BIOTECHNICAL SLOPE PROTECTION
AND EARTH SUPPORT

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ABSTRACT

The combined or integrated use of vegetation and structures provide an attractive and cost effective method of supporting earth masses and preventing erosion and shallow slope failures. This combined approach is termed biotechnical slope protection. Biotechnical measures include contour-wattling, brush layering, staking of unrooted cuttings, reed-trench terracing, brush matting, and conventional slope plantings in combination with breast walls or other low structures at the toe of slopes. Vegetation can be grown in the interstices of porous revetments where plant roots are able to permeate and indurate the soil beneath. Vegetation can likewise be planted and established on the benches of tiered retaining wall systems or in the vertical faces of porous retaining structures.

INTRODUCTION

Biotechnical slope protection entails the use of both mechanical elements (or structures) in combination with biological elements (or plants) to support earth masses and to arrest or prevent shallow slope failures and erosion. Both biological and mechanical elements must function together in an integrated and complementary manner. The principles and general approach of biotechnical slope protection are outlined in this paper. Detailed guidelines and specifications for design and implementation of various biotechnical measures can be found elsewhere (Schiectl, 1980; Gray and Leiser, 1981).

There are a number of advantages or reasons for a biotechnical approach to slope protection. Actual field studies (White, 1979) have shown that in many instances combined structural-vegetative slope protection systems are more cost effective than the use of either vegetation or structures alone. Vegetative treatments are usually much less expensive than earth retaining

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structures or other constructed protection systems. On the other hand, their effectiveness in terms of preventing soil loss or arresting slope movement under severe conditions may also be much lower.

Biotechnical slope protection systems blend into the landscape. The structural or mechanical components which are typically used do not visually intrude upon the landscape as much as conventional earth retaining structures. Examples of such structures include log or timber cribs; welded wire walls; gabion and rock breast walls; and reinforced earth. In addition, opportunities arise to incorporate vegetation into the structure itself. This is done either by planting in the voids or interstices between structural members or upon the benches purposely designed into a structure.

Biotechnical slope protection systems emphasize the use of natural, locally available materials - earth, rock, timber, vegetation - in contrast to man-made artifical materials such as steel and concrete. The distinction here is one of emphasis. In many instances or critical situations an effective design may require the use of steel and concrete. But even in this case opportunities for biotechnical design still exist. A good example is a porous or open face crib retaining wall whose front face can be vegetated with a variety of plants and vines. Such retaining walls not only support but also lend an attractive appearance to cut slopes and embankments as shown in Fig. 1.

Biotechnical slope protection measures and systems tend to be more labor-skill intensive as opposed to energy-capital intensive. The nature of biotechnical slope protection systems is such that well supervised, skilled labor can often be substituted for high cost, energy intensive materials. A good example would be slope protection by willow wattling (see Fig. 2).

A variety of situations and examples can be cited where biotechnical slope protection methods have been applied successfully and effectively. These include stablization of cut and fill slopes along major highways (Bowers, 1950; Leiser et al., 1974; and Schiechtl, 1978) and secondary roads (Kraebel, 1936). The latter included access or timber haul roads in forested areas. With the exception of Schiechtl's work all these examples are drawn from California.

Rehabilitation of slopes and watersheds severely damaged by resource exploitation, e.g., mining or timber harvesting, is an important application. Rehabilitation work in Redwood National Park (Madej et al., 1980; Kelsey and Stroud, 1981) provides a good example. Severe constraints may operate in this case to limit the type of slope protection measures that can be employed, viz., cost limitations, requirements for use of labor-skill intensive measures, prohibition against use of stark or massive retaining structures, etc. In such cases biotechnical methods are particularly attractive alternatives.

