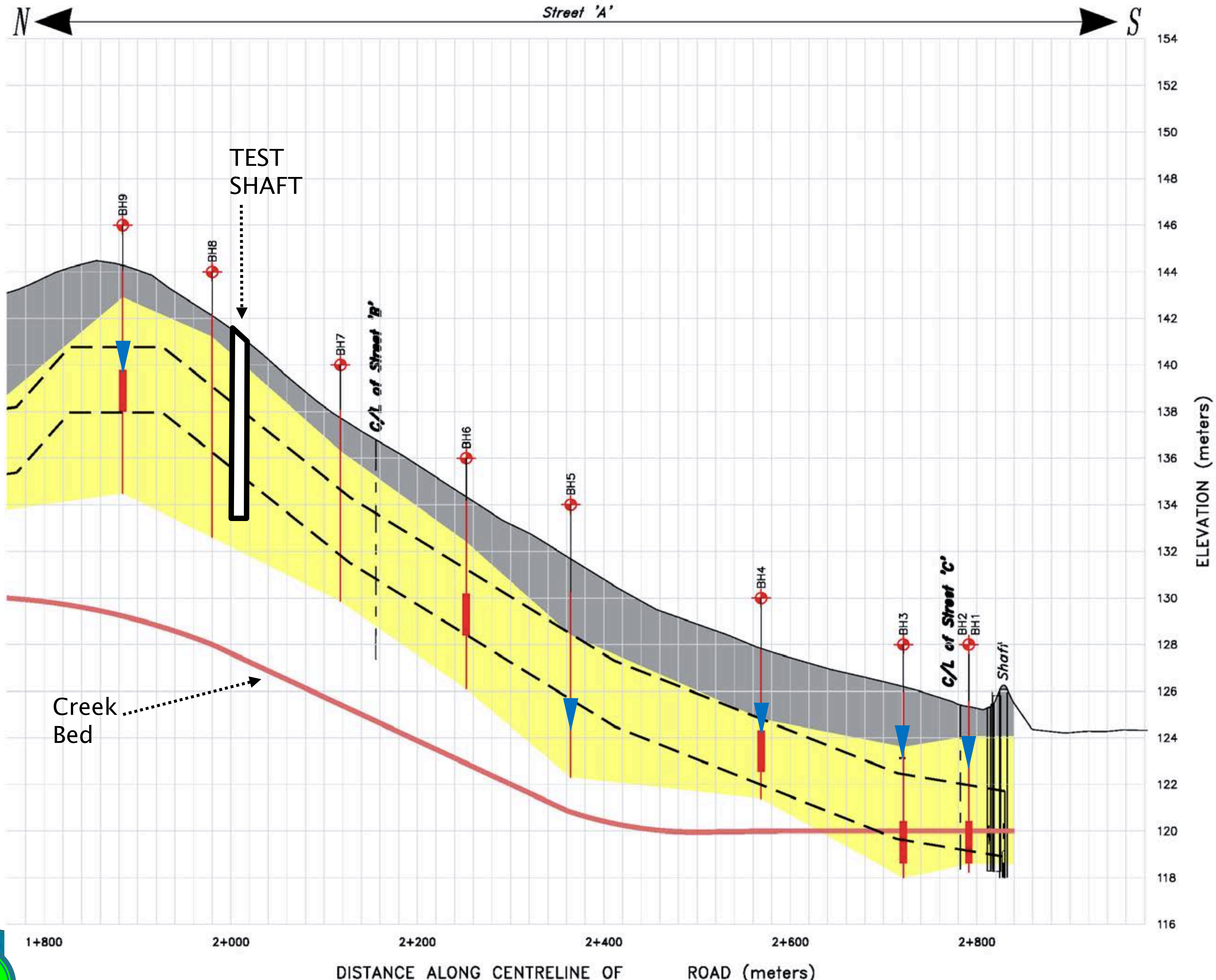
38%


N
Street 'A'
S
TEST SHAFT
BH9
BH8
BH7
C/L of Street 'B'
BH6
BH5
BH4
BH3
C/L of Street 'C'
BH2
BH1
Shaft
154
152
150
148
146
144
142
140
138
136
134
132
130
128
126
124
122
120
118
116
ELEVATION (meters)
1+800
2+000
2+200
2+400
2+600
2+800
DISTANCE ALONG CENTRELINE OF ROAD (meters)

39%

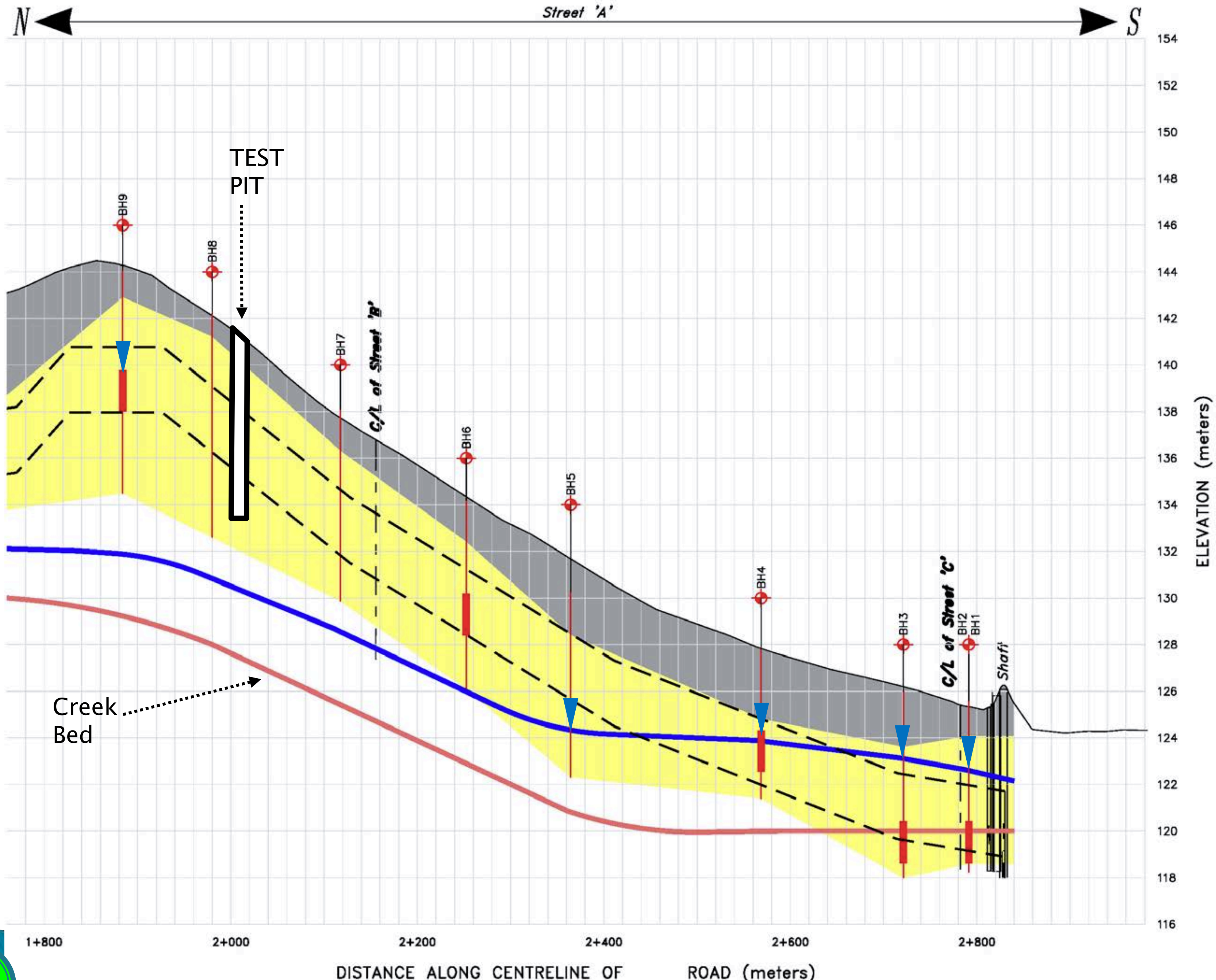


40%



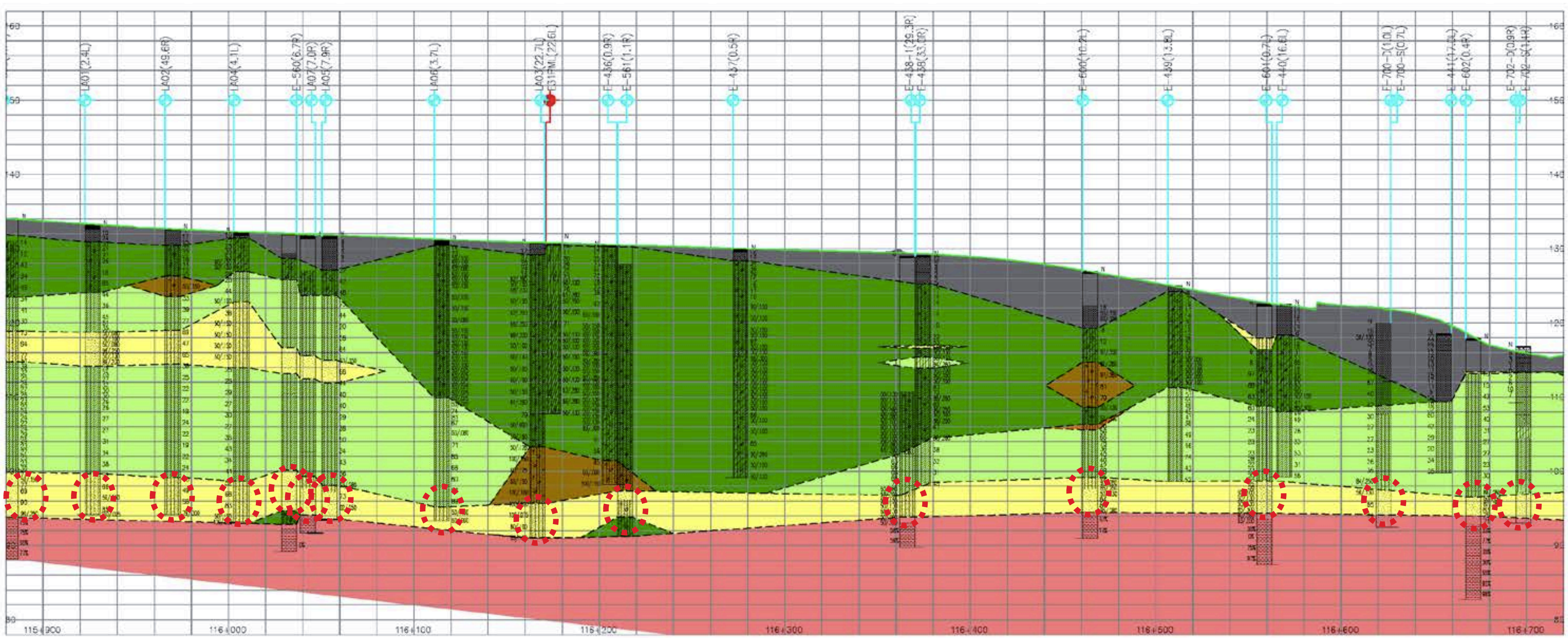
N
Street 'A'
S
TEST
SHAFT
BH9
BH8
BH7
C/L of Street 'B'
BH6
BH5
BH4
BH3
C/L of Street 'C'
BH2
BH1
Shaft
Creek
Bed
154
152
150
148
146
144
142
140
138
136
134
132
130
128
126
124
122
120
118
116
ELEVATION (meters)
1+800
2+000
2+200
2+400
2+600
2+800
DISTANCE ALONG CENTRELINE OF ROAD (meters)

41%

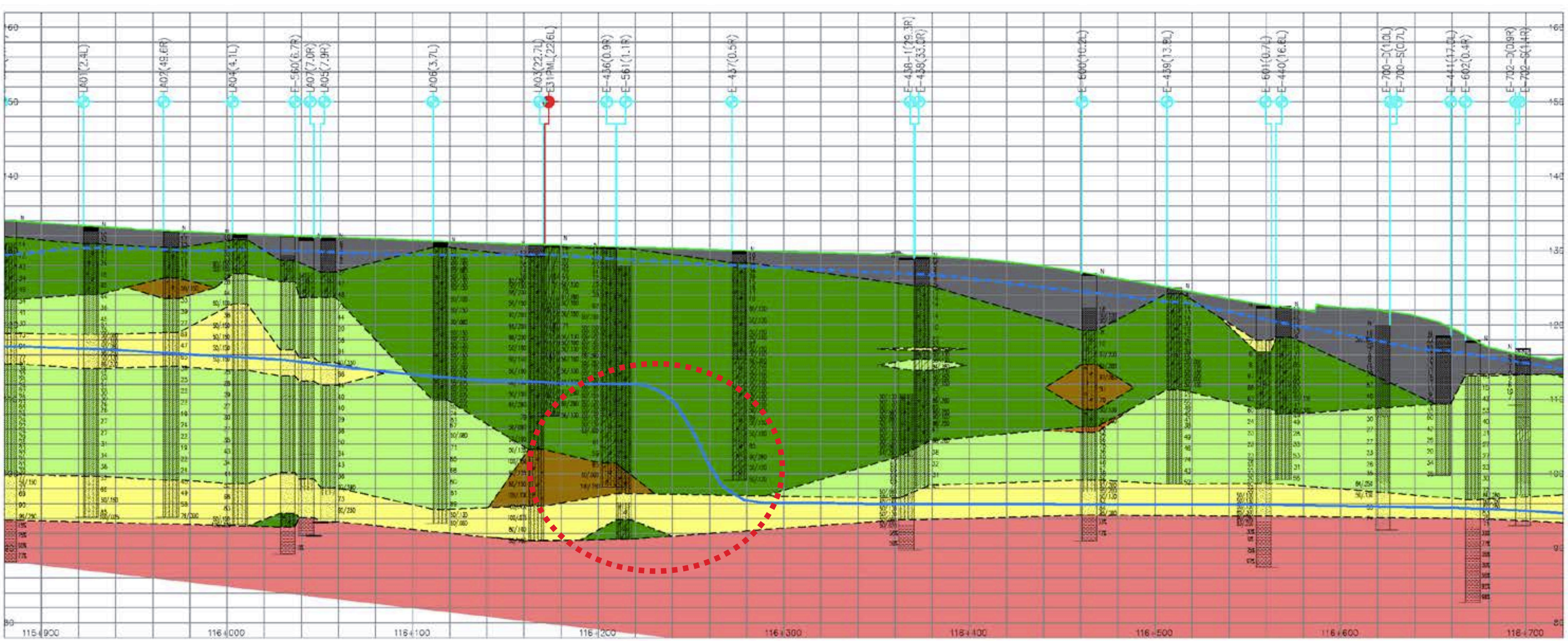


N
Street 'A'
S
TEST PIT
Creek Bed
BH9
BH8
BH7
BH6
BH5
BH4
BH3
BH2
BH1
C/L of Street 'B'
C/L of Street 'C'
Shaft
154
152
150
148
146
144
142
140
138
136
134
132
130
128
126
124
122
120
118
116
ELEVATION (meters)
1+800
2+000
2+200
2+400
2+600
2+800
DISTANCE ALONG CENTRELINE OF ROAD (meters)
42%

