Biotechnical Stabilization of Steepened Slopes

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The use of tensile inclusions makes it possible to repair slope failures or to construct steepened slopes along highway rights-of-way. Live cut brush layers can be used in place of or 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 brush layering, the live cut stems and branches provide immediate reinforcement; secondary stabilization occurs as a result of adventitious rooting along the length of buried stems. Imbedded brush layers 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 brush layer–reinforced fills. A case study is reviewed in which live brush-layer inclusions were used to stabilize steep slopes along a roadway. A brush-layer 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 with stability analyses eventually dictated the use of a composite, drained rock, and earthen brush-layer 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.

Reinforced or mechanically stabilized earth (MSE) embankments have been used in highway construction for the past 2 decades. This approach offers several advantages over more traditional methods of grade separation that use either vertical walls or conventional fills with relatively flat slopes (2H:1V or less). The most prominent use of MSE is probably the 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 rights-of-way, and often speeds construction. Design procedures, advantages, and several case histories of steepened, reinforced highway slopes can be found elsewhere (*1*).

The principal components of reinforced or mechanically stabilized earth embankments are shown schematically 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 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. 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 used for permanent, critical highway slopes. Lower-strength tensile inclusions can be used close to the face as secondary reinforcements. The latter are typically 0.92–1.8 m (3–6 ft) long and are spaced 203–914 mm (8–36 in.) 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 brush layers as a supplement or alternative to inert tensile inclusions and to provide some guidelines for the design and installation of brush-layer 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 brush layers 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 arranged and imbedded in the ground in selected patterns and arrays to prevent surficial erosion and to 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 (*2*). Biotechnical stabilization (*3*) refers to the integrated or combined use of living vegetation and inert structural. Soil bioengineering (*4*) is a more restrictive term that refers primarily to the use of live plants and plant parts alone. Live cuttings and stems are 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 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), brush layering, and so forth, fall into this category. The U.S. Department of Agriculture, Soil Conservation Service (*5*) now includes in its *Engineering Field Manual* guidelines for the use and installation of these soil bioengineering methods.

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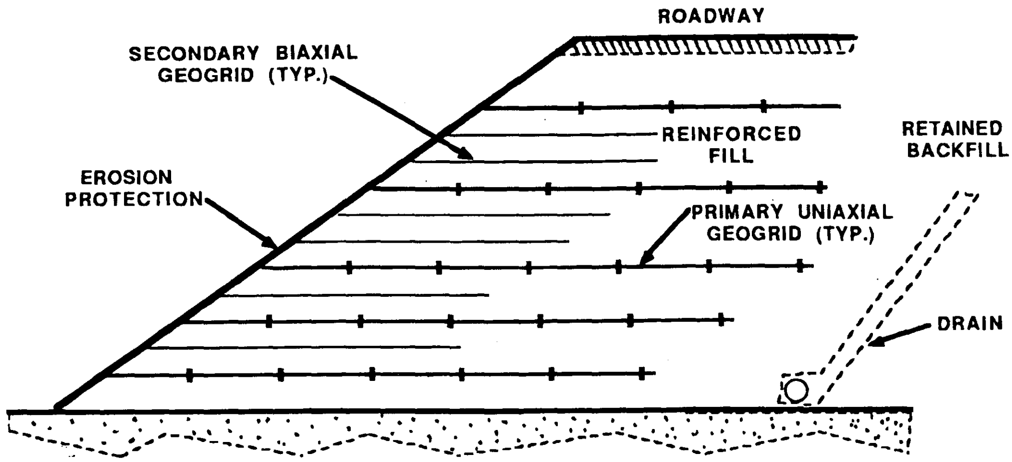

FIGURE 1 Material and structural components of a typical, reinforced steepened slope (*1*).

Brush layering 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 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 filter 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 brush layers root along their lengths and also act as horizontal slope drains. This drainage function is very important and can greatly improve mass stability.

Brush layers 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 brush layers. This latter approach is illustrated schematically in Figure 3. Guidelines are presented later in the paper for deciding whether geogrids must be used in conjunction with live brush layers.

BIOTECHNICAL STABILIZATION OF HIGHWAY CUT AND FILL SLOPES

Biotechnical stabilization has been used successfully to stabilize and repair steep slopes along highways. One of the earliest applications was reported in a work by Kraebel (*6*), 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 found in

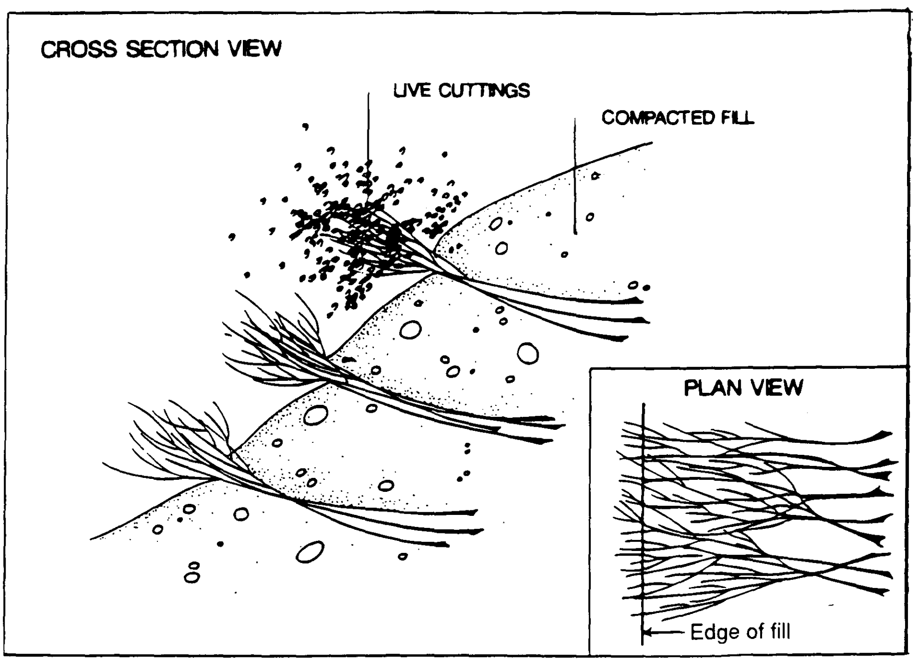

FIGURE 2 Fill slope stabilization using live brush layers place between lifts of compacted soil.

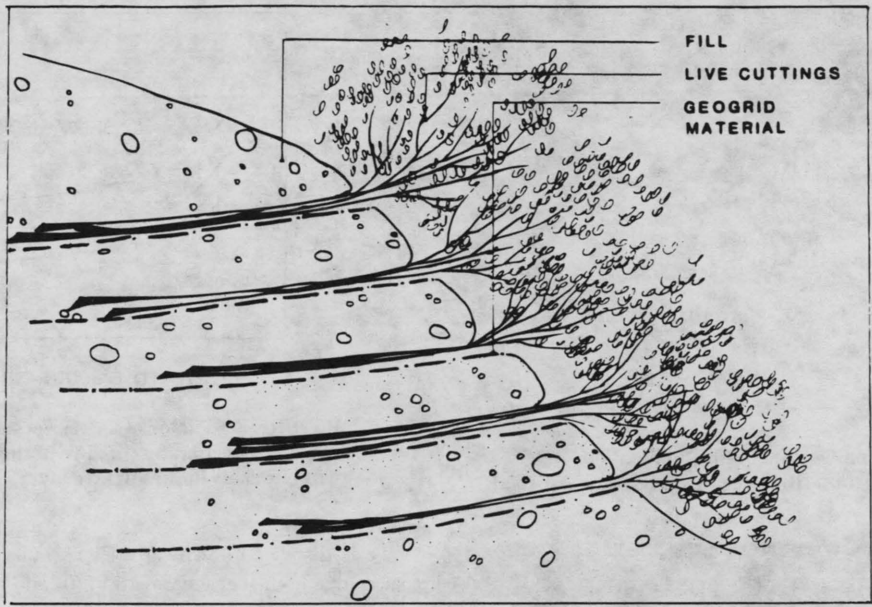

FIGURE 3 Live brush layers used with geogrids or geotextiles.

a work by Gray and Sotir (*7*). They also describe the use of brush-layering to repair a high, steep fill slope along a highway in North Carolina (*8*). An earthen brush-layer 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 brush-layer stabilization of a steep high-embankment slope along the Brenner Pass highway in Austria are shown in Figures 6 and 7.

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 it 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: (a) they act as wick and horizontal drains that intercept seepage and favorably modify the hydrologic regime; (b) they root along their length, and these adventitious roots provide secondary reinforcement or root cohesion near the slope face; (c) the growing tips of the brush layers slow and filter sediment from the slope runoff; and (d) the presence of the brush layers enhance the establishment of other vegetation on the slope face.

The effectiveness of mechanisms a and b 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, $\Phi = 35°$ and $\gamma = 118$ pcf (18.5 kN/m^3), with very low cohe-

FIGURE 4 Brush-layer buttress fill immediately after construction (winter 1990, Greenfield Road, near Route 112, Colrain, Mass.).

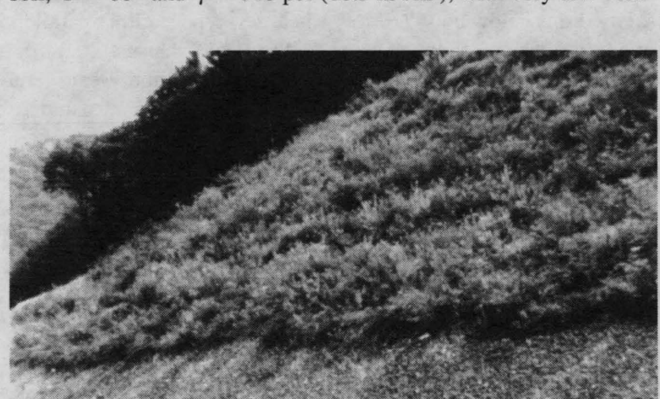

FIGURE 5 Brush-layer buttress fill after 2 years showing extensive vegetative establishment (Greenfield Road, Colrain, Mass.).

FIGURE 6 Brush-layer embankment fill stabilization immediately after construction (Brenner Pass highway, Austria).

FIGURE 7 Brush-layer embankment fill stabilization after 2 years showing grass and brush establishment (Brenner Pass highway, Austria).

sion, $c = 0.2$ psi (1.4 kPa). Factors of safety can be computed as a function of vertical depth to the sliding surface (H) and seepage direction (θ) 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 1 ft (0.3 m).

Brush layers and associated roots markedly improve surficial stability. The presence of fibers (roots) provides a measure of apparent cohesion (*9,10*). 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 (*9,11*) on root and fiber permeated sands indicate a shear strength increase per unit of fiber concentration ranging from 7.4 to 8.7 psi per pound of root per cubic foot of soil (3.2 to 3.7 kPa per kg of root/m^3 of soil).

Root concentrations reported in actual field tests (*12,13*) were used to estimate likely root cohesion (c_R) as a function of depth. A low to medium root concentration with depth was used in the 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 sur-

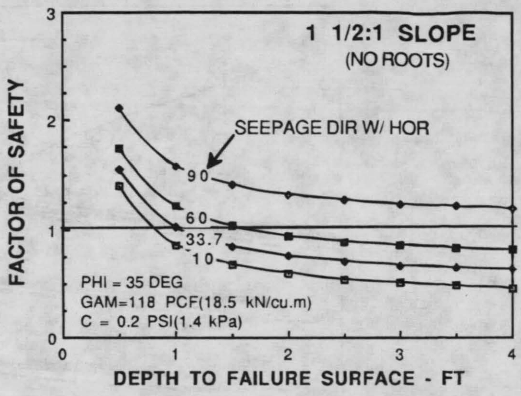

FIGURE 8 Factor of safety versus depth and seepage direction for 1.5:1 hypothetical slope without roots in the surface layer.

face is displaced downward. The results of the stability analyses show that both seepage direction (θ) and presence of root cohesion (c_R) 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 brush layers 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 brush layer itself. Redirection of seepage flow downward in this manner results in greatly improved resistance to face sliding or sloughing (*14*). Redirection of seepage from parallel flow direction ($\theta = 33°$) to vertical flow ($\theta = 90°$) 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:1.0V) 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

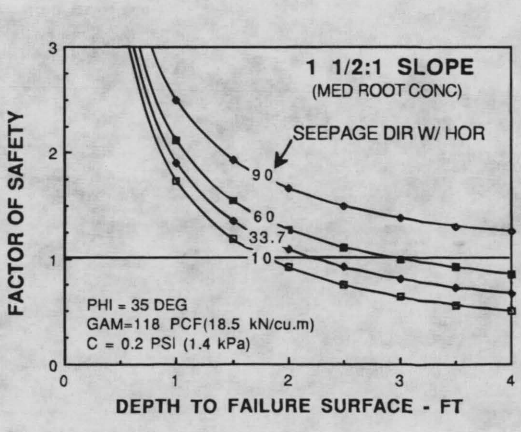

FIGURE 9 Factor of safety versus depth and seepage direction for 1.5:1 hypothetical slope with roots in the surface layer.

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 brush-layer fill slope protection system must also be considered. This is especially true when a brush-layer fill is used as a protective veneer or buttress fill against an unstable cut or natural slope. Sufficient tensile inclusions, either live brush layers or inert geogrids, or both, 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 brush-layer fill (i.e., the resistance of the brush reinforcement layers to pullout and tensile failure) can be analyzed using conventional methods developed for earth slopes reinforced with geotextiles or geogrids (*15,16*). 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 brush layer can be calculated from the known tensile strength of the brush stems, their average diameter, and number of stems placed per unit width (*7*).

