Reinforced Soil Highway Slopes

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Reinforced soil highway slopes are an economical alternative to conventional grade separations within limited rights-of-way, such as flattened slopes, selected-fill embankments, or vertical retaining walls. Reinforced soil slopes are applied in six main areas of highway construction: steepened slopes, surficial reinforcement, compound slopes for road widening, repair of landslides, embankments over soft foundations, and vertical slopes or walls. Critical applications with a design life of 50 to 75 years and, therefore, grid geosynthetic reinforcement, are emphasized. Those applications are defined and illustrated and their relative economics are reviewed. Steepened embankment slopes are examined in detail. Economics are presented and compared with alternatives. Design of steepened slopes is reviewed with emphasis on stability analysis procedures and appurtenant features. Also, long-term reinforcement material property requirements and specification writing are evaluated. Brief case histories are presented to illustrate applicability, aesthetics, and construction of reinforced soil slopes in highway works, showing that reinforced soil slopes are a proven method of construction having broad applicability in highway construction. It is concluded that highway planners and route layout engineers should consider the reinforced soil slope alternative(s) when faced with grade separations that must fit within limited rights-of-way.

A better angle on highway grade separations is one that provides economic benefits while maintaining or improving safety and aesthetics. Traditionally, separations are created with embankment or vertical retaining wall structures as illustrated in Figures 1a and 1b. An embankment would be at an angle that would be stable against deep-seated and surficial slope failures. Also, embankment slopes are usually constructed flat enough (4H:1V to 2.5H:1V) to allow mowing of grass. Reinforced soil walls, or mechanically stabilized earth (MSE) embankments, have been used extensively in highway construction since the mid-1970s. Reinforced soil walls offer the advantages of precast concrete facing, structural flexibility, and lower cost than does traditional cast-in-place concrete construction. Most of those walls use steel strip or grid-reinforcing elements and a select granular backfill.

A better angle for grade separations is one that lies between the flatter 4H:1V (14 degrees) slope and the vertical (90 degrees) wall, as illustrated in Figure 1c. Aesthetically, the slope may have a vegetated face, which is often more acceptable to the public than are vertical concrete faces. Low-growth, maintenance-free vegetation is typically specified. A steepened, reinforced slope requires less fill and rights-of-way (ROW) than do flat slopes. Steepened slopes eliminate precast or cast-in-place concrete used for facings, thus saving material costs and construction time. The requirement of select granular backfill can also be waived when chemically resistant, structural polymer grid-reinforcing elements are used.

Geogrids, polymer-based grids specifically developed for long-term critical structures, were introduced into North America in the early 1980s (*1*) and typically differ from geotextiles in long-term load carrying definition and in soil interaction characteristics. Critical highway structures reinforced with geogrids are addressed next.

Since the early 1980s, reinforced slopes have typically been used by transportation agencies in problem areas but not as a routine construction alternative for grade separations. The goal of this paper is to familiarize route layout and structural highway engineers with where and how reinforced slopes may be used and with their economic and aesthetic benefits.

COMPONENTS OF REINFORCED SLOPES

The material components of a reinforced slope are labeled in Figure 2. Inclusions of tensile elements in the fill soil create a structurally stable composite mass. Tensile elements used with the reinforced fill to create the stable mass are termed primary reinforcement. Secondary, or surficial, reinforcing elements at the slope face are used to aid in compaction, for alignment control, and to minimize sloughing. The soil at the outer edge of the slope is also faced to prevent or minimize soil erosion. External and internal drainage provisions should also be included in the design.

The reinforcing element typically used is a polymer geogrid. Structural limitations, such as allowable tensile load and design life, are specific to polymer type and product manufacturing process. Extruded, uniplanar geogrids have been used for permanent, critical highway slope and retaining wall construction.

Additional components of reinforced slopes include design, specifications, installation, and inspection. The reinforcement, design, erosion protection, and installation assistance can all be specified to be supplied from one prequalified manufacturer. This is similar to the way "vertical slopes," or MSE walls, are now specified by most transportation agencies. An exception is the supplier should be responsible for all aspects of structural stability and not just internal stability. Alternatively, the specifying agency may provide its own design and specify reinforcing materials. Inspection is routinely conducted by the specifying agency.