Biotechnical slope protection measures can be employed in the coastal zone for relatively low cost protection of backshore slopes against the ravages of both erosion and mass-movement. Some interesting and successful examples of biotechnical protection of slopes in the coastal regions of

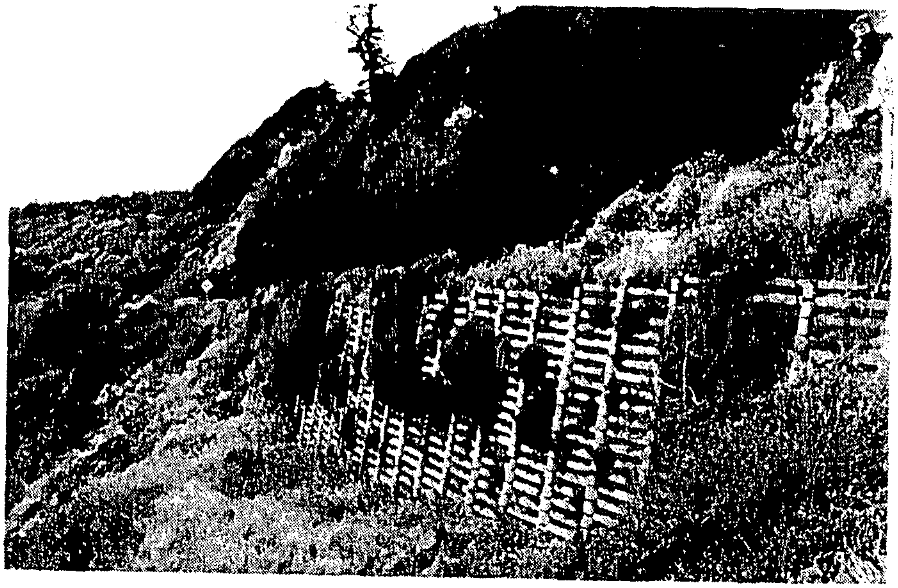

Fig. 1. Vegetated, open-front crib wall supporting coastal roadway. Colorful native shrubs and plants have become established in the openings between structural members at the face of the wall. Trinidad Beach, California.

Fig. 2. Slope protected by contour wattling. Partially buried and staked willow wattles protect slope against erosion. Wattles root and sprout thus further stabilizing slope. Redwood National Park, California.

the USA have been documented in the literature (USDA, 1940; Reid, 1969; Knutson, 1977). Biotechnical methods can also be employed to protect streambanks and channels against bank erosion primarily through use of vegetated, porous or cellular revetments (U.S. Army Corps of Engineers, 1978).

Control of gully erosion provides yet another instance where biotechnical methods are appropriate and effective. The long-term goal of gully control is establishment of vegetative cover. This can seldom be accomplished, however, without short-term assistance from various structural-mechanical measures (Heede, 1976).

ELEMENTS OF BIOTECHNICAL PROTECTION

Biotechnical slope protection systems consist of both structural-mechanical and vegetative elements working together in a complementary or integrated manner. This approach can be viewed and understood best by placing it in a spectrum of different approaches to slope protection and erosion control as shown in Table 1. Basic approaches are divided into three major categories according to type of construction which is involved, viz., live, mixed, or inert construction. Live construction entails the use of conventional plantings along, e.g., grasses and shrubs. Vegetation in this case is used mainly to prevent surficial erosion by providing a good ground cover. At the other extreme is inert construction, which entails the use of conventional structures alone, e.g., gravity and cantilever retaining walls. These type of structures are required when slope movement is deeper seated or lateral earth stresses high. The role of vegetation in this case would be mainly decorative.

Biotechnical methods fall into the middle category of mixed construction. In this case plants have multiple and important functional roles to play; they should not be regarded as cosmetic adjuncts to the structure. Vegetation may be planted on the face of a slope above a low toe wall (Fig. 3). Alternatively, the interstices of the structure may be planted with vegetation whose roots ultimately will permeate and indurate the soil or backfill within or behind the structure. Vegetated rock breast walls, crib walls, gabion walls, and welded-wire walls fall into this category (Figs. 3 and 4) as do vegetated grid or cellular revetments (Fig. 5). Another combination consists of planting vegetation on the steps of a tiered, retaining wall system (Fig. 6). Procedures for designing, constructing, and vegetating these structures are described by Gray and Leiser (1981).

Contour-wattling and brush-layering can be viewed as either quasi-vegetative or quasi-mechanical means of slope stablization (Figs. 7 and 8). In both cases parts of woody shrubs are used as the soil stablizing and reinforcing material. Although natural vegetation is used for the most part, the stablizing mechanism is largely of a mechanical nature particularly in the case of brush layering.

