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16. Abstract

Geosynthetics provide a means to mechanically stabilize earth structures by improving strength through tensile reinforcement. When incorporating these polymeric materials in the application of stabilizing steep slopes, geosynthetic reinforcement can accommodate budgetary restrictions and alleviate space constraints. TxDOT currently has limited use of geosynthetics in steep slope construction. Therefore, a synthesis study of geosynthetic reinforced steep slopes has been conducted to enhance the present understanding of this technology. The study summarized the benefits and limitations of utilizing geosynthetic reinforcement and investigated current design and construction methods in order to determine best practices. Additionally, the cost effectiveness of geosynthetic reinforced steep slopes was examined. Case studies were also identified and assessed to determine optimal soil conditions, geometry of the slope, design criteria, construction specifications, and performance measures. The synthesis study summarized best practices, existing methodologies, and recommendations for the use of geosynthetic reinforced steep slopes in Texas.

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GEOSYNTHETIC REINFORCED STEEP SLOPES

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of TxDOT. This report does not constitute a standard, specification, or regulation. This report is not intended for construction, bidding, or permit purposes. The researcher in charge of the project was Dr. Yoo Jae Kim.

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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER I: INTRODUCTION

This study provides a thorough synthesis of and report on the state of practice of geosynthetic reinforced steep slopes (GRSS). Findings from state, national, and international sources were summarized and compared to establish best practices for the Texas Department of Transportation (TxDOT). The research team synthesized information gathered from a literature review, interviews, and surveys of transportation agencies, educational institutions, consulting engineers, manufacturers, material suppliers, and construction contractors.

The survey utilized in the study was developed by the research team based on the technical objectives of the project and uploaded to an online survey site (surveymonkey.com). The online survey allowed each respondent to take the survey remotely on their own time frame and then stored responses internally to be accessed and downloaded by the research team at their convenience. The survey was sent to 393 recipients, and responses were received from 52 for a response rate of 13 percent.

Based on the survey results, researchers identified sources that could provide information to develop case studies where the construction of GRSS had been recently completed. A case study template was subsequently produced that focused on numerous characteristics of existing slopes, including foundation and embankment soil conditions, geometry of the slope prior to and after construction, design equations and criteria, construction methods, material performance, location, and cost. The template was sent to 43 survey respondents that have experience designing or constructing GRSS, and responses were received from two. Additional historical project information was acquired from publications and manufacturers in order to compile a total of 60 case studies.

To obtain supplementary information and professional insight, experts were also identified from the survey and interviewed via telephone. A questionnaire was developed and used as a guideline for the interviews. The research team interviewed six experts regarding GRSS design and construction methods.

SCOPE

GRSS can yield potential savings in material costs and construction time for new permanent embankments and recurring slope failures. However, an understanding of design and construction is required to effectively use this method of mechanically stabilizing earth. Consequently, a synthesis of the following information was performed:

1. Identify GRSS case studies.
2. State the foundation and embankment soil conditions.
3. State the geometry of the slope.
4. Identify the design methods used for GRSS.
5. Identify the construction specifications, sequence, and problems.
6. State the performance of the case studies.

To accomplish the technical objectives, the researchers carried out a comprehensive work plan that covered the following tasks:

- Review current practices of GRSS as well as previous literatures.
- Conduct survey of transportation agencies, educational institutions, consulting engineers, manufacturers, material suppliers, and construction contractors.
- Perform interviews of selected experts for additional information.
- Summarize the results with conclusions and recommendations.

The following chapters of this report document each of the tasks conducted in the research project:

- Chapter I: Introduction.
- Chapter II: Design Methods and Materials.
- Chapter III: Construction Practices.
- Chapter IV: Performance Measures and Cost Effectiveness.
- Chapter V: Case Studies.
- Chapter VI: Conclusions and Recommendations.

Supplementary information is presented in Appendices A through I, including survey and interview results as well as design examples, case studies, transportation agency specifications, and construction checklists.

RESEARCH SIGNIFICANCE

Geosynthetics have been used in the United States as a reinforcement element for soil structures since 1972 (Jones et al., 1987). The literatures on geosynthetics document an increase in use for the repair of failed slopes and for new construction (Holtz et al., 1998). However, there is a need to evaluate the factors that contribute to cost in order to optimize the use of geosynthetics. Furthermore, to apply the technology and techniques in an effective manner, it is critical to determine the factors leading to the successes and failures of GRSS, including the investigation of site conditions, material properties, design methods and construction practices.

DEFINITION

Reinforced slopes are a form of mechanically stabilized earth that incorporates planar reinforcing elements for the construction of sloped structures with inclinations less than 70°. Structures with inclinations over 70° are classified as walls (Holtz et al., 1998). For uniform fill soil, there is a limiting slope angle under which an unreinforced slope may be built safely. The limiting angle of the slope is equal to the friction angle of the soil in the case of a cohesionless and dry material. Therefore, a slope with an angle greater than the limiting slope angle is referred to as a steep slope, which requires additional forces to maintain equilibrium (Rimoldi et al., 2006).

The purpose of steep slope construction is to solve problems in locations of restricted right-of-way and at marginal sites with difficult subsurface conditions and other environmental constraints. Since soil has limited tensile strength, similar to concrete, reinforcement must be used to overcome this weakness (S&P, 2009). To improve strength and make a soil structure self-supporting, tensile reinforcing elements are placed in the soil. The reinforcing elements can also withstand bending from shear stresses, providing increased stability to steep slopes (Elias et al., 2001).

BACKGROUND AND HISTORY

Soil reinforcement concepts and technologies originated in prehistoric times. Straw, sticks, and branches were traditionally used to improve the quality of adobe bricks, reinforce mud dwellings, and even reinforce soil for erosion control (Elias et al., 2001). However, modern techniques for mechanically stabilizing soil were introduced in the 1960s. First used in France, a method known as "reinforced earth" used embedded narrow metal straps to reinforce soil (Vidal, 1969). In 1972, this technique was adopted in the United States by the California Division of Highways for construction of retaining walls. Many other soil reinforcement methods were researched and implemented following the first applications in the United States (Jones et al., 1987).

Through scientific advances in construction material technology, it has been possible to construct larger and more elaborate structures. Moreover, major developments in the fields of civil and structural engineering have been strongly influenced by the rapid growth of geosynthetic products. In 1970, during the initial industrial development phase of geosynthetic materials, there were only five or six geosynthetics available. However, due to their positive influence on engineering and construction practices, there are now over 600 geosynthetic products available. In some applications, the use of geosynthetics has even replaced many traditional construction materials. Valued at approximately $1.5 billion, the worldwide annual consumption of geosynthetics is nearly one billion square yards (Holtz, 2001).

Geosynthetic reinforcement of steep slopes was initially utilized to repair failed slopes. In lieu of importing soil to reconstruct the slopes, the slide debris was salvaged and reused with the addition of the geosynthetic reinforcement, resulting in cost savings. To provide stability, multiple layers of geosynthetic materials were placed in a fill slope during reconstruction. As per Figure 1, in addition to repairing failed slopes, steep slope reinforcement has also been introduced for the construction of new embankments, the widening of existing embankments, and as an alternative to retaining walls (Holtz, 2001).

As GRSS became constructed to perform as permanent structures, the structural analysis method used for near vertical reinforced walls was adopted, which relies on analytical predictions, factors of safety, and reduction factors. Consequently, design methods for reinforced steep slopes are reasonably conservative (Leshchinsky et al., 1995). Furthermore, as the availability of geosynthetics increased and its competitiveness encouraged more frequent use, there was a paralleled growth in technological developments and applications (Jones et al., 1987). Research efforts regarding the design and application of geosynthetics are rapidly increasing on the international level as well, including investigations in Canada, Taiwan, and the United Kingdom (McGown et al., 2005; Pathak and Alfaro, 2005; Hsieh, 2005).

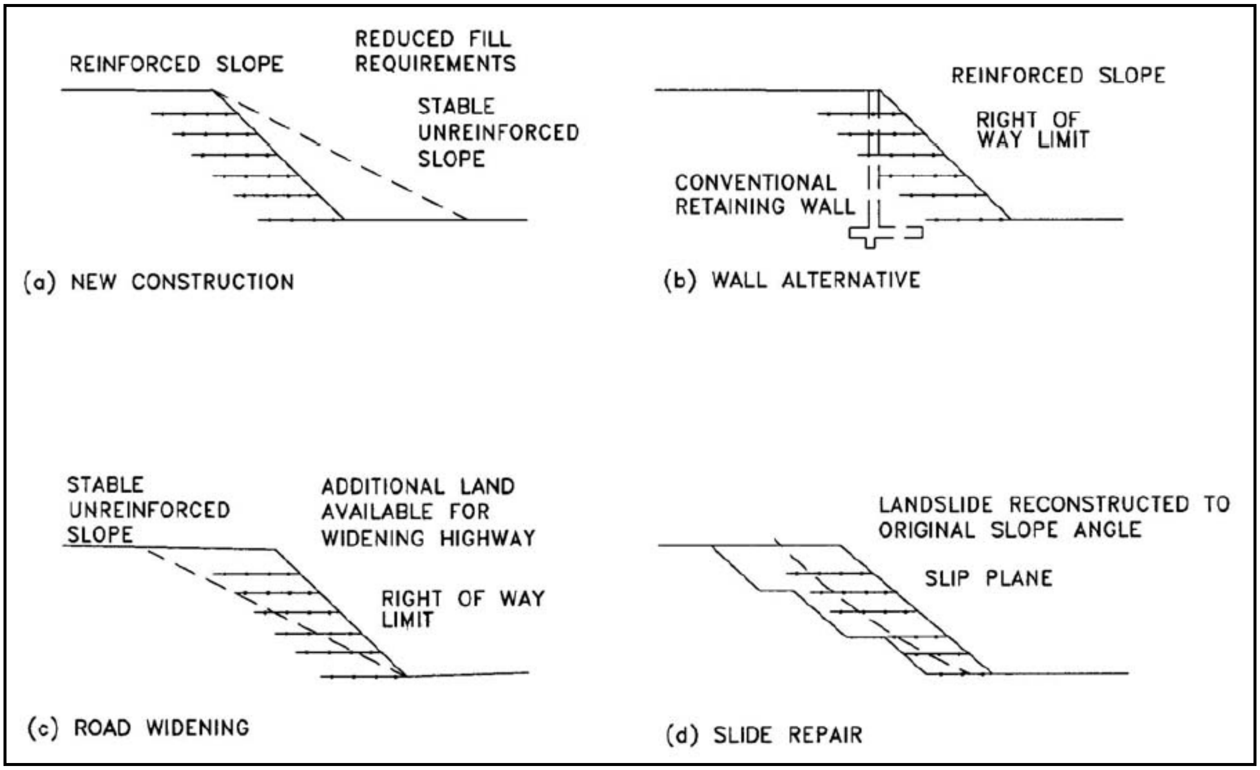


Figure 1. Geosynthetic Reinforced Steep Slope Applications (Berg et al., 2009).

GEOSYNTHETICS

Geosynthetics are artificial materials used to improve soil conditions by providing tensile resistance and stability. When compared to conventional geotechnical designs and construction alternates, such as retaining walls or unreinforced slopes, geosynthetics can increase safety factors, improve performance, and reduce costs (Holtz, 2001). Geosynthetics are typically manufactured from petrochemical-based polymers, making them resistant to biological decomposition. Therefore, the longevity of geosynthetic reinforcement in normal soil environments is a fundamental benefit. However, petrochemicals and ultraviolet light can still cause some geosynthetics to deteriorate. As part of a civil engineering project or system, geosynthetics can be employed on or in soil and may perform multiple functions. The polymeric reinforcement materials provide a means to separate, confine, and distribute loads to improve level-grade and sloped-grade conditions. Geosynthetics are also used to reinforce soil, prevent soil movement, and control water pressure (Brown, 2006). Although over 150 applications have been identified, geosynthetics have six primary functions: filtration of soil particles subjected to hydraulic forces, drainage of fluids and gases, separation of soil types, reinforcement of soils to enable construction of steep slopes, barrier of soils to prevent contamination, and protection to prevent punctures (Holtz, 2001; GEOfabrics Limited, 2011). In the case of soil reinforcement, a primary application of geosynthetics involves reinforcing steep slopes. With the use of geosynthetics, the construction of reinforced steep slopes is often more affordable and technically feasible when compared to traditional construction techniques (Holtz, 2003). Furthermore, geosynthetic reinforcement is a cost effective solution for stabilizing recurring slope failures and constructing new permanent embankments (Leshchinsky et al., 1995; Rowe and Jones, 2000).

CHAPTER II: DESIGN METHODS AND MATERIALS

To meet the technical objectives of the study, the research team identified and evaluated GRSS design methods and material selection guidelines. Design procedures from multiple sources were analyzed, including those recommended by state, national, and international agencies. Computer software that aids in the design of GRSS was also reviewed, obtained, and tested.

DESIGN METHODS

The majority of survey respondents recommended the use of the Federal Highway Administration (FHWA) guidelines for the design of GRSS as per Figure 2. The technique has been adopted by many transportation agencies in the United States and South America (Ehrlich and Becker, 2010). Less advocated approaches included Eurocode and other design methods, such as EBGEO and British Standard 8006. Additionally, 88 percent recommended the use of geogrid or a combination of geogrid and geotextile for slope reinforcement, while the others recommended independent use of geotextile. Some prefer high strength geotextiles over geogrids, as they provide a separation function and can be more cost effective in certain cases.