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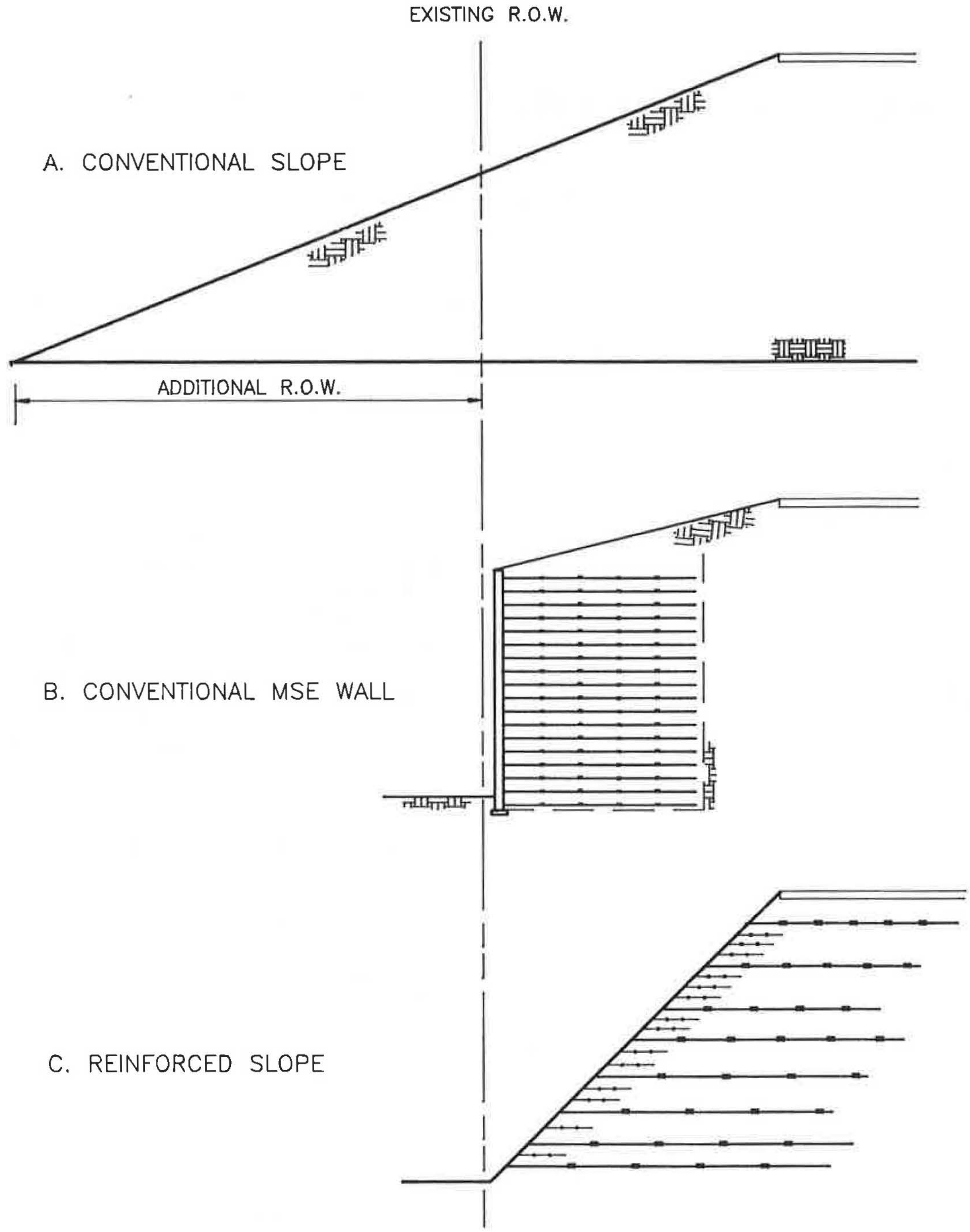

FIGURE 1 Grade separation options.

APPLICATIONS

The primary application of reinforced slopes in highway construction is steepened slopes. Related reinforced slope applications include surficial reinforcement, compound slope construction, landslide repair, and embankments over soft foundations and are briefly reviewed in this and in the Case Histories section.

Steepened Slopes

A steepened slope may be defined as a reinforced mass that would have a factor of safety against slope instability of less than 1 if it were unreinforced. A typical steepened slope is illustrated in Figure 2. On the basis of current design procedures, a structure with a slope angle up to 80 degrees can be classified as a steepened slope. A structure with a slope

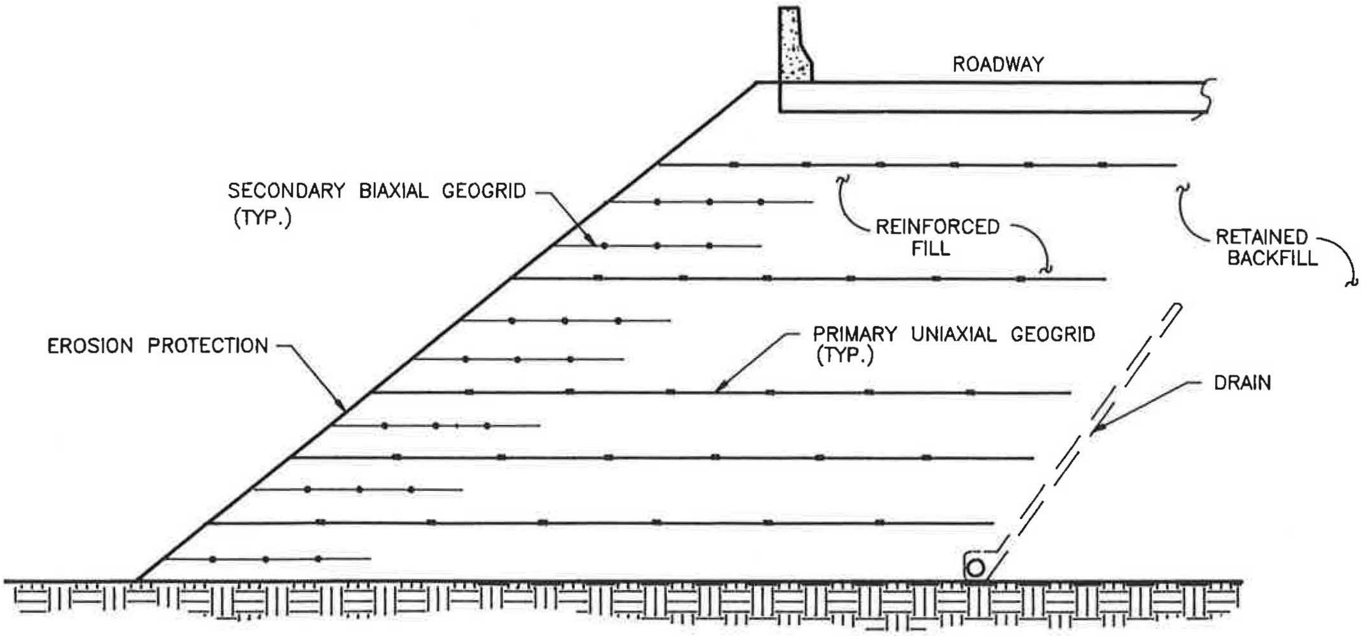

FIGURE 2 Components of a reinforced slope.