Wattling consists of tied bundles of plant stems or branches, usually willow or other easy to root species. The bundles are laid in trenches on contour along the slope face (Fig. 7) and staked into position, then the trenches are backfilled. Construction stakes are commonly used for this

TABLE 1 APPROACHES TO SLOPE PROTECTION AND EROSION CONTROL

CATEGORY	EXAMPLES	APPROPRIATE USES	STABILIZING MECHANISM OR ROLE OF VEGETATION
LIVE CONSTRUCTION Conventional plantings	· Grass seeding · Transplants	- Control of surficial rainfall & wind erosion - Minimize frost effects	- bind & restrain soil particles - filter soil from runoff - intercept raindrops - maintain infiltration - change thermal character of ground surface
MIXED CONSTRUCTION: Woody plants used as reinforcement & as barriers to soil movement	· Live staking · Contour wattling · Brush layering · Reed-trench terracing · Brush mats	- Control of surficial rainfall erosion (rilling & gullying) - Control of shallow (translational) mass movement	Same as above...but also reinforce soil & resist downslope movement of earth masses by buttressing & soil arching action
MIXED CONSTRUCTION: Woody plants grown in interstices of low, porous structures or benches of tiered structures	· Vegetated revetments (riprap, grids, gabion mats, blocks) · Vegetated retaining walls (open cribs, gabions, stepped-back walls, & welded-wire walls)	- Control of shallow mass movements & resistance to low-mod. earth forces - Improvement of appearance & performance of structures	- reinforce & indurate soil or fill behind structure into monolithic mass. - deplete & remove moisture from soil or fill behind structure.
MIXED CONSTRUCTION: Toe-walls at foot of slope used in conjunction w/ plantings on the face	· Low, breast walls (stone, masonry etc.) with vegetated slope above (grasses and shrubs).	- Control of erosion on cut & fill slopes subject to undermining at the toe	- stop or prevent erosion on slope face above retaining wall
INERT CONSTRUCTION Conventional structures	· Gravity walls · Cantilever walls · Pile walls · Reinforced earth walls	- Control of deepseated mass movement & restraint of high lat. earth forces - Retention of toxic or agressive fills & soil	mainly decorative role

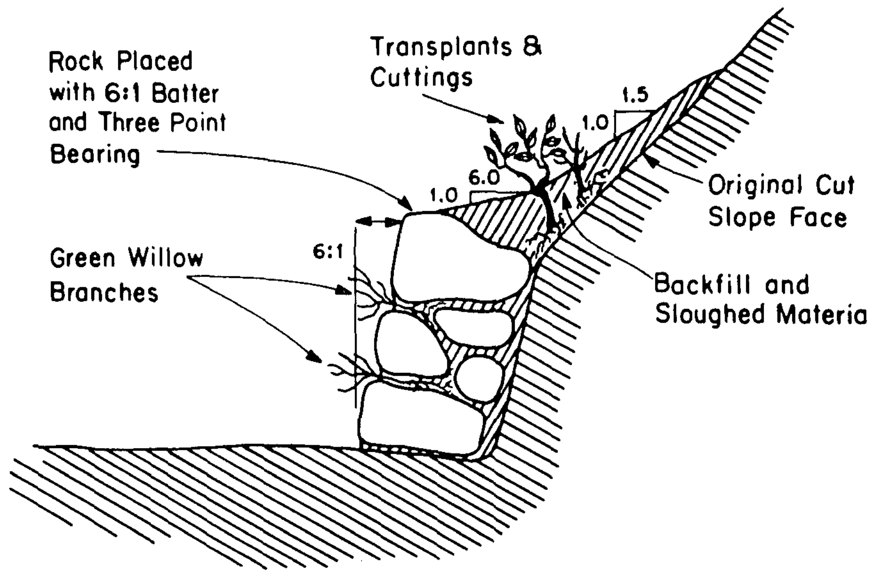

Fig. 3. Vegetated breast wall design for protecting the toe of an earth slope. Plants and live cuttings are placed on the bench or backfill above the wall. Green willow branches or other live cuttings can also be inserted into the backfill through openings between rocks as shown. Plant roots eventually permeate the backfill and help to anchor and reinforce the breast wall.

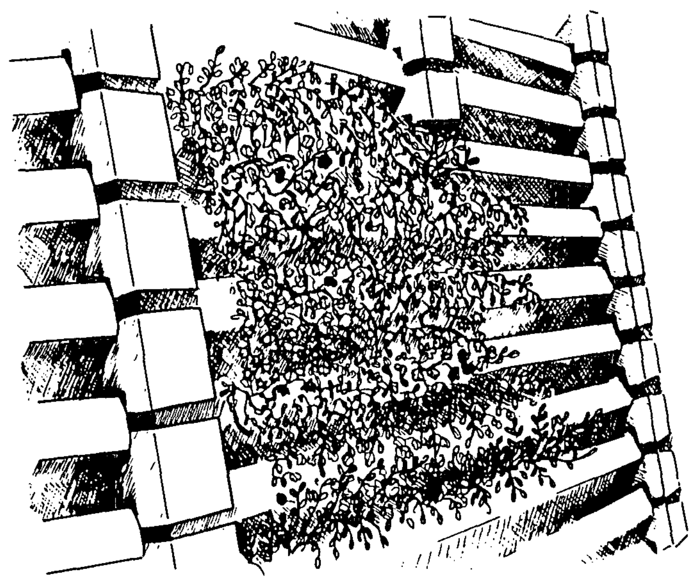

Fig. 4. Vegetated, open-face crib wall design. Cribbing is erected "log cabin" fashion with a batter of 1:6. Suitable vegetation is planted in the open bays between structural members at the front of the crib wall. This procedure not only provides secondary reinforcement of the cribfill (via plant roots) but also opportunities for imaginative landscaping on near vertical surfaces.

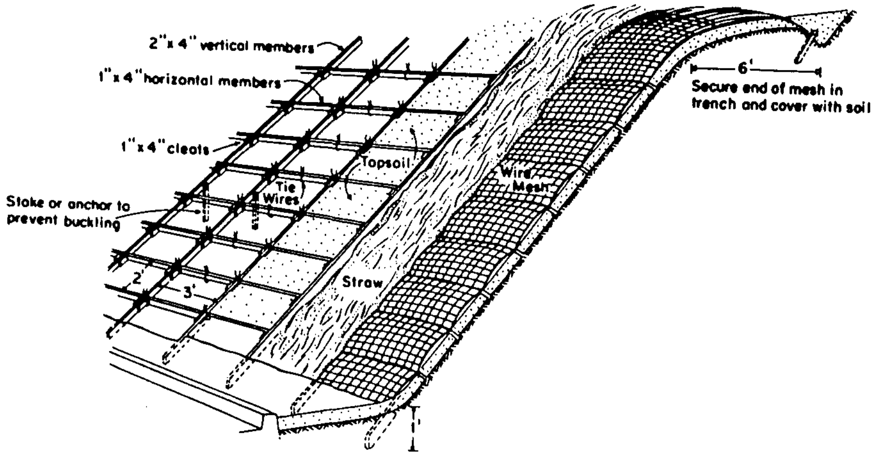

Fig. 5. Cut slope stabilization using an anchored timber grid to hold topsoil and slope plantings in place. Structural grid provides temporary slope protection and permits establishment of vegetation. Once established the plants provide long term slope protection and erosion control.