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 (c = 300 psf or 14.3 kPa), slope inclinations less than 1.5H:1.0V, slope heights (H) less than 60 ft (18.3 m) as shown in Figure 10. Live brush layers 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. 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 brush layers on internal stability and rely solely on the presence of inert tensile inclusions (e.g., geogrids, used in conjunction with the brush layers as shown in Figure 3).

Conventional geotechnical procedures can be used to analyze the global or deep-seated stability of brush-layer slope protection systems. A brush-layer reinforced outside edge of an embankment fill or alternatively a brush-layer 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

Project Site

The project site is located along Greenfield Road, just off State Route 112, in northern Massachusetts near the village of Colrain. Widening and 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 ft (6.1 to 18.3 m). 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.

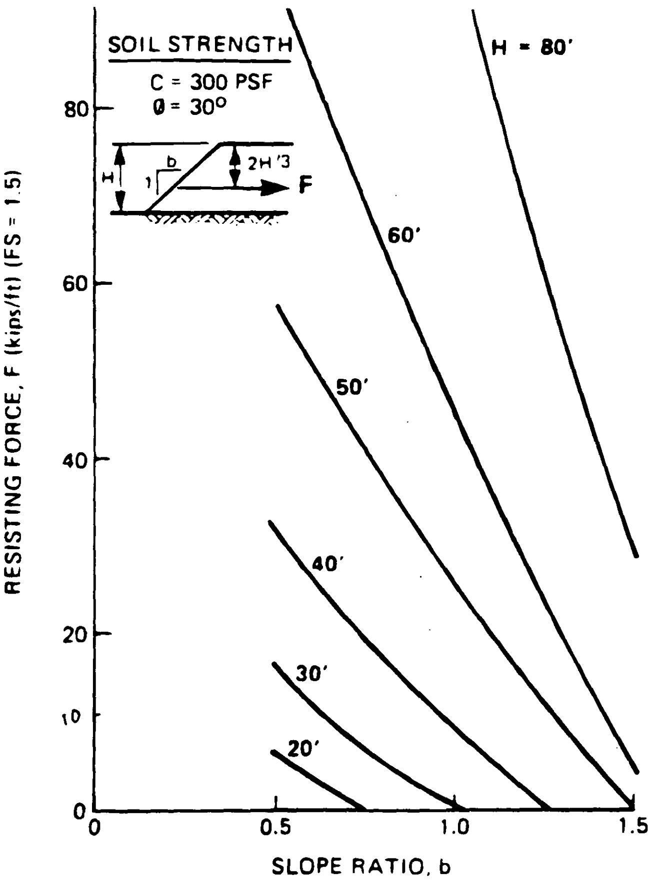

FIGURE 10 Chart solution for determining the required reinforcement or lateral resisting force for fills constructed from low-plasticity soils (*17*).

Alternative Slope Treatments

The initial stabilization treatment of choice was a crushed rock blanket. This system is used frequently by Massachusetts Department of Transportation for cut slope stabilization. The main objection to this system was its stark and harsh appearance, which was 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 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 brush-layer buttress fill. Reservations were expressed by the project engineer about the ability of an earthen brush-layer 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 brush layer. Because of these expressed concerns two modified brush-layer fill designs were proposed: (a) a crushed rock blanket with earthen brush-layer inclusions at periodic intervals and (b) a crushed-rock section at the base and brush-layer fill on top. The latter design was ultimately adopted; stability analyses were conducted 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

Because of these findings, a decision was made to use the composite rock toe and earthen brush-layer 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-plane 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 1989. A view of the cut slope after installation of the brush-layer buttress fill is shown in Figure 4. The appearance of the same slope some 2 years later is shown in Figure 5. In 2 years, 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.