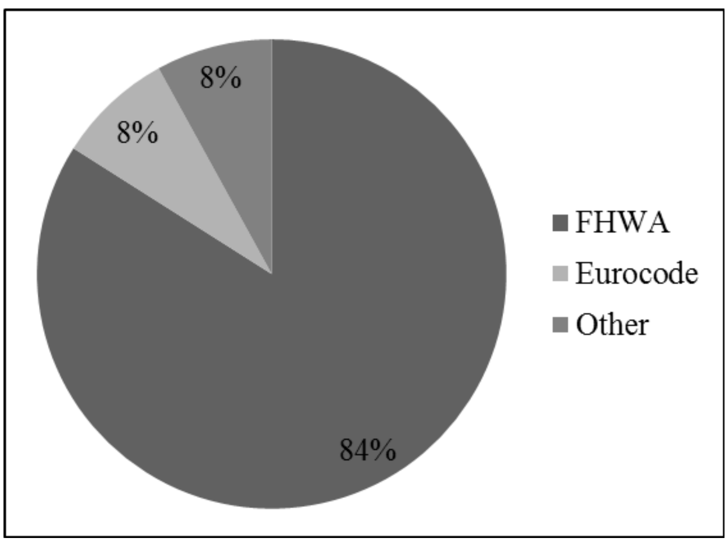


Figure 2. Recommended Design Methods.

The internal stability of a soil slope can be determined by four basic factors, including the slope angle (β), soil weight (W), cohesion (c), and internal friction angle (ϕ) as per Figure 3. The cohesion is a measure of the forces that cement particles of soil, and the internal friction angle is a measure of the shear strength of soils due to friction. The force causing failure, the resisting strength, and the factor of safety are also dependent upon the length of the plane of weakness (L) as follows (Abramson, 2002):

- Force Causing Failure = (W × sinβ).
- Resisting Strength = (c × L) + (W × cosβ × tanϕ).
- Factor of Safety = (Resisting Strength / Force Causing Failure).

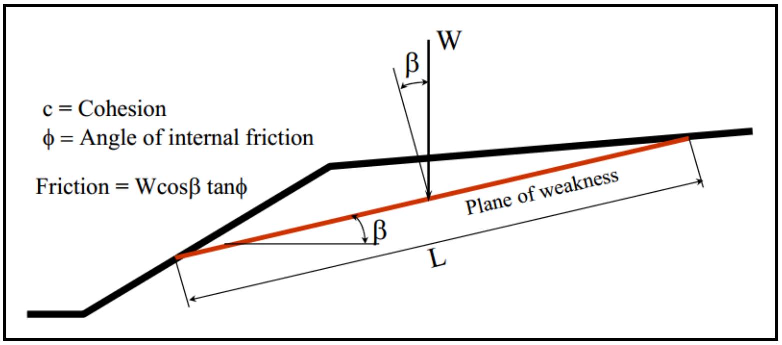


Figure 3. Internal Stability of a Soil Slope.

The factor of safety is the ratio of the resisting strength to the force causing failure, which is indicative of the stability of a slope. The forces are in equilibrium when the factor of safety is equal to 1.0. If the forces causing failure are greater than the resisting strength, then the factor of safety is less than 1.0 and the slope will fail. However, a higher factor of safety designates a greater resistance to collapse.

Granular soils (sand and gravel) do not display cohesive behavior under unconfined conditions. A small amount of apparent cohesion may exist due to negative pore water pressure within unsaturated soil particles, although it should not be relied upon for the design of slopes. Additionally, the high permeability of granular soils effectively prevents excess pore water pressure. Conversely, considerable cohesive strength is found in fine grained soils (clay and silt) due to inherent negative pore water pressure that leads to increased effective stress. Since pore water pressure increases in a soil mass with low permeability, the analysis for fine grained soils may be performed using an undrained Mohr-Coulomb failure envelope with an internal friction angle equal to zero (Abramson, 2002).

According to the Mohr-Coulomb failure criteria theory, a material fails because of a combination of normal stress and shear stress. The combination of stresses creates a more critical limiting state than would exist if the principal stresses were acting individually. This concept is illustrated by the Mohr-Coulomb failure envelope in Figure 4. Circle A is indicative of a safe stress state since it is plotted below the failure line. Conversely, a critical stress combination is evident for Circle B, which is tangential to the failure envelope.

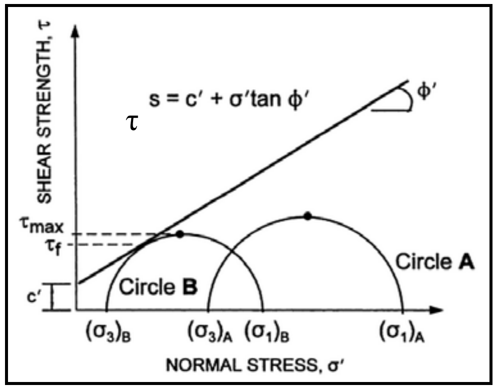


Figure 4. Mohr-Coulomb Failure Envelope for Shear Strength of Soils (Abramson, 2002).

The shear strength (τ) of an undrained saturated soil is controlled by the material properties and effective stress conditions (Wilson et al., 1999):

$$\tau = c' + [(\sigma_n - \mu_w) \times \tan\phi']$$

where:
c' = effective cohesion of the soil.
σ_n = normal stress.
μ_w = pore water pressure.
ϕ' = effective internal friction angle of the soil.

Bishop Method

To define the limit-equilibrium conditions, Bishop (1955) investigated the use of the slip circle in the stability analysis of slopes as per Figure 5. The circular failure analysis is performed on a cross-section by dividing it into vertical slices, resolving forces on each slice to calculate the factor of safety, and summing all slice results over the entire slope to obtain an overall factor of safety. It is typically used for a quick analysis of a simple slope composed of unconsolidated materials. The following equation is used to calculate the factor of safety (FS):

$$FS = \frac{\Sigma\{[(c' \times b) + [W + (P \times \cos\beta) - (\mu_w \times b \times \sec\alpha)] \times \tan\phi'] / m_\alpha\}}{\Sigma(W \times \sin\alpha) - [(\Sigma M_P) / R]}$$

where:
c' = effective cohesion of the soil.
b = width of the slice.
W = weight of the slice.
P = total normal force on the base of the slice.
β = slope angle.
μ_w = pore water pressure.
α = inclination angle of the base of the slice.
ϕ' = effective internal friction angle of the soil.
m_α = $\cos\alpha + [(\sin\alpha \times \tan\phi') / F]$.

M_P = moment about the center of the circle produced by P.
R = radius of the circle.

An iterative, trial and error procedure is required to solve the equation since the factor of safety appears on both sides. Factors of safety calculated by the Bishop method are comparable with those calculated using other methods. Investigators have shown that it is typically within 5 percent of other solutions (Whitman and Bailey, 1967; Fredlund and Krahn, 1977). However, since horizontal forces are not satisfied, it is not recommended for seismic analysis where additional horizontal forces are applied.

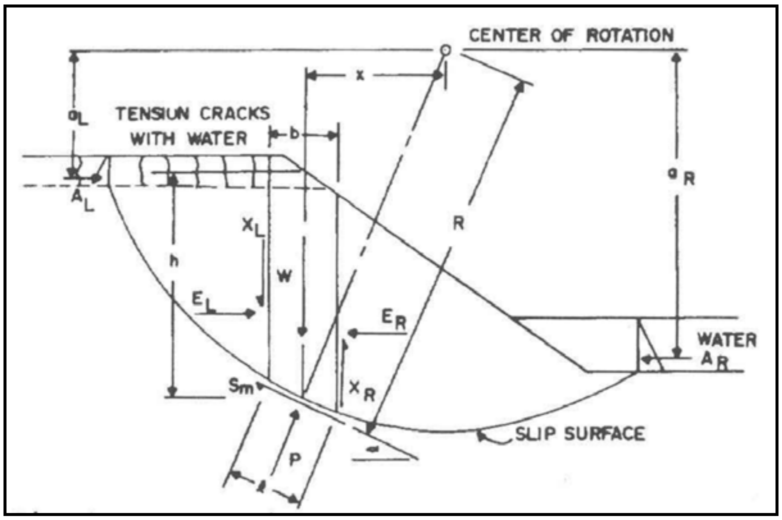


Figure 5. Vertical Slice Parameters for Internal Stability Analysis (Fredlund and Krahn, 1977).

Spencer Method

Spencer (1967) developed another method of analysis for embankment stability by assuming parallel interslice forces as per Figure 6. It can be used for both circular and non-circular failure surfaces in simple structures and can verify a Bishop analysis. Also, whereas the Bishop method only satisfies the vertical force and moment equilibrium, the Spencer limit-equilibrium technique balances the horizontal force, vertical force, and moment equilibrium. An iterative, trial and error procedure is repeated in which values for the factor of safety and side force inclination are assumed until all conditions of force and moment equilibrium are satisfied for each slice. The following equations are used to calculate the uphill and downhill interslice forces as well as the net system moment:

$$Z_u = \frac{[(c / FS) \times b \times \sec\alpha] - (\gamma \times \sin\alpha) + \{(\tan\phi / FS) \times [(\gamma \times \cos\alpha) - (\mu \times b \times \sec\alpha)]\}}{\cos(\alpha - \delta_u) \times \{1 + [(\tan\phi / FS) \times \tan(\alpha - \delta_u)]\}}$$

$$Z_d = \frac{\cos(\alpha - \delta_d) \times \{1 + [(\tan\phi / FS) \times \tan(\alpha - \delta_d)]\}}{\cos(\alpha - \delta_u) \times \{1 + [(\tan\phi / FS) \times \tan(\alpha - \delta_u)]\}}$$

$$M_n = \Sigma\{0.5 \times Z_d \times [(\sin\delta_d \times (b_i + b_j)) - [\cos\delta_d \times ((b_i \times \tan\alpha_i) + (b_j \times \tan\alpha_j))]]\}$$

where:

Z_u = interslice force on the upslope side.
Z_d = interslice force on the downslope side.
M_n = net system moment.
c = cohesion of the soil.
FS = factor of safety.
b = width of the slice.
α = inclination angle of the base of the slice.
γ = unit weight of the soil.
ϕ = internal friction angle of the soil.
μ = pore pressure.
δ = angle of interslice force.
u,d = upslope or downslope side of the slice.
i,j = slice number.

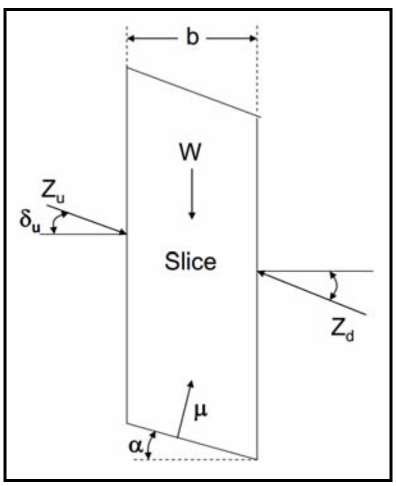


Figure 6. Spencer Method of Internal Stability Analysis.

The interslice force can vary between slices and the value of the angle is represented by the following function:

$$\tan\delta_i = (k_i \times \tan\theta)$$

where:

δ_i = angle of interslice force on the upslope side.
k_i = 1 (linearly reduced to 0 over the last 20 percent of slices).
θ = constant angle (Spencer's theta).

Equilibrium is reached for the factor of safety and the value of Spencer's theta for which the resultant moment and the upslope side interslice force on the last slice are equal to zero. Moreover, the following force and moment equations must be satisfied:

$$Z_n(F,\theta) = 0$$

$$M_n(F,\theta) = 0$$

The Spencer method requires computer software to perform the calculations to satisfy the moment and force equilibrium for every slice. Calculations are also repeated for a number of trial factors of safety and interslice force calculations. This stability analysis method is used when a statically complete solution is desired, and it can be checked using the force equilibrium procedure (USACE, 2003).

Sarma Method

Stability analysis of slopes was also researched by Sarma (1979), who implemented a different approach to determining the factor of safety that is intended for only non-circular failure surfaces. First, a horizontal acceleration is applied to the material above the failure surface, and then the factor of safety is calculated for the soil mass. A factor of safety equal to 1.0 is achieved by reducing the soil strength parameters until no horizontal acceleration is required for failure. The engineering properties are reduced by trial and error to reach a critical acceleration (K_c) of zero. A state of equilibrium is produced when the resisting strength of the material equals the driving forces. This method was developed specifically to predict deformation due to seismic loading.

Jewell Method

Jewell (1980) investigated the effects of reinforcement on the mechanical behavior of soils. Findings indicated that the state of stress was modified due to the shear generated by the tensile reinforcement. The horizontal forces required to maintain equilibrium are calculated as a gross force as follows:

$$T = (0.5 \times K \times \gamma \times H^2)$$

where:
T = tensile force.
K = equivalent earth pressure coefficient.
γ = unit weight of the soil.
H = height of the slope.

Additional design equations and charts were also developed by Jewell (1990) that allow for determination of the earth pressure coefficient and the length of reinforcement as a function of the slope angle, soil friction angle, and water pressure parameter. These charts are applicable for steep slopes reinforced with geogrids that have the following conditions:

- Slope is uniform with a horizontal crest and a slope angle in the range of 30° to 90°.
- Foundation is leveled and with adequate bearing capacity.
- Fill material is of a single type.
- Fill characteristics are expressed in terms of effective stresses with $c' = 0$.
- Maximum pore water pressure (r_μ) is expressed as: $\max[\mu(z) / (z \times \gamma)]$.
- Surcharge loading on the crest (if present) is uniformly distributed.
- Reinforcement is continuous and is placed horizontally in the fill.

The charts do not allow for:

- Totally submerged slopes.
- Point or line loading on the crest or loading on the slope face.
- Dynamic loading.
- Soil shear strength expressed in terms of total stresses.

According to the Jewell method, the following step by step design chart procedure is used for determining the reinforcement required to stabilize a steep slope. A GRSS design example is also provided in Appendix E.

1. Define the geometrical configuration of the slope and the uniformly distributed surcharge loading on the top of the slope. Calculate the apparent height:

$$H' = H + (q / \gamma)$$

where:
H' = apparent height of the slope.
H = height of the slope.
q = surcharge load.
γ = unit weight of the soil.

2. Define the design factor of safety (FS_{design}) and geogrid factors of safety ($FS_{grid} = FS_{creep} \times FS_{junction} \times FS_{construction} \times FS_{chemical} \times FS_{biological}$). Then, calculate the allowable resistance (P) for the reinforcement using the following equations in terms of the long-term design strength of the grid:

$$T_{allow} = T_{ult} / FS_{grid}$$

$$P = T_{allow} / FS_{design}$$

3. Define the soil parameters and the maximum pore water pressure (r_μ):

   $r_\mu = \max[\mu(z) / (z \times \gamma)]$

where:
$\mu(z)$ = pore water pressure at depth z under the crest of the slope.

4. Using the slope angle and soil internal friction angle, calculate the coefficient of earth pressure and the ratios of reinforcement length to embankment height for overall stability $(L/H)_{ovrl}$ and direct sliding $(L/H)_{ds}$ using the charts in Figure 7. Select the charts based on the pore water pressure value, and select the reinforcement length as follows:

a) If $(L/H)_{ovrl} > (L/H)_{ds}$ then the reinforcement length (L) shall be constant and equal to:

$$L = H' \times (L/H)_{ovrl}$$

b) If $(L/H)_{ovrl} < (L/H)_{ds}$ then the reinforcement length can be constant and equal to:

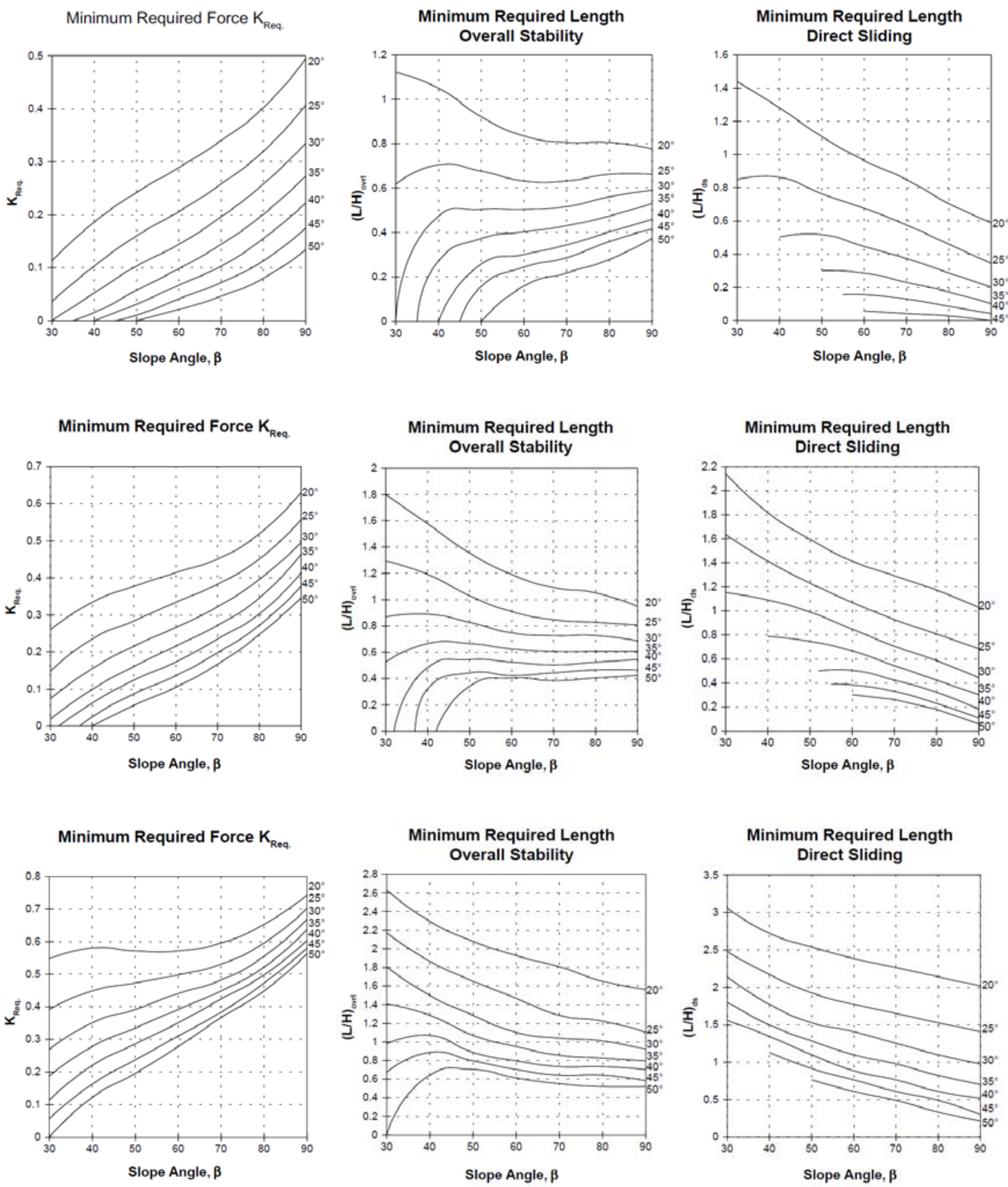
$$L = H' \times (L/H)_{ds}$$

Or the reinforcement length can vary uniformly from the length at the base:

$$L = H' \times (L/H)_{ds}$$

To the length at the crest:

$$L = H' \times (L/H)_{ovrl}$$



$r_{\mu} = 0.00$

$r_{\mu} = 0.25$

$r_{\mu} = 0.50$

Figure 7. Geosynthetic Reinforced Steep Slope Design Charts (Jewell, 1990).

5. Select the minimum vertical spacing for a single layer of compacted soil and calculate the spacing constant (Q):

   $Q = P / (K \times \gamma \times v)$

where:

P = allowable resistance of the reinforcement.

K = equivalent earth pressure coefficient.
γ = unit weight of the soil.
v = vertical spacing.

6. Define the zones for reinforcement layers spaced equally at v, 2v … nv as shown in Table 1. If $H' < Q$ the minimum spacing at the base of the slope will have to be reduced or a more resistant geogrid has to be selected.

Table 1. Calculation of Reinforcement Spacing.

i	Spacing (S_{vi})	Depth (Z_i)	Thickness (s_i)
1	$S_{v1} = v$	$Z_1 = Q / (Q / 2)$	$s_1 = H' - (Q / 2)$
2	$S_{v2} = 2v$	$Z_2 = (Q / 2) / (Q / 3)$	$s_2 = (Q / 2) - (Q / 3)$
n	$S_{vn} = nv$	$Z_3 = (Q / n) / (q / \gamma)$	$s_n = (Q / n) - (q / \gamma)$

7. Calculate the number of required reinforcement layers. The first layer is placed on the foundation at the base of the slope, and the other layers are calculated starting from the base. As per Table 2, the thickness of every zone is divided by the spacing of the reinforcement layers to calculate the number of grids in a zone. The result is rounded to the nearest whole number. Then, the remaining thickness of the zone is calculated and added to the thickness of the next zone. If the top layer of reinforcement is more than 2 ft below the slope crest, an additional layer should be added near the crest.
8. Calculate the gross horizontal force required for equilibrium:

$$T = [0.5 \times K \times \gamma \times (H')^2]$$

where:
T = tensile force.
K = equivalent earth pressure coefficient.
γ = unit weight of the soil.
H′ = apparent height of the slope.

Table 2. Calculation of Reinforcement Layers.

i	s_i' / S_{vi}	Number of Grids (N_i)	Remaining Thickness (R_i)	s_{i+1}'
0			$R_0 = 0.0$ ft	$s_1' = s_1 + R_0$
1	s_1' / S_{v1}	$N_1 = (s_1' / S_{v1})_{\text{whole number}}$	$R_1 = s_1' - (S_{v1} \times N_1)$	$s_2' = s_2 + R_1$
2	s_2' / S_{v2}	$N_2 = (s_2' / S_{v2})_{\text{whole number}}$	$R_2 = s_2' - (S_{v2} \times N_2)$	$s_3' = s_3 + R_2$
n	s_n' / S_{vn}	$N_n = (s_n' / S_{vn})_{\text{whole number}}$	$R_n = s_n' - (S_{vn} \times N_n)$	

9. Verify that the average required force for every layer is less than the safe design strength of the geogrid. If this condition is not verified, then increase the number of geogrid layers or repeat the procedure after changing the minimum spacing.

$(T / N_{total}) \leq P$

where:
N_{total} = total number of geogrids.
P = allowable resistance of the reinforcement.

10. The embankment facing can be built by wrapping geogrids around the face as per Figure 8. Wrapped faces are typically required for slopes steeper than 45° and for uniformly graded soils to prevent face sloughing. When using the wrap-around facing technique, calculate the wrapping length (L_r) for every layer as follows:

$$z_i' = z_i + (q / \gamma)$$

$$L_{ri} = \{FS_{wrap} \times K \times [z_i' + (S_{vi} / 2) \times S_{vi}]\} / (z_i' \times f_{ds} \times \tan\phi')$$

$$L_r = \max(L_{ri})$$

where:
z_i = depth for each spacing zone ($z_0 = Q$; $z_1 = Q / 2$; $z_2 = Q / 3$ …).
q = surcharge load.
L_r = wrapping length.
FS_{wrap} = geogrid wrap factor of safety (typically 1.2 to 1.4).
S_v = reinforcement spacing.
f_{ds} = factor of direct sliding (0.7 to 1.0 depending on soil).
ϕ' = effective internal friction angle of the soil.
i = reinforcement layer number.

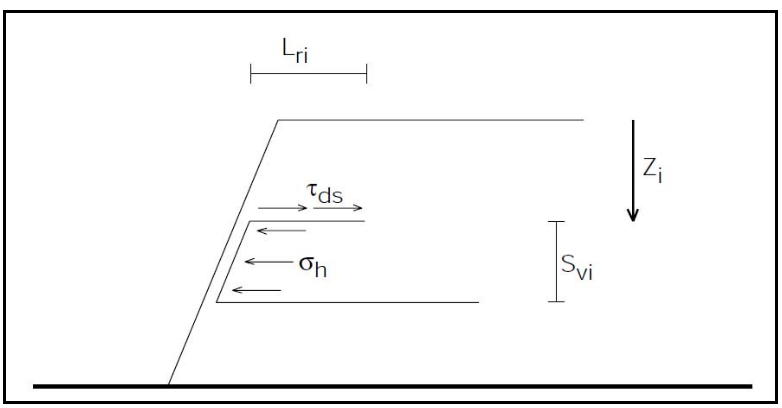


Figure 8. Wrap-Around Facing Technique for Geosynthetic Reinforced Steep Slopes.

Leshchinsky Method

An approach for stability analysis of GRSS over firm foundations has also been presented by Leshchinsky and Boedeker (1989) based on satisfying limit-equilibrium requirements. A homogeneous soil mass with no pore pressure contained between the slope and slip surfaces is shown in Figure 9. The slip surface is often taken as a log spiral extending between the crest and toe. For the reinforcement capacity to meet the required design tensile resistance, it must be embedded beyond the slip surface. To achieve equilibrium, the pullout resistance should equal its design tensile resistance:

$$t_j = 2 \times k \times \tan\phi \times \sigma \times L_{ej}$$

where:
t_j = pullout resistance per unit width of geosynthetic sheet (j).
k = coefficient of friction at the soil-geosynthetic interface.
ϕ = internal friction angle of the soil.
σ = average normal stress.
L_{ej} = embedment length of geosynthetic sheet (j) beyond the slip surface.

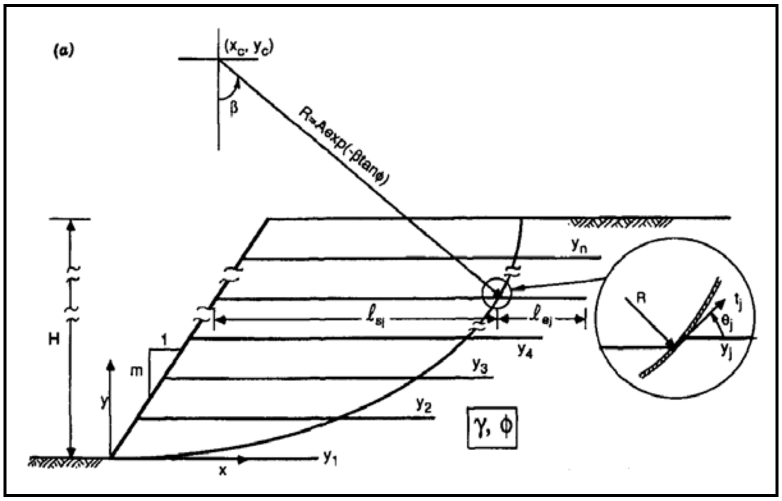


Figure 9. Leshchinsky Method of Internal Stability Analysis (Leshchinsky and Boedeker, 1989).

Internal and external stability charts were developed by Leshchinsky and Boedeker (1989) to aid in the following step by step design procedure based on a given slope inclination, height, soil unit weight, internal friction angle, and the ratio between the coefficient of friction at the soil-reinforcement interface:

1. Select a factor of safety for internal stability.
2. Calculate the maximum internal friction angle:

$$\phi_m = \tan^{-1}[\tan(\phi / FS)]$$

where:
ϕ_m = maximum internal friction angle of the soil.
ϕ = internal friction angle of the soil.
FS = factor of safety.

3. Use Figure 10 to estimate the nondimensional mobilized equivalent tensile resistance (T_m) for the given slope inclination (m). Since the actual reinforcement inclination is unknown, the user may select a value bracketed by the two extreme possibilities: horizontal with $\theta_j = 0$ (most conservative) and orthogonal with $\theta_j = \beta$ (least conservative).

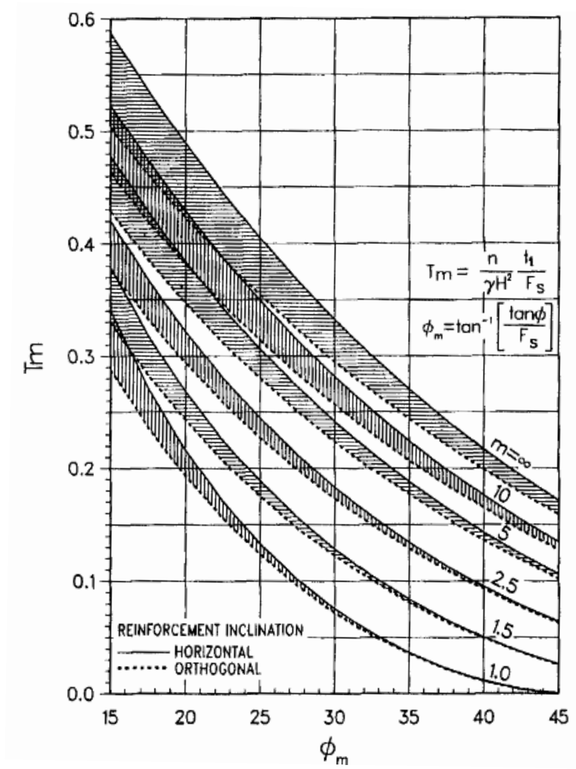


Figure 10. Design Chart for Required Tensile Resistance (Leshchinsky and Boedeker, 1989).

4. Select the number of equally spaced reinforcement sheets and calculate the pullout resistance:

$$t_l = (T_m \times FS \times \gamma \times H^2) / n$$

where:

t_l = pullout (tensile) resistance.
T_m = normalized pullout resistance $[t / (\gamma \times H^2)]$.
FS = factor of safety.
γ = unit weight of the soil.
H = height of the slope.
n = number of equally spaced reinforcement sheets.

5. Choose the proper chart from Figure 11 based on the slope inclination and determine the embedment length between the slope and slip surface (L_{sj}).

6. For each reinforcing sheet located at elevation, calculate the required anchorage length beyond the potential sliding mass as follows:

$$t_j = t_1 \times [1 - (y_j / H)]$$

$$t_j = 2 \times k \times \tan\phi \times \sigma \times L_{ej}$$

where:

t	= pullout (tensile) resistance.
y	= elevation of reinforcement sheet (y = 0 is the toe elevation).
H	= height of the slope.
k	= coefficient of friction at the soil-geosynthetic interface.
ϕ	= internal friction angle of the soil.
σ	= average normal stress.
L_e	= embedment length beyond the slip surface.
j	= reinforcing sheet number.

7. Determine the total embedment length ($L_j = L_{sj} + L_{ej}$) required for each reinforcing sheet.
8. Select a factor of safety for external stability.
9. Calculate the maximum internal friction angle:

$$\phi_m = \tan^{-1}[\tan(\phi / FS)]$$

where:

ϕ_m	= maximum internal friction angle of the soil.
ϕ	= internal friction angle of the soil.
FS	= factor of safety.

10. Based on the free body diagram shown in Figure 12, a bilinear wedge external stability analysis was used to determine standard force equilibrium conditions. Select the appropriate chart from Figure 13 based on the slope inclination and determine the required length (L_j) for bilinear wedge external stability at all elevations (y_j).
11. For each reinforcing sheet (j = 1, 2 … n) choose the longer length found from Steps 7 and 10.

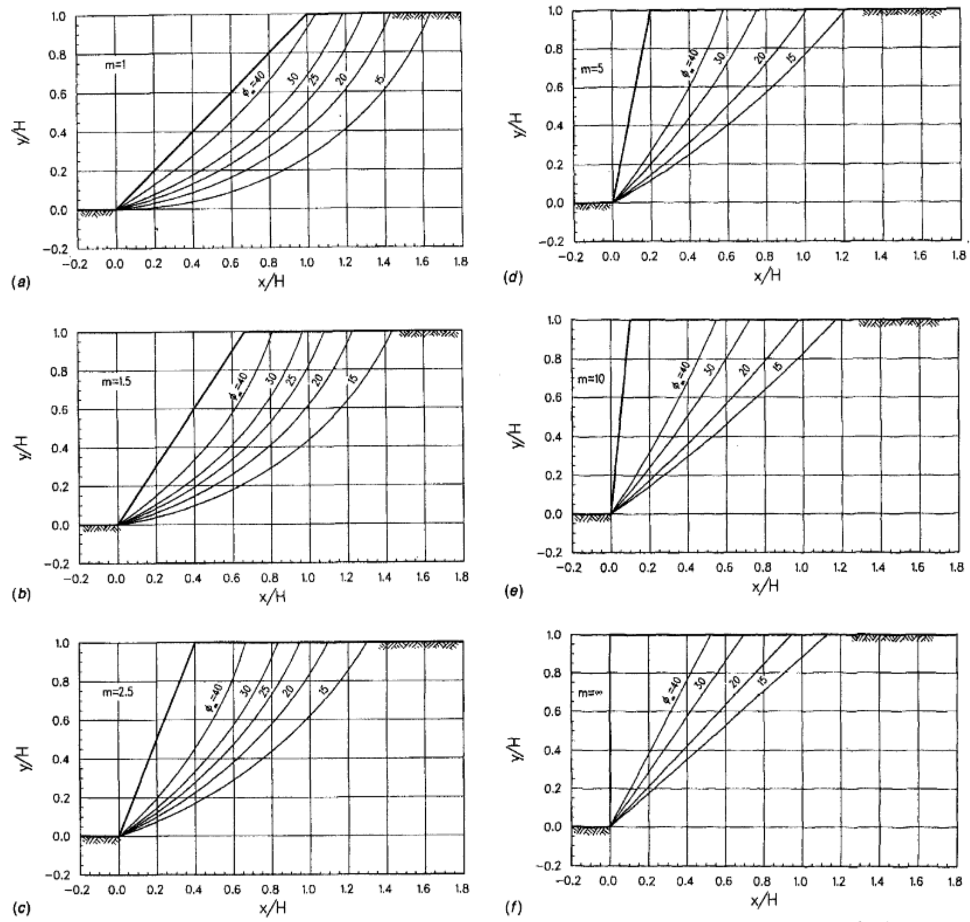


Figure 11. Design Chart for Slip Surface Trace and Embedment Length: (a) m = 1.0; (b) m = 1.5; (c) m = 2.5; (d) m = 5; (e) m = 10; (f) m = ∞ (Leshchinsky and Boedeker, 1989).

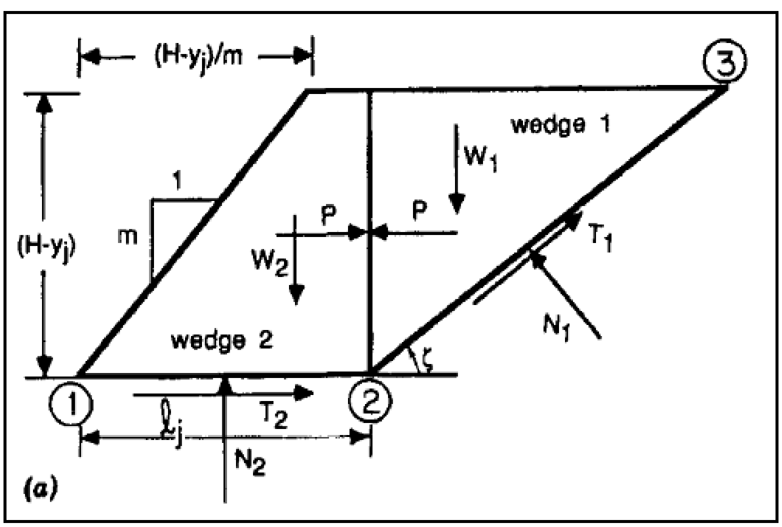


Figure 12. Bilinear Wedge External Stability Analysis (Leshchinsky and Boedeker, 1989).

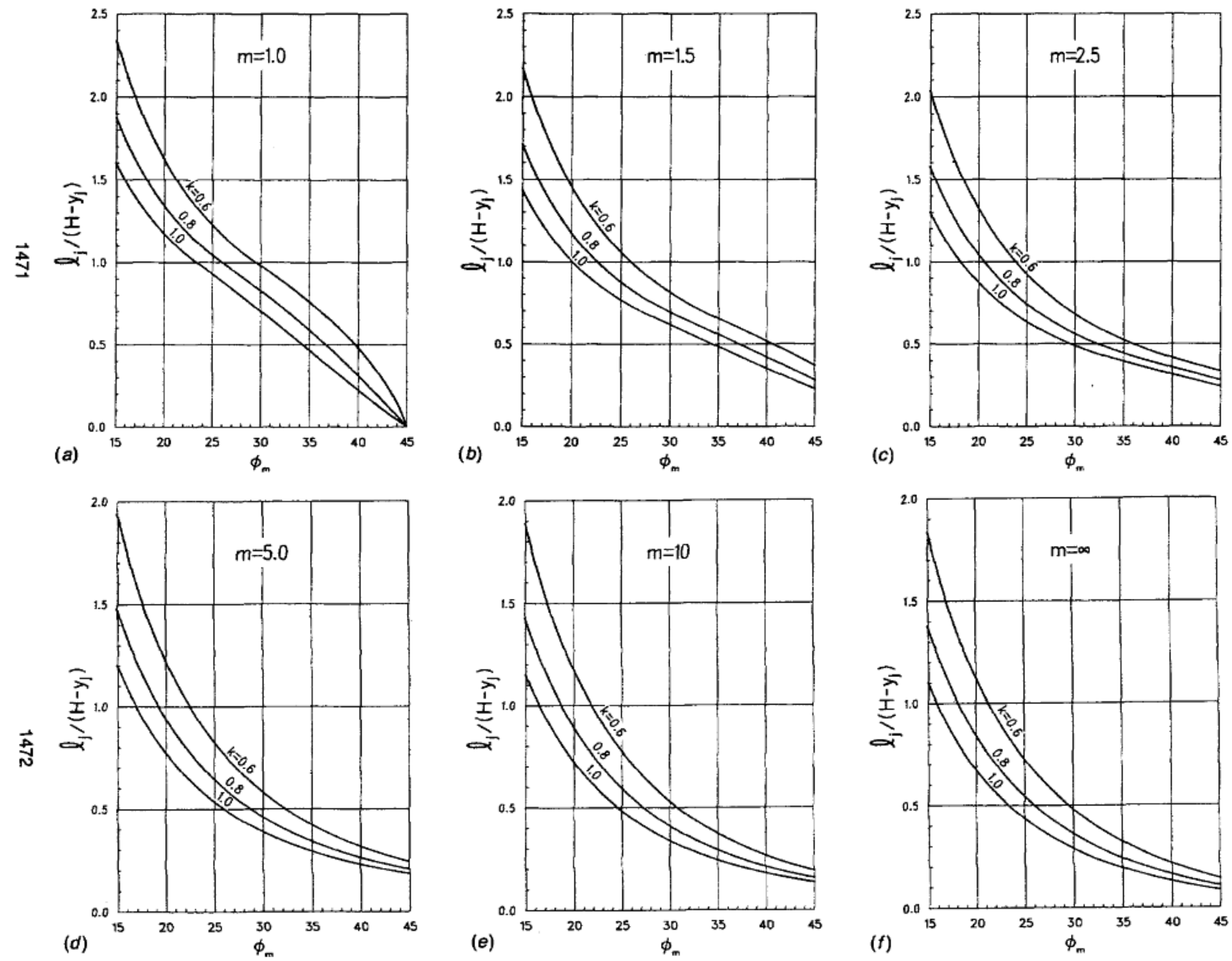


Figure 13. Design Chart for External Stability and Embedment Length: (a) m = 1.0; (b) m = 1.5; (c) m = 2.5; (d) m = 5; (e) m = 10; (f) m = ∞ (Leshchinsky and Boedeker, 1989).

FHWA DESIGN GUIDELINES

Global safety factors and performance limits are traditionally used to establish the adequacy of earthwork and structural foundation design features in the United States. In the FHWA design guidelines, the maximum tension that acts on each level of the reinforcement is determined by considering the necessary tensile strength of reinforcement and soil shear resistance to reach local equilibrium (Leshchinsky and Boedeker, 1989). Although various methods of vertical slices have significantly refined the design technique, the traditional limit-equilibrium approach is purely static as it assumes that soil at failure obeys the perfectly plastic Mohr-Coulomb criterion (Yu et al., 1998). This type of procedure is limited, however, as it does not consider the reinforcement stiffness and compaction effects in the analysis (Abramento and Whittle, 1993). Some authors have proposed methods based on working stress conditions to overcome the deficiencies of the limit-equilibrium method (Ehrlich and Mitchell, 1994; Dantas and Ehrlich, 2000). Others have proposed formulations for estimating geosynthetic reinforcement behavior under pullout efforts, but the current practice is to adopt conservative estimates (Bergado and Chai, 1994; Teixeira, 2003).

Berg et al. (2009) established a step by step design approach that has been verified through extensive experimental evaluation by the FHWA. The following FHWA design guidelines are recommended for reinforced soil slopes with emphasis on the use of geosynthetics as primary reinforcement material. A GRSS design example is also provided in Appendix E.

Step 1: Establish the Geometric, Loading, and Performance Requirements for Design

The geometric and loading requirements of the slope must first be determined through careful consideration of the purpose of the design and its overall dimensions (slope height and slope angle). Surcharge load, temporary live load, and seismic acceleration must also be considered. Then, factors of safety establish the performance requirements of the slope. These considerations include sliding, overall stability, lateral squeeze, dynamic loading, compound failure, internal slope stability, and time rate based on project requirements as per Table 3.

Table 3. Factors of Safety for Stability Analysis (Berg et al., 2009).

$FS_{sliding}$	≥ 1.3
$FS_{overall\ stability}$	≥ 1.3
$FS_{lateral\ squeeze}$	≥ 1.3
$FS_{dynamic\ loading}$	≥ 1.1
$FS_{compound\ failure}$	≥ 1.3
$FS_{internal\ stability}$	≥ 1.3

Step 2: Determine the Engineering Properties of the In-Situ Soils

Soil profiles, strength parameters, unit weights, consolidation parameters, location of groundwater table, and piezometric surfaces should be investigated. As per Figure 14, the following factors are considered:

H = slope height.
β = slope angle.
T_{al} = allowable strength of reinforcement.
L = length of reinforcement.
S_v = vertical spacing of reinforcement.
q = surcharge load.
d_w = depth to ground water table in slope.
c_r, c_b, and c_u = cohesion of soil (r = reinforced; b = backfill; u = foundation).
γ_r, γ_b, and γ_u = unit weight of soil (r = reinforced; b = backfill; u = foundation).
ϕ_r, ϕ_b, and ϕ_u = internal friction angle of soil (r = reinforced; b = backfill; u = foundation).

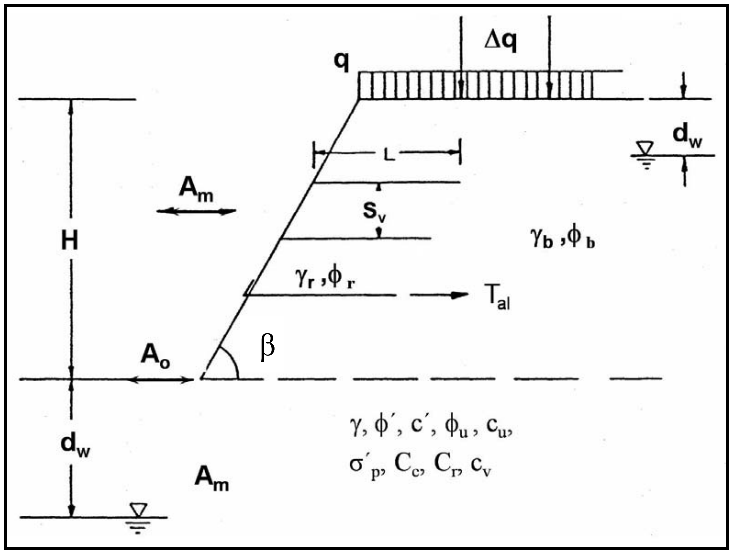


Figure 14. Design Parameters for Geosynthetic Reinforced Steep Slopes (Berg et al., 2009).

Step 3: Determine the Properties of Reinforced Fill and, if Different, the Retained Backfill

Many physical properties should be considered, including gradation, plasticity index, compaction characteristics, compacted lift thickness, shear strength parameters, and pH level.

Step 4: Evaluate Design Parameters for the Reinforcement

The geosynthetic material design parameters should be established next. Pullout resistance recommendations include a factor of safety equal to 1.5 for granular soils and a factor of safety equal to 2.0 for cohesive soils. A minimum anchorage length of 3 ft should also be used. The allowable reinforcement strength (T_{al}) is determined as follows:

$$T_{al} = (T_{ult} / RF) = [T_{ult} / (RF_{ID} \times RF_{CR} \times RF_{D})]$$

where:

T_{ult} = Ultimate Tensile Strength (strength per unit width). The tensile strength of the reinforcement is determined from wide strip tests per ASTM D4595 (geotextiles) or D6637 (geogrids) based on the minimum average roll value (MARV) for the product.

RF = Reduction Factor. The product of all applicable reduction factors.

RF_{ID} = Installation Damage Reduction Factor. A reduction factor that accounts for the damaging effects of placement and compaction of soil or aggregate over the geosynthetic during installation. A minimum reduction factor of 1.1 should be used to account for testing uncertainties.

RF_{CR} = Creep Reduction Factor. A reduction factor that accounts for the effect of creep resulting from long-term sustained tensile load applied to the geosynthetic.

RF_{D} = Durability Reduction Factor. Typically varies from 1.1 to 2.0. A reduction factor that accounts for the strength loss caused by chemical degradation (aging) of the polymer used in the geosynthetic reinforcement (e.g., oxidation of polyolefins, hydrolysis of polyesters).

In the absence of certified experimental data, recommended factors of reduction due to installation damage, creep, and durability are presented in Table 4,

Table 5, and Table 6. The highest values refer to severely unfavorable environments, strongly acidic for polyolefin, and strongly alkaline for polyester (Azambuja, 1999).

Table 4. Reduction Factors for Installation Damage (Berg et al., 2009).

Geosynthetic	**Type 1 Backfill** Max Size of 4 in	**Type 2 Backfill** Max Size of ¾ in
HDPE Uniaxial Geogrid	1.20 – 1.45	1.10 – 1.20
PP Biaxial Geogrid	1.20 – 1.45	1.10 – 1.20
PVC Coated PET Geogrid	1.30 – 1.85	1.10 – 1.30
Acrylic Coated PET Geogrid	1.30 – 2.05	1.20 – 1.40
Woven Geotextiles (PP & PET)	1.40 – 2.20	1.10 – 1.40

Table 5. Reduction Factors for Creep (Berg et al., 2009).

Polymer	**RF_{CR}**
Polyester (PET)	1.6 – 2.5
Polypropylene (PP)	4.0 – 5.0
High Density Polyethylene (HDPE	2.6 – 5.0

Table 6. Reduction Factors for Durability of PET (Berg et al., 2009).

PET Geosynthetic	**$5 \leq pH \leq 8$**	**$3 \leq pH \leq 5$ or $8 \leq pH \leq 9$**
Geotextile Molecular Weight < 20,000 Carboxyl End Groups: 40 – 50	1.60	2.00
Coated Geogrid & Geotextile Molecular Weight > 25,000 Carboxyl End Groups < 30	1.15	1.30

Step 5: Check Unreinforced Stability

Determine where reinforcement is required using both circular-arc and sliding-wedge methods, and consider failure through the toe, through the face (at several elevations), and deep-seated below the toe. Then, determine the size of the critical zone to be reinforced by examining the full range of potential failure surfaces found to have an unreinforced safety factor less than or equal to the required safety factor. Plot all of these surfaces on the cross-section of the slope. The surfaces that just meet the required safety factor roughly envelope the limits of the critical zone to be reinforced as shown in Figure 15.

Critical failure surfaces extending below the toe of the slope are indications of deep foundation and edge bearing capacity problems that must be addressed prior to completing the design. Where foundation problems are indicated, a more extensive foundation analysis is needed, and foundation improvement measures should be considered.

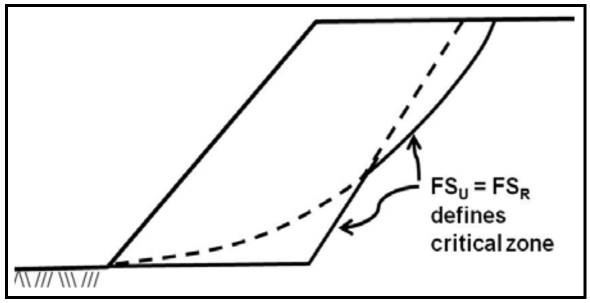


Figure 15. Critical Zone Defined by Rotational and Sliding Surfaces (Berg et al., 2009).

Step 6: Design Reinforcement to Provide a Stable Slope

The rotational shear approach is illustrated in Figure 16 and defines the required strength of reinforcement. Use the following formulas to calculate the total reinforcement tension per unit width of slope (T_S) that is required to obtain the required factor of safety (FS_R) for each potential failure surface in the critical zone that extends through or below the toe of the slope:

$$FS_U = (M_R / M_D)$$

$$T_S = (FS_R - FS_U) \times (M_D / D)$$

where:

T_S = sum of the required tensile force per unit width of reinforcement (considering rupture and pullout) in all reinforcement layers intersecting the failure surface.
M_R = resisting moment about the center of the failure circle.
M_D = driving moment about the center of the failure circle.
D = moment arm of T_S about the center of the failure circle.
FS_R = target minimum reinforced slope factor of safety.
FS_U = unreinforced slope factor of safety.
$T_{S\text{-}MAX}$ = largest T_S calculated (establishes the total design tension).

Determine the total design tension per unit width of slope ($T_{S\text{-}MAX}$) using the Figure 18 charts and compare with solution from the equation in Step 6. If greatly different, check the validity of the charts based on the following limiting assumptions and recheck Step 5 and the equation from the beginning of Step 6:

- Extensible reinforcement.
- Slopes constructed with uniform cohesionless soil.
- No pore pressures within slope.
- Competent and level foundation soils.
- No seismic forces.

- Uniform surcharge not greater than $0.2\gamma_r H$.
- Relatively high soil/reinforcement interface friction angle ($\phi_{sg} = 0.9\phi_r$).

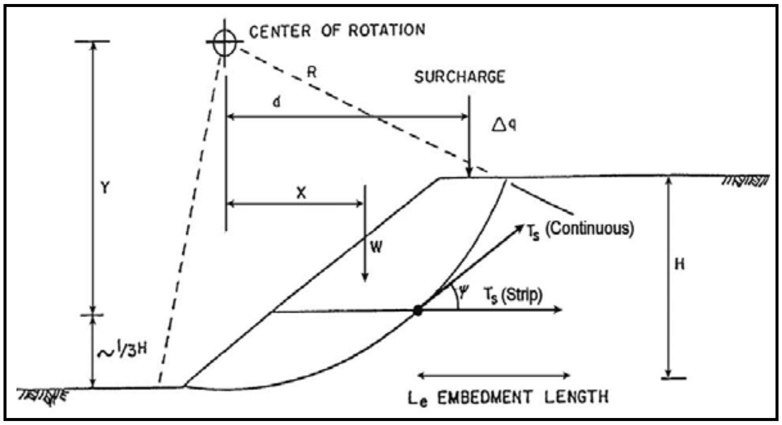


Figure 16. Rotational Shear Approach to Determine Required Strength of Reinforcement (Berg et al., 2009).

The chart procedure is used to determine the geogrid force coefficient (K) from Figure 18 and the total design tension:

$$\phi_f = [\tan^{-1} \times (\tan\phi_r / FS_R)]$$

$$T_{S\text{-}MAX} = 0.5 \times K \times \gamma_r \times (H')^2$$

where:

ϕ_f = maximum internal friction angle.
ϕ_r = internal friction angle of reinforced soil.
FS_R = target minimum reinforced slope factor of safety.
$T_{S\text{-}MAX}$ = total design tension.
K = earth pressure coefficient.
γ_r = unit weight of reinforced soil.
H′ = apparent height of the slope $[H + (q / \gamma_r)]$.
q = uniform surcharge load.

To determine the distribution of reinforcement for slopes with a height less than 20 ft, use $T_{S\text{-}MAX}$ to determine spacing or the required tension requirements for each reinforcement layer. For slopes with a height greater than 20 ft, either a uniform reinforcement distribution may be used (preferable) or the slope may be divided into two (top and bottom) or three (top, middle, and bottom) reinforcement zones of equal height using a factored $T_{S\text{-}MAX}$ in each zone for spacing or design tension requirements as per Figure 17. The force is assumed to be uniformly distributed over the entire zone, and the total required tension in each zone is found from:

For 1 Zone: Use $T_{S\text{-}MAX}$

For 2 Zones:
$T_{Bottom} = 3/4\ T_{S\text{-}MAX}$
$T_{Top} = 1/4\ T_{S\text{-}MAX}$

For 3 Zones:
$T_{Bottom} = 1/2\ T_{S\text{-}MAX}$
$T_{Middle} = 1/3\ T_{S\text{-}MAX}$
$T_{Top} = 1/6\ T_{S\text{-}MAX}$

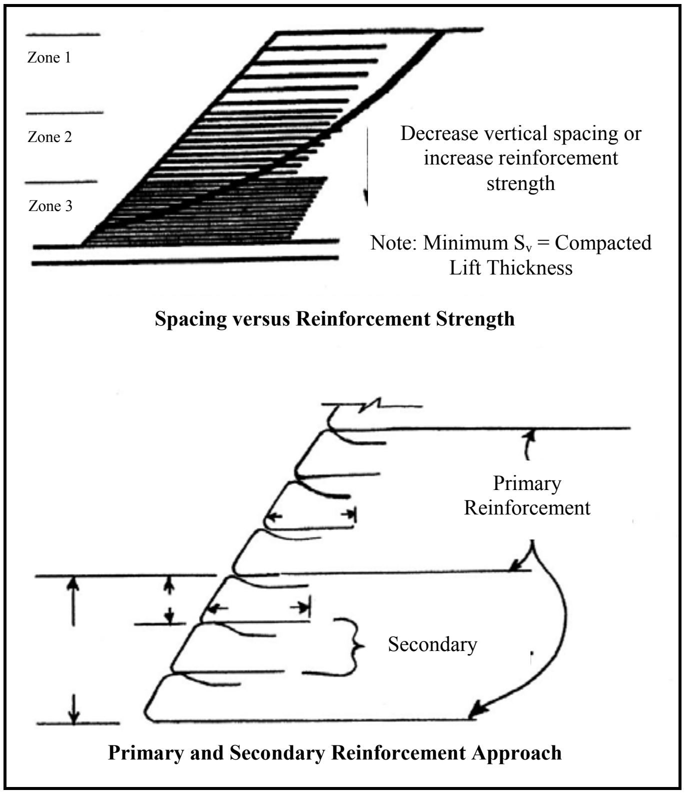


Figure 17. Reinforcement Spacing Considerations for Tall Slopes (Berg et al., 2009).

Determine the required reinforcement length at the top L_T and bottom L_B of the slope. Limiting assumptions include extensible reinforcement, slopes constructed with uniform cohesionless soil, no pore pressures within slope, level foundation soils, no seismic forces, uniform surcharge no greater than $0.2\gamma_r H$ and relatively high soil/reinforcement interface friction angle $\phi_{sg} = 0.9\phi_r$ (may not be appropriate for some geosynthetics).

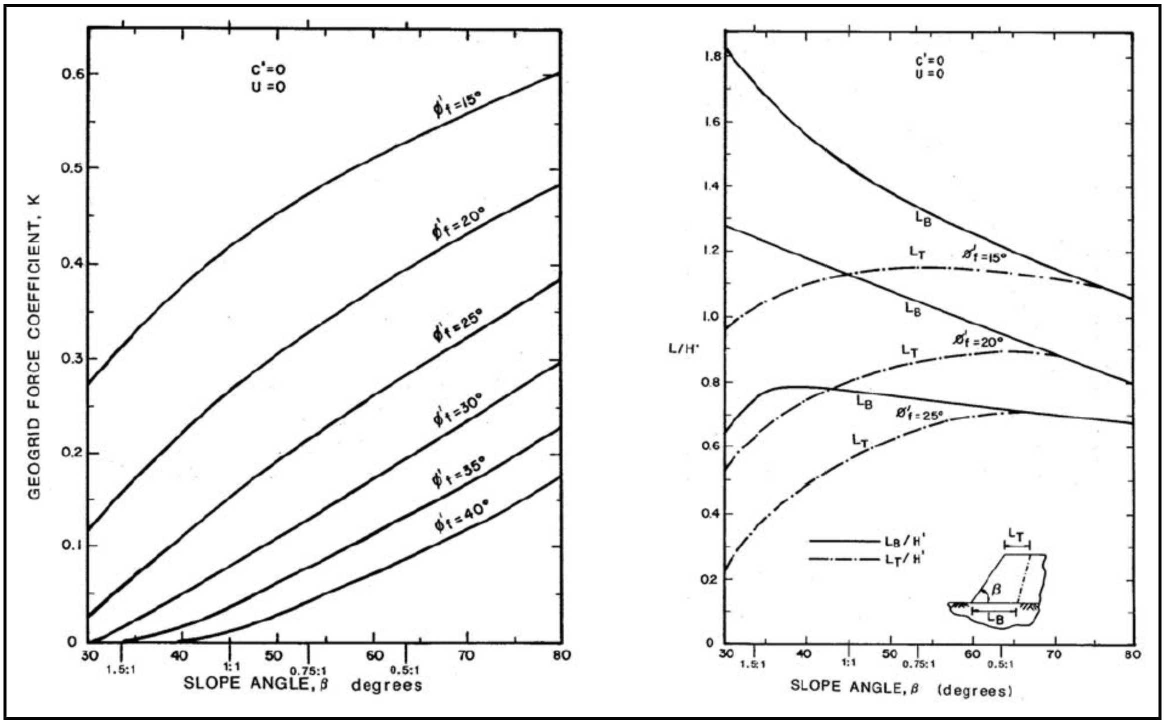


Figure 18. Chart Solution for Determining Reinforcement Strength Requirements (Schmertmann et al., 1987).

Next, determine the reinforcement vertical spacing or the maximum design tension requirements for each reinforcement layer. For each zone, calculate T_{MAX} based on an assumed S_v or, if the allowable reinforcement strength is known, calculate the minimum vertical spacing and number of reinforcing layers (N) required for each zone based on:

$$T_{MAX} = [(T_{zone} \times S_v) / H_{zone}] = (T_{zone} / N) \leq (T_{al} \times R_c)$$

where:

T_{MAX} = maximum design tension for each reinforcement layer, lb/ft.
T_{zone} = maximum reinforcement tension required for each zone, lb/ft.
= $T_{S\text{-}MAX}$ for low slopes (H < 20 ft).
S_v = vertical spacing of reinforcement; multiples of compacted layer thickness are recommended for ease of construction, ft.
H_{zone} = height of zone, ft.
= T_{Top}, T_{Middle}, and T_{Bottom} for high slopes (H > 20 ft).
N = number of reinforcement layers.
T_{al} = $T_{ult} / (RF_{ID} \times RF_{CR} \times RF_D)$, lb/ft.
R_c = coverage ratio of the reinforcement, which equals the width of the reinforcement divided by the horizontal spacing S_h (equal to 1 in the case of continuous reinforcement).

Use short 4 ft to 6.5 ft lengths of intermediate reinforcement layers to maintain a maximum vertical spacing of 16 in or less for face stability and compaction quality. For slopes flatter than 1H:1V, closer spaced reinforcements (i.e., every lift or every other lift, but no greater than 16 in) preclude having to wrap the face in well graded soils (e.g., sandy gravel and silty and clayey sands). Wrapped faces are typically required for slopes steeper than 45° and for uniformly graded soils to prevent face sloughing. Other vertical spacings could be used to prevent this but a face stability analysis should be performed using:

$$FS_{face} = \frac{(c' \times H) + (\gamma_g - \gamma_w)(H \times z)(\cos^2\beta)(\tan\phi') + \{F_g \times [(\cos\beta \times \sin\beta) + (\sin^2\beta \times \tan\phi')]\}}{(\gamma_g \times H \times z \times \cos\beta \times \sin\beta)}$$

where:
FS_{face} = factor of safety for face stability.
c' = effective cohesion of the soil, lb/ft^2.
H = height of the slope, ft.
γ_g = unit weight of saturated soil, lb/ft^3.
γ_w = unit weight of water, lb/ft^3.
z = vertical depth to failure plane defined by the depth of saturation, ft.
β = slope angle, degrees.
ϕ' = effective internal friction angle of the soil, degrees.
F_g = summation of geosynthetic resisting force, lb/ft.

Intermediate reinforcement should be placed in continuous layers but does not have to be as strong as the primary reinforcement. It must be able to survive construction and provide tensile reinforcement to the surficial soils. If the interface friction angle of the intermediate reinforcement is less than the primary reinforcement, then the friction angle of the intermediate reinforcement should be used in the analysis for the portion of the failure surface intersecting the reinforced soil zone. To ensure that the reinforcement force distribution is adequate for critical or complex structures, recalculate T_S using the equation from the beginning of Step 6 to determine potential failure above each layer of primary reinforcement. To determine the reinforcement lengths required, the embedment length (L_e) of each reinforcement layer beyond the most critical sliding surface (circle found for $T_{S\text{-}MAX}$) must be sufficient to provide adequate pullout resistance based on:

$$L_e = [FS_{PO} \times (T_{S\text{-}MAX} / N)] / (F^* \times \alpha \times \sigma'_v \times R_c \times C)$$

where:
L_e = embedment or adherence length in the resisting zone behind the failure surface, ft.
FS_{PO} = pullout factor of safety.
$T_{S\text{-}MAX}$ = total design tension, lb/ft.
N = number of reinforcement layers.
F* = pullout resistance or friction bearing interaction factor (conservatively taken as $0.67\tan\phi$, where ϕ is the peak friction angle of the soil).
α = scale effect correction factor to account for a nonlinear stress reduction over the embedded length of highly extensible reinforcements based on laboratory data (generally 1.0 for metallic reinforcements, 0.8 for geogrids, and 0.6 for geotextiles).
σ'_v = effective vertical stress at the soil reinforcement interfaces, lb/ft^2.

R_c = reinforcement coverage ratio (equal to 1 for continuous reinforcement).
C = reinforcement effective unit perimeter (equal to 2 for sheets, strips, and grids).

The minimum value of L_e is 3 ft. Plot the reinforcement lengths based on the rough limits of the critical zone determined in Step 5. The length required for sliding stability at the base will control the length of the lower levels. Lower layer lengths must extend at least to the limits of the critical zone as shown in Figure 19. If there are deep-seated failure problems, longer reinforcements may be required. Upper levels of reinforcement are not required to extend to the limits of the critical zone as long as the lower levels provide the factor of safety for resistance for all circles within the critical zone.

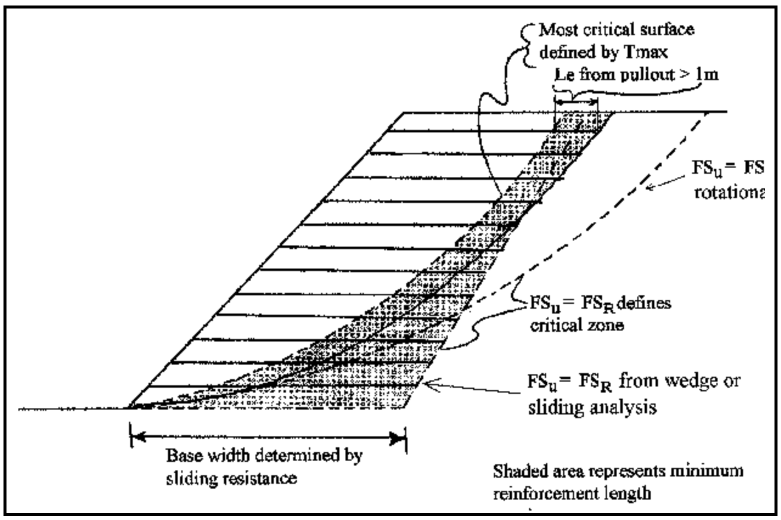


Figure 19. Geosynthetic Reinforcement Lengths for Steep Slopes (Berg et al., 2009).

Check that the sum of the reinforcement forces passing through each failure surface is greater than T_S required for that surface. Only count reinforcement that extends 3 ft beyond the surface to account for pullout resistance. If the available reinforcement force is not sufficient, increase the length of reinforcement not passing through the surface or increase the strength of lower level reinforcement.

Simplify the layout by lengthening some reinforcement layers to create two or three sections of equal reinforcement length for ease of construction and inspection. Reinforcement layers do not generally need to extend to the limits of the critical zone, except for the lowest levels of each reinforcement section. Check the length obtained using the Figure 7 chart based on the slope angle and the maximum internal frictional angle. The corresponding ratio of reinforcement length to embankment height (L/H) is then used to calculate the top (L_T) and bottom (L_B) reinforcement lengths, which already include the embedment length (L_e).

When checking a design that has zones of different reinforcement length, lower zones may be over-reinforced to provide reduced lengths of upper reinforcement levels. In evaluating the length requirements for such cases, the pullout stability for the reinforcement must be carefully checked in each zone for the critical surfaces exiting at the base of each length zone.

Step 7: Check External Stability

External stability should also be checked, including sliding resistance, deep-seated global stability, lateral squeeze, and foundation settlement. To check sliding resistance, evaluate the width of the reinforced soil zone at any level to resist sliding along the reinforcement. Use a two-part wedge type failure surface defined by the limits of the reinforcement (the length of the reinforcement at the depth of evaluation defined in Step 5). The analysis can best be performed using a computerized method, which takes into account all soil strata and interface friction values. If the computer program does not account for the presence of reinforcement, the back of the failure surface should be angled at $45 + \phi/2$ or parallel to the back of the reinforced zone, whichever is flatter (i.e., the wedge should not pass through layers of reinforcement to avoid an overly conservative analysis). The frictional resistance provided by the weakest layer, either the reinforced soil, the foundation soil, or the soil-reinforcement interface, should be used in the analysis. To check deep-seated global stability as illustrated in Figure 20, evaluate potential failure surfaces behind the reinforced soil zone to provide:

$$FS_{GS} = (M_R / M_D) \geq 1.3 \text{ minimum}$$

where:
FS_{GS} = factor of safety against deep-seated global failure.
M_R = resisting moment.
M_D = driving moment.

A factor of safety for global stability greater than or equal to 1.3 is recommended as a minimum and that value should be increased based on the criticality of the slope (slopes beneath bridge abutments and major roadways) and/or confidence in geotechnical conditions (soil properties and location of groundwater).

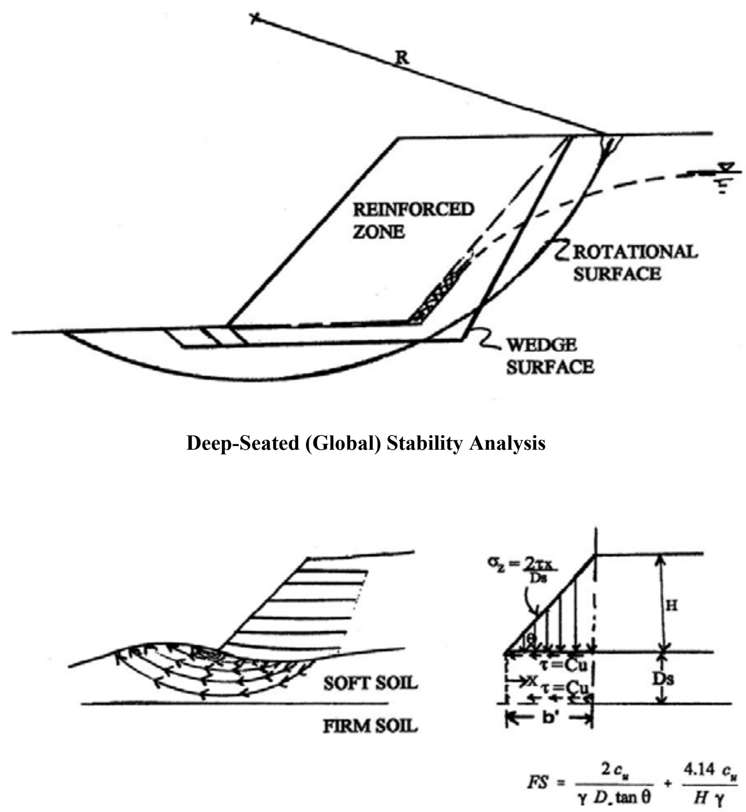


Figure 20. External Stability Analysis of Geosynthetic Reinforced Steep Slopes (Berg et al., 2009).

The analysis performed in Step 5 should provide the factor of safety for failure surfaces behind the reinforced soil zone. However, as a check, classical rotational slope stability methods such as Bishop (1955), Morgenstern and Price (1965), Spencer (1967), or others may be used. Appropriate computer programs may also be employed.

To determine local bearing failure at the toe (lateral squeeze), it must first be determined if the weak soil layer beneath the slope has a depth less than the width of the slope. If this is the case, the factor of safety against failure by squeezing may be calculated from:

$$FS_{squeezing} = [(2 \times c_u) / (\gamma_r \times D_s \times \tan\theta)] + [(4.14 \times c_u) / (H \times \gamma_r)] \geq 1.3$$

where:
$FS_{squeezing}$ = factor of safety against failure by lateral squeezing.
c_u = undrained cohesion of soft soil beneath slope.
γ_r = unit weight of reinforced soil.
D_s = depth of soft soil beneath slope base.
θ = angle of slope.
H = height of slope.

Caution is advised and rigorous analysis (numerical modeling) should be performed when $FS_{squeezing} < 2$. This approach is somewhat conservative as it does not provide any influence from the reinforcement. When the depth of the soft layer (D_S) is greater than the slope base width (b′), general slope stability will govern design.

Step 8: Check Seismic Stability

To determine dynamic stability, perform a pseudo-static type analysis using a seismic ground coefficient (A) obtained from local building code and a design seismic acceleration (A_m) equal to A/2. Reinforced soil slopes are clearly yielding type structures more so than walls and A_m can be taken as A/2 as allowed by AASHTO (2002).

In the pseudo-static method, seismic stability is determined by adding a horizontal and/or vertical force at the centroid of each slice to the moment equilibrium equation as per Figure 21. The additional force is equal to the seismic coefficient times the total weight of the sliding mass. It is assumed that this force has no influence on the normal force and resisting moment so that only the driving moment is affected. The liquefaction potential of the foundation soil should also be evaluated.

Step 9: Evaluate Requirements for Subsurface and Surface Water Runoff Control

Design of subsurface water drainage features should address flow rate, filtration, placement, and outlet details. Drains are typically placed at the rear of the reinforced zone as shown in Figure 22. Geocomposite drainage systems or conventional granular blanket and trench drains could be used.

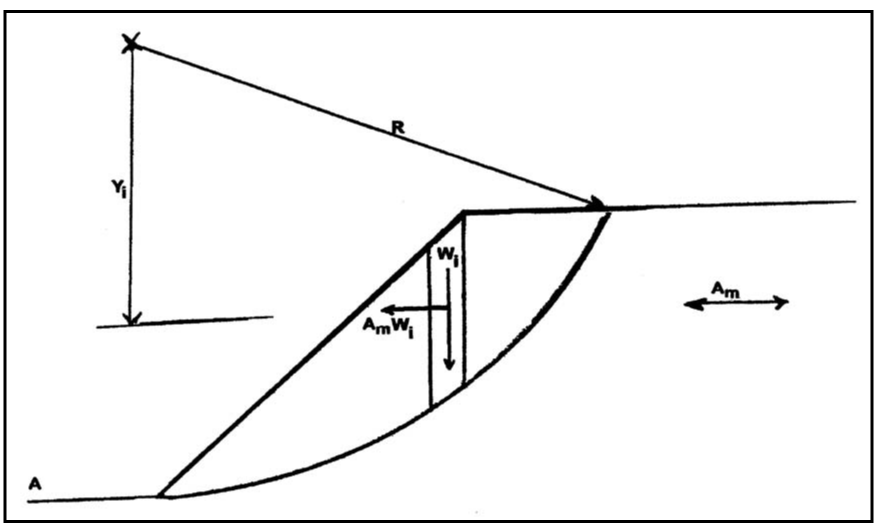


Figure 21. Seismic Stability Analysis of Geosynthetic Reinforced Steep Slopes (Berg et al., 2009).

Long-term performance should be taken into account for drainage design. Geosynthetics may be used with consideration to geotextile filtration and clogging, long-term compressive strength of polymeric core, reduction of flow capacity due to intrusion of geotextile into the core, and long-term inflow and outflow capacity. The design pressure on a geocomposite core should be limited to either the maximum pressure sustained on the core in a test of 10,000 hours minimum duration or the crushing pressure of a core, as defined with a quick loading test, divided by a factor of safety of 5.

Note that crushing pressure can only be defined for some core types. For cases where a crushing pressure cannot be defined, suitability should be based on the maximum load resulting in a residual thickness of the core adequate to provide the required flow after 10,000 hours, or the maximum load resulting in a residual thickness of the core adequate to provide the required flow as defined with the quick loading test divided by a factor of safety of 5.

Intrusion of the geotextiles into the core and long-term outflow capacity should be measured with a sustained transmissivity test as per the ASTM D4716. The test procedure should be modified for sustained testing and for use of sand sub-stratum and super-stratum in lieu of closed cell foam rubber. Load should be maintained for 100 hours or until equilibrium is reached, whichever is greater.

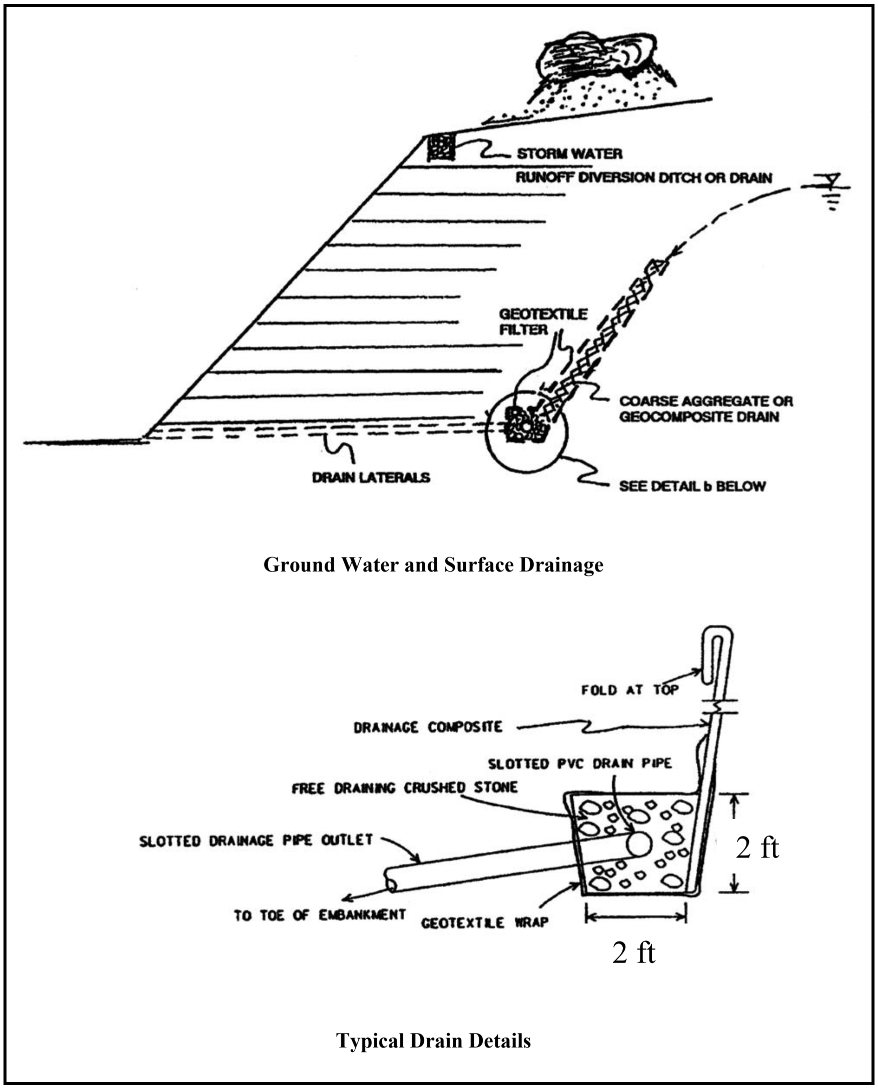


Figure 22. Drainage Considerations for Geosynthetic Reinforced Steep Slopes (Berg et al., 2009).

Slope stability analysis should account for interface shear strength along a geocomposite drain. Geotextiles must be more permeable than fill material to prevent build-up during precipitation. Special emphasis on the design and construction of subsurface drainage features is recommended for structures where drainage is critical for maintaining slope stability. Redundancy in the drainage system is also recommended for these cases. Surface water runoff should be collected above the reinforced slope and channeled or piped below the base of the slope.

Select a long-term facing system to prevent or minimize erosion due to rainfall and runoff on the face. Intermediate layers placed on every other soil lift prevent against shallow or sloughing types of slope failures. Calculate flow induced tractive shear stress on the face of the reinforced slope by:

$$\lambda = (d \times \gamma_w \times s)$$

where:
λ = tractive shear stress.
d = depth of water flow.
γ_w = unit weight of water.
s = vertical to horizontal angle of slope face.

For $\lambda < 2$ lb/ft^2, consider vegetation with temporary or permanent erosion control mat. For $\lambda > 2$ lb/ft^2, consider vegetation with permanent erosion control mat or other armor type systems (riprap, gunite, prefab modular units, fabric formed concrete). Select vegetation based on local horticultural and agronomic considerations and maintenance. Synthetic (permanent) erosion control mats can also be used to protect against ultraviolet light, soil born chemicals, and bacteria. Erosion control mats and blankets vary widely in type, cost, and applicability to project conditions.

DESIGN SOFTWARE

Interactive software programs exist to aid in the design of GRSS. The FHWA developed Reinforced Slope Stability Analysis (ReSSA) in cooperation with ADAMA Engineering, which relies upon the Bishop and Spencer methods to check internal stability. The designer can investigate rotational and direct sliding failures, adequacy of geosynthetics, and layout and strength of the soil slope. ReSSA allows the user to input multiple variables, including soil strata, use of tension crack, varieties of surcharge loads, seismicity, and water pressure. It calculates the pullout resistance along each layer based on interaction parameters and safety factors. Figure 23 is a screenshot of ReSSA software (Leshchinsky, 2001).

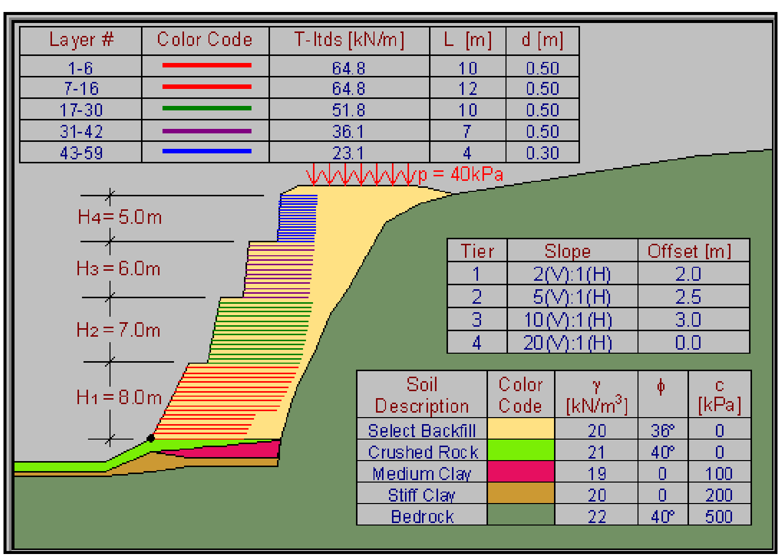


Figure 23. ReSSA Software Screenshot (Leshchinsky, 2001).

Most geosynthetic manufacturers create their own software for use in designing slopes that use their particular product. However, other software programs are available for engineers to independently design and analyze projects. Geo-Slope/W software uses input parameters to analyze slope stability. Stresses computed by a finite element stress analysis may be used in addition to limit-equilibrium computations (Geo-Slope, 2013). Oasys Slope software offers methods for calculating slope stability by using a two-dimensional analysis including interslice forces. It also includes slip circle, horizontal, and constant inclined methods (Oasys, 2013).

FOUNDATION AND BACKFILL MATERIALS

To ensure successful construction of GRSS, an adequate subsurface investigation should be performed for the existing foundation as well as behind and in front of the structure to assess overall performance behavior. Foundation soil engineering considerations include the bearing resistance, global stability, settlement potential, and position of groundwater levels. The subsurface exploration program generally consists of soil soundings, borings, and test pits. The type and extent of the exploration should be decided after review of the preliminary data obtained from the subsurface investigation, and in consultation with a geotechnical engineer or an engineering geologist. The exploration must be sufficient to evaluate the geologic and subsurface profile in the area of construction. Ground improvement techniques that account for major foundation weakness and compressibility may be required to achieve adequate bearing capacity or limited total or differential settlement (Elias et al., 2001; Berg et al., 2009).

In general, select fill materials are more expensive than lower quality materials. The fill specifications depend on the application and final performance requirements of the structure. Detailed project reinforced fill specifications should be provided by the contracting agency. A high quality embankment fill meeting gradation requirements to facilitate compaction and minimize reinforcement is recommended. Table 7 presents the FHWA requirements for granular reinforced fill. The use of retained soil for reinforced fill is acceptable as long as the percent of fines passing #200 sieve is less than 50 percent, and the liquid limit and plasticity index should be less than 40 percent and 20 percent, respectively (Berg et al., 2009).

Table 7. Granular Reinforced Fill Requirements (Berg et al., 2009).

<table>
<tr><td rowspan="5">Gradation (AASHTO T-27)</td><td>Sieve Size</td><td>Percent Passing</td></tr>
<tr><td>4″</td><td>100</td></tr>
<tr><td>#4</td><td>100 - 20</td></tr>
<tr><td>#40</td><td>60 - 0</td></tr>
<tr><td>#200</td><td>50 - 0</td></tr>
<tr><td>Plasticity Index (AASHTO T-90)</td><td colspan="2">PI ≤ 20</td></tr>
<tr><td>Soundness (AASHTO T-104)</td><td colspan="2">Magnesium sulfate soundness loss less than 30% after 4 cycles, based on AASHTO T-104 or equivalent sodium sulfate soundness of less that 15% after 5 cycles.</td></tr>
</table>

West Virginia DOT (2010) specifies for all backfill material in the structure volume to be reasonably free from organic or otherwise deleterious material. Prior to incorporating the soil, they require the contractor to perform one pH test in each soil type each day of operation, and the pH of the soil shall be within the allowable limits of the design for the geosynthetic material used. For most geosynthetic materials, California DOT (2005) and Florida DOT (2010) recommend a pH level for backfill material in the range of 5 to 10. Additionally, fill should meet the minimum required shear strength parameters as determined by direct shear or consolidated-drained triaxial tests. Pennsylvania DOT (2007) requires for the material to have a minimum angle of internal friction of 32° if no minimum shear strength parameters are indicated.

Weak Foundation Soil

Horizontal earth pressures tend to laterally spread embankments constructed on weak foundation soils. Weakened areas may be caused by sink holes, thawing ice, old stream beds, or layers of soft silt, clay, or peat. Failure will result if the foundation soil does not have adequate shear resistance to the stresses. Therefore, the design guidelines for reinforced embankments on weak soils should also consider bearing failure, rotational failure, and lateral spreading as per Figure 24 (Haliburton et al., 1978).

Classical bearing capacity theory should be used when the thickness of the soft soil is much greater than the width of the embankment (Chai and Zhu, 2009):

$$q_{ult} = (\gamma \times H) = (c_u \times N_c)$$

where:

q_{ult} = ultimate bearing pressure.
γ = unit weight of the soil.
H = height of the slope.
c_u = undrained cohesion of the soil.
N_c = bearing capacity factor.

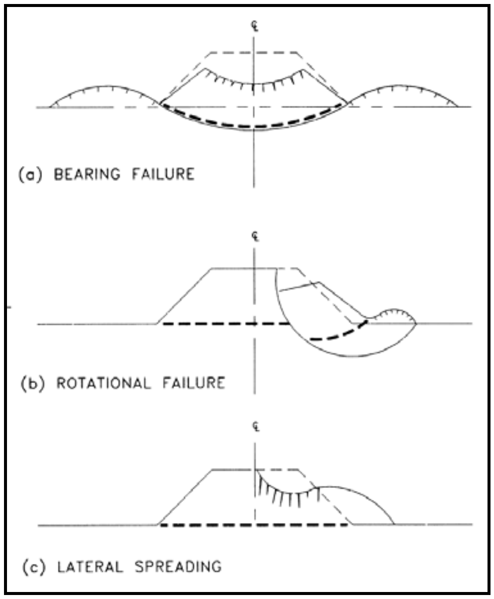


Figure 24. Embankment Failure Modes on Weak Foundation Soils (Haliburton et al., 1978).

If the factor of safety for bearing capacity is insufficient, the following project parameters should be considered: increasing the embankment width, flattening the slopes, adding toe berms, or improving the foundation soils. A rotational slip surface analysis can also be used to determine the critical failure surface and the factor of safety against shear instability (Holtz et al., 1998):

$$T = [(FS \times M_D) - M_R] / [R \times \cos(\theta - \beta)]$$

where:

T	= tensile strength of reinforcement.
FS	= factor of safety.
M_D	= driving moment.
M_R	= resisting moment.
R	= radius.
θ	= angle from horizontal to tangent line.
β	= 0 for brittle strain-sensitive foundation soils.
	= $\theta/2$ for depth/width ratio < 0.4 and moderately compressible soils.
	= θ for depth/width ratio ≥ 0.4 and highly compressible soils.

Finally, a lateral spreading or sliding wedge stability analysis should be performed. Cohesion is assumed to equal zero for extremely soft soils and low embankments. The factor of safety is calculated as follows (Bonaparte and Christopher, 1987):

$$FS = (b \times \tan\phi') / (K \times H)$$

where:
FS = factor of safety.
b = width of the wedge.
ϕ' = effective internal friction angle of the soil.
K = earth pressure coefficient.
H = height of the slope.

The elastic modulus of geosynthetic reinforcement is relied upon to control lateral spreading over weak foundation soils. By limiting the deformation behavior of the reinforcement, excessive deformation of the embankment can be mitigated. The distribution of lateral pressure and strain is assumed to vary linearly, increasing from zero at the toe to a maximum value beneath the crest of the embankment. The maximum strain in the reinforcement should be equal to twice the average strain in the embankment. Tolerable deformation requirements are calculated as follows:

$$J = T / \varepsilon$$

where:
J = reinforcement modulus.
T = tensile strength of reinforcement.
ε = strain limit based on type of fill soil materials.
= 5 percent to 10 percent for cohesionless soils.
= 2 percent for cohesive soils.
= 2 percent to 10 percent for peats.

Marginal Backfill Soil

Compaction difficulties and pore water pressure can create unstable conditions in slopes with marginal backfill consisting of low quality, cohesive, fine grained soil. Although granular soils are preferred due to their high strength and low pore water pressure, project budgets may require the use of marginal soils when select fill is not readily available. Design considerations include accounting for excess pore water pressure development by incorporating reinforcement-drainage composites that promote lateral drainage within the soil mass. Internal and external seepage forces must also be accounted for during the design process. It is recommended for a two-phase analysis to be performed, including a total stress analysis that ignores the reinforcement lateral drainage and an effective stress analysis that accounts for full lateral drainage. This analysis neglects the dissipation of pore water pressures through the permeable inclusions to provide a conservative estimate and then accounts for full drainage to provide a realistic evaluation of the long-term stability. Tensile strength, pullout resistance, drainage, and filtration are the main characteristics that should be considered when selecting a geosynthetic material for marginal backfill. Higher reinforcement strength and transmissivity is typically required for marginal backfill soils, and filtration requirements should limit clogging (Christopher et al., 1998).

GEOSYNTHETIC MATERIALS

Survey respondents claimed that many geosynthetic reinforcing materials provided by a variety of manufacturers can be used to construct steep slopes. A significant issue to be dealt with is the deformation behavior of such slopes, particularly if lower quality fill materials are used. In order to use materials with fines in excess of 15 percent, both the strength and deformation behavior of the soil and reinforcement needs to be considered, including both the short- and long-term behavior.

The American Society for Testing and Materials (ASTM) defines a geosynthetic as a planar product manufactured from a polymeric material used with soil, rock, earth, or other geotechnical-related material as an integral part of a civil engineering project, structure, or system (Berg and Suits, 1999). Geosynthetics are identified by the type of polymer, type of fiber or yarn, type of geosynthetic, mass per unit area or thickness, and any additional clarification needed to describe the geosynthetic (Holtz, 2001). Table 8 displays various geosynthetic types, properties, and test methods.

Table 8. Geosynthetic Types, Properties, and Test Methods (Holtz et al., 1998).

Geosynthetic Type	Weight[2] (lb/yd^3)	Ultimate[3] Tensile Strength (lb/ft)	Strain at[3] Ultimate Tensile Strength (%)	Secant[3] Modulus at 10% Strain (lb/ft)	Grab[4] Strength (lb)	Puncture[5] Strength (lb)	Burst[6] Strength (lb/in^2)	Tear[7] Strength (lb)	Equivalent[8] Darcy Permeability (ft/sec)
Monofilament Polypropylene Geotextile	0.2-0.4	1100-4800	20-40	4800-17800	150-520	70-160	400-700	40-100	10^{-4}-10^{-2}
Silt Film Geotextile	0.1-0.3	800-3100	20-40	3400-17800	70-360	20-130	200-700	40-360	10^{-4}-10^{-3}
Fibrillated Tape and Multifilament Polypropylene Geotextile	0.4-1.3	2400-14400	15-40	12000-48000	160-1390	160-250	600-1500	100-400	10^{-4}-10^{-3}
Multifilament Polyester Geotextile	0.2-1.2	1700-24000	10-30	12000-72000	160-2020	40-310	500-1500	80-520	10^{-4}-10^{-3}
Polypropylene Geogrid	0.2-0.4	500-2400	10-20	6200-15800	n/a	n/a	n/a	n/a	>10
High Density Polyethylene Geogrid	0.4-1.2	500-6200	10-20	3700-4800	n/a	n/a	n/a	n/a	>10
Polyester Geogrid	0.4-1.2	2400-9600	5-15	24000-178000	n/a	n/a	n/a	n/a	>10

1. The data in this table represent an average range. There may be products outside this range. No relation should be inferred between maximum and minimum limits for different tests.
2. Method 1.1.84, Appendix B, FHWA Geotextile Engineering Manual
3. Wide Width Method, ASTM D-4595
4. ASTM D-4632
5. ASTM D-4833
6. ASTM D-3786
7. ASTM D-4533
8. ASTM D-4491

* Limited by test machine

Geotextiles are defined as any permeable textile used with foundation soil, rock, earth, or any other geotechnical engineering-related material as an integral part of a manmade project, structure, or system. In manufacturing geotextiles, elements such as fibers or yarns are combined into planar textile structures. The fibers can be continuous filaments, which are very long thin strands of a polymer, or staple fibers, which are short filaments, typically 1 inch to 4 inch long (Holtz, 2001). Woven geotextiles are cloth-like fabrics that are formed by uniform and regular interweaving of threads or yarns in two directions. They have regular visible construction patterns and, where present, have distinct and measurable openings. Woven geotextiles are mostly used for soil separation, reinforcement, load distribution, filtration, and drainage, and they tend to have a high tensile strength and relatively low strain compared to non-woven geotextiles (Brown, 2006).

Geogrids are open grid-like materials of integrally connected polymers and are stronger than most geotextiles. Their primary use is soil reinforcement, because they can withstand heavy tension loads without much deformation and have low strain compared to geotextiles. There are three different manufacturing processes for geogrids. The first heats and stretches polymer that has been pre-punched with a regular pattern of holes. The second type of manufacturing process comprises bundles of polymer fibers in a mesh pattern that are coated with bitumen or polyvinyl chloride. The third takes sheathed bundles of fibers that are then welded together (GEOfabrics Limited, 2011).

Even though different geosynthetics may be manufactured with the same base polymer, their tensile strengths can vary widely. The tensile properties of geosynthetics are affected by factors such as creep, installation damage, aging, temperature, and confining stress. Some may also be more susceptible to environmental damage, including exposure to chemicals, heat, and ultraviolet light (GEOfabrics Limited, 2011). The effect of long-term stress should be determined from laboratory creep tests in accordance with ASTM D5262 and extrapolated to the desired design life or carried out to rupture when possible (Berg et al., 2009). In ascending order, the most creep susceptible polymers are polyester, polypropylene, and polyethylene. An increase in temperature significantly accelerates creep for polypropylene (Muller-Rochholz and Reinhard, 1990). Confinement may also change the creep properties of nonwoven geotextiles; however, for woven geotextiles and geogrids, the effect of confinement on creep is negligible (McGown et al., 1982; Becker, 2001).

For soil slope applications, Alabama DOT (2012) specifies that the geosynthetic reinforcement (either geogrid or geotextile) shall be constructed of polyester, polypropylene, or polyethylene, resistant to all naturally occurring alkaline and acidic soil conditions, and resistant to heat, ultraviolet light, and to attack by bacteria and fungi in the soil. Reinforcement for soil slopes shall be any geosynthetic whose strength in the machine direction equals or exceeds the values provided in the specification. California DOT (2005) requires for the percentage of the open area for geogrids to range from 50 percent to 90 percent of the total projection of a section of the material, and geotextiles shall have an irregular or regular open area with the spacing of open areas being less than 0.25 in in any direction. West Virginia DOT (2010) also requires the geosynthetics to be capable of withstanding 150 hours of testing as per ASTM D4355 with no measurable reduction in the ultimate tensile strength or deterioration of the coating. Table 9 provides additional recommendations for geosynthetic material based on soil environment.

Table 9. Geosynthetic Resistance to Specific Soil Environments (Berg et al., 2009).

Soil Environment	PET	PE	PP
Acid Sulphate Soils	NE	ETR	ETR
Organic Soils	NE	NE	NE
Saline Soils (pH < 9)	NE	NE	NE
Ferruiginous Soils	NE	ETR	ETR
Calcereous Soils	ETR	NE	NE
Modified Soils (Lime, Cement, etc.)	ETR	NE	NE
Sodic Soils (pH > 9)	ETR	NE	NE
Soils with Transition Metals	NE	ETR	ETR
NE = No Effect ETR = Exposure Tests Required			

CHAPTER III: CONSTRUCTION PRACTICES

The construction of GRSS is similar to normal embankment construction, as the reinforcement can be easily incorporated into the backfill material (Jones et al., 1987). Current guidelines for construction practices are provided in Special Specification 5165: Geogrid Reinforcement for Embankments (TxDOT, 2004). Information from transportation agencies, manufacturers, and engineers was synthesized by the research team to supplement the current specifications in Texas.

CONSTRUCTION SEQUENCE

The following step by step procedure is recommended by the FHWA for the construction sequence of GRSS:

1. Site preparation.
2. Place the first reinforcing layer.
3. Place backfill on reinforcement.
4. Compaction control.
5. Face construction.
6. Continue with additional reinforcing materials and backfill.
7. Field inspection.

During site preparation, contractors clear and grub the site and remove all slide debris. A level subgrade is then prepared. The foundation must also be inspected and drainage features should be placed as required (USACE, 2008).

The reinforcement is then placed with the principal strength direction perpendicular to the face of the slope, pulled taut, and secured with retaining pins to prevent movement during fill placement as per Figure 25. The geosynthetic materials should extend back from the slope face to the specified embedment distance at the elevations shown on the drawings. Adjacent reinforcement must also be butted together side by side without overlap unless specified (Holtz et al., 1998).

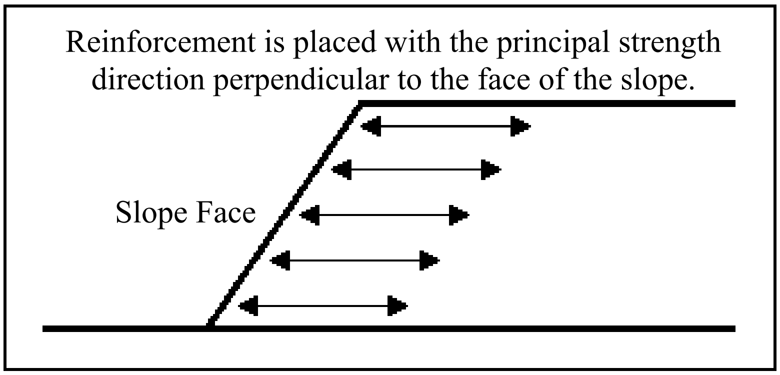


Figure 25. Placement of Geosynthetic Reinforcement for Steep Slope Construction.

Backfill material is placed and compacted without deforming or moving the reinforcement, utilizing lightweight compaction equipment near the slope face to maintain alignment. Maintain a minimum of 6 inch of fill between the reinforcement and the wheels or tracks of construction equipment. Never operate tracked equipment directly upon the reinforcement (TenCate, 2010). Sudden braking and sharp turning should be avoided. Tracked equipment should not turn within the reinforced fill zone to prevent tracks from displacing the fill and damaging the reinforcement. Rubber tired equipment may operate directly on the reinforcement if the travel is infrequent, equipment travels slow, turning is minimized, and no damage or displacement to the reinforcement is observed. Water content and backfill density must be monitored to control compaction (USACE, 2008). Fill should be compacted to at least 95 percent of the standard AASHTