BIOTECHNICAL STABILIZATION OF STEEPENED SLOPES

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by

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ABSTRACT

The use of tensile inclusions makes it possible to repair slope failures or to construct steepened slopes along highway right-of-ways. Live, cut brushlayers can be used in lieu of or in conjunction with synthetic fabrics or polymeric geogrids for this purpose. This approach, which is termed biotechnical stabilization or soil bioengineering, entails the use of living vegetation, primarily cut, woody plant material that is purposely arranged and imbedded in the ground to prevent surficial erosion and to arrest shallow mass movement. In the case of brushlayering the live cut stems and branches provide immediate reinforcement; secondary stabilization occurs as a result of adventitious rooting along the length of buried stems. Unlike most inert reinforcements, imbedded brushlayers also act as horizontal drains and wicks that favorably modify the hydrologic regime in the slope.

The basic principles of biotechnical stabilization are described. Guidelines are presented for analyzing the surficial, internal, and global stability of brushlayer reinforced fills. A case study is reviewed in which live, brushlayer inclusions were used to stabilize steep slopes along a roadway. A brushlayer, buttress fill was used to repair an unstable cut slope along a highway in Massachusetts. Several repair alternatives were considered in this case. Scenic and environmental considerations in combination with stability analyses eventually dictated the use of a composite, drained rock and earthen brushlayer fill. The rock section was placed at the bottom to intercept critical failure surfaces that passed through the toe of the slope. Biotechnical stabilization resulted in a satisfactory and cost effective solution; the treated slope has remained stable and it blends in naturally with its surroundings.

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INTRODUCTION

Reinforced or mechanically stabilized earth (MSE) embankments have been used in highway construction for the past two decades. This approach offers several advantages over more traditional methods of grade separation that employ either vertical walls, on the one hand, or conventional fills with relatively flat slopes (2H:1 V or less) on the other. The most prominent use of MSE is probably for widening and reconstruction of existing roads and highways. The use of reinforced steepened slopes to widen roadways improves mass stability, reduces fill requirements, eliminates additional right-of-way, and often speeds construction. Design procedures, advantages, and several case histories of steepened, reinforced highway slopes have been reviewed in detail by Berg et al (1990).

The principal components of reinforced or mechanically stabilized earth embankments are schematically shown in Figure 1. Tensile inclusions (reinforcements) in the fill soil create a structurally stable composite mass. These main tensile elements are referred to as "primary' reinforcement. Shorter, intermediate inclusions may be placed near the slope face. These "secondary" reinforcing elements are used to minimize sloughing or face sliding and to aid in compaction and alignment control. The soil at the outer edge of the slope may also be faced with some kind of netting (e.g., coir or jute) to prevent or minimize soil erosion.

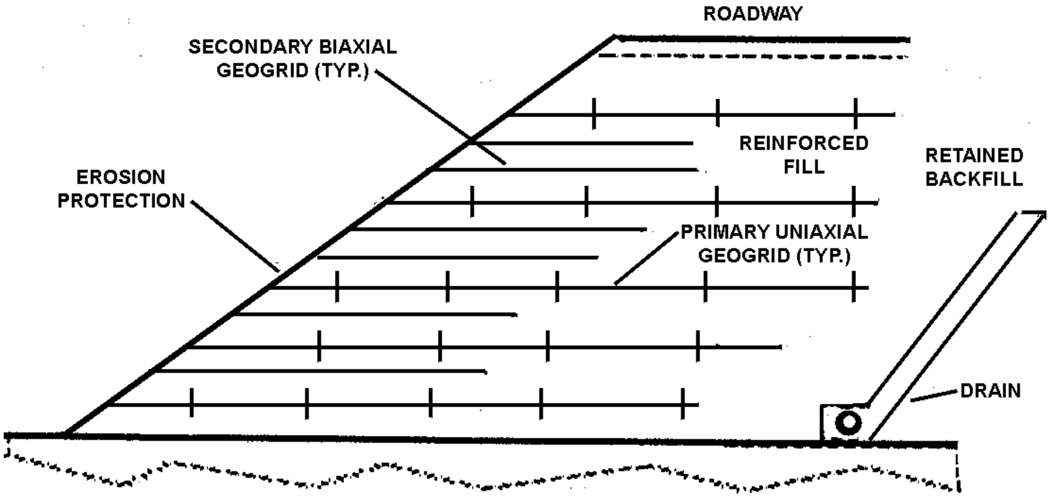

Figure 1. Material and structural components of a typical, reinforced steepened slope (adapted from Berg et. al., 1990)

This last component can be eliminated, however, by simply "wrapping" the secondary reinforcement around the slope face of successive lifts or layers of soil as the embankment is raised. Stability considerations also dictate that appropriate external and internal drainage provisions be incorporated in the design.

Metallic strips, geotextiles, and polymer and wire grids have all been used as reinforcing elements in earthen slopes. Higher strength, primary reinforcements are typically used for permanent, critical highway slopes. Lower strength tensile inclusions can be used close to the face as secondary reinforcements. The latter are typically 3 - 6 feet long and are spaced 8 - 36 inches vertically apart as shown in Figure 1. Selection of the appropriate reinforcement depends on the allowable tensile load, deformation, and design life of the structure.

The purpose of this paper is to describe the use of live, cut brushlayers as a supplement or alterative to inert tensile inclusions and to provide some guidelines for the design and installation of brushlayer reinforcements. The live brush can be substituted for the secondary reinforcements or, in some cases, actually replace both secondary and primary reinforcements. Unlike most inert reinforcements, imbedded brushlayers also act as horizontal drains and wicks that favorably modify the hydrologic regime near the face of the slope. This approach which is termed biotechnical stabilization or soil bioengineering, entails the use of living vegetation, primarily cut woody plant material, that is purposely arranged and imbedded in the ground in selected patterns and arrays to prevent surficial erosion and arrest shallow mass movement.

PRINCIPLES OF BIOTECHNICAL STABILIZATION

Live cut brush, woody stems, and roots can be used to create a stable, composite earth mass. The functional value of vegetation in this regard has now been well established (Coppin et al., 1990). *Biotechnical stabilization* refers to the integrated or combined use of living vegetation and inert structural components (Gray and Leiser, 1982). Soil bioengineering is a more restrictive term that refers primarily to the use of live plants and plant parts alone (Schiechtl, 1980). Live cuttings and stems are purposely imbedded and arranged in the ground where they serve as soil reinforcements, horizontal drains, barriers to earth movement, and hydraulic pumps or wicks. Live plants and plant parts can be used alone or in conjunction with geotextiles or geogrids. The live cut stems and branches provide immediate reinforcement; secondary stabilization occurs as a result of adventitious rooting that occurs along the length of buried stems. Techniques such as live staking, wattling (fascines), brushlayering, etc. fall into this category. The US Dept. of Agriculture, Soil Conservation Service now includes in its Engineering Field Manual guidelines for the use and installation of these soil bioengineering methods (USDA, 1992).

Brushlayering consists of inserting live, cut branches or brush between successive lifts or layers of compacted soil as shown in Figure 2. This process works best when done in conjunction with the construction of a fill slope. The tips of the branches protrude just beyond the face of the fill where they intercept rainfall, slow runoff and fitter sediment out of the slope runoff. The stems of the branches extend back into the slope in much the same manner as conventional, inert reinforcements, e.g., geotextiles and geogrids, and act immediately as tensile inclusions or reinforcements. Unlike conventional reinforcements, however, the brushlayers root along their lengths and also act as horizontal slope drains. This drainage function is very important and can greatly improve mass stability.

Brushlayers alone will suffice to stabilize a slope where the main problem is surficial erosion or shallow face sliding. Sandy slopes with little or no cohesion fall into this category. Deeper seated sliding tends to occur in embankment slopes composed of more fine grained, cohesive soils. This situation may require the use of geogrids in combination with live brushlayers. These latter approaches are illustrated schematically in Figures 3. Guidelines are presented later in the paper for deciding if geogrids must be used in conjunction with live brushlayers.

BIOTECHNICAL STABILIZATION OF HIGHWAY CUT & FILL SLOPES

Biotechnical stabilization has been used successfully to stabilize and repair steep slopes along highways. One of the earliest applications was reported by Kraebel (1936) who used contour wattling to stabilize steep, fill slopes along the Angeles Crest highway in southern California Recent examples of soil bioengineering solutions for the stabilization of a highway cut slopes are discussed by Gray and Sotir (1992). They also describe the use of brushlayering to repair a high, steep fill slope along a highway in North Carolina (Sotir and Gray, 1989). An earthen brushlayer, buttress fill was used to repair an unstable cut along a scenic highway in Massachusetts as shown in Figures 4 and 5. The cut slope consisted of residual silty sand overlying fractured bedrock. Large amounts of groundwater seeped from fractures in the bedrock and through exposed soil in the cut. Other examples of brushlayer stabilization of a steep, high embankment slope along the Brenner Pass highway in Austria are shown in Figures 6 and 7.

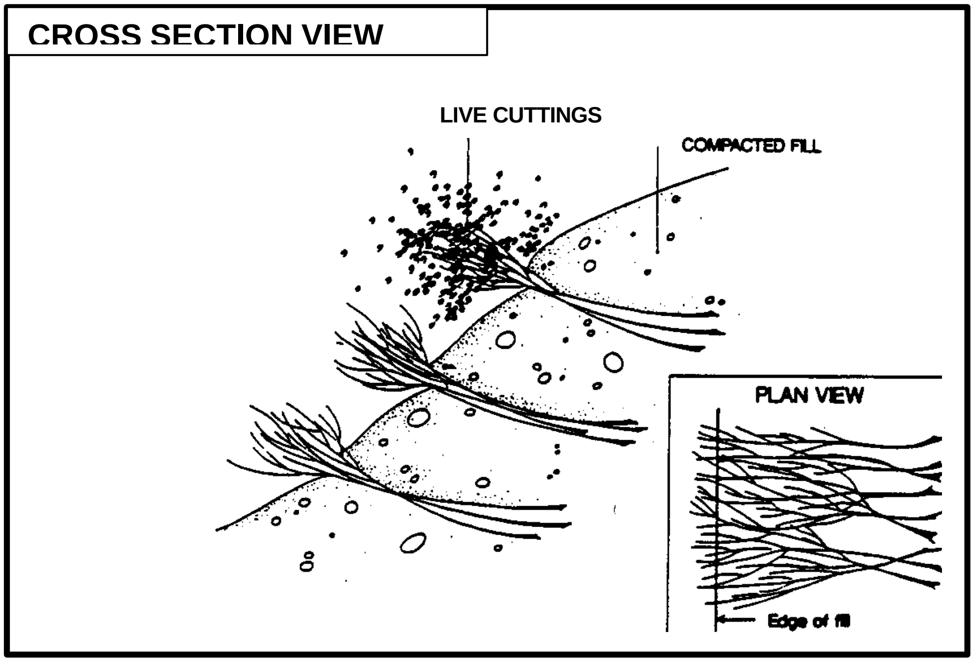

Figure 2. Schematic illustration of fill slope stabilization using live brushlayers

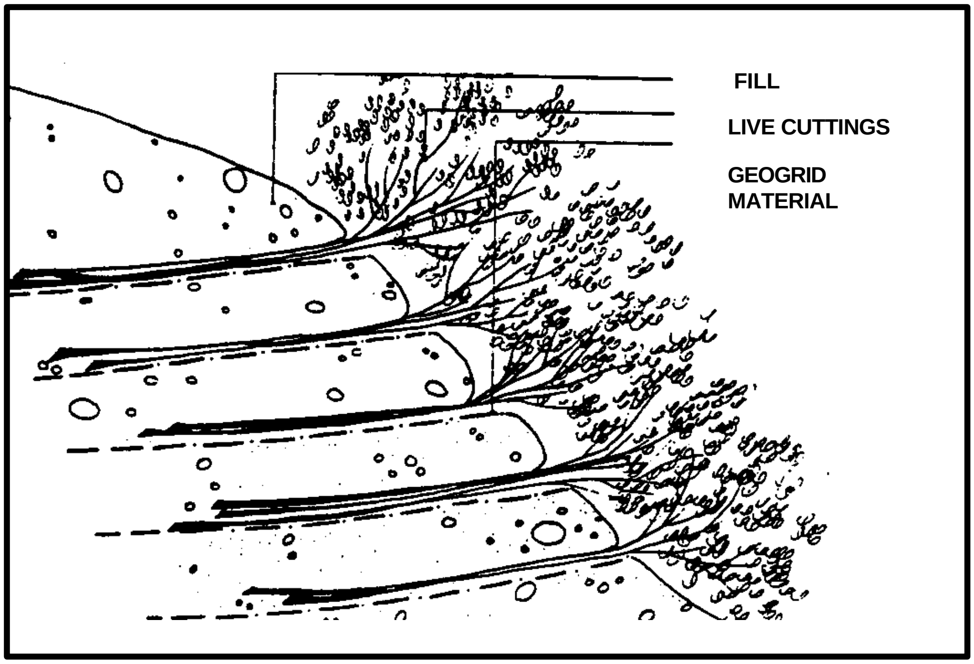

Figure 3. Schematic illustration of live brushlayers used in combination with geogrids or geotextiles.

Figure 4. Brushlayer buttress fill immediately after construction. Winter 1990. Greenfield Rd., nr. Route 112, Colrain, Mass.

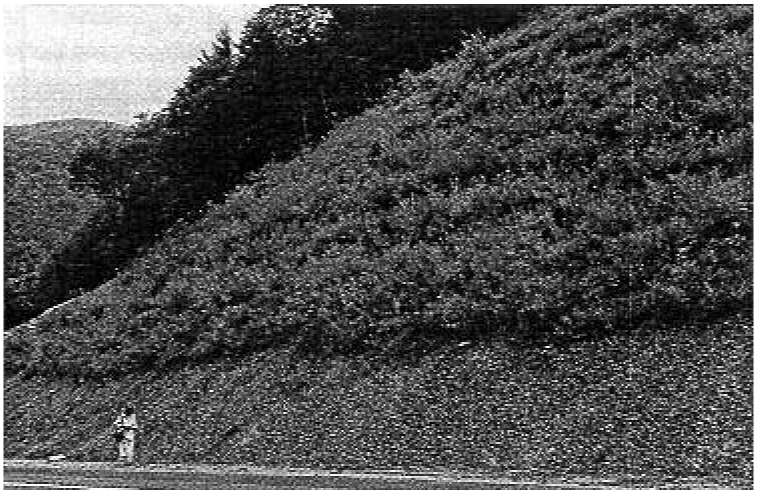

Figure 5. Brushlayer buttress fill after two years showing extensive vegetative establishment. Greenfield Road, Mass.

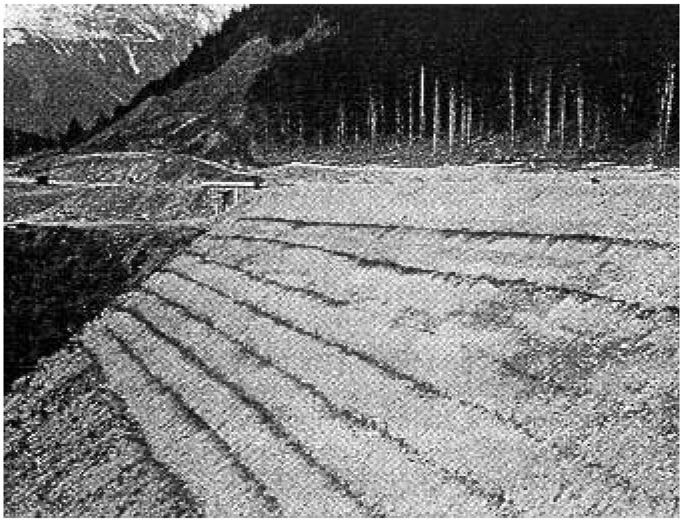

Figure 6. Brushlayer embankment fill stabilization immediately after construction Brenner Pass highway, Austria.

Figure 7. Brushlayer embankment fill stabilization after two years showing both grass and brush establishment. Brenner Pass highway, Austria.

STABILITY CONSIDERATIONS

Surficial Stability

One of the problems with embankment fills is the danger of erosion and sloughing along the outside edge of the fill. Several factors can contribute to this problem, namely, poor compaction at the outside edge and loss of shear strength caused by moisture adsorption and low confining stresses. Attempts to improve compaction may be counterproductive because this impedes establishment of vegetation, which in the long run, provides the best protection against erosion.

Brush layers are very effective in preventing shallow sliding and sloughing for the following reasons: 1) they act as wick and horizontal drains that intercept seepage and favorably modify the hydrologic regime, 2) they root along their length, and these adventitious roots provide secondary reinforcement or root cohesion near the slope face, 3) the growing tips of the brushlayers slow and filler sediment from the slope runoff, and 4) the presence of the brushlayers enhance the establishment of other vegetation on the slope face.

The effectiveness of mechanisms 1 and 2 cited above can be demonstrated by "infinite slope" type analyses, which are appropriate for analyzing the surficial stability of slopes. For purposes of discussion consider a marginally stable, oversteepened (1.5H:1.0V) slope in a sandy soil with very low cohesion (118 pcf, 0=350, X0.2 psi). Factors of safety can be computed as a function of vertical depth to the sliding surface (H) and seepage direction (8) with respect to a horizontal reference plane as shown in Figure 8. In the absence of additional root cohesion, the factor of safety drops below unity (F<1) when the seepage either parallels or emerges from the slope face at depths greater than one foot.