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

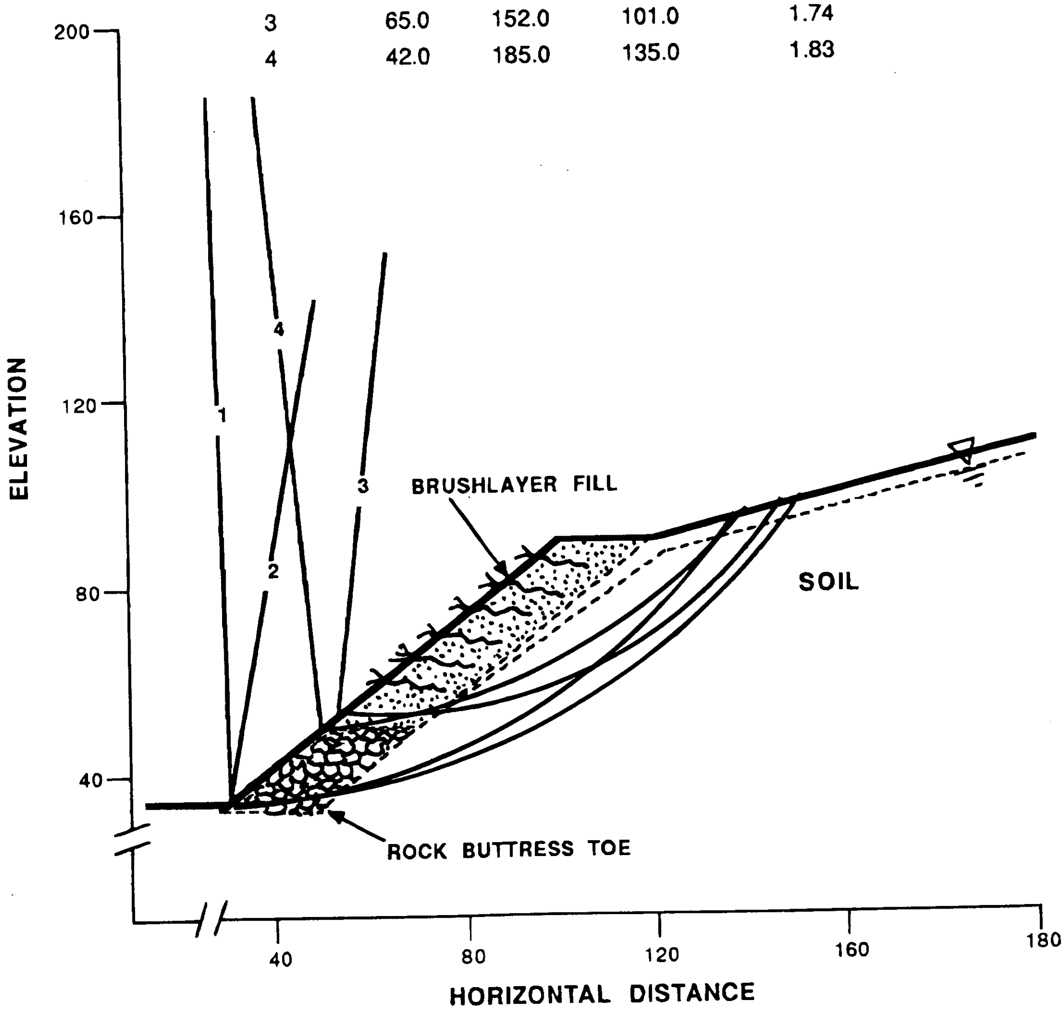

FIGURE 11 Factor of safety calculated by Bishop Slope Stability analysis of cut slope stabilized by composite drained rock and earthen brush-layer fill (Colrain, Mass.).

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. 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 varied by only \$2.90/m^2 (\$0.37/ft^2) from one location to another.

The rock blanket costs included expenses for transporting, handling, and placing of 38 mm (1.5-in.) trap stone in a toe buttress or blanket 3 m (10 ft) high and 2.4 m (8 ft) 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: rock blanket 2.5 m (8 ft) thick, \$60.30/m^2 (\$5.60/ft^2); soil bioengineering, \$145.30/m^2 (\$13.50/ft^2); concrete crib walls, \$371.40/m^2 (\$34.50/ft^2). Accordingly, the soil bioengineering costs were 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 often placed rock blankets but had no previous experience with soil bioengineering. A cost comparison 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 with an aerial survey. Stems and branches up to 76 mm (3 in.) in diameter of willow, dogwood, alder, poplar, and viburnum shrubs are generally suitable for brush-layer treatments. They 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 after harvesting as possible. In the case of brush-layer installations, the cut stems and branches are laid atop successive lifts of compacted soil in a crisscross fashion (as shown schematically in Figure 2). Soil overlying each brush layer must be worked in between the branches to ensure contact between the brush and soil. The vertical spacing between brush layers normally varies from 0.30 to 0.91 m (1 to 3 ft) 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 can be found elsewhere (*5*).

CONCLUSION

Soil bioengineering solutions can be used to stabilize and repair slope failures along highway rights-of-way. Live brush layers can be used with or in place of inert polymeric reinforcements in oversteepened slopes. The growing tips of the brush layers filter soil from runoff and mitigate surficial erosion. The stems and adventitious roots in the brush layers reinforce the soil. The brush layers 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 that root easily from cuttings (such as willow and alder) should be used. In addition, construction and installation should be carried out during the dormant season.

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