angle greater than 80 degrees will typically be classified as a retaining wall. Steepened slopes from 2 : 1 (26.6 degrees) to 0.35 : 1 (70 degrees) are routinely constructed. Construction details and erosion protection requirements vary between those extremes, as is illustrated in the Case Histories section.

Steepened slopes are used in lieu of flatter slopes to create more useable land on top of a slope or to minimize land take or ROW requirements at the bottom of a slope. Cost savings over retaining walls are realized by elimination of concrete facings and, in the case of steel-reinforced MSE walls, by use of on-site or nonselect fill. Aesthetically, a vegetated slope is usually more appealing than the vertical concrete facing.

Related Applications

Surficial Reinforcement

Shallow slope failures are not an uncommon sight along many roadways. Some of those slides can be attributed to lack of soil compaction near the edge of the slope, resulting in a weaker soil that more readily takes in surface water and further weakening the soil and leading to sloughing. Reinforcement allows soil compaction equipment to operate effectively on the slope edge (illustrated in Figure 3), thus achieving desired compaction and preventing future sloughing. Reinforcement for this application is typically 3- to 6-ft long and is spaced at 8- to 36-in. centers, vertically.

FIGURE 3 Surficial reinforcement on a 1:1 fill.

Compound Slope Construction

Compound slope construction refers to construction of a steepened reinforced slope into an existing stable, unreinforced slope and differs from the previous applications because analysis and construction details vary. Global stability of the overall system may be more difficult to assess.

The most prominent use of this application is in widening of existing roads (see Figure 10). In the near future, many of the nation's freeways and tollways need to be widened, which may either be in the direction of the median, space permitting, or along the exterior lanes. The exterior widening of tall embankments requires large amounts of fill and additional ROW if the new slope is constructed at the same angle as is the existing one. Stability of new fill may be questionable if compaction of the soil at the edge of the existing fill was not achieved during (or maintained since) original construction. The use of a reinforced compound slope to widen roadways facilitates the assurance of global stability, reduces fill requirements, eliminates additional ROW, and often speeds construction.

Landslide Repair

Landslides in soil cut or fill areas can be repaired with a reinforced gravity mass structure that must extend back beyond the slope failure plane and should incorporate drainage provisions. On-site soils are typically used in the reconstruction when tensile-reinforcing elements are incorporated into the reconstructed soil mass. Tensile reinforcement allows the reuse of "failed" soil and reconstruction of the slope to its original lines and grades.

Embankments Over Soft Foundations

Roadway embankment construction over soft soils and high water tables can pose several challenges to the design engineer and contractor. Geogrid reinforcement placed across soft soils increases load distribution and reduces contact pressures and enables the contractor to gain access to place an initial soil lift. Higher strength reinforcement designed to prevent global instability can then be placed on top of this lift. Side slopes of the embankment may also be steepened to reduce weight and therefore decrease consolidation settlements. This method of construction is more economical than dump and displace techniques or pile-supported systems. Soil reinforcement has also been used in conjunction with other techniques, such as deep dynamic compaction, stone columns, geotextiles, and wick drains, to create cost-effective systems.

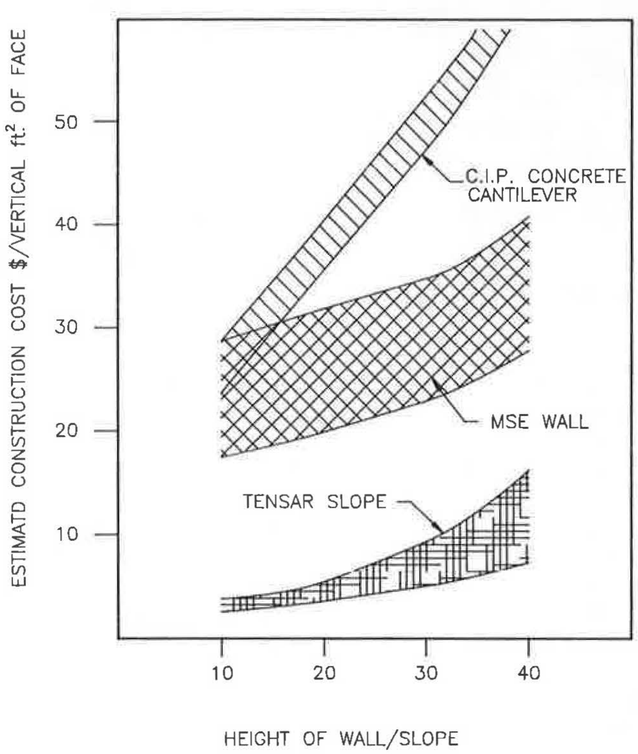

FIGURE 4 Estimated construction costs for grade separation structures.

ECONOMICS OF STEEPENED SLOPES

Steepened slopes are nearly always more economical than retaining wall alternatives and are often more economical than flatter slopes. Savings are realized both from material and construction time reductions and by reduced ROW requirements. Approximately 50 percent of the material cost of an MSE highway wall is in the precast concrete panel facing, which can be eliminated by use of a vegetated, reinforced slope.

Significant material savings over MSE walls in most areas also can be realized by use of local on-site fills. Geogrids were specifically developed to be used with fine or coarse grained soils or both (*1*). Clean, granular fills for use with metal-reinforced MSE walls typically range from $5.00 to $15.00 per cubic yard (in 1990). On-site fill can typically range from $2.00 to $5.00 per cubic yard. This differential will be slightly offset by the additional fill required by a slope, assuming the top of wall/slope is held constant. Therefore, steepened slopes options should be examined during the route layout and cut and fill balancing operations of a project to maximize cost savings.

The cost savings of a geogrid-reinforced steepened slope over other grade separation options is illustrated in Figure 4. The parameters used to develop this graph are listed next. Cost ranges shown for components are in-place costs. Although local economics will vary, it is clear that steepened slopes are a cost-effective alternative to retaining walls.

1. Steepened slope: $\phi' = 28$ to 34 degrees; $\beta = 26$ to 45 degrees; F.S. = 1.5.
   - Erosion protection: \$1.25 to \$4.00/yd²
   - On-site fill: \$2.00 to \$3.50/yd³
   - Reinforcement: \$0.25 to \$9.15/vertical sq. ft. face (no allowance for any additional R.O.W.)
2. MSE Wall: $\phi' = 34$ degrees; F.S. = 1.5; L/H = 0.75.
   - Select fill: \$5.00 to \$10.00/yd³
   - Facing panels, reinforcement, and design: \$17.00 to \$26.00/ft² face (\$9.00 to \$13.50 for materials and design and \$8.00 to \$13.00 for erection)
3. C.I.P. Concrete Cantilever: $\phi' = 34$ degrees; F.S. = 1.5.
   - On-site fill: \$2.00 to \$3.50/yd³
   - Reinforced concrete: \$300.00 to \$400.00/yd³

DESIGN OF STEEPENED SLOPES

As with any earthen structure, several aspects to design exist. Material properties of the different components of the soil structure must be assessed to ensure performance over the life of the structure. Stability analyses should then be performed and appurtenant features designed. Writing the specifications is the next step and is of crucial importance to ensure that the structure built meets the design requirements and functions as intended over the design life. Finally, inspection is required to ensure proper construction. A thorough summary of soil-reinforcement design with geosynthetics has been presented by Bonaparte et al. (*2*).

Material Properties

Soil

Fill soils may come from designated on-site sources or from undefined off-site borrow locations. In the first case (designated on-site sources), material parameters may be defined by standard geotechnical field exploration and laboratory testing practices before bid. Variabilities may be addressed by using conservative values in design or by parametrically investigating their affects on stability. Soils adjacent to a reinforced mass, which will remain in situ, and phreatic surfaces should also be defined by standard geotechnical practices. In the second case (undefined off-site borrow locations), a material specification for fill must be prepared.

Reinforcement

Two key reinforcement parameters used in design are (a) long-term design strength and (b) soil reinforcement interaction coefficients. Accurate definition of those parameters are required to ensure the slope structure will perform as intended over its entire design life. This is particularly true for critical highway structures.

Procedures for determining long-term design strength of geosynthetic reinforcement are being developed by the AASHTO-AGC-ARTBA Task Force 27 (*3*) and by the Geosynthetic Research Institute (*4*). (Both works were still in draft form and not publicly available when this paper was prepared, though final documents are pending from both organizations.) Other procedures have been presented by Bonaparte and Berg (*5*) and by Jewell and Greenwood (*6*). All procedures are similar and typically address creep of the polymer product, chemical degradation, biological degradation, damage during installation, strength of connections and junctions, and soil-reinforcement interaction characteristics.

Potential degradation of polymer reinforcement over the life of the structure, long-term creep, and long-term soil interaction mechanisms must be quantified. Those are areas that may be glossed over owing to their complexity. Reliance is typically heavily based on manufacturer's recommendations. Polymer materials may be subject to chemical or biological degradation or both in a soil environment. Product-specific studies should be conducted to determine durability reduction or safety factors for application to long-term design strength and to soil-interaction coefficients.

For time-dependent tensile characteristics the general rule in the plastics industry is not to extend creep predictions more than one order of magnitude beyond actual test data. Obviously, this is impractical for highway structures with a design life of 50 to 75 years, because tests of 5 to 7.5 years in duration would be required. Conservative approaches and techniques (*6–8*), such as time-temperature superposition, are used to extend 1.2-year creep data by two orders of magnitude to 120 years. Therefore, it is critical that an acceptable technique for extrapolation of long-term properties be specified and then be accurately documented.

Interaction coefficients between tensile elements and the soil it reinforces are functions of the soil type, soil density, overburden pressure, reinforcement geometry, and long-term load transfer mechanisms of the reinforcement. The geogrid-soil interaction consists of both frictional and passive components. Test procedures used for quantifying the interaction values must therefore account for long-term effects, such as creep and degradation on materials of the grid structure, that are transferring frictional and passive loads.

Analysis Techniques

Limit equilibrium methods are commonly used in analyses of reinforced soil slopes. The designer must be aware of the assumptions used in development of the implemented analysis procedures. Modified Bishop's procedure, Simplified Bishop's procedure, two-part wedge, and three-part wedge methodologies are commonly used in analysis of steepened reinforced slopes. Those methods were existing analysis techniques adapted to analyze reinforced soil structures. Therefore, it is also important to check the assumptions used in adaptation of those procedures, because versions of different design charts and computer programs vary. The reinforcing properties and soil/reinforcement interaction assumptions used also must be checked for validity to the case at hand.

Design charts, such as those presented by Jewell et al. (*9*), Tensar Corp. (*10*), Schmertmann et al. (*11*), and Christopher and Holtz (*12*) may be used for final design if all of the assumptions used in their development are met. It should be noted that those charts are based on specific soil-reinforcement interaction parameters and are especially useful for conceptual cost estimating and for checking reasonability of computerized slope analyses of more complicated slopes.

A computerized search for potential failure planes in steepened highway slope structures is recommended for structures that do not meet design chart assumptions. Some existing slope stability programs have been modified to incorporate tensile reinforcement elements, such as the STABGM (*13*) program modified from STABR. The failure plane search must directly incorporate the reinforcing effects into the factor of safety computation. Further, the search must examine compound type of failures (*14*) in addition to internal and external failures. Internal, external, and compound failure planes are illustrated in Figure 5.

Decisions to use a system such as a reinforced slope often are based on experience. Details such as constructability, construction movements, and site damage factors therefore are based on specifics of those prior projects. Soil type, analysis procedures, reinforcement product, and construction control variances from early projects can affect the performance of the proposed structure. The design and specification process should address possible variances and make allowances for or prevent variances from occurring.

Appurtenant Features

As with any earth structure the design does not end with the stability analyses. The structure must be constructible and must perform over its design life. The stability of the tem-

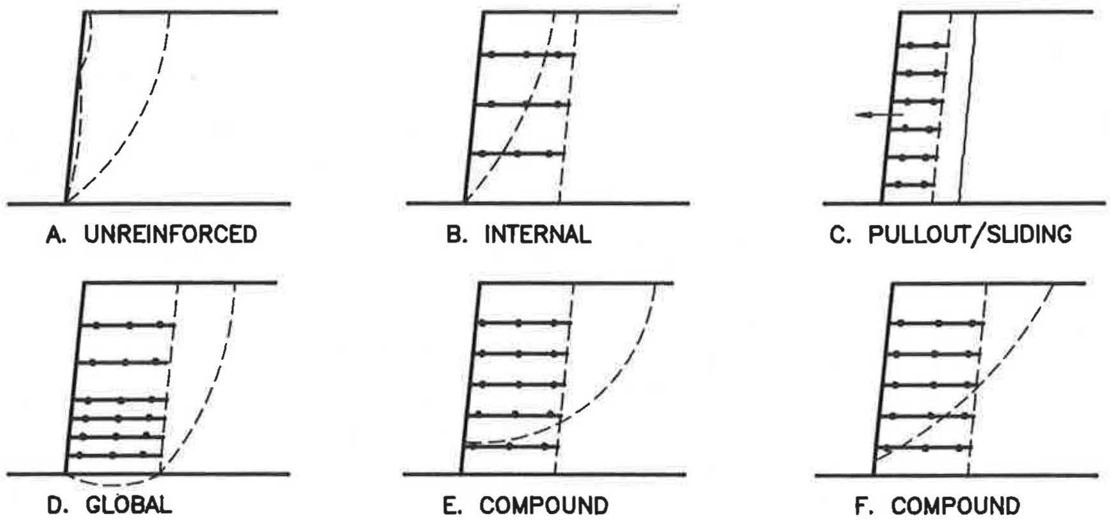

FIGURE 5 Reinforced steepened slope failure modes (*14*).

porary backcut must be assured for cut situations. Either the engineer specifies the maximum cut angle and accepts liability or the backcut stability is specified to be the contractor's responsibility. The backcut should also be benched to interlock the reinforced mass with the retained backfill soils and negate the potential formation of a linear failure plane.

Water or lack of proper drainage is a common culprit of soil structures failing or not performing as designed. Drainage both during construction and for the completed structure is an important detail that should not be overlooked during design. Surface water runoff should be diverted away from open construction cuts to minimize potential erosion and saturation of the reinforced fill soils. Partially completed fills should be sloped away from the face at the end of each work day to minimize water runoff across the slope face. Internal drains behind the reinforced mass should be installed if groundwater is, or may become, present. Often, drains are installed as an added degree of assurance even if groundwater is not anticipated.

Construction forming of some type is required for slopes steeper than about 45 to 50 degrees, depending on cohesiveness of the soil. Details of a forming system may be specified on the construction drawings or be left to the contractor's discretion. Experienced designers and contractors will know if forming is needed and, if so, which systems will work for a particular project.

Erosion control of the face of the finished slope must be considered in design. The authors recommend that a method of erosion protection be clearly specified by the designer and not be left to the discretion of the contractor or reinforcement supplier. Cost and performance of erosion control systems can vary significantly, and lack of tight specification can create a performance problem with the structure.

Specifications

As with MSE highway wall structures, two options exist in specifying reinforced slopes. One option is for the system to be preapproved by the agency and a line and grade approach be used. The system supplier will then be responsible for design, materials, and site assistance during construction. Design should include responsibility of global and compound failure modes (unlike the current MSE practice). The soil profiles and properties, required factors of safety, and analysis method should be supplied by the specifying agency. The other option is for the highway department to fully design the reinforced slope. This, of course, requires some experience of such structures. With this approach the written reinforcement specification is key to achieving desired results.

With either option, long-term design strength and long-term soil interaction characteristics of the reinforcement should be specified by using the proposed Task Force 27 Guidelines (*3*) or the Geosynthetic Research Institute Standard of Practice: GG4 (*4*) or both. The Task Force 27 guideline is specifically written for retaining walls but may be considered for slopes with minor revisions. Fill soil requirements should be modified to allow use of nonselect soils, erosion protection should be addressed, and stability factors of safety should be specified per slope application practice.

Construction Inspection

As with any earthwork construction the soil type, compaction, and moisture content should be monitored during construction. The other materials in a steepened slope (i.e., reinforcement and erosion protection) should also be inspected during construction. The grade of reinforcement, its length, and the elevations at which it is installed should be monitored by the owner's construction inspectors. Proper installation is key to satisfactory performance of an erosion control system and should therefore be closely inspected.

CASE HISTORIES

The following case histories are representative of where geogrid reinforced slopes have been used in highway construction to date. Steepened slope projects are emphasized because they have the broadest applicability to highway construction. References to technical papers, when available, are provided for further information.

Project Name: Van Duzen, Peanut, California Forest Highway and Federal Lands, Highway 4-1(5)

- *Owner*: USDA Forest Service and Caltrans
- *Specifying agency*: U.S. Department of Transportation, Federal Highway Administration, Central Direct Federal Division
- *Designer*: U.S. DOT, FHWA, Central Federal Division
- *Slope heights*: Approximately 20 to 60 ft
- *Slope angle (H:V)*: 1:1
- *Facing system*: Turf reinforced with a polymer mat
- *Alternative*: Retaining walls/flattened slopes
- *Reinforcement type*: TENSAR UX1600, UX1500, UX1400, BX1100 geogrids
- *Construction date*: Sept. 1987 to Nov. 1988

Five side-hill fills of a new federal roadway through scenic Redwood Forest of northern California were constructed with steepened slopes. The 1 : 1 slopes were constructed with polymer soil-reinforcing geogrids. The steepened embankments range from 100 to 400 ft long and are 20 to 60 ft high. A typical reinforcement layout is illustrated in Figure 6. The fill soils were cohesionless and could ravel during and after construction. Intermediate reinforcing geogrids were used to minimize raveling during construction. The finished slopes were faced with native grasses, which were seeded into a three-dimensional polymer turf-reinforcing mat to prevent post-construction raveling.

The Central Direct Division of the FHWA designed the geogrid-reinforced steepened slopes and administered construction, which was completed in fall 1988. Working in conjunction with the U.S. Forest Service and Caltrans, the FHWA selected geogrid-reinforced slopes over retaining walls for their economy, aesthetics, and safety in this mountainous terrain.

Project Name: Cannon Creek

- *Specifying agency/owner*: Arkansas State Highway and Transportation Department
- *Designer*: Raymond Technical Facilities
- *Slope height*: 76 ft
- *Slope angle (H:V)*: 2:1
- *Facing system*: vegetation
- *Reinforcement type*: TENSAR UX1500 geogrid
- *Alternative*: new geometry and purchase of additional right-of-way
- *Cost savings*: $200,000

A large embankment was planned to carry State Highway 16 over Cannon Creek. The proposed 100,000-yd^3 embankment had a maximum height of 76 ft and was to be constructed with on-site clay soils and 2 : 1 side slopes. A cast-in-place concrete box culvert was first constructed to carry the creek under the embankment. Embankment construction started but was stopped quickly when several small slope failures occurred. It then became apparent that the embankment fill could not be safely constructed at 2 : 1 slopes.

With the box culvert in place there were two options for continuation of embankment construction. A gravelly soil could be used for embankment fill or on-site soils could be used with geogrid reinforcement. Both options were bid as alternatives, and the geogrid option, as illustrated in Figure 7, was used in construction. The geogrid reinforcement option was estimated to be $200,000 less expensive.

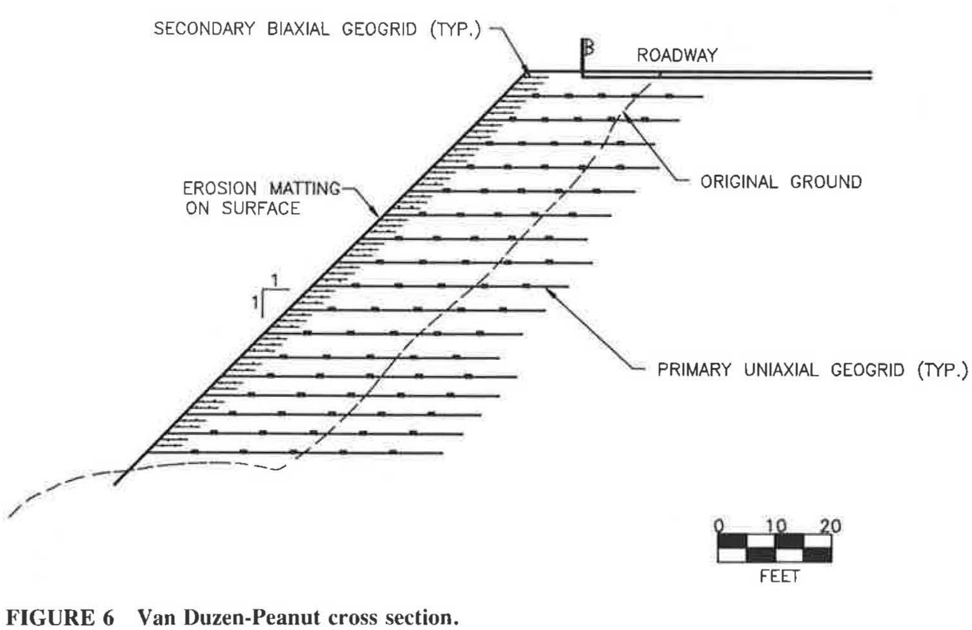

FIGURE 6 Van Duzen-Peanut cross section.