Example 2



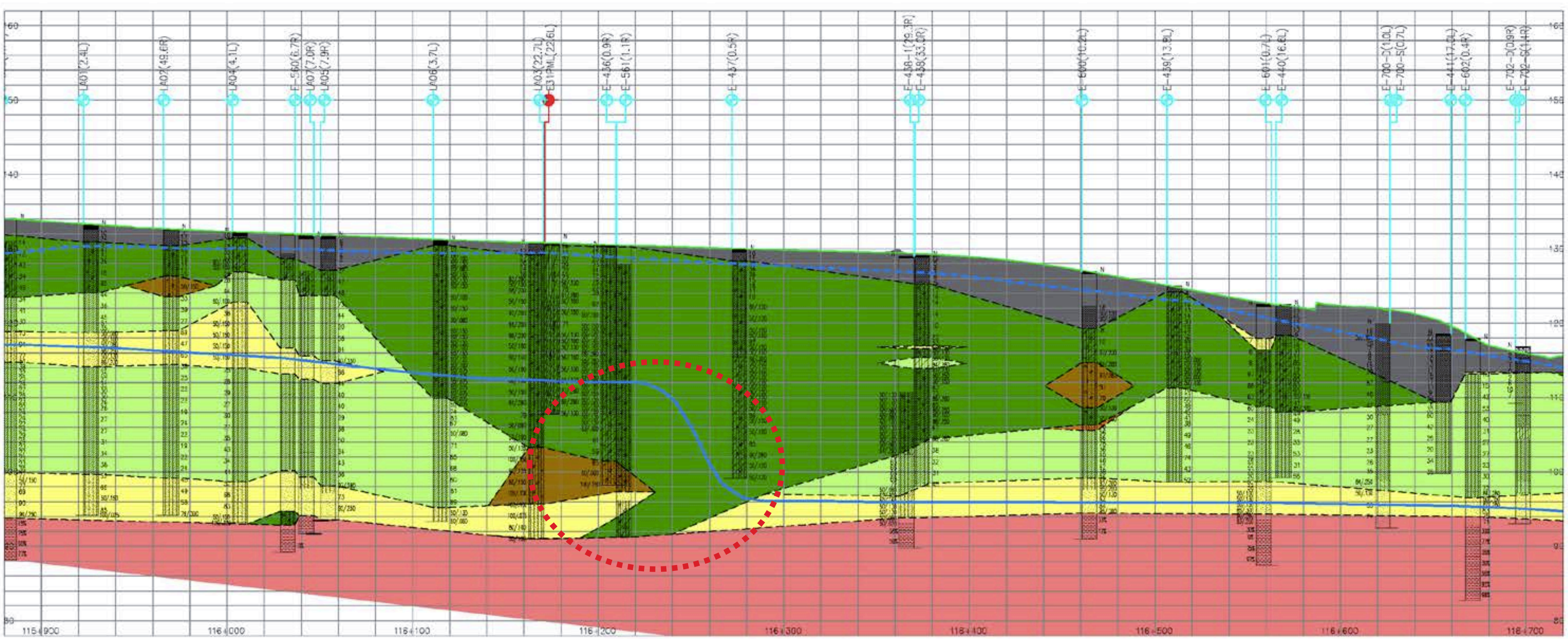
Example 2



160
150
140
115+900
116+000
116+100
116+200
116+300
116+400
116+500
116+600
116+700

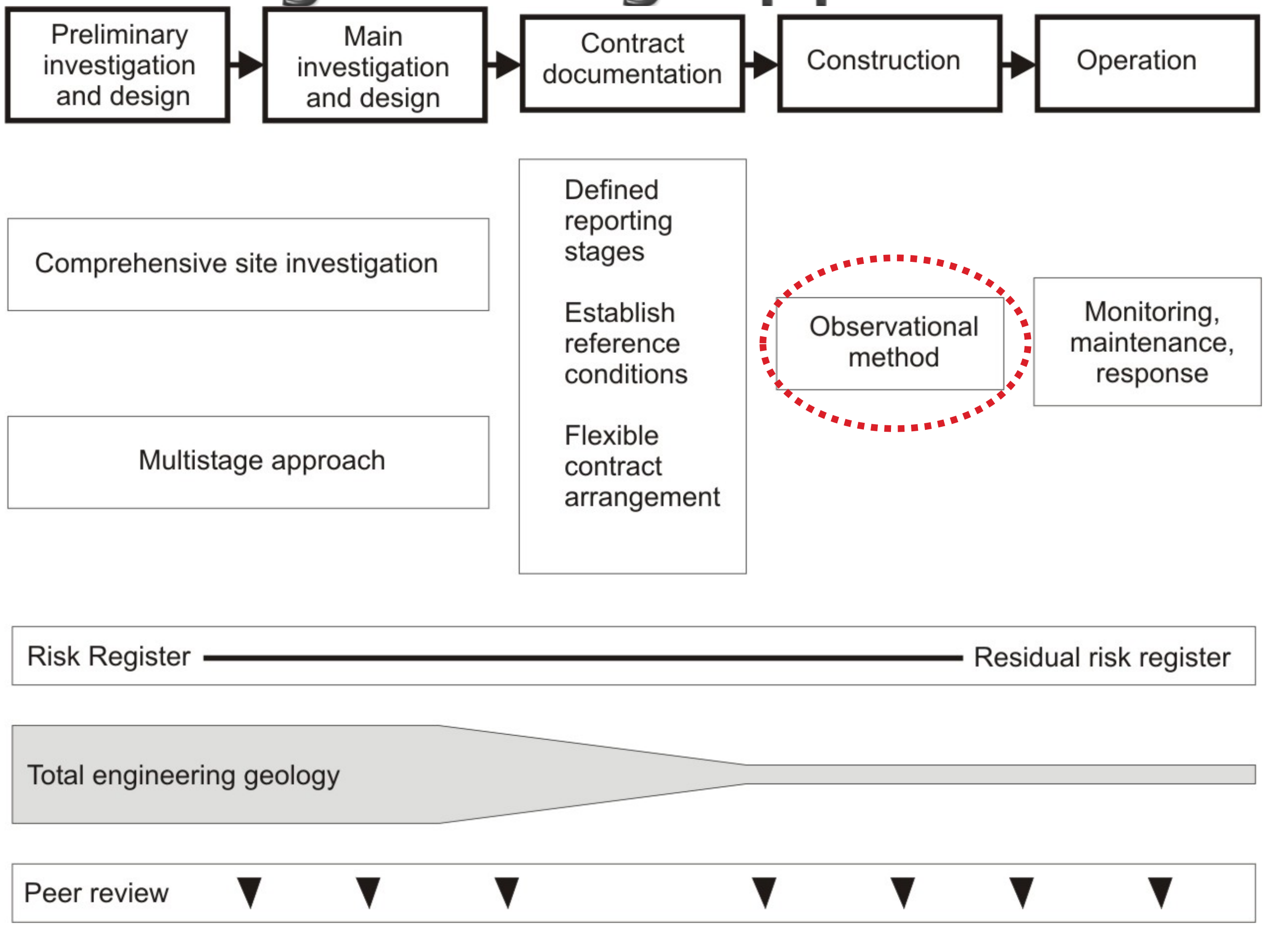
45%

Example 2


160
150
140
130
120
110
100
90
80
115+900
116+000
116+100
116+200
116+300
116+400
116+500
116+600
116+700

46%

Total Geoengineering Approach



- A team of geotechnical engineers and engineering geologists must be involved in the total project life

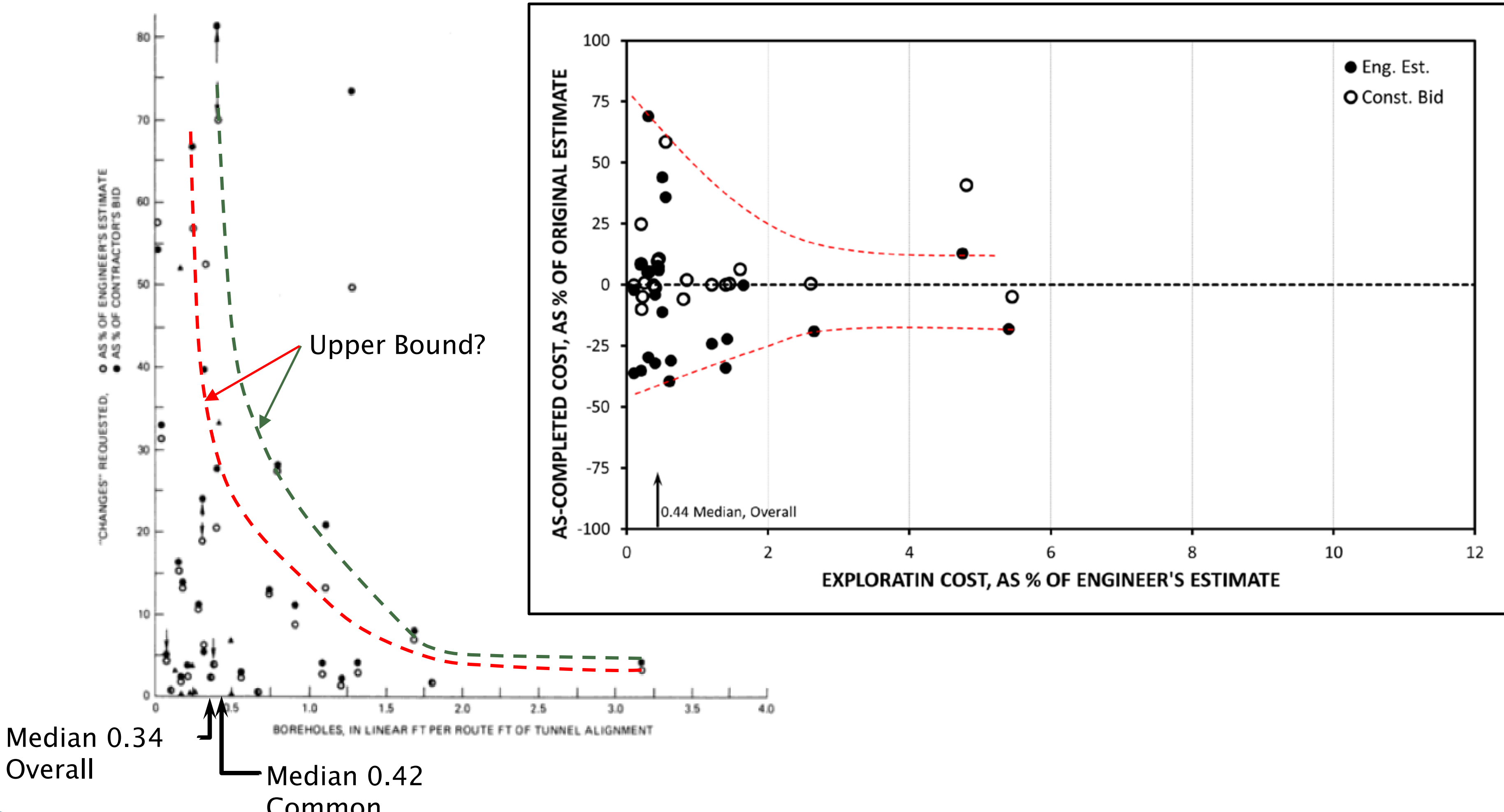
47%

Staged Investigations Progressively Reduce Risk

ACTIVITIES		STAGE	OBJECTIVE
		PRELIMINARY INVESTIGATIONS	
Desk study - compile all the available geological information onto a map and consider the engineering implications		Pre-feasibility	Route concept, identify terrain units and geohazards, develop a broad cost estimate
↓			
Air photo interpretation, site reconnaissance, broad engineering geological and geomorphological mapping, engineering implications	*REVIEW*	Feasibility	Provisional alignment or corridor, identify engineering geological formations, investigate geohazards Cost estimate +/- 20%
↓		MAIN INVESTIGATIONS	
Phase I test pitting and boreholes, lab testing, detailed mapping, design evaluation, develop models	*REVIEW*	Design	Design alignment, collect and document detailed information, establish Reference Conditions Cost estimate +/- 10%
↓			
MAIN DESIGN			
↓			
Phase II test pitting and boreholes, locating borrow, detailed design evaluation of any problematic areas, careful documentation	*REVIEW*	Detailed design	Finalize alignment, definition and communication of ground conditions using Reference Conditions, finalize contract documentation for project implementation, establish risk management strategies to build project within cost estimate
↓			
TENDER AND AWARD			
↓			
Construction supervision, logging, additional borrow, observational method	*SEVERAL REVIEWS*	CONSTRUCTION	Manage construction corridor, application of the Observational Method
↓	*REVIEW*		
Commissioning report, monitor and maintain		OPERATION	Manage asset corridor, ongoing risk management

48%

Engineering Assessment and Quality of Investigation

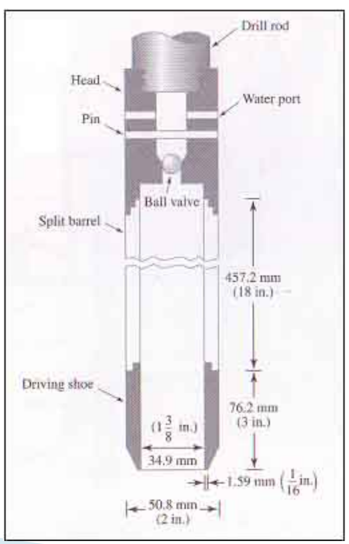


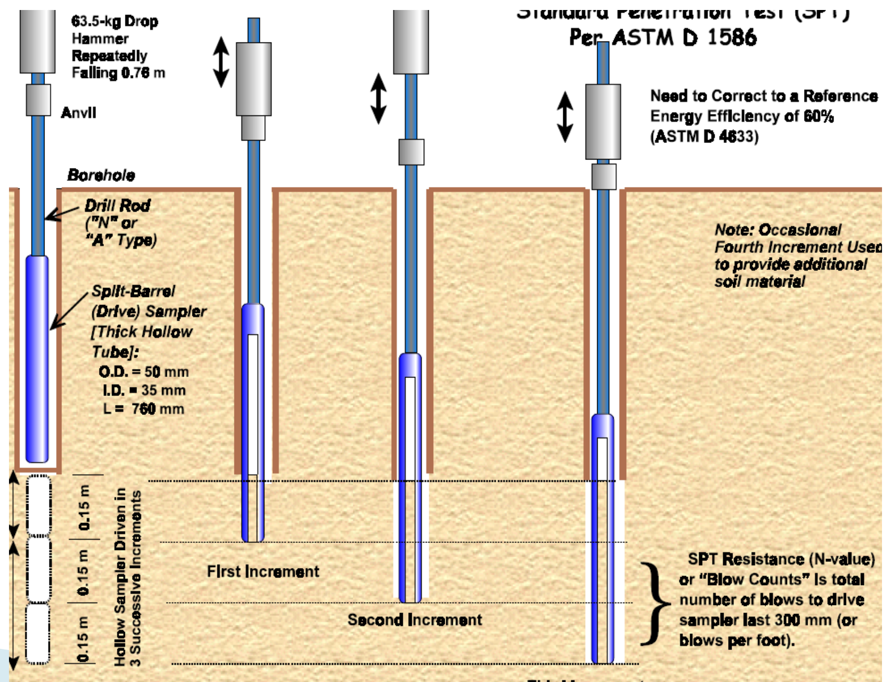
USNCTT – 1984

49%

Traditional Geotechnical Investigation Standard Penetration Test (SPT)

- Introduced by Raymond Pile Company in 1902
- Collects disturbed samples
- Measured resistance is correlated to various soil parameters