Brushlayers and associated roots markedly improve surfcial stability. The presence of fibers (roots) provides a measure of apparent cohesion (Gray and Ohashi, 1983; Maher and Gray, 1990). This fiber or root cohesion can make a significant difference in the resistance to shallow sliding or shear displacement in sandy soils with little or no intrinsic cohesion. Actual shear tests in the laboratory and field on root/fiber permeated sands indicate a shear strength increase per unit fiber concentration ranging from 7.4 to 8.7 psi per lb of root/cu ft of soil or 3.2 to 3.7 kPa per kg of root/cu m of soil (Gray and Ohashi, 1983; Ziemer, 1981).

Root concentrations reported in actual field tests were used to estimate likely root cohesion (cR) as a function of depth (Riestenberg, 1983; Shields and Gray, 1992). A low to medium root concentration with depth was used in the

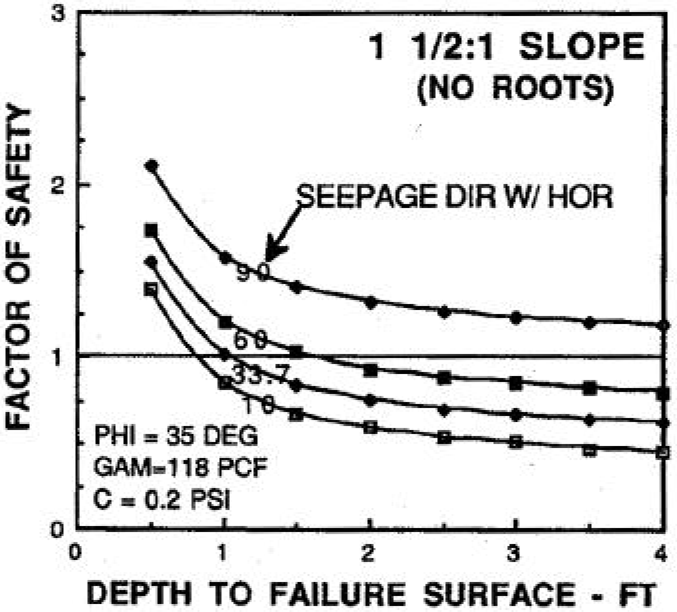

Figure 8. Factor of safety vs. depth and seepage direction for 1.5:1 hypothetical slope without roots in the surface layer.

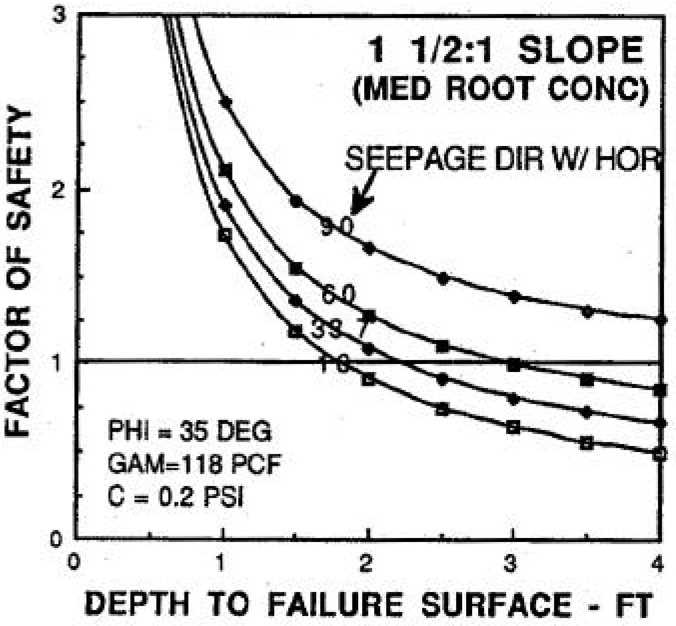

Figure 9. Factor of safety vs. depth and seepage direction for 1.5:1 hypothetical slope v 'y~h roots in the surface layer.

stability analyses to ascertain the likely influence of slope vegetation on mass stability. Factor of safety is shown plotted as a function of depth and seepage direction in the presence of root reinforcement for the same 1.5:1 slope in Figure 9. With roots present the safety factor is increased significantly near the surface and the critical sliding surface is displaced downward. The results of the stability analyses show that both seepage direction (9) and presence of root cohesion (cR) have a significant effect on the factor of safety. Even a small amount of root cohesion can increase the factor of safety substantially near the surface. This influence is pronounced at shallow depths where root concentrations are highest and reinforcement effects therefore greatest.

The brushlayers also act as horizontal drains and favorably modify the hydrologic regime near the face of the slope. They intercept groundwater flowing along the loose, outer edge of a compacted fill, divert the flow downward, and then convey it out laterally through the brushlayer itself. Redirection of seepage flow downward in this manner results in greatly improved resistance to face sliding or sloughing (Cedergren, 1989). Redirection of seepage from parallel flow direction (9=330) to vertical flow (9=900) greatly increases the factor of safety at all depths as shown in Figure 9.

In the case of highly erosive soils (fine sands and silty sands) and very steep slopes (> 1.5H:1.OV) it may be advisable to also use an erosion control netting or mat on the face of the slope between the brush layers. A biodegradable netting with relatively small apertures (e.g., coir netting) placed over long straw mulch will work well in this regard. The netting and mulch provide additional protection against erosion and promote establishment of vegetation on the slope face. The easiest way to install and secure the netting is by wrapping it around the outside edge of successive lifts of compacted fill.

Internal and Global Stability

The internal stability and global stability of a brushlayer fill slope protection system must also be considered. This is especially true when a brushlayer fill is used as a protective "veneer" or buttress fill against an unstable cut or natural slope. Sufficient tensile inclusions, either live brushlayers and/or inert geogrids, must be imbedded in the fill to resist the unbalanced lateral force acting on the earthen buttress. The brush stems and branches reinforce a fill in much the same manner as conventional polymeric grid or fabric reinforcements; accordingly, the internal stability of a brushlayer fill, i.e., the resistance of the brush reinforcement layers to pullout and tensile failure can be analyzed using conventional methods (Thielen and Collin, 1993; Leschinskyet al., 1985) developed for earth slopes reinforced with geotextiles or geogrids. The required vertical spacing and imbedded length of successive brush reinforcement layers are determined from the specified safety factor, allowable unit tensile strength, and interface friction properties of the reinforcement layer. The allowable unit tensile resistance for a brushlayer can be calculated from the known tensile strength of the brush stems, their average diameter, and number of stems placed per unit width (Gray and Sotir, 1992).

In the case of earthen fills that contain moderate amounts of low plasticity fines the requirement for internal reinforcement is greatly reduced. The total required lateral resisting force approaches zero for fills with moderate cohesion (300 psf), slope inclinations less than 1.5H:1.OV, slope heights (H) less than 60 feet as shown in Figure 10. Live brushlayers used alone will suffice in this case to provide some additional internal stability, significantly increase surficial stability, and compensate for possible loss of intrinsic cohesion near the face.

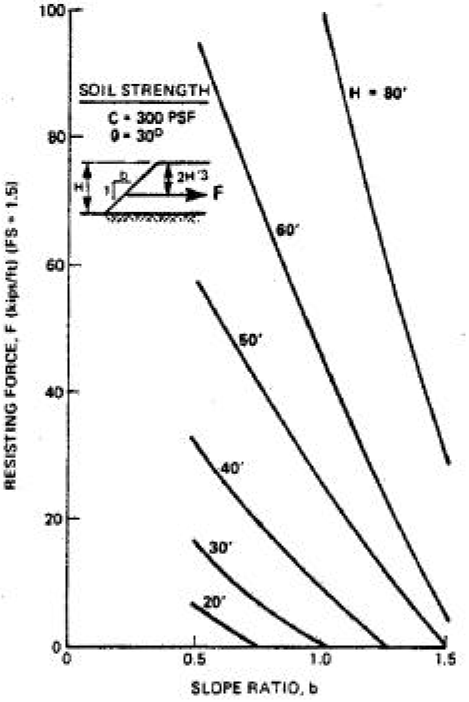

Figure 10. Chart solution for determining the required reinforcement or lateral resisting force for fills constructed from low plasticity soils (from Lucia and Callanan, 1987).

On the other hand, in the case of very high, steep slopes, a conservative design procedure would be to discount the influence of the live brushlayers on internal stability and rely solely on the presence of inert tensile inclusions, e.g., geogrids, used in conjunction with the brushlayers as shown in Figure 3.

Conventional geotechnical analyses can be used to analyze the global or deep seated stability of brushlayer slope protection systems. A brushlayer reinforced outside edge of an embankment fill or alternatively a brushlayer reinforced buttress fill or veneer placed against an unstable cut or natural slope is simply treated as a coherent gravity mass that is part of the slope. An example from an actual case study will be used to demonstrate this analysis procedure.

CASE STUDY EXAMPLE

<u>Project Site</u>: The project site is located along Greenfield Road, just off State Route 112, in northern Massachusetts near the village of Colrain. Widening & improvement of this scenic road resulted in encroachment on an adjacent, unstable hillside, which triggered cut slope failures. The slope stratigraphy consisted of a residual soil, a silty sand, overlying a fractured quartz-mica schist bedrock. The cut was excavated back at a design slope angle of 1.5:1; the inclination of the natural slope above the cut was approximately 3:1. Cut slope heights varied in general from 20 to 60 feet. Slope failures were characterized by small slipouts and slumping. A substantial amount of groundwater flowed out of the cut. This water seeped out of both fractures in the underlying bedrock and through the exposed face of the soil mantle.

<u>Alternative Slope Treatments</u>: The initial stabilization treatment of choice was a crushed rock blanket. This system is employed frequently by Massachusetts DOT for cut slope stabilization. The main objection to this system was its stark and harsh appearance, which were inconsistent with the scenic nature of the highway. The main design consideration in the case of a rock blanket was to determine the thickness required to provide a specified global safety factor of 1.5. In point of fact, a crushed rock blanket placed the entire length of the slope was not required to satisfy mass stability. Instead, a drained, rock buttress at the toe would have sufficed. A toe buttress, however, would have left upper portions of the slope exposed and vulnerable to piping and surficial erosion.

The soil bioengineering alternative proposed for the site was a drained, brushlayer buttress fill. Reservations were expressed by the project engineer about the ability of an earthen, brushlayer fill to resist large shear stresses at the base or toe of the slope and to provide a required global safety factor of 1.5. Some concern was also expressed about the possibility of a critical shear surface developing through the earthen fill adjacent and parallel to a brushlayer. In view of these expressed concerns two modified brushlayer fill designs were proposed: (1) a crushed rock blanket with earthen brushlayer inclusions at periodic intervals, and (2) a crushed rock section at the base and brushlayer fill on top. The latter design was ultimately adopted; stability analyses were carried out on various configurations of this hybrid or composite system. The results of stability analyses on this composite system (see Figure 11) showed that it provided the required global factor of safety and that the most critical failure surfaces passed through the basal rock section at the toe of the slope.

Biotechnical Solution: In view of these findings a decision was made to use the composite rock toe and earthen brushlayer buttress fill design to stabilize the cut. An important caveat in this decision was the requirement that the earthen fill remain in a drained condition---a key assumption in the stability analyses. This requirement along with the large quantity of groundwater seeping out of the cut dictated that a suitable filter course or vertical drain be interposed between the earthen fill and cut face. This requirement was met by placing either a gravel filter course or a geotextile filter with adequate in-plain drainage capacity against the cut face during construction. Water from the bottom edge of the filter discharged into the rock toe at the base.

The construction work at the Colrain field site began in November of 1989. A view of the cut slope after installation of the brushlayer, buttress fill is shown in Figure 4. The appearance of the same slope some 2 years later is shown in Figure 5. After this amount of lapsed time the brush had fully leafed out and native vegetation had become well established on the slope. The slope is stable and has an attractive, natural appearance. Cost Analysis: The costs of several conventional slope stabilization treatments were determined and compared with the soil bioengineering treatment. The conventional treatment costs included a rock blanket and concrete crib wall respectively. Cost analyses for the soil bioengineering treatment were conducted at two different stations or work locations on the project. The cost per square foot for the soil bioengineering treatment only varied by $0.37 per square foot from one location to another.

The rock blanket costs included expenses for transporting, handling, and placing of 1 1/2-inch trap stone in a toe buttress or blanket 10-feet high and

Simplified Bishop Slope Stability Analysis

PROJECT: SLOPE REPAIR WITH COMPOSITE DRAINED ROCK ANDEARTH BUTRESS

LOCATION: COLRAIN, MASSACHUSETTS

COMPLETE SLOPE CROSS SECTION

CIRCLE	X	Y	RADIUS	FS
1	32.0	185.0	145.0	1.50
2	50.0	144.0	105.0	1.46
3	65.0	152.0	101.0	1.74
4	42.0	185.0	135.0	1.83

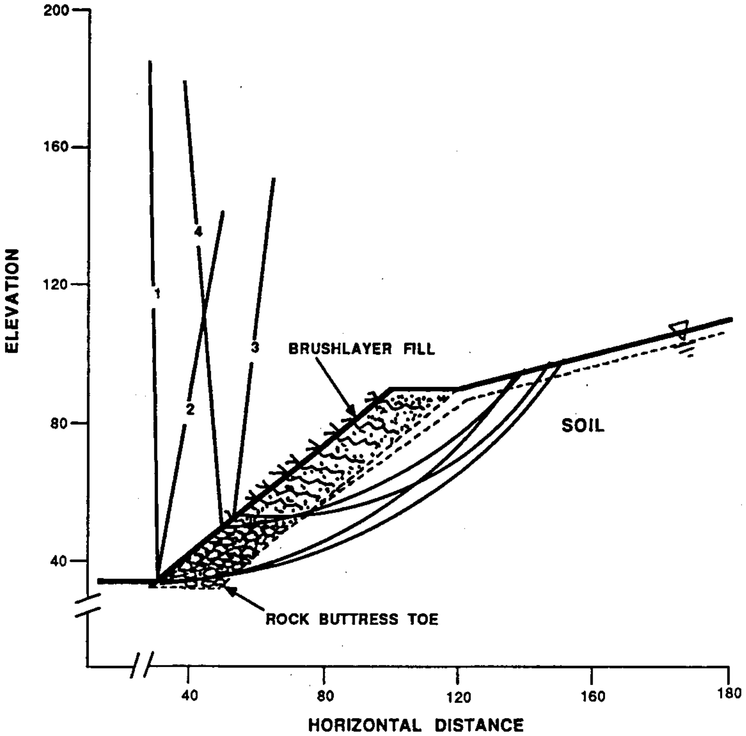

Figure 11. Factor of safety of cut slope stabilized by composite drained rock and earthen brushlayer fill. Colrain, Massachusetts.

8-feet wide. Placement of the rock higher up the slope entails greater difficulty and would have increased costs another 5- to 10 percent. The cost per square foot of front face for the crib wall includes footings and an estimated cost for the crib fill. The cost per square foot for the three alternative treatments was estimated as follows:

Rock Blanket (8-ft thick)	$5.60 per sq. ft.
Soil Bioengineering	13.50 " " "
Concrete Crib Walls	34.50 " " "

Accordingly, the soil bioengineering costs were intermediate between those of a rock blanket and a concrete crib retaining wall. It should be kept in mind, however, that the contractor on the project had placed rock blankets on many previous occasions whereas he had no previous experience with soil bioengineering. A cost comparisons between these two methods was thus skewed slightly by unfamiliarity and a learning curve associated with the soil bioengineering method.

INSTALLATION GUIDELINES

Procedures for the harvesting, handling, storage, and installation of live plant material should be followed carefully. Successful biotechnical construction requires that harvesting and placement of live cuttings in the brush layers be carried out during the dormant season…..usually November through April.

Harvesting sites with suitable plant materials can be located by means of an aerial survey ahead of time. Stems and branches up to three inches in diameter of willow, dogwood, alder, poplar, and viburnum shrubs are generally suitable for brush layer treatments. These are cut at the harvesting site, bundled, and transported to the project site on covered flatbed or dump trucks.

Live, cut material should be placed in the ground as soon as possible after harvesting. In the case of brushlayer installations, the cut stems and branches are laid atop successive lifts of compacted soil in a criss-cross fashion as shown schematically in Figure 2. Soil overlying each brushlayer must be worked in between the branches to insure intimate contact between the brush and soil. The vertical spacing between brush layers normally vary from 1 to 3 feet with closer spacings used at the bottom. The length of the cut stems should extend the full width or as far as possible into an earthen buttress fill. A gravel drainage course, vertical chimney drains, or fabric filter with good in-plane drainage capacity must be placed between an earthen buttress fill and the cut face of a slope. Detailed guidelines and instructions for the selection, harvesting, handling, storage, and installation of live, cut plant materials are presented elsewhere (USDA, 1992).

CONCLUSIONS

Soil bioengineering solutions can be used to stabilize and repair slope failures along highway right-of-ways. Live brushlayers can be used in conjunction with or in lieu of inert polymeric reinforcements in over-steepened slopes. The growing tips of the brushlayers filter soil from runoff and mitigate surficial erosion. The stems and adventitious roots in the brush layers reinforce the soil. The brushlayers also act as horizontal drains and hydraulic wicks that favorably modify the hydrologic regime near the face of a slope. Stems and branches of plant species must be used that root easily from cuttings such as willow and alder. In addition construction and installation must be carried out during the dormant season.

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