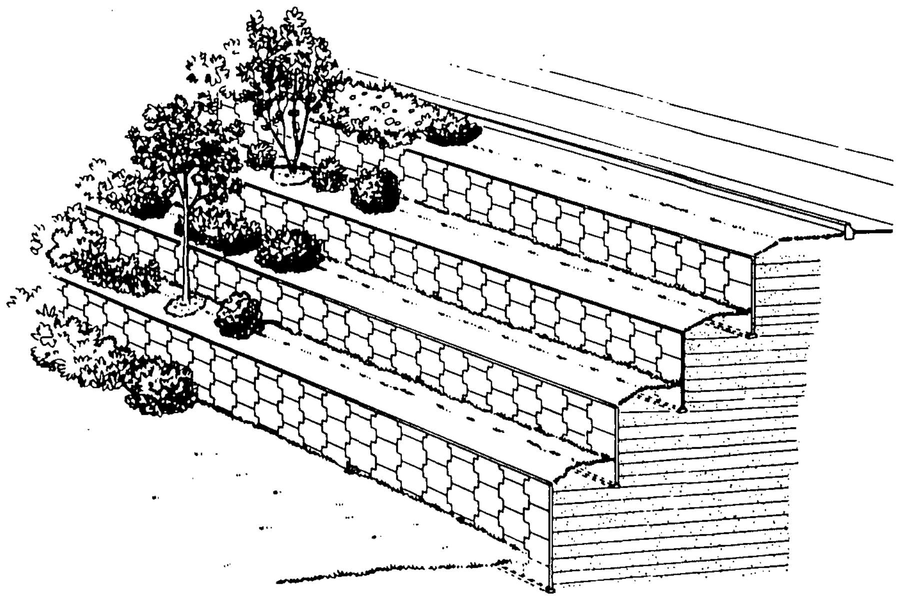

Fig. 6. Tiered, Reinforced Earth wall design with landscaped benches. Lateral earth support is provided mainly by metallic strips which extend back into the slope and which are connected to thin facing elements at the front of the wall. Roots of vegetation growing on the benches provide secondary reinforcement.

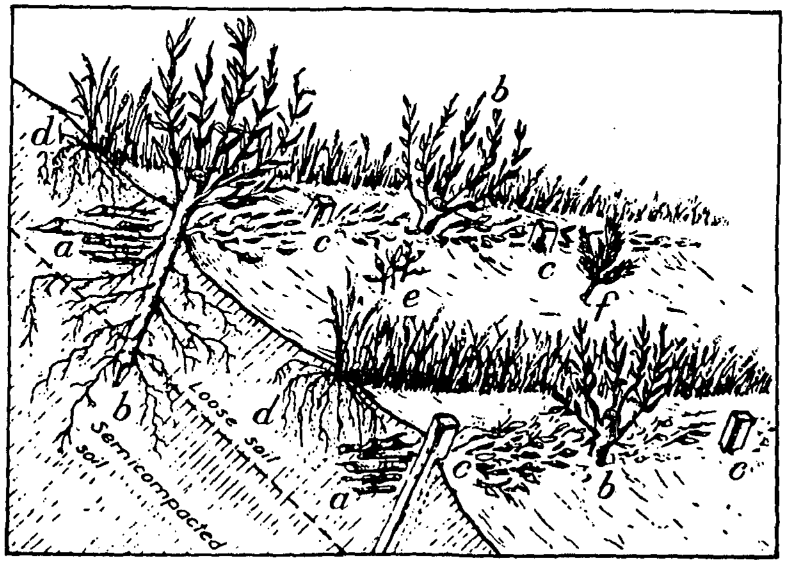

Fig. 7. Fill slope protected by contour wattling. Shown schematically are (a) stems of cut brush "wattles" (b) live willow stakes which have rooted (c) inert construction stakes driven through the wattles (d), (e), and (f) vegetation (grasses, shrubs, and trees). The wattles of bundled brush are laid in shallow trenches on contour and partially backfilled as shown (from Kraebel, 1936).

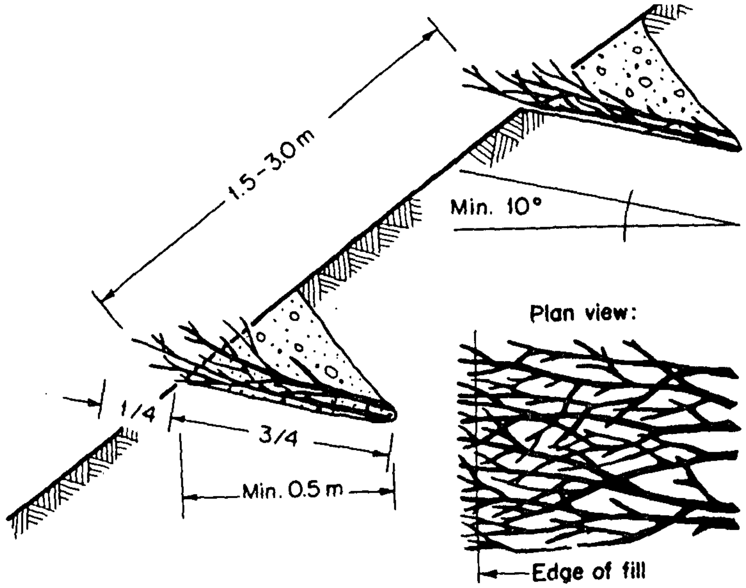

Fig. 8. Fill slope protected by brush layering, Green cuttings and branches of sprouting shrub and tree species are "layered" between successive lifts of fill in horizontal rows at the face of the slope. The branches are placed randomly with some criss crossing of stems. Buttends angle down slightly into the slope and the tips are allowed to protrude slightly beyond the face of the slope as shown (adapted from Schiechtl, 1978).

purpose; these are driven through the wattles into the ground. The stakes act as "dowels" and help anchor the soil to the slope, thereby minimizing shallow debris slides. Alternatively, live willow stakes may be used. These are more difficult to drive in hard ground but provide the additional advantage of rooting and sprouting which will further enhance stability of the slope.

Countour brush-layering consists of imbedding green branches of shrub or tree species, preferably those which will root, on successive horizontal rows or contours in the face of a slope. Rooted cuttings have also been used in lieu of brnahces. The method is schematically illustrated in Fig. 8. Brush-layering may be incorporated for slope protection purposes, during construction of a fill or embankment or alternatively used as a rehabilitation measure for seriously eroded and barren slopes. Brush layers have been incorporated into embankments during construction to stabilize erodible slopes along highways in California (Bowers, 1950). The function of the brush layer in this case was primarily to minimize formation of gullies, in event the surface protection on the slope face should fail. Brush layering is similar to contour wattling in its function and purposes but there are some important differences and advantages, viz.,

(a) It lends itself more readily to partial mechanization. There are no willow bundles to tie and the benches can be excavated with a small tractor.

(b) The branches are inserted into the slope (perpendicular to the strike) rather than parallel. The reinforcement is better oriented, therefore, to resist shallow shear failures or slipouts.

(c) The need for staking is eliminated.

(d) It may be reinforced with wire mesh or other materials.

Brush matting is essentially a mulch of hardwood brush fastened down with stakes and wire (Fig. 9). This measure is used to protect streambanks. The brush is laid shingle fashion with the buttends pointed upstream. Speckled alder and purple-osier willow are ideal species for this purpose, but any convenient streamside brush may be used. Brush matting is employed primarily in conjunction with other stream bank protection measures. Used alone it provides a certain amount of bank protection and erosion control; it can resist temporary inundation, but not scour and undercutting. Structural measures such as groins and revetments are necessary if the bank undercutting is a problem.

Brush matting was employed very effectively for steambank erosion control work along the Winooski River in Vermont (Edminster, et al., 1949). It was an integral component of a combination of measures which were found the most successful on the Winooski project. Thse measures included bank sloping, riprapping at the toe, brush matting, and planting.

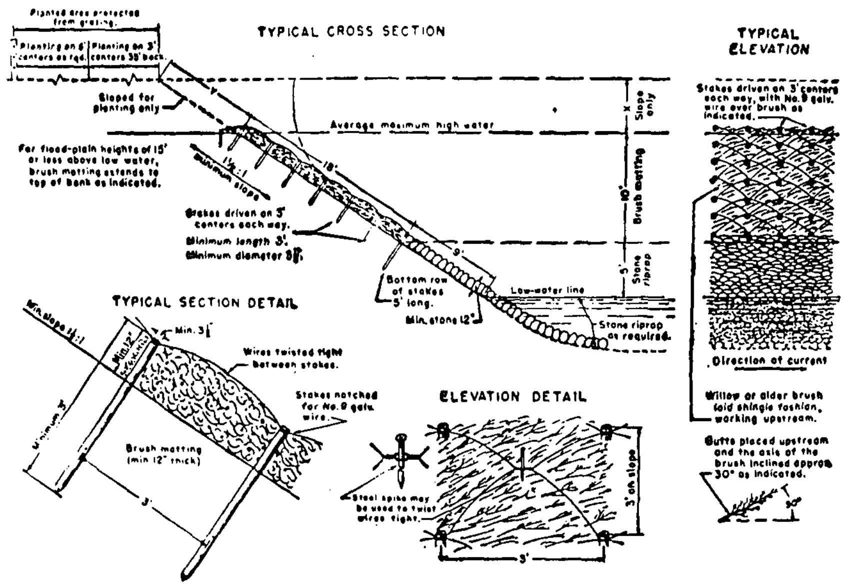

Fig. 9. Construction procedure and details for streambank protection using brush matting. The brush is laid shingle fashion with the butt ends pointed upstream and is fastened down with stakes and wire (from Edminster et al., 1949).

Fig. 10. Steep slope in granitic terrain stablized by willow staking and wattling. Unrooted willow cuttings were planted on two-foot centers. This previously denuded highway cut, about one acre in area, was producing over 100 cu. yds. of sediment per year. Erosion and bank sloughing problems have been virtually eliminated at this iste. State Highway #89, near Luther Pass, California.

Live staking is a quick and effective method of securing a vegetative cover for control of soil erosion and shallow sliding. Live staking, also known as sprigging, consists of planting or driving unrooted cuttings from a live tree or bush. Species which root easily such as willow, poplar, and cottonwoods should be used. These species will grow readily from cuttings set in moist soil. Several species of willow will also grow from cuttings in much less favorable soils, e.g., road cuts and gullies in bare denuded land. Even in very unfavorable sites willow cuttings will often grow vigorously for a few years before they die out. In the meantime they will have served the important function of stabilizing and modifying the soil so that other plants can become established.

Live staking has been used to help stablize shallow slope failures where excess soil moisture is a problem. It has also been used: (a) to establish a vegetative cover on barren, highly erodible highway cuts or fills (Fig. 10), (b) to vegetate porous revetments, (c) as an adjunct to contour wattling, and (d) to provide secondary protection to gully control structures, e.g., check dams and gully head plugs.

Care and attention are required in the selection, sizing, handling, and placement of live materials in all these methods. The same attention that is applied to design standards and specifications for structures also applies to plants. Gray and Leiser (1981) provide guidelines and specifications in this regard.

ROLE OF VEGETATION AND STRUCTURAL ELEMENTS

Vegetation and structures have mutually reinforcing and complementary roles in biotechnical slope protection systems. It is instructive to examine their respective roles and function.

Role of Vegetation: Vegetation offers the best long term protection against surficial erosion on slopes and provides some degree of protection against shallow mass-movement. The stablizing mechanisms and role of vegetation in each case are summarized in Table 1. A detailed review of this topic has been given by Gray (1978).

Vegetation is self regulating and self repairing to a certain extent. Vegetation slope protection measures are also less costly *per se* than structural measures (White and Franks, 1978). On the other hand, vegetation suffers from several limitations and disadvantages. It is of little use for preventing deep seated, rotational slope failures and it is vulnerable to disease, drought, browsing, trampling, and erosion from wave action or stream bank scour. Vegetation may also be difficult to establish on steep slopes. Many of these limitations can be overcome, however, by (a) selecting the right type of vegetation, (b) planting and maintaining the vegetation correctly, and (c) using the vegetation in combination with structural-mechanical elements.

Role of Structure: Properly designed structures help to stablize a slope against mass-movement and they protect the toe or face of a slope against scour and erosion by running water. Structures are generally capable of resisting much higher lateral earth pressures and shear stresses than vegetation. Structures can also be used to divert and convey running water away from critical areas or dissipate the energy of flowing water in a defended area within the structure.

Structures can be built from a number of materials both natural and artificial. Natural materials include earth, rock, stone, and timber. These materials normally cost less, are environmentally more compatible, and better suited to vegetative treatment or modification. Artificial materials include steel and cement. Structures made from the latter materials are stronger and generally more durable, but also more energy and capital intensive. Some structures are comprised of both natural and artificial materials; examples include concrete crib walls, steel bin walls, gabion walls or revetments, welded-wire walls, and reinforced earth. Steel and concrete in this case mostly provide the rigidity, strength, and reinforcement while stone, rock and soil provide the mass. These type of structures can often be planted or vegetated using techniques alluded to previously.

A retaining structure of some type will usually be required to protect and stabilize oversteepened slopes. A low toe-wall or retaining structure at the foot of a slope permits oversteepening of the slope at its base and flattening above. The latter makes it possible to establish vegetation on the slope and the former reduces the amount of clearance required between the base of a slope and an adjacent right-of-way or existing use. This advantage and other applications of retaining structures and toe-walls in combination with vegetative treatments are discussed by Gray and Leiser (1981) and Gray *et al*. (1980).

Revetments and grade stabilization structures are used where protection is required against scour and erosion by running water. A revetment is a structural armoring on a slope. The weight or mass of revetment may also buttress the slope to some extent and increase its resistance to mass-movement. Revetments may consist of a variety of different materials including dumped rubble rock, concrete facings, slotted or cellular concrete grids, articulated blocks, rubber-tire mats, or gabion mattresses. Revetments are commonly used to protect streambanks and channels where water velocities are high and bank materials, weak.

A grade stablization structure is used to reduce grade and dissipate the energy of flowing water within the structure itself or nearby defended area. Debris and sediment tend to be deposited and trapped upstream of the structure which further stablizes the ground. Grade stabilization structures may range from a series of simple, board check dams to earth enbankments with pipe spillways. Mechanical box structures of concrete, masonry, steel, treated wood or gabions have also been used. Grade stabilization structures or check dams as they are commonly known are often employed in gully control work. Effective and inexpensive check dams can be constructed from loose rock in combination with wire mesh fencing and steel posts (Heede, 1976).

Gully control provides a good example of the combined use of structures and vegetation. The long term goal of gully control is establishment of a vegetative cover. This goal can seldom be realized unless severe gully conditions can be altered first. Vegetation alone, for example, will rarely stabilize headcuts because of active piping and concentrated flow of water there. The immediate or short term objective, therefore, is to stabilize critical locations with structural or mechanical measures. Critical locations where structural measures may be required include nick-points on the gully bed, headcuts, and gully reaches close to the gully where deepening, widening, and deposition alternate frequently with differing flows. The ultimate function of these structural-mechanical measures, however, is to help establish and rehabilitate vegetation which provides long term control and protection. Effective gully control requires in short a "biotechnical" solution to the problem. Various gully control systems and structures are described in considerable detail by Heede (1976).

COMPATIBILITY BETWEEN ENGINEERING AND BIOLOGICAL REQUIREMENTS

At first glance biotechnical construction methods may seem unworkable because of compatibility problems, i.e., engineering requirements or conditions imposed by the structure may clash with biological requirements of the vegetation. While indeed some difficulty with incompatibility does exist, much of this concern is either misplaced or can be mitigated. Part of the problem arises from a lack of understanding on the part of both engineers who design the structure and horticulture specialists who design plantings as to each other's design requirements and constraints. An example will serve to illustrate these points.

The backfill or cribfill behind a retaining structure should have certain specified mechanical and hydraulic properties if the structure is to perform properly. Ideally the fill should be coarse grained, free draining, granular material. The presence of excessive amount of clay, silt, and organic matter is not desirable. Gabions should be filled with rock no smaller than 4" in diameter. Reinforced earth structures have very tight specifications on allowable amount of fines in the backfill; the pH is also of concern because of possible corrosion problems with the ties.

The requirement of free drainage - so essential to the mechanical stability of an earth retaining structure - is also important to vegetation, which cannot tolerate water logged soil conditions. Establishment of vegetation, on the other hand, usually requires the presence of fines in the soil in order to provide some moisture and nutrient retention. In many instances these biological requirements can be satisfied without compromising engineering performance by incorporating minor amounts of fines or other amendments in the backfill. These fines or other soil amendments can be put in the backfill either in a surface layer at the top or in small scattered pockets near the face. The former approach would be used in the case of a tiered or bench structure where the objective is to vegetate the horizontal steps; the latter in an open crib structure (timber or concrete) where the objective is to vegetate the face. In the case of gabions, soil can be drifted into the gabion after they are already filled with rock in order to facilitate growth of vegetation. Conversely, cuttings of sprouting plant species (e.g., Salix) can be inserted through the baskets during filling into the soil or backfill beyond.

A frequently voiced concern or fear about the use of plants in conjunction with structures is that the roots will pry and tear the structure apart. The evidence for this is scant. The opposite is more likely. Over time the roots will permeate and bind the fill together into a monolithic mass, thereby improving its internal stability. Furthermore, plant roots exhibit a property termed "edaphoecotropism" (Vanicek, 1973) or simply, stress avoidance. This means that plant roots will tend to avoid the face of a porous, open retaining structure because of phototropic response in the roots and because of high soil moisture tensions (moisture deficiencies) in this zone. The main danger from prying or wedging would most likely arise instead from species with trunks or stem sizes which exceed the diameter or size of openings in the face of structures or revetments. It is important, therefore, not to plant seedlings which will mature into large diameter trees in the frontal interstices of a structure.

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