SPT Correlations

Clay

$S_u/P_a = 0.06 \times N \rightarrow E_u = 500 \times S_u$

Sand

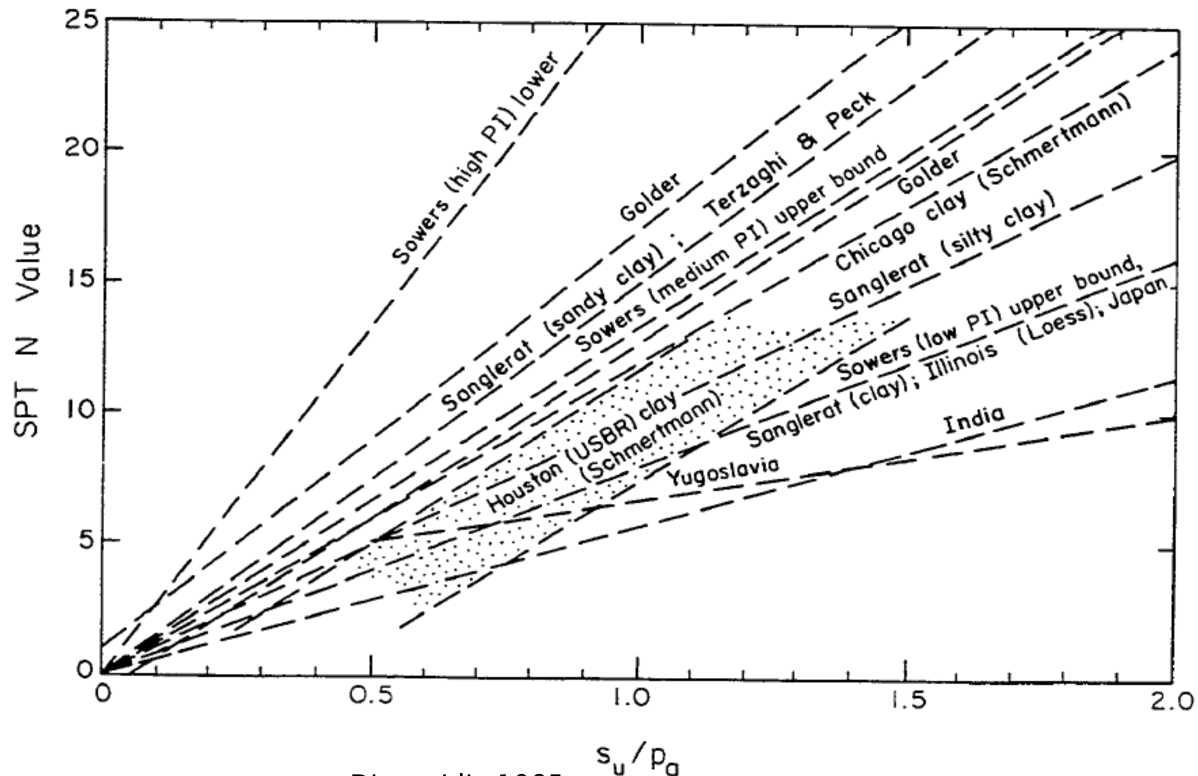
$E/P_a = 5 \text{ to } 15 \times N$

52%

SPT Correlations

Clay

$S_u/P_a = 0.06 \times N$

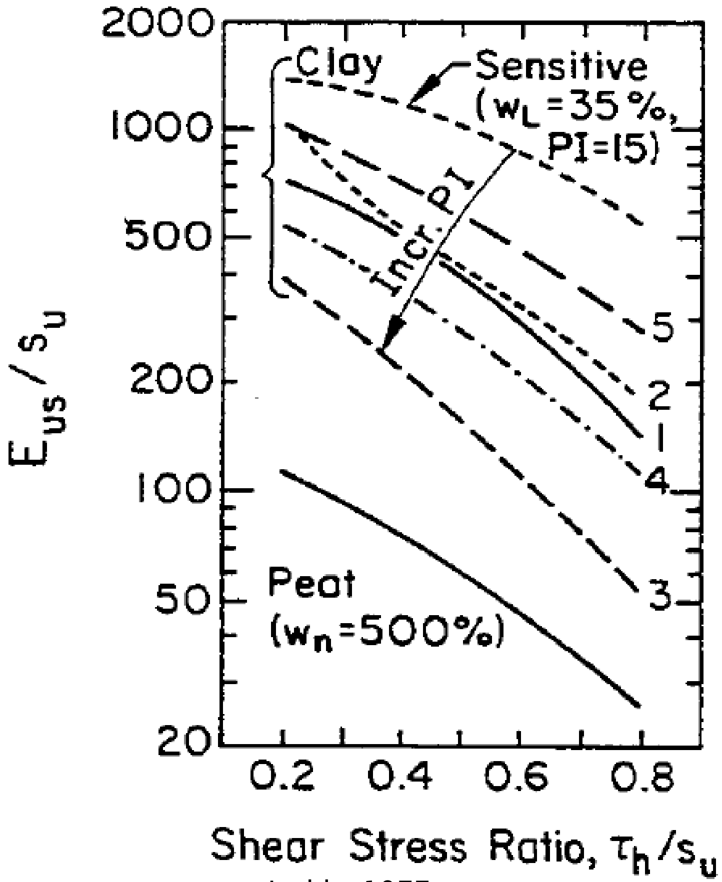


Djoenaidi- 1985

SPT Correlations

Clay

→ $E_u = 500 \times S_u$



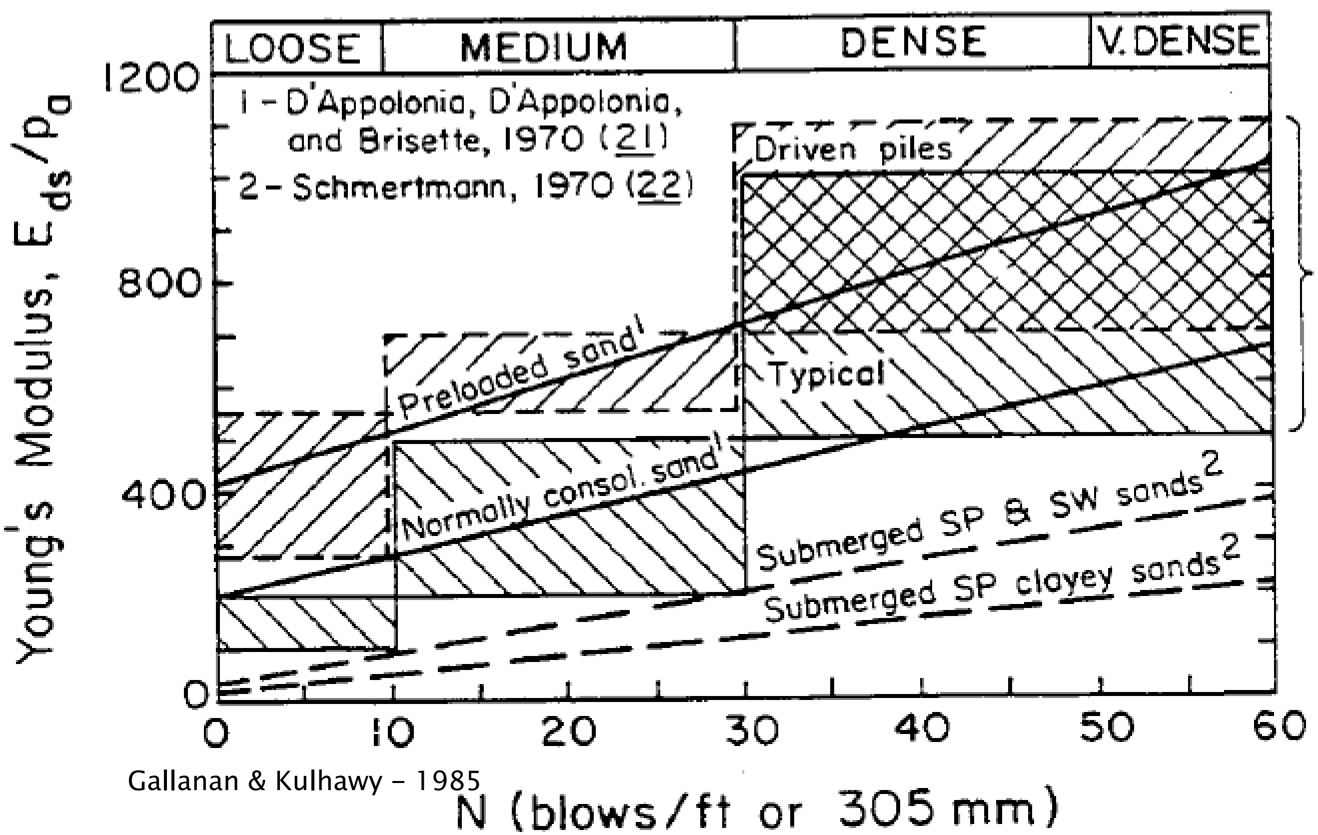
Ladd – 1977

52%

SPT Correlations

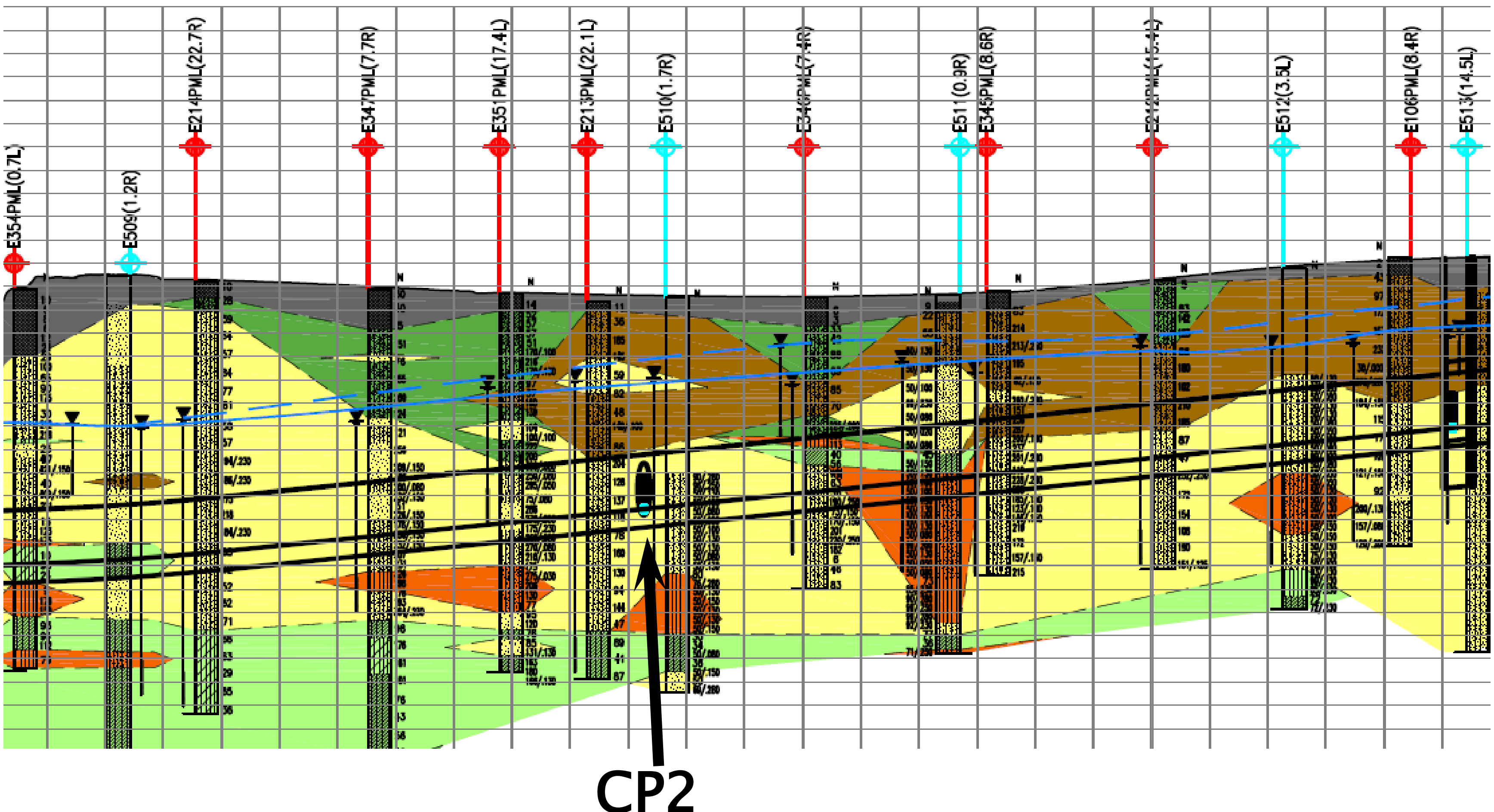
Sand

$E/P_a = 5 \text{ to } 15 \times N$

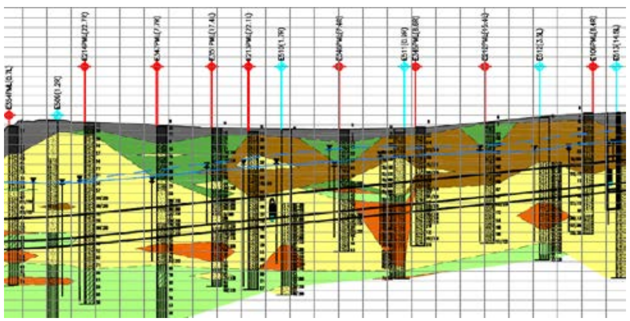


Gallanan & Kulhawy - 1985

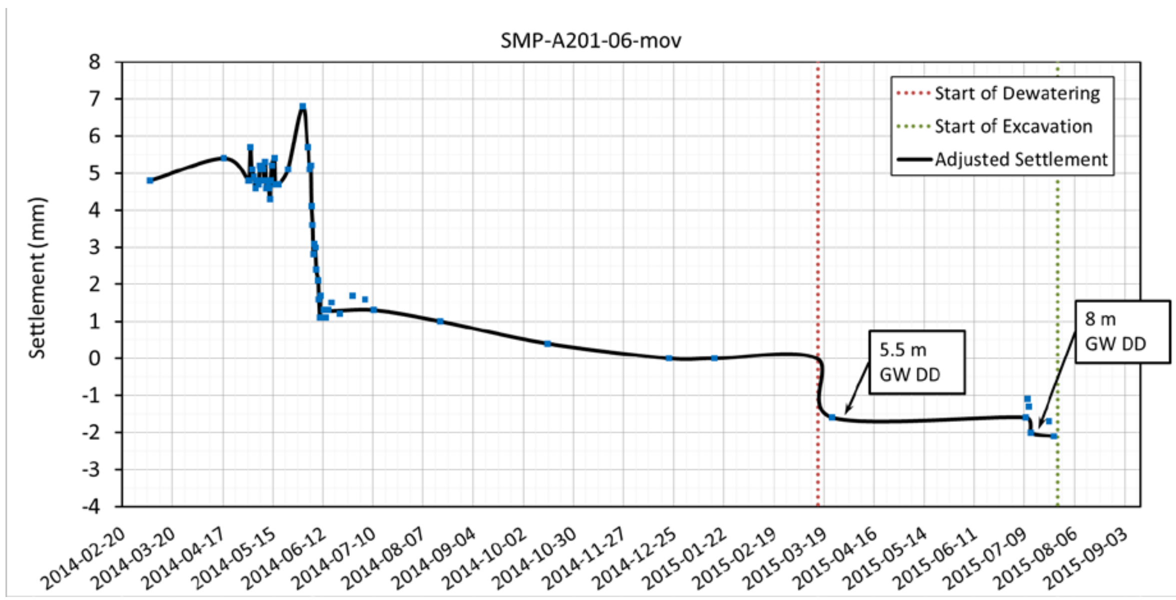
Example: Settlement Due to Dewatering



Example: Settlement Due to Dewatering



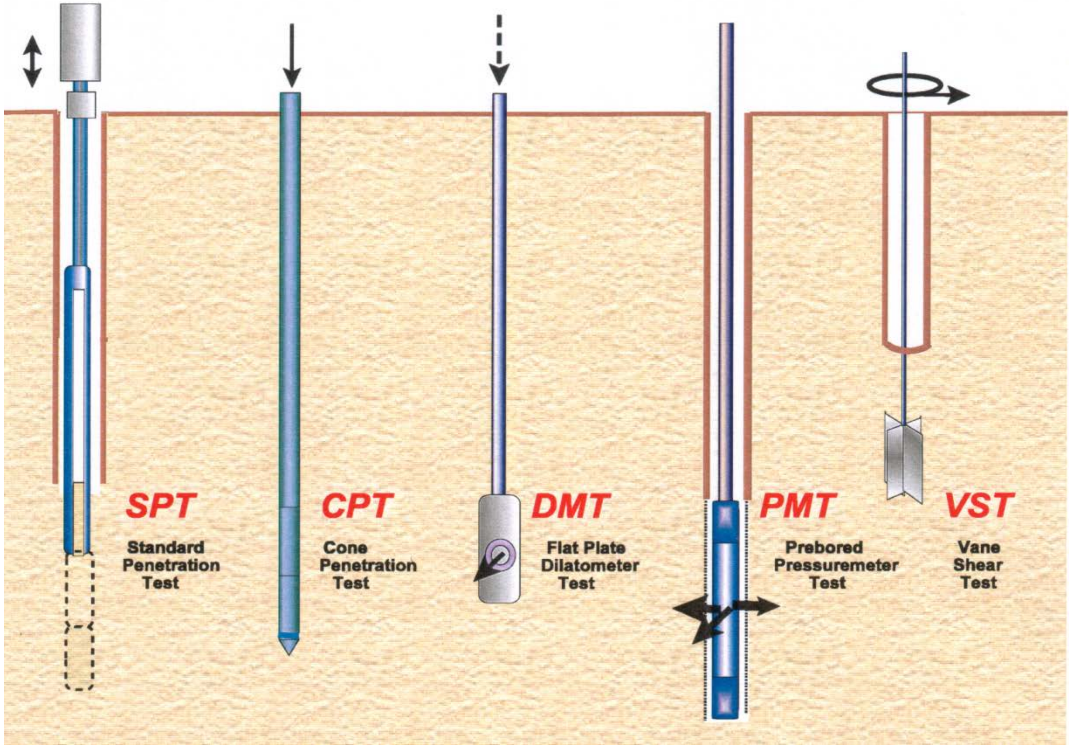
At 8 m Groundwater Drawdown			
Predicted (Parameters Based on SPT)	Predicted (Parameters Based on SPT and Good Engineering)	Predicted (Parameters Based on Enhanced Methods)	Actual
20 mm	15 mm	3 ~ 4 mm	2~2.5 mm