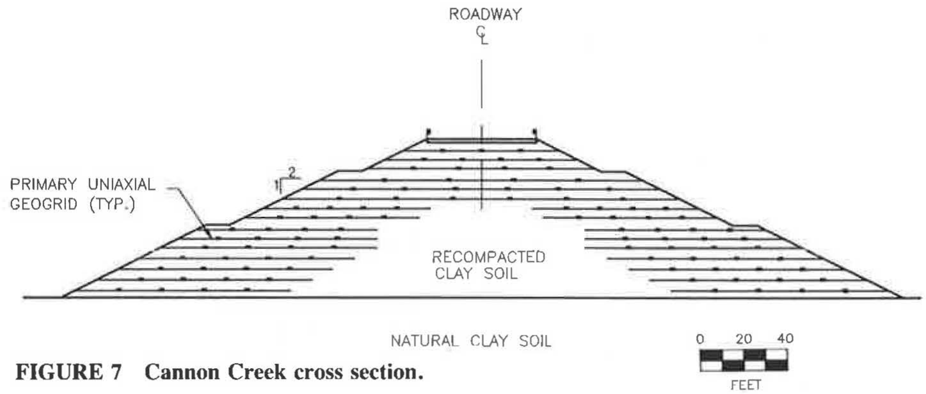

FIGURE 7 Cannon Creek cross section.

Project Name: Maryland Route 410

- *Specifying agency/owner*: Maryland Department of Transportation
- *Designer*: Tensar Engineering, Inc.
- *Slope height*: 48 ft
- *Slope angle* (H:V): 1.5:1
- *Facing system*: vegetation
- *Reinforcement type*: TENSAR UX 1400 and UX 1500
- *Alternative*: imported select fill or retaining walls
- *Construction date*: Summer 1989

A new interchange on U.S. Route 50 at MD Route 410 and MD Route 450 was designed by the Maryland Department of Transportation. Existing ROW were not wide enough to accommodate the new embankments. Embankments at slopes of 2.5 : 1 could be carried to the ROW limits and retaining walls constructed to contain the fill or additional ROW could be purchased. However, part of the existing embankment was an uncontrolled fill that could not be widened by building on top of it. It would need to be excavated and removed or recompacted.

Steepened geogrid-reinforced slopes were selected for construction. The 1.5H:1V slopes stayed within existing ROW limits and eliminated the need for retaining walls (see Figure 8). Some of the original uncontrolled fill was excavated and recompacted during installation of the stabilizing reinforcement. A view of the slope under construction is presented in Figure 9. Slopes were faced with native vegetation and did not require a permanent erosion mat system. Drains were installed behind the reinforced mass to intercept any possible groundwater.

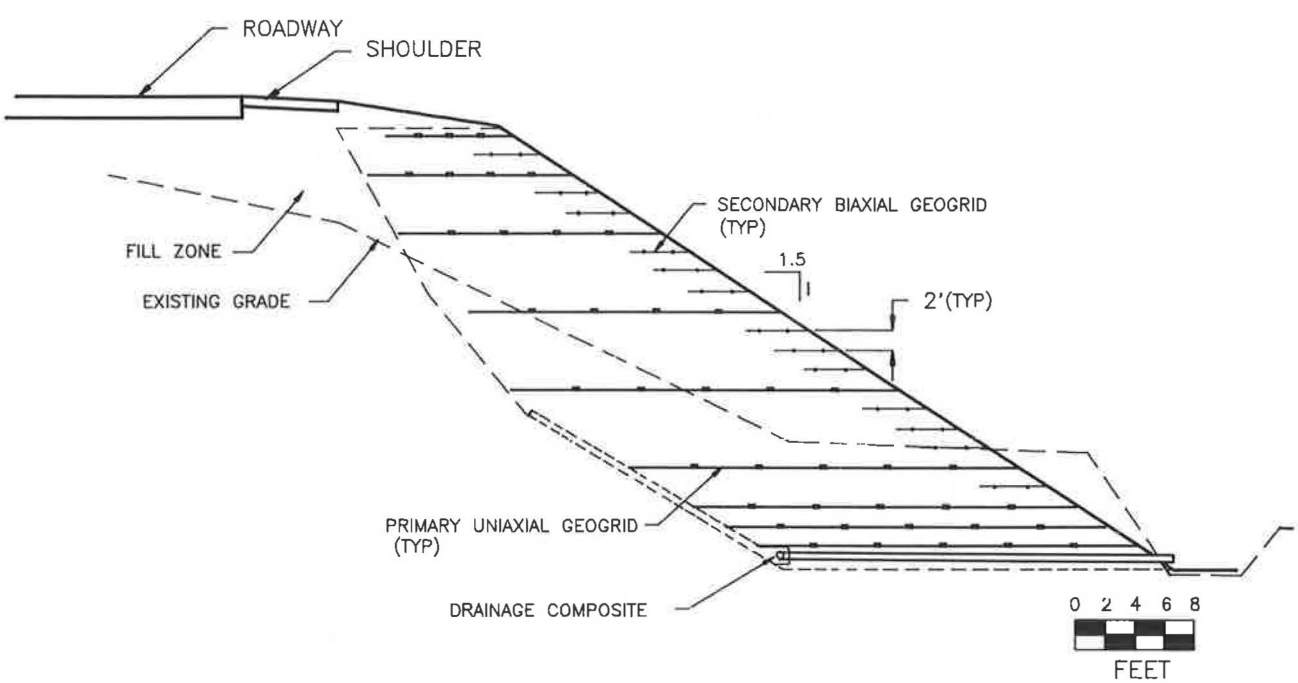

FIGURE 8 Maryland Route 410 cross section.