54%

Enhanced Geotechnical Investigation

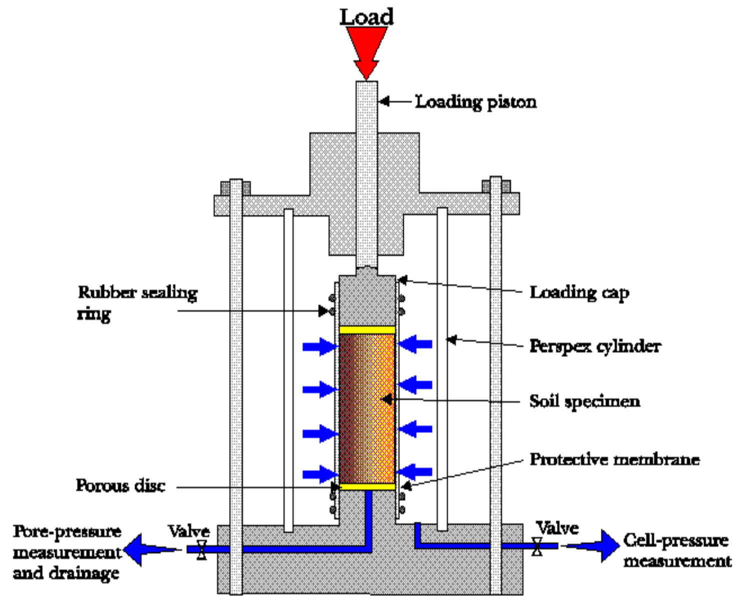
- Advanced Laboratory testing
  - Triaxial
  - Consolidation
- Advanced In-situ Testing
- Piezocone (CPTu)
- Pressuremeter Testing
- Flat Plate Dilatometer



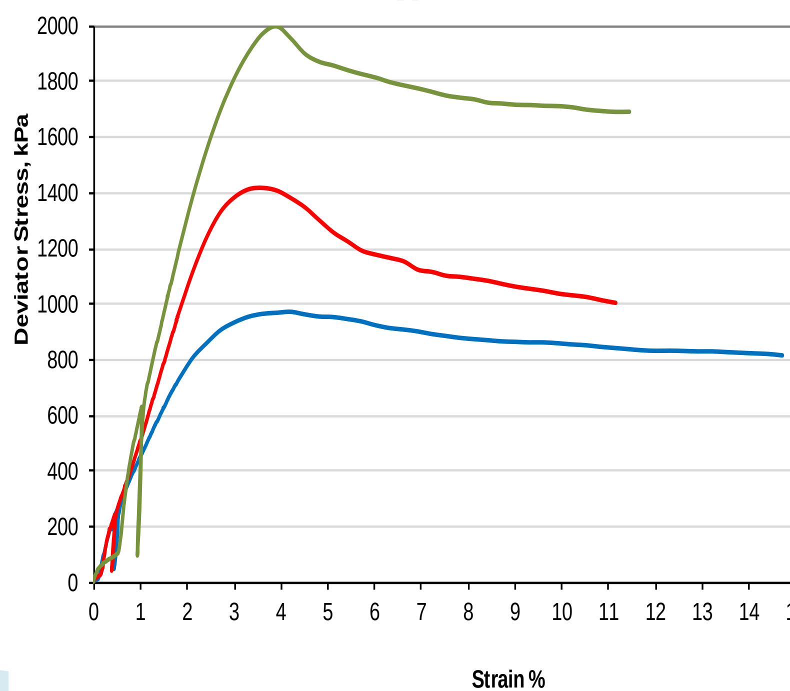
55%

Triaxial Test

- Shear strength parameters are measured directly
- Enables various loading patterns (static or dynamic)
- Enables various stress paths

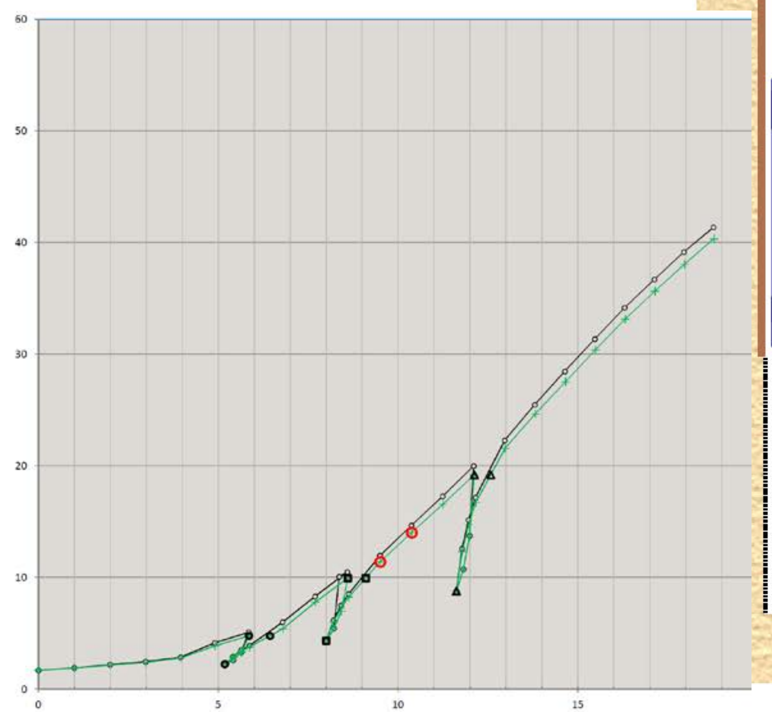


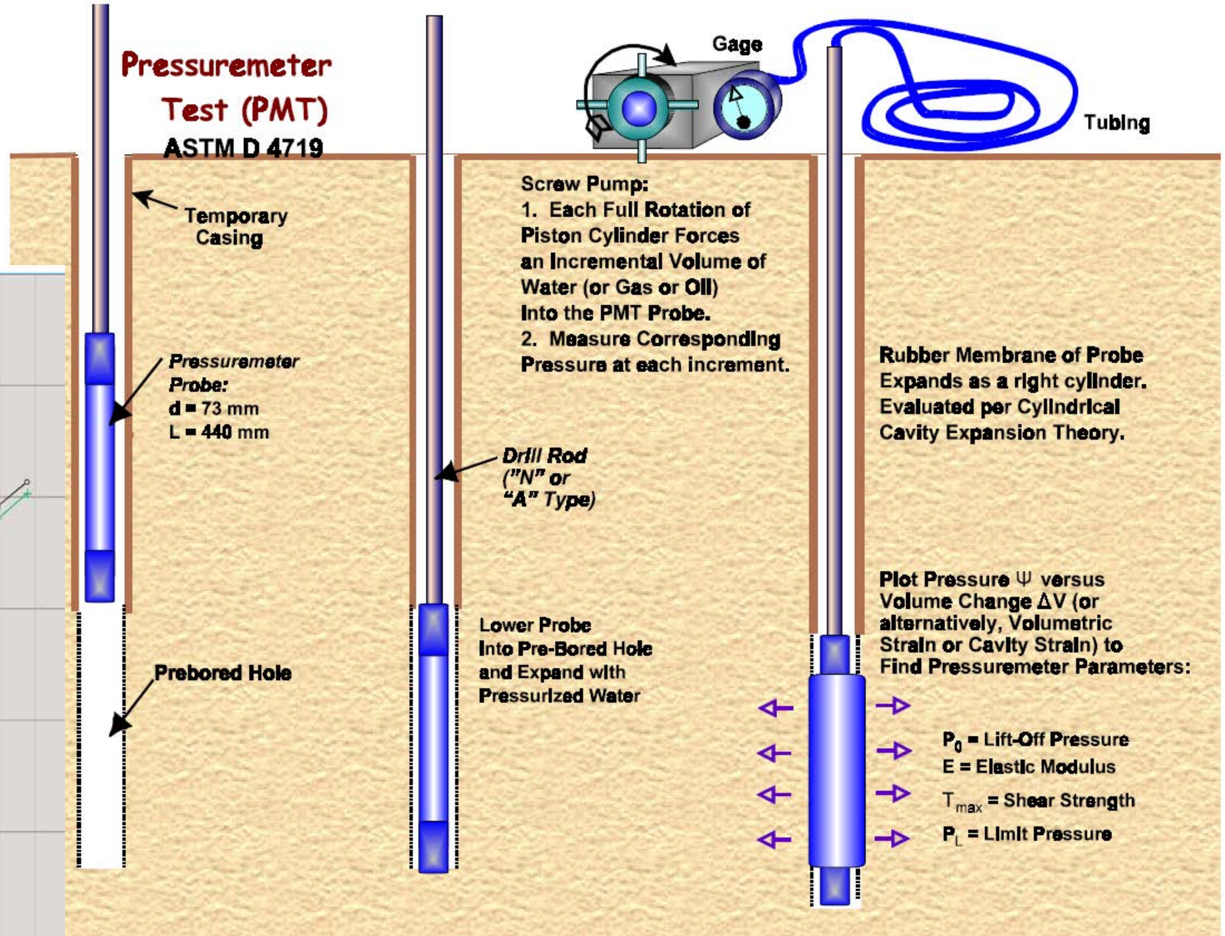
Triaxial apparatus



56%

Pressuremeter Testing (PMT)





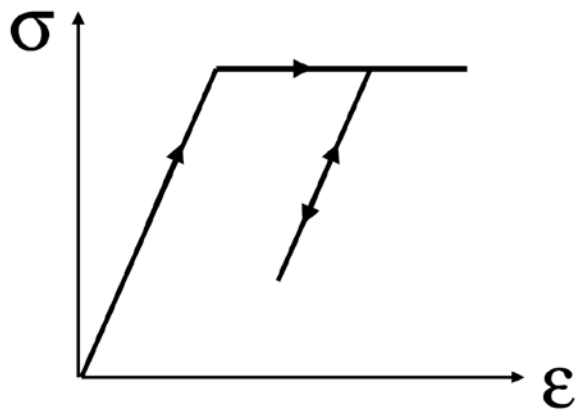
Enhanced Geotechnical Investigation

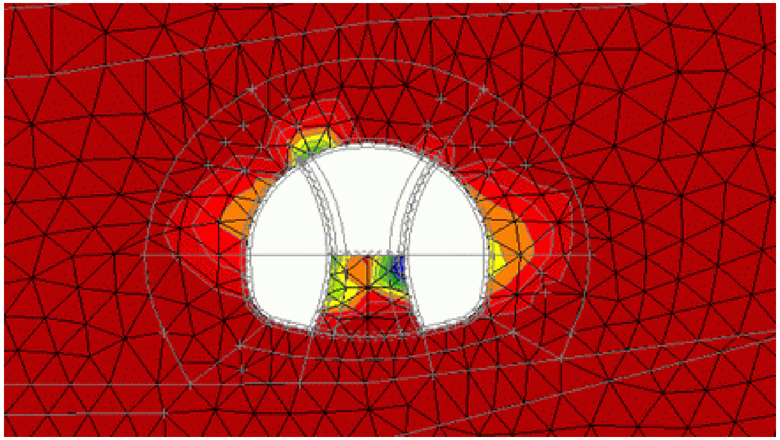
- A necessity for advance analyses and design such as FEM
- Very effective by providing more accurate, less conservative parameters

	Original Investigation		Supplemental Investigation
Friction Angle	34°		40°
Kp	3.5	→ 31%	4.6

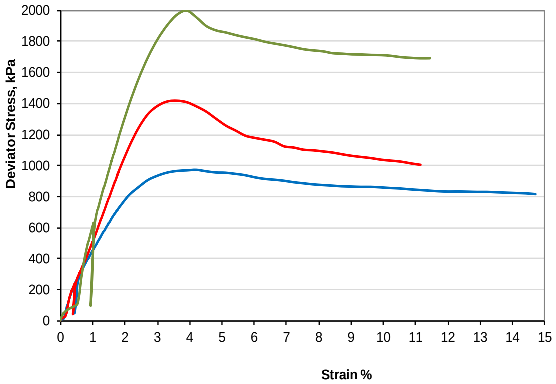
Behavioral Modeling Of Soil

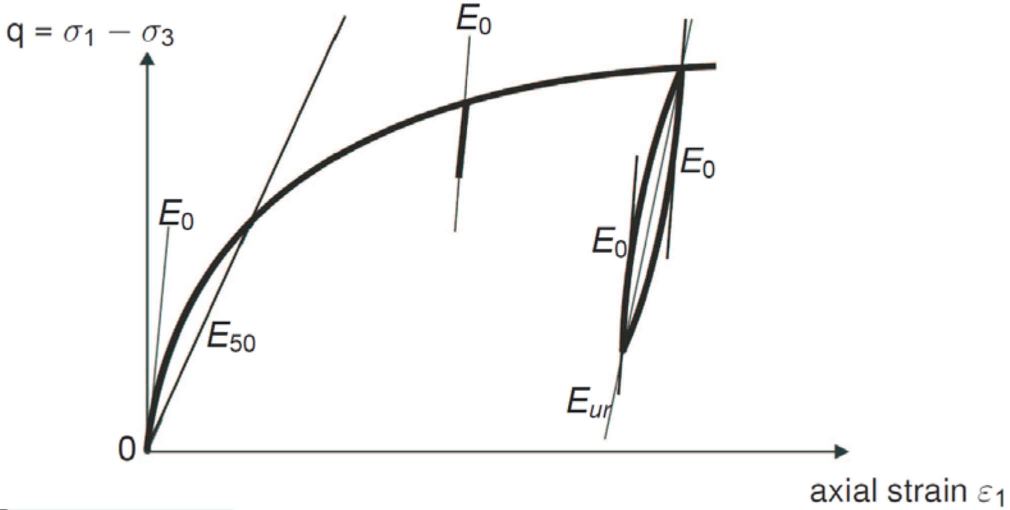
- Elastic-Plastic Models such as LEPP



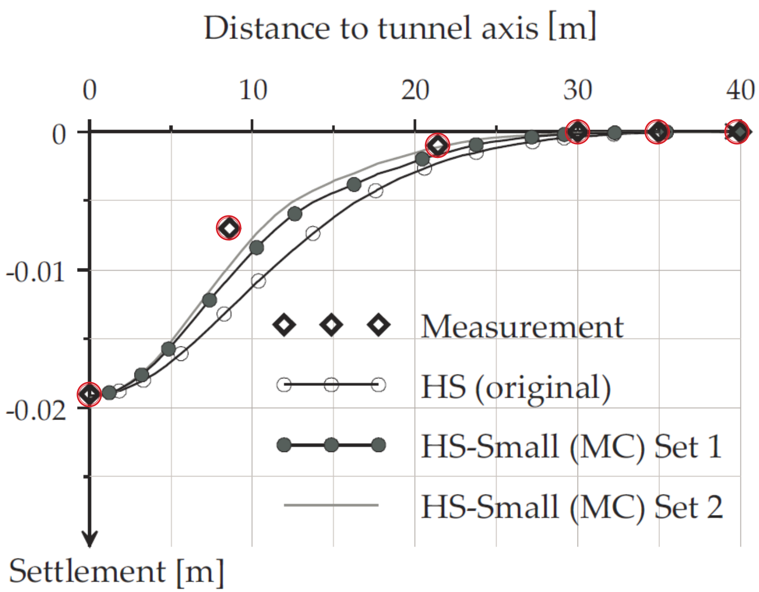


- Elasto-Plastic Models: fully analytical or hybrid

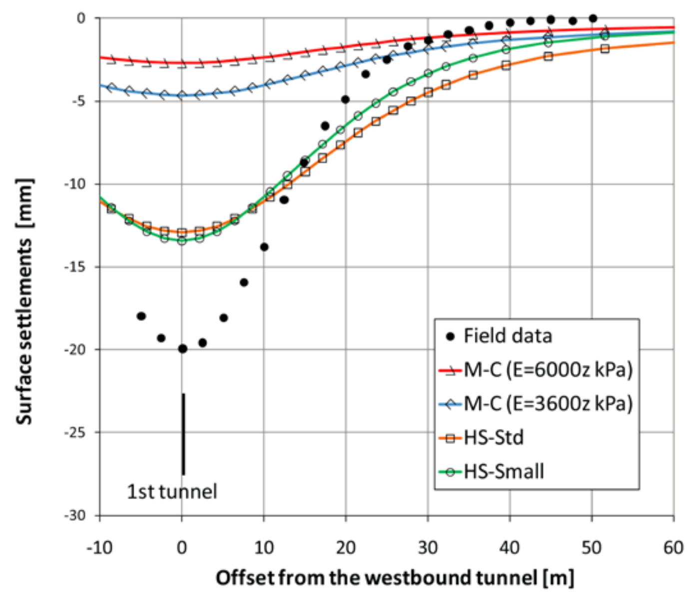




Constitutive Soil Model–Tunnel Settlement



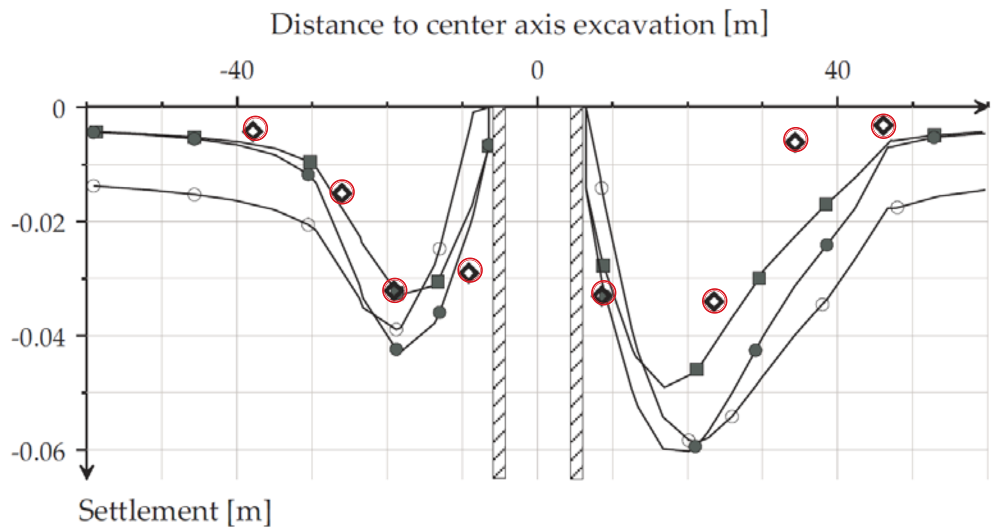
Steinhaldenfeld NATM Tunnel, Stuttgart–T.Benz 2007

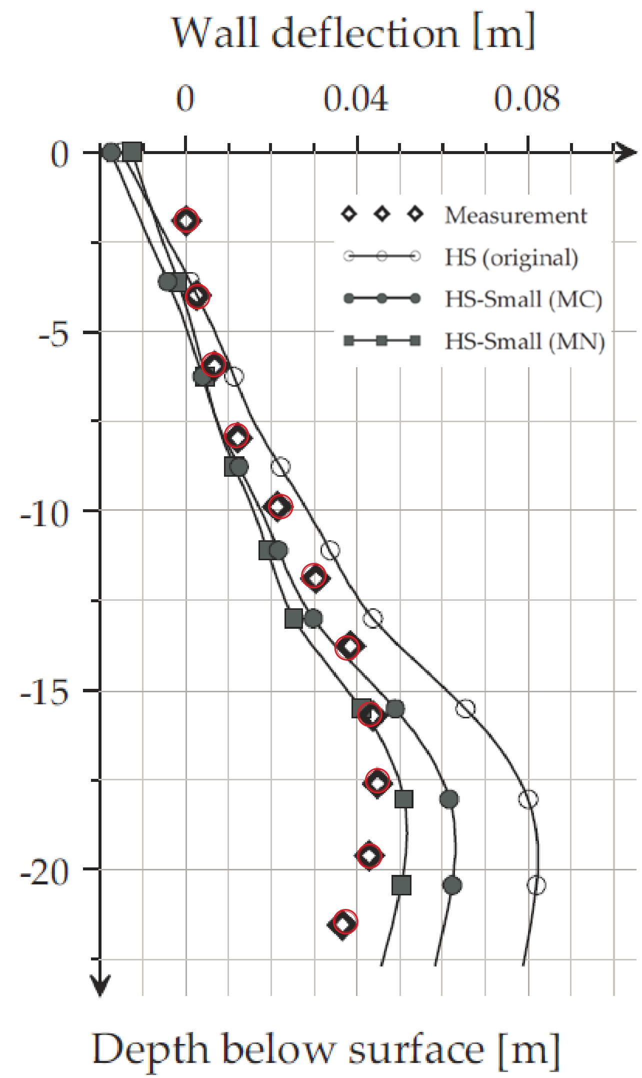


Jubilee Line Extension Project, St James's Park, UK–R.F.Obrzud 2010

61%

Constitutive Soil Model – Excavation

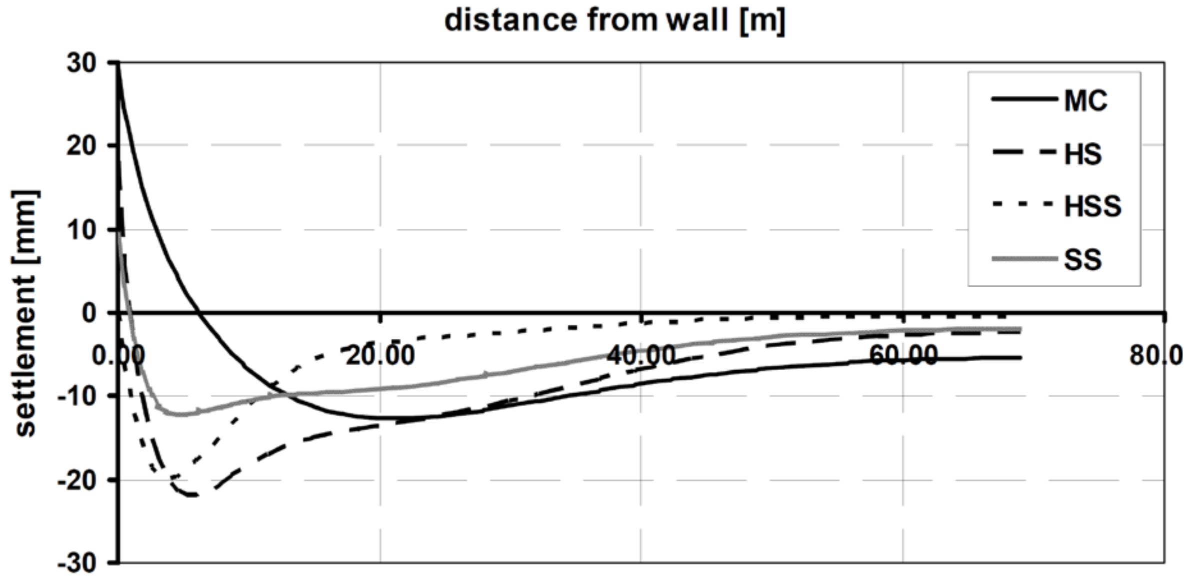




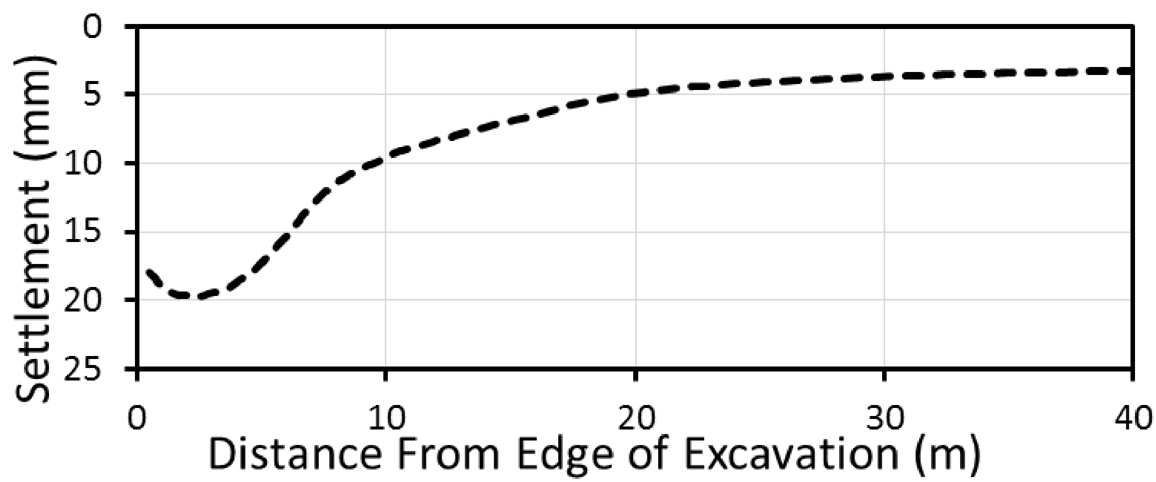
Excavation in Ruple Clay
Offenbach, T.Benz 2007

Constitutive Soil Model – Excavation

H.F. Schweiger – 2010



M. Manzari & A. Drevininkas – 2014



64%

New Codes and Level of Site Investigation

- Geotechnical Resistance Factors

Old CHBDC 2006

Application	Resistance factor
Shallow foundations	
Bearing resistance	0.5
Passive resistance	0.5
Horizontal resistance (sliding)	0.8
Ground anchors (soil or rock)	
Static analysis — Tension	0.4
Static test — Tension	0.6
Deep foundations — Piles	
Static analysis	
Compression	0.4
Tension	0.3
Static test	
Compression	0.6
Tension	0.4
Dynamic analysis — Compression	0.4
Dynamic test — Compression (field measurement and analysis)	0.5
Horizontal passive resistance	0.5

65%

New Codes and Level of Site Investigation

- Geotechnical Resistance Factors

New CHBDC 2014

Application	Limit state	Test Method/Model	Degree of understanding Low	Degree of understanding Typical	Degree of understanding High	
Retaining systems	Bearing, ϕ_{gu}	Analysis	0.45	0.50	0.60	ULS
	Overturning, ϕ_{gu}	Analysis	0.45	0.50	0.55	
	Base sliding, ϕ_{gu}	Analysis	0.70	0.80	0.90	
	Facing interface sliding, ϕ_{gu}	Test	0.75	0.85	0.95	
	Connections, ϕ_{gu}	Test	0.65	0.70	0.75	
	Settlement, ϕ_{gs}	Analysis	0.7	0.8	0.9	SLS
	Deflection/tilt, ϕ_{gs}	Analysis	0.7	0.8	0.9	
Embankments (fill)	Bearing, ϕ_{gu}	Analysis	0.45	0.50	0.60	ULS
	Sliding, ϕ_{gu}	Analysis	0.70	0.80	0.90	
	Global stability — temporary condition, ϕ_{gu}	Analysis	0.70	0.75	0.80	
	Global stability — permanent condition, ϕ_{gu}	Analysis	0.6	0.65	0.7	
	Settlement, ϕ_{gs}	Analysis	0.7	0.8	0.9	SLS
		Test	0.8	0.9	1.0	

65%

Conclusions

- Geotechnical risk can be minimized, shared, transferred or accepted; it cannot be ignored, nor eliminated
- Geotechnical investigation is one element of the overall geotechnical risk management for the project
- Project delivery method should not significantly affect the total scope of the investigation that is suitable for the project
- Clarifying behavioral characteristics of the soil, as it pertains to the planned construction, is the essence of the geotechnical investigation; classification of the soil and stratigraphic profile are not enough
- Behavior of the ground is not exclusively a property of the soil as it is influenced by construction methods
- Each project is unique and requires specific planning for a cost effective geotechnical investigation

Conclusions

- Develop a multi-phased site investigation to provide the necessary information for various stages of the design and construction. For smaller projects, conduct exploration in at least two phases
- Budget and fund for all phases of the geotechnical investigation costs ranging from 1.5 to 2.2 percent of construction cost and boring length ranging from 0.7 to 1.2 times route length (1/2 to 3/4 of the USNCTT guidelines)
- Have a contingency up to 3.0 percent of construction cost
- Use the contingency when only necessary
- Scale/cost of investigation is not the only issue determining the effectiveness of the geotechnical investigation
- Site investigation cost may be reduced, without increasing the risk, by appropriate choice of investigation methods

Conclusions

- Regional geology and hydrogeology model must be developed prior to planning the geotechnical investigation
- Prior tunneling knowledge in project area and existing geotechnical databases are very important
- Sensitivity of the construction method to the soil behaviour is a key factor on planning the investigation
- Geophysical methods are advantageous and must be used in coordination with boreholes
- Quality of investigation and engineering assessment have profound influence on cost effective design and selection of construction methodology
- The geotechnical investigation should not be isolated from design and construction. It is a continuous process throughout the design, construct and operation

Conclusions

- Savings in the bid price have been achieved on the order of 4 to 15 times the cost of increased investigation
- Groundwater investigations warrant greater attention
- Laboratory testing of the soil should provide information for predicting the behaviour
- A multi-disciplined team including geotechnical engineers, design engineers and a construction specialist should develop subsurface data and evaluate their impact
- Communication is a key to success
- Designers and geotechnical engineers should have knowledge of construction methods
- Geotechnical information from design phases and as-built tunnel mapping with construction procedures should be compiled in a report detailing project completion

Ultimate Conclusion

YOU PAY FOR A SITE INVESTIGATION WHETHER YOU HAVE ONE OR NOT

(Institution of Civil Engineers, Inadequate Site Investigation, 1991)

71%

Section II – Innovation
A Brief Introduction to Reliability-Based Design

THURBER

Tunnelling Association of Canada
Association Canadienne Des Tunnels

72%

Safety Performance and Design

- Any project is referred to a target level of safety and performance
- This is achieved through proper design and construction
- An absolute confidence in engineering estimate is an unattainable objective
- There is always risk of deviation from our target level of safety and performance

73%

What is Risk

Risk = f (Hazard and Consequences)

Risk = f (H, V, E)

H =Hazard (temporal probability of a threat)

V =Vulnerability of element(s) at risk

E =Utility (or value) of element(s) at risk

Risk = Hazard . Consequences

Risk = H.V.U

Risk and Uncertainties

- Uncertainties are the source of risk

- ISO definition of Risk:

"Risk is the effect of uncertainties on objectives"

- Uncertainty is caused by natural variation, lack of understanding, or insufficient data

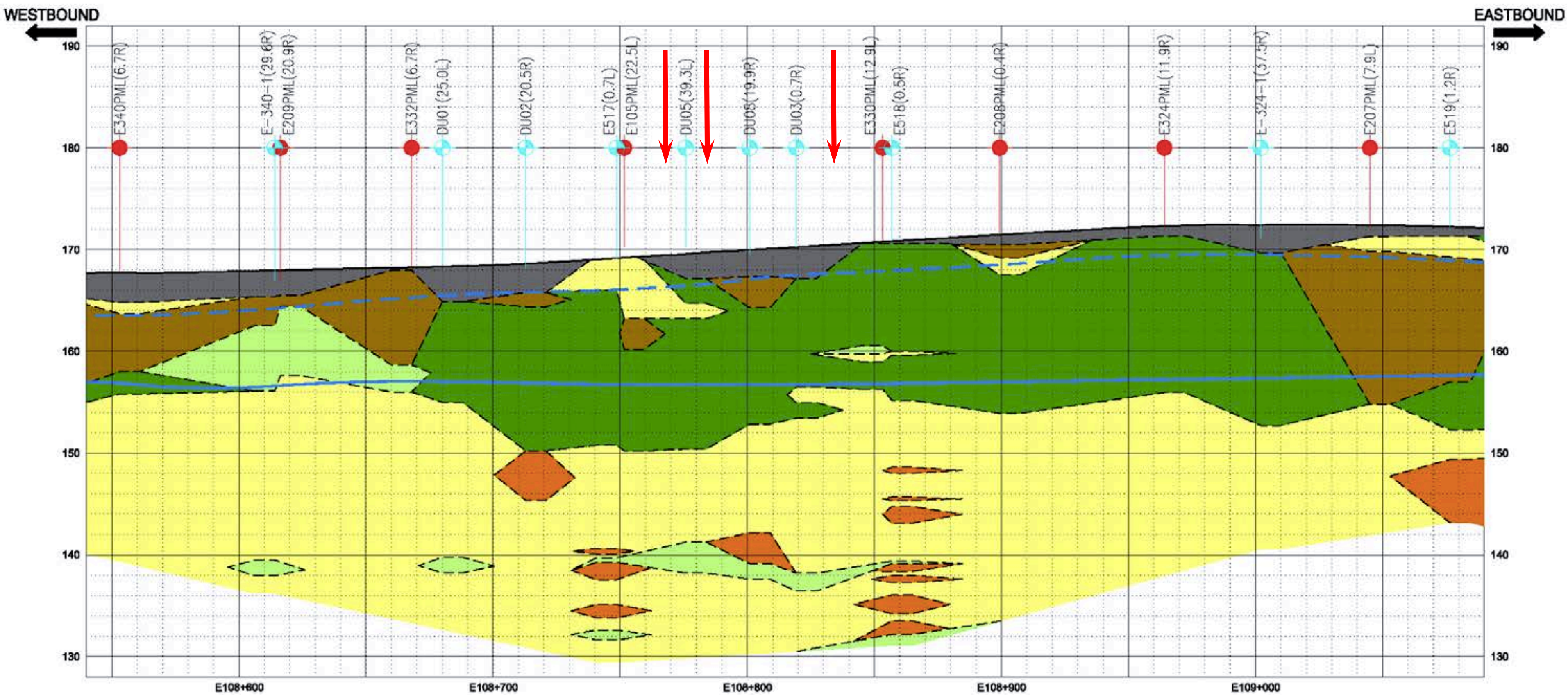
75%

Classification of Uncertainties

- **Aleatory Uncertainty**: Inherent variability due to the natural randomness of a phenomenon
  - Spatial variability – e.g., variation of soil deposit, variation of soil property
  - Temporal variability – e.g., Groundwater level, Wave
- **Epistemic uncertainty:** Due to lack of knowledge
  - Parameter uncertainty– e.g., Testing uncertainty , Estimation uncertainty
  - Transformation uncertainty

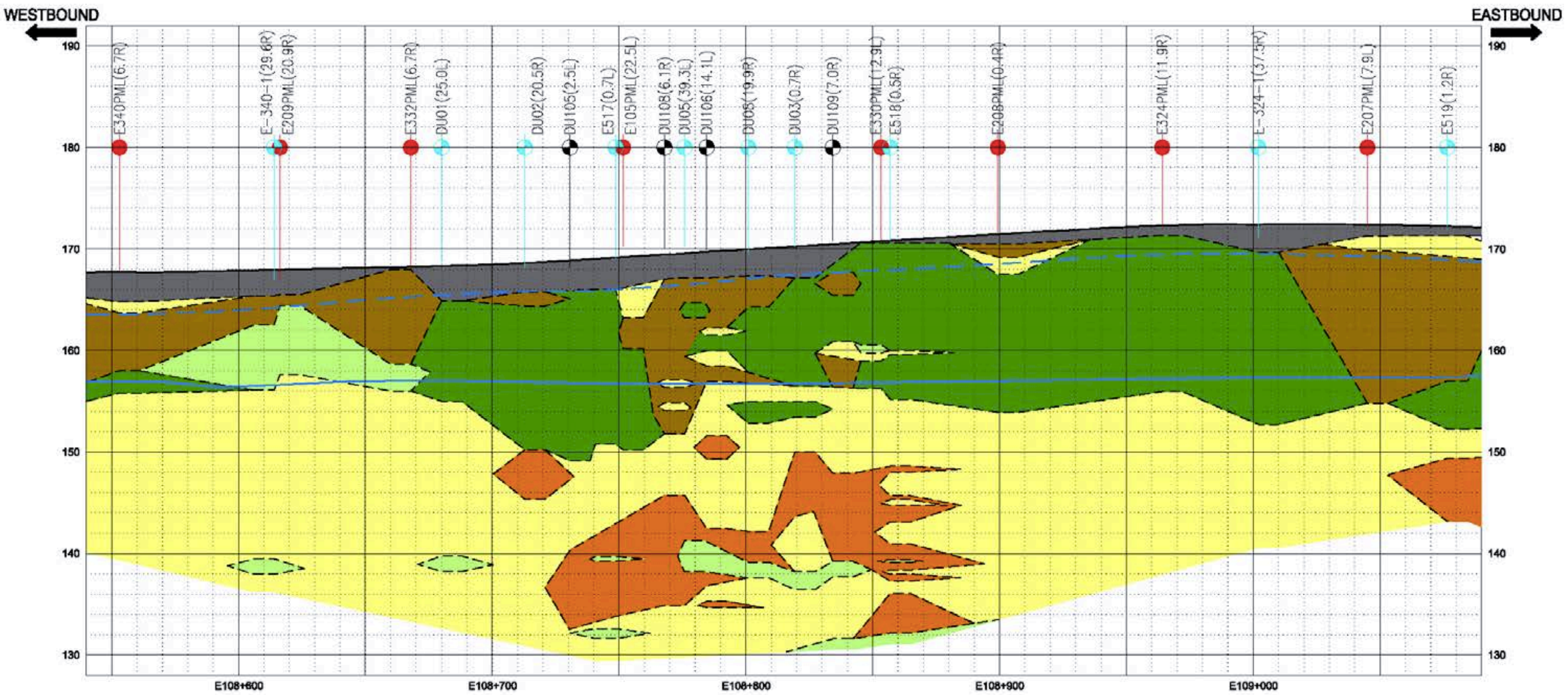
76%

Spatial variability – variation of soil deposit



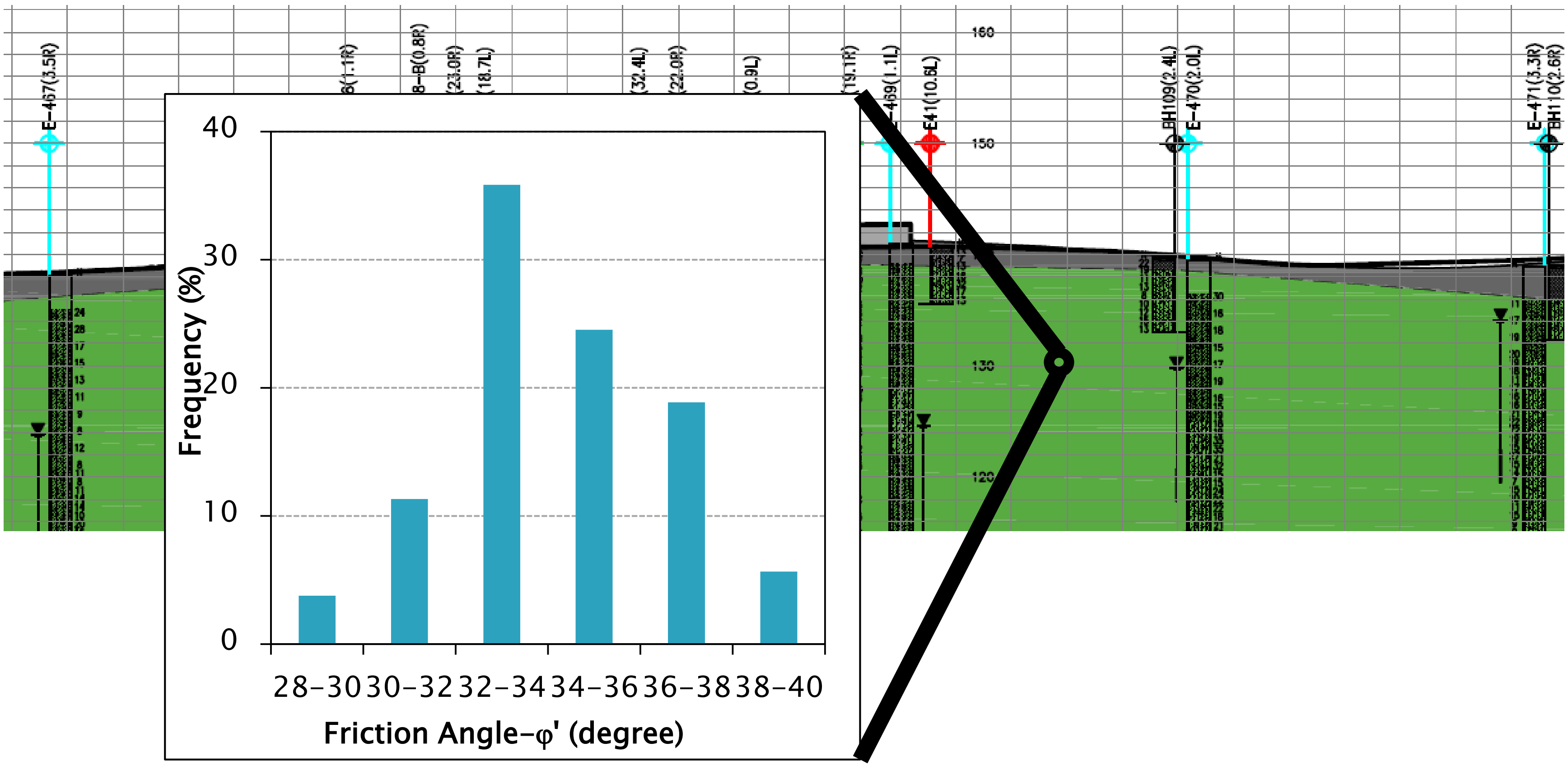
78%

Spatial variability – variation of soil deposit



79%

Spatial variability – variation of soil property



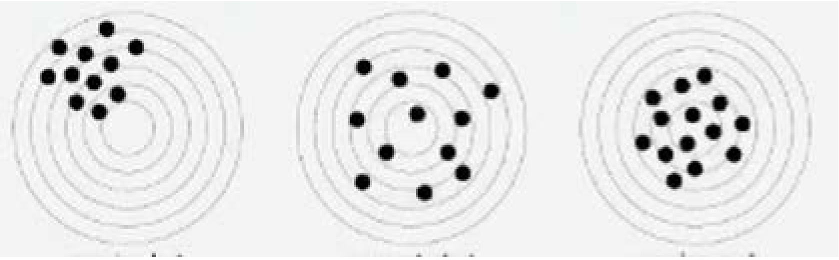
Plastic Glacial Till

M. Manzari & A. Drevininkas, 2013

80%

Epistemic uncertainty:

- Testing inaccuracy

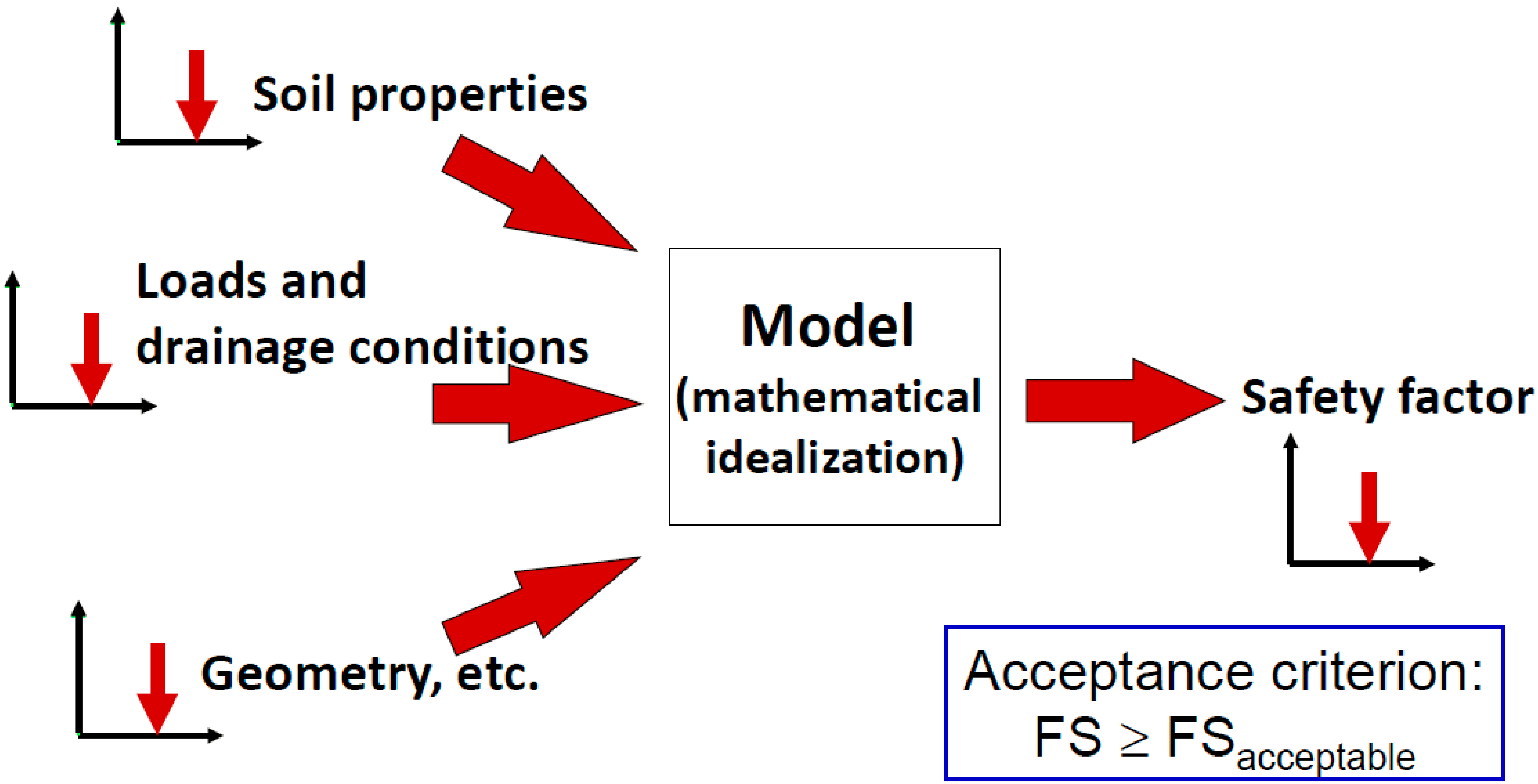


Precise, not Accurate

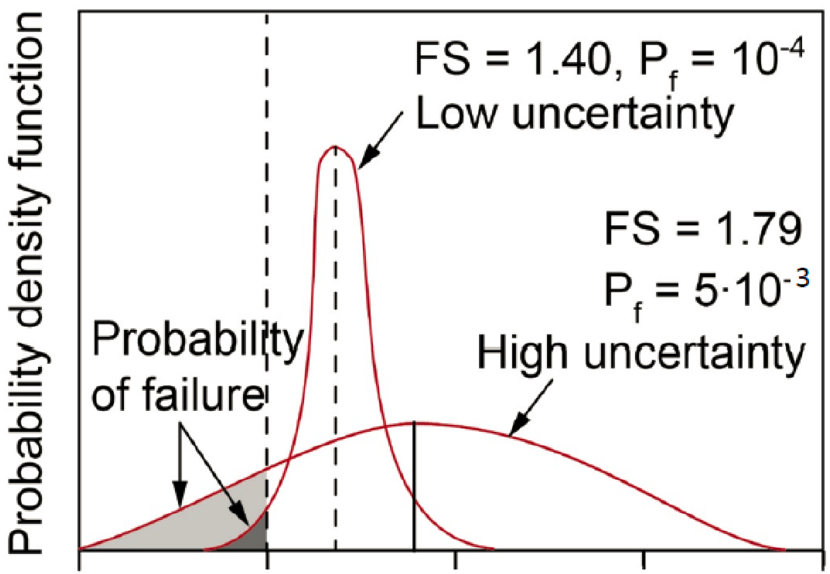
Accurate, Not Precise

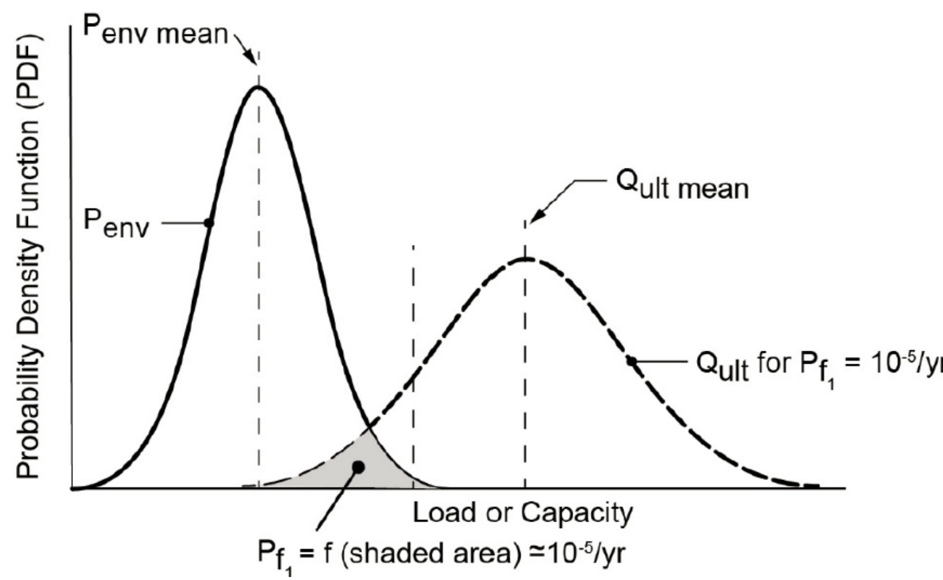
Precise, Accurate

Deterministic Analysis



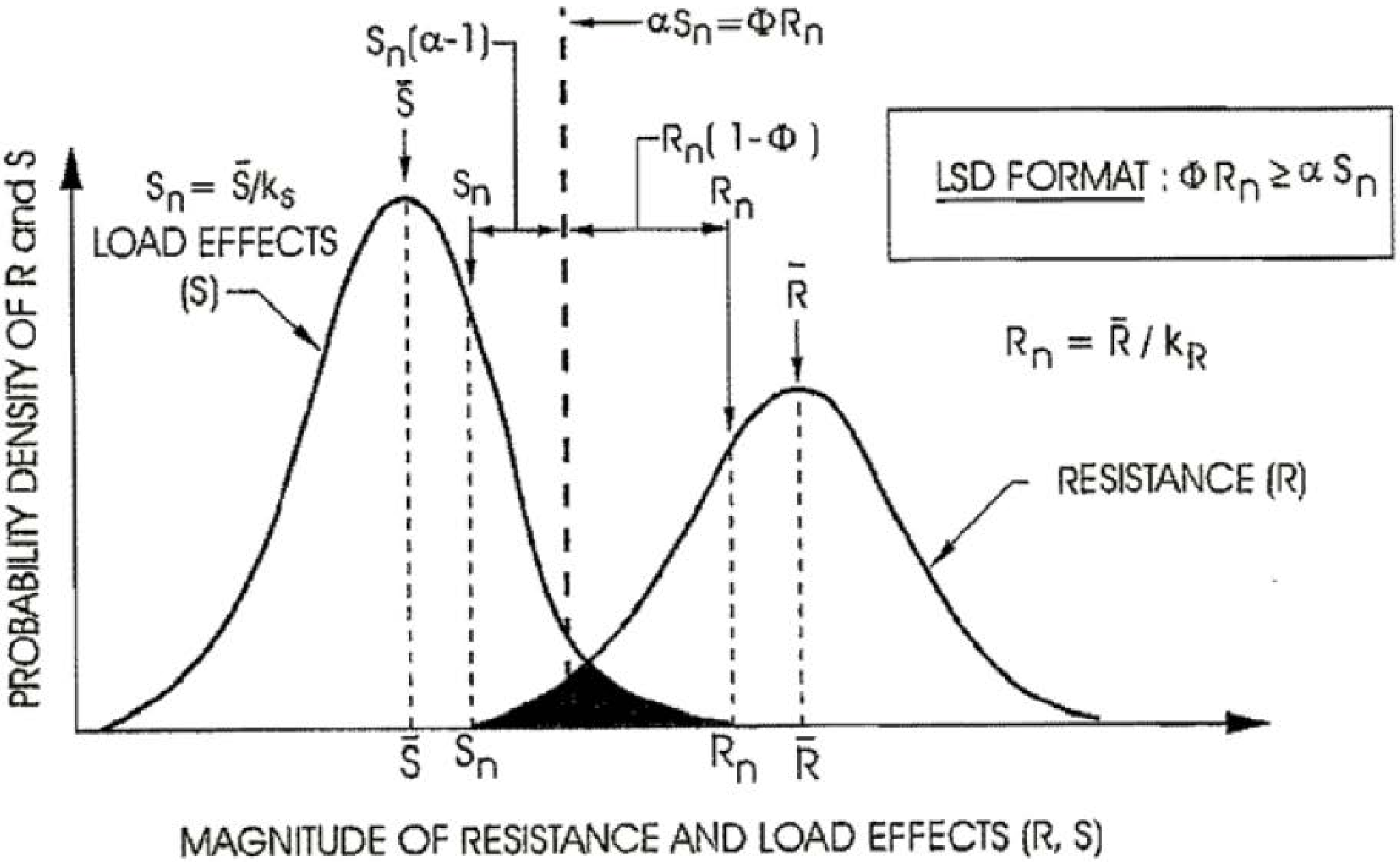
Factor of Safety and Probability of Failure



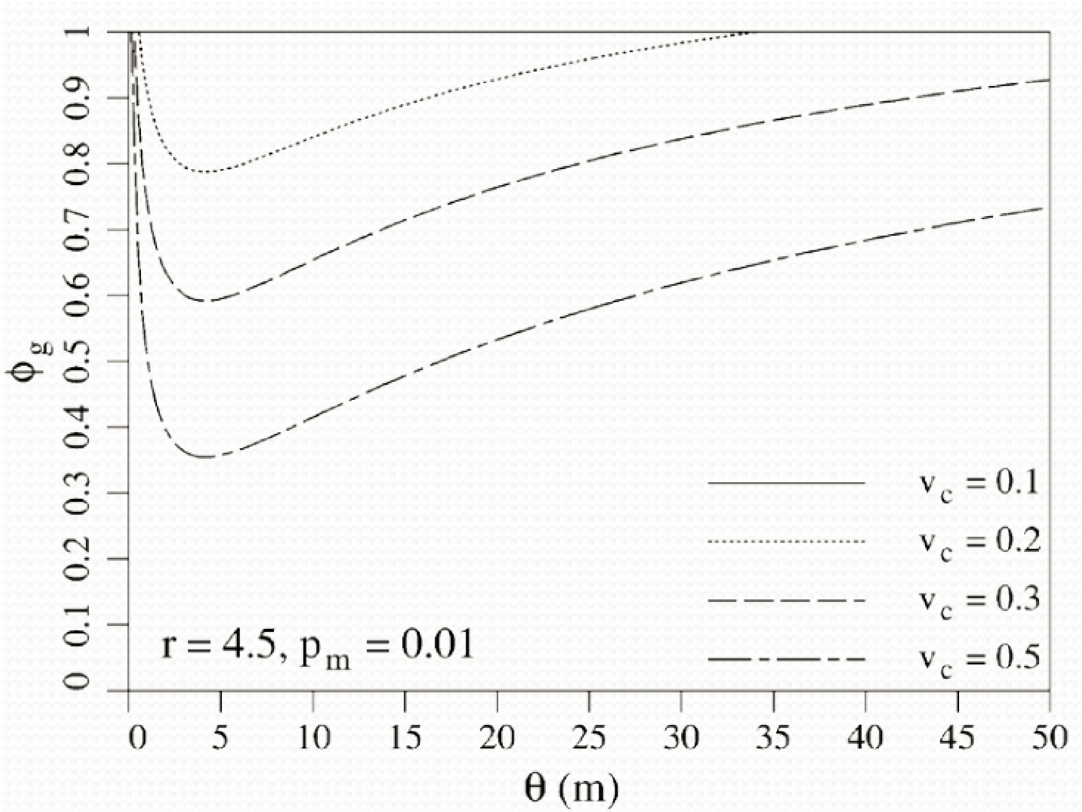


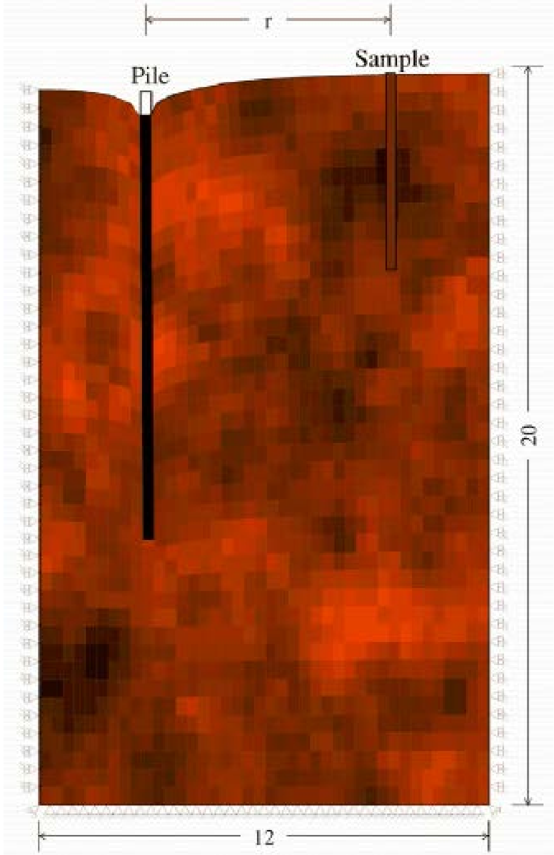
84%

Limit State Design

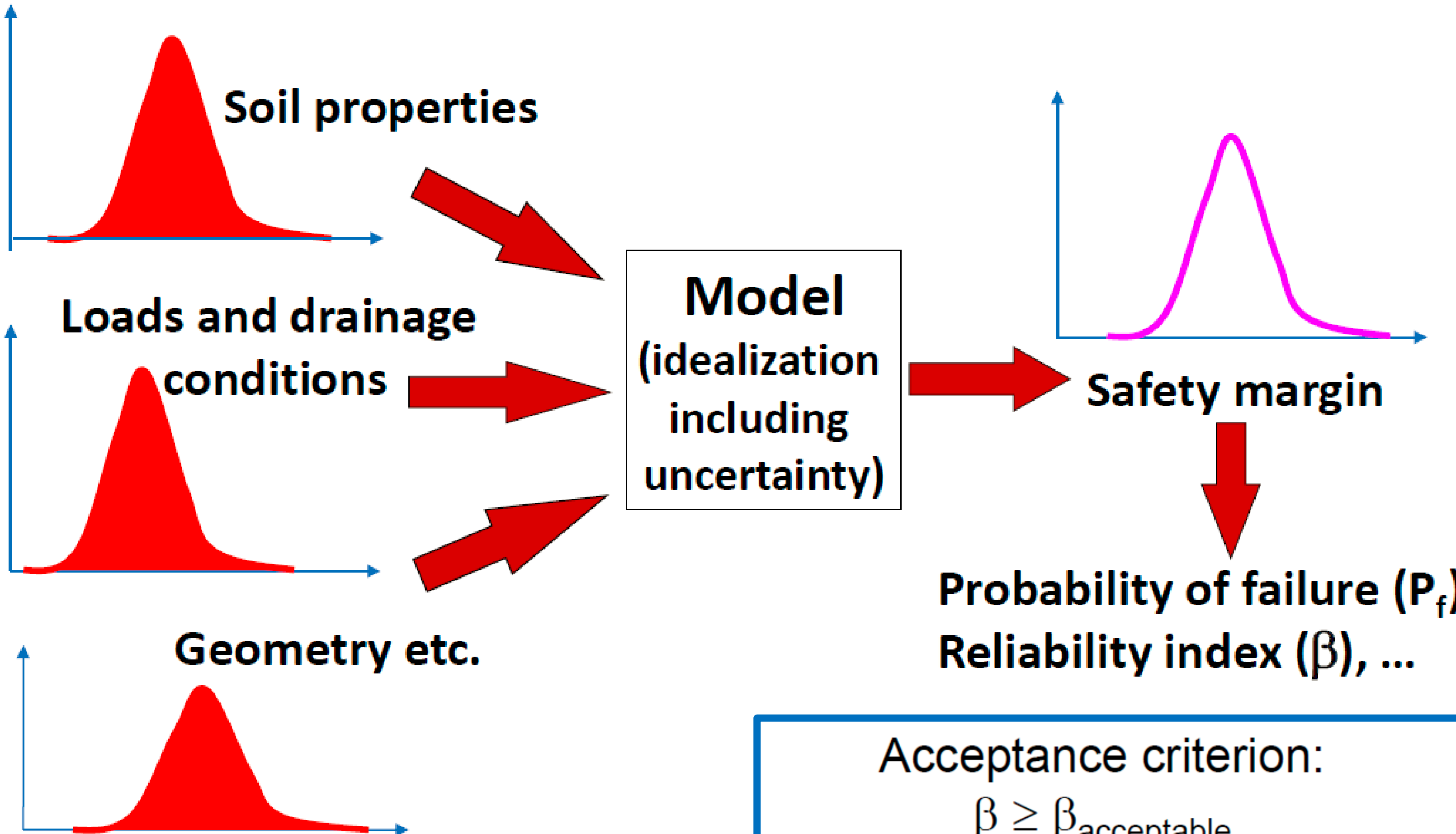


Resistance Factor





Probabilistic Analysis



Acceptance criterion:

$$\beta \geq \beta_{acceptable}$$

$$P_f < P_{f\ tolerable/acceptable}$$

S. Lacasse-2015

87%

Methods of Probabilistic Analyses of Engineering Problem

- Monte Carlo Simulation
- First-Order, Second Moment (FOSM)
  - Not recommended to use
- First-and Second-Order Reliability Methods (FORM & SORM)
- Event Trees
  - Not based on deterministic analyses

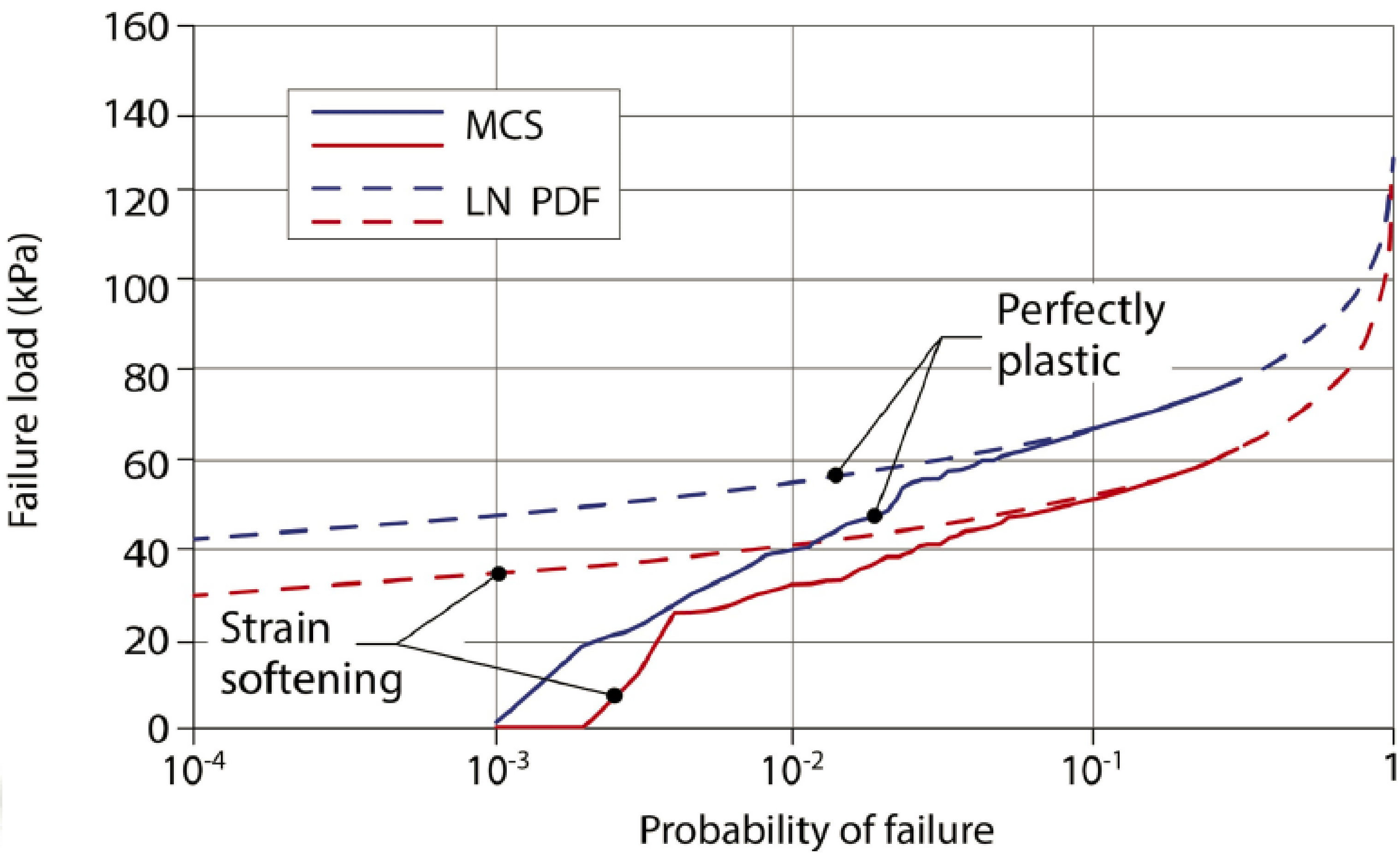
88%

Monte-Carlo Simulation (MCS)

- MCS is a general method, which can be applied to any problem for which a physical model exists
- MCS relies on repeated random sampling of input to predict the outcome
- Requires numerous calculation particularly for problem with low probability of faire

89%

MCS and Tails of PDF



S. Lacasse-2015

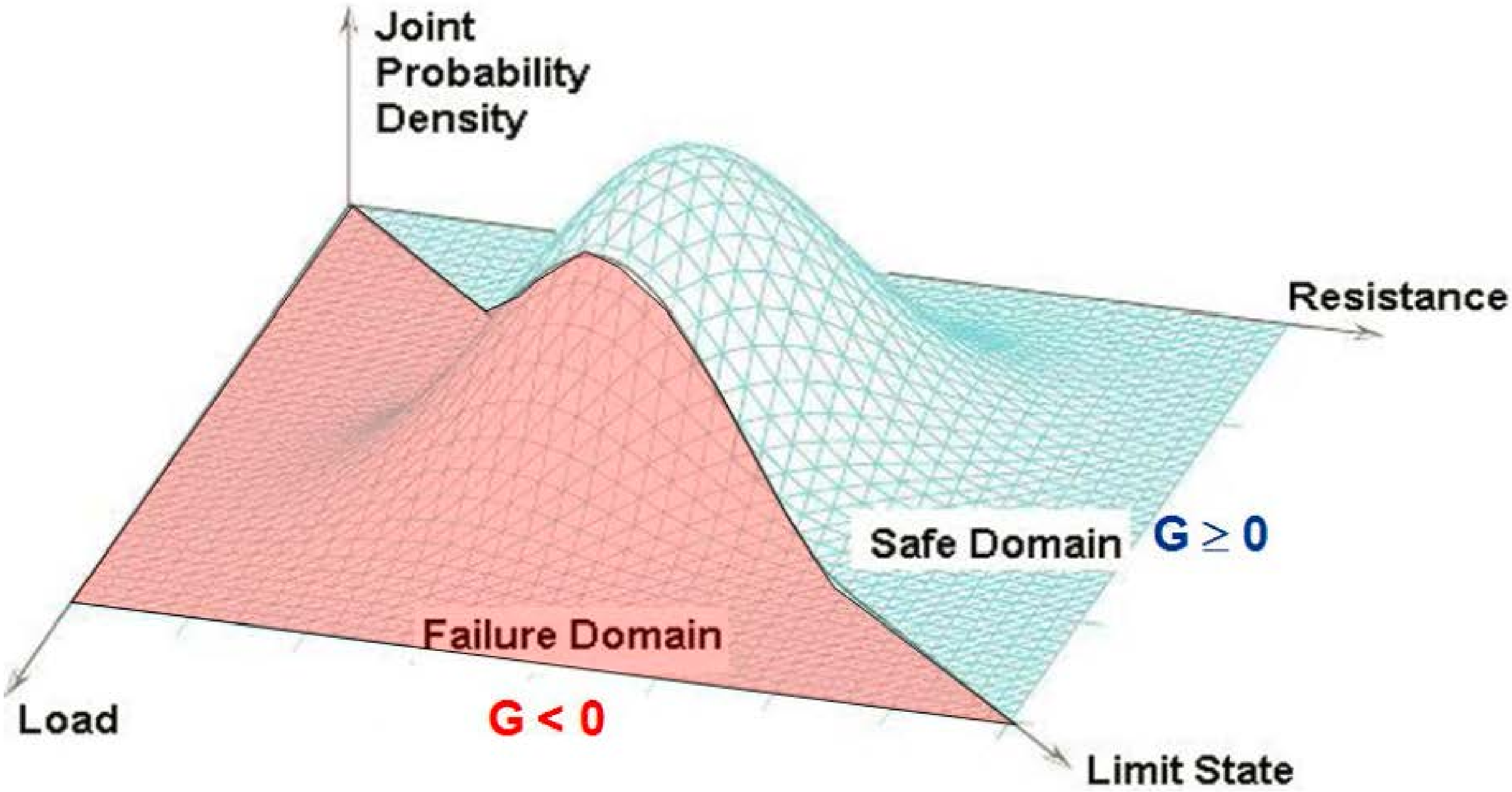
91%

FORM (and SORM) Approximation

- First-and second-order reliability methods (FORM & SORM) are the most popular approach in structural reliability analyses
- Very efficient when probability of failure is low
- Reliability index and probability of failure are independent of the safety format used
- Valuable additional information (sensitivity factors and most likely combination of variables leading to failure)

92%

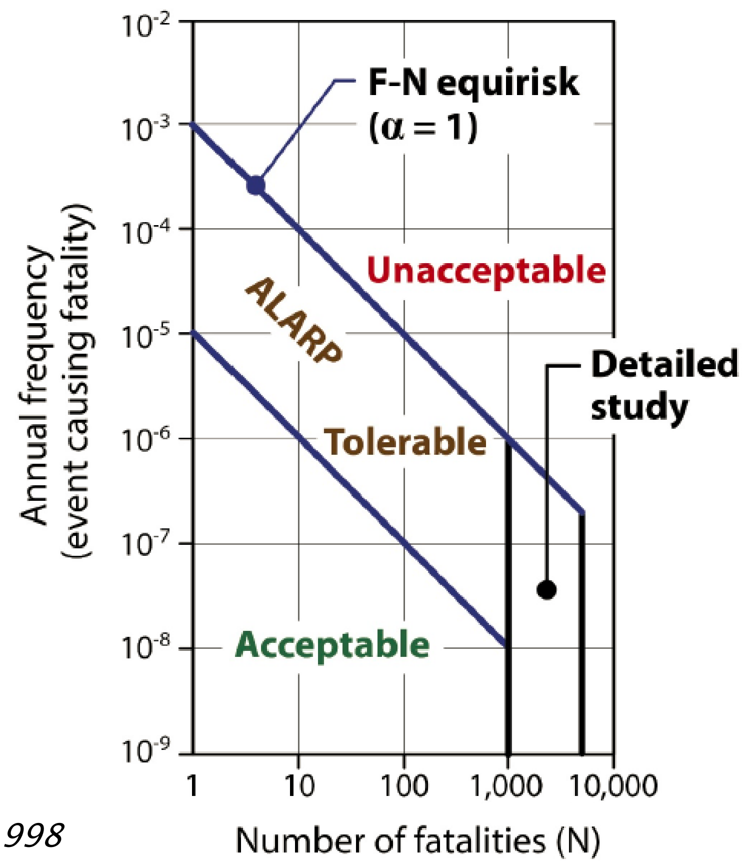
Limit State Function or Performance Function



Target Probability of Failure

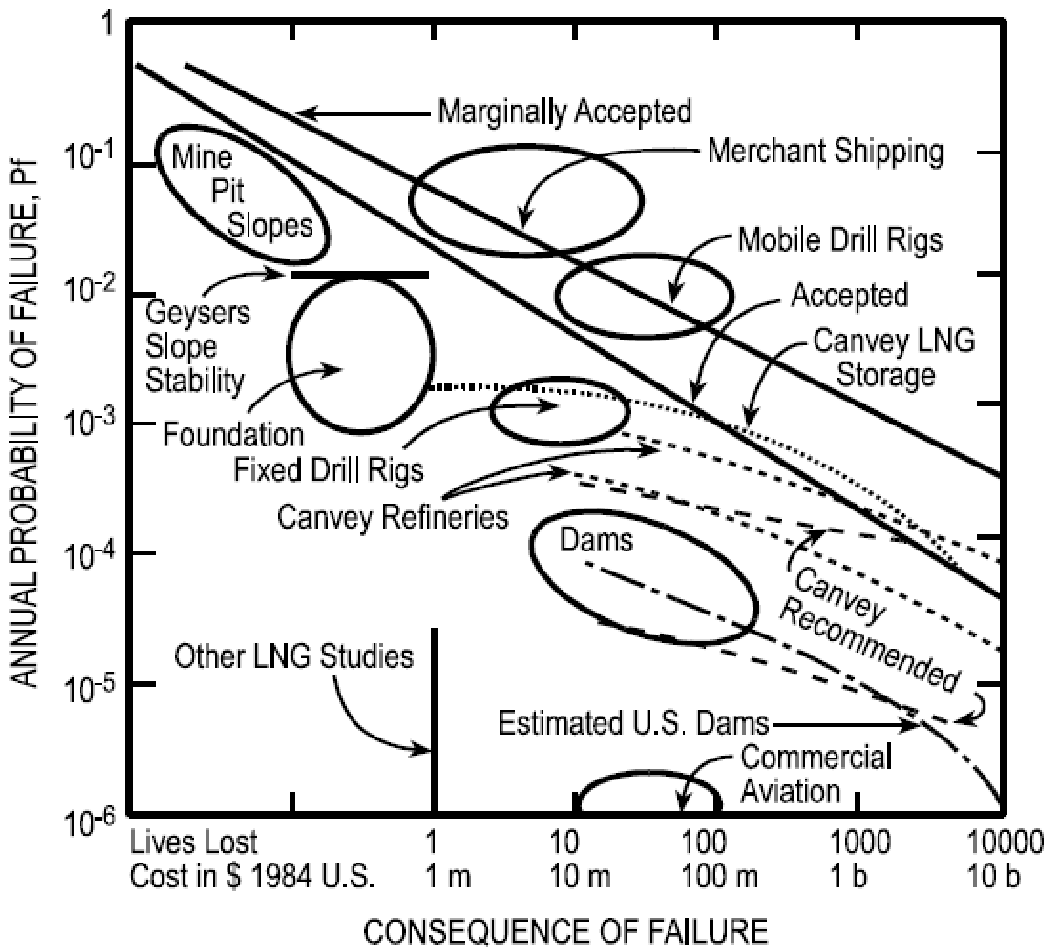
- Acceptable Societal Risk is generally based on expected number of fatalities
- A single event with many fatalities is less acceptable to the society than several accidents with few fatalities

GEO–1998



94%

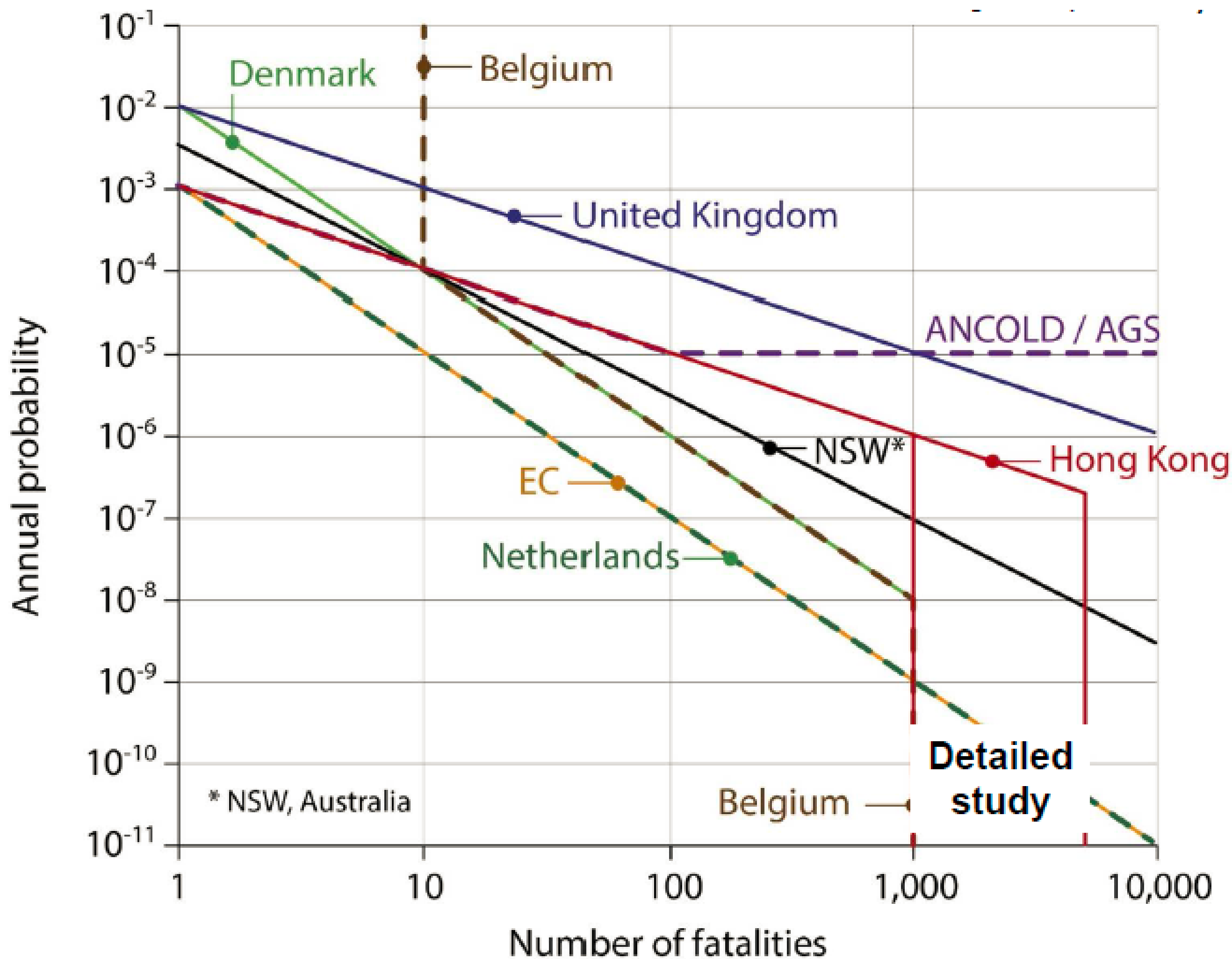
Example of F-N Curve



Whitman

95%

Comparison of F-N



GEO-1998

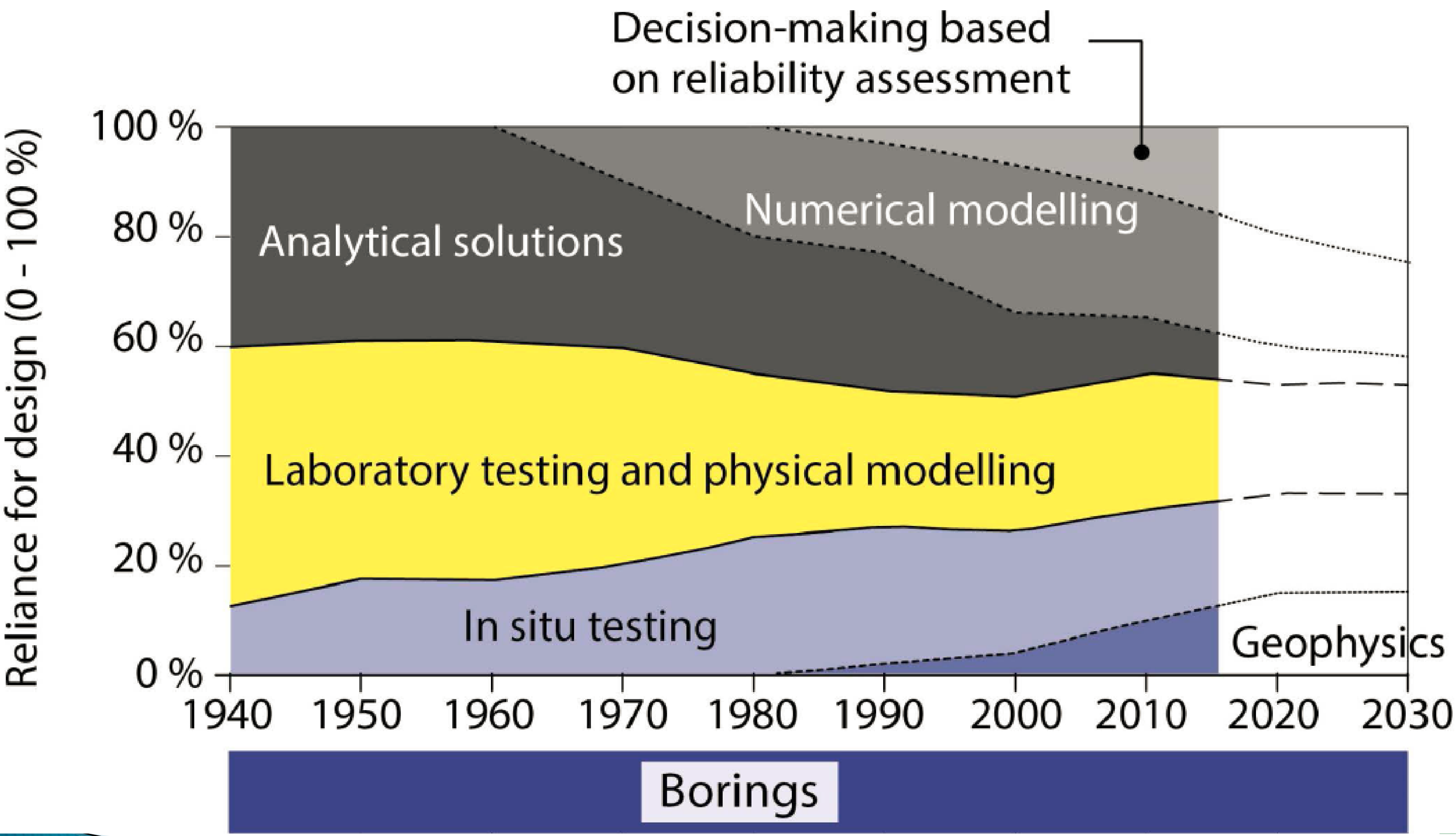
96%

Role of Analyses

- Reliability approaches do not remove uncertainty, and do not alleviate the need for judgment in dealing with the problem at hand
- They however provide a way to quantify the uncertainties and to handle them consistently
- Integrating deterministic and probabilistic analyses in a complementary manner brings together the best of our profession, including the required engineering judgment from the geo-practitioners and from the risk analysis proponents

98%

Evolution of Geotechnical Practice



S. Lacasse-2015

Many Thanks to ……

- Mr. Iqbal Hassan from Metrolinx for permission to use material from Eglinton Crosstown Tunnel project in this presentation
- Mr. Andrew Drevininkas from TTC for his cooperation in some of the research material
- Mr. Andre Soleki from HMM for his assistance on analyzing the results of settlement monitoring
- and special thanks to Dr. Suzanne Lacasse from NGI for providing material of 55th Rankine Lecture and permission to reference