FIGURE 9 Maryland Route 410 project photo.

Project Name: Pennsylvania Turnpike-PTC 6902-86-628

- *Specifying agency/owner*: Pennsylvania Turnpike Authority
- *Designer*: Baker Engineers
- *Slope heights*: 13 ft reinforced; 35 ft total height
- *Slope angle (H:V)*: 1:1 on upper reinforced slope; maximum 1.5:1 on unreinforced slope below
- *Facing system*: geogrid wrap with vegetation
- *Reinforcement type*: TENSAR UX 1600, UX 1400, BX 1100 geogrids
- *Alternative*: retaining wall
- *Construction date*: Summer 1988

The Pennsylvania Turnpike Authority began widening the existing 50-year-old turnpike along the exterior lanes. On this project a geogrid-reinforced slope was used in existing fill sections to add a 10-ft-wide paved shoulder (as shown in Figure 10). A 1 : 1 backcut was used in construction, which allowed traffic to be maintained on the existing traffic lanes.

The reinforced slope option provided an estimated 25 percent cost savings over retaining walls and even a greater savings over a conventional slope. Soil borings from the original construction 50 years ago and performance of existing slopes were used to select soil parameters. This method of road widening has now become a standard procedure with the Pennsylvania Turnpike Authority.

CONCLUSIONS

1. Geogrid-reinforced slopes have broad applicability to highway construction and are (a) an economic alternative to conventional grade separation construction methods; (b) used to build steepened slopes, provide surficial reinforcement, build compound slopes for road widening, repair landslides, construct embankments over soft foundations, and build retaining walls; and (c) a proven method of construction used by a variety of transportation agencies and major design consultants.

2. Steepened slopes can cost up to 50 percent less than retaining walls.

3. Steepened, reinforced highway slopes may be specified as (a) packaged systems, where lines and grades are presented in the bid package and materials, design, and technical assistance are supplied by a single source or (b) designed in-house with the reinforced material a specified item.

4. Geogrid-reinforcement elements should be specified with consideration of installation damage, long-term soil inter-

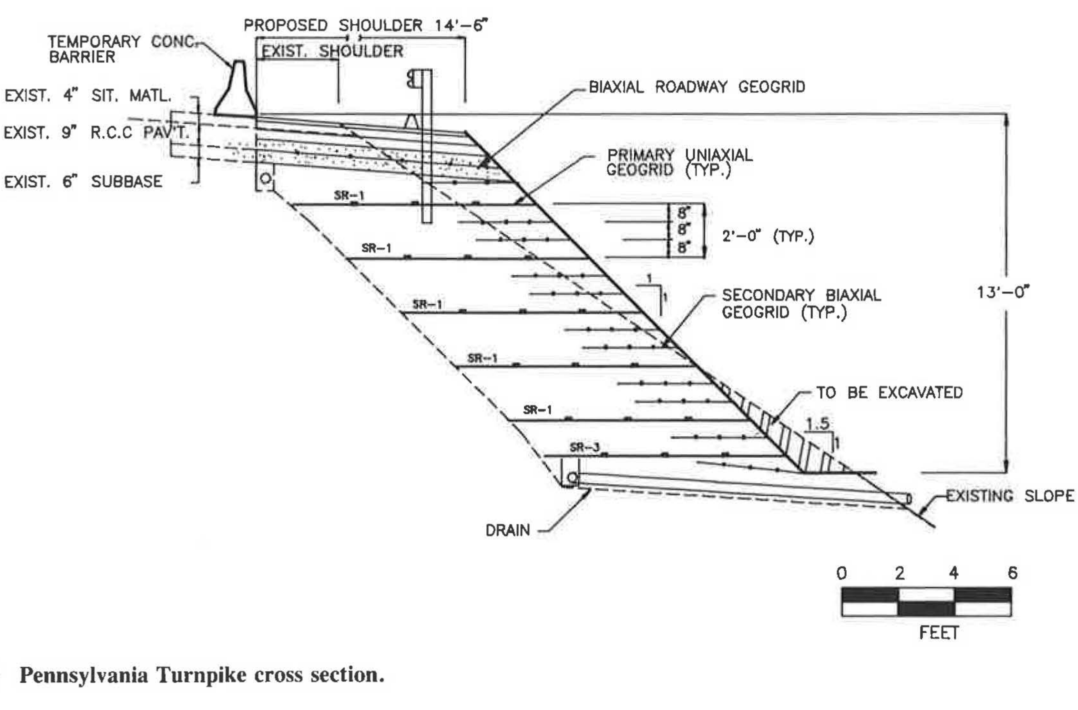

FIGURE 10 Pennsylvania Turnpike cross section.

action characteristics, long-term creep, and chemical and biological degradation potential over the design life of the structure.

5. Steepened, reinforcement slopes may be specified as an alternative grade separation method to retaining walls or flat slopes or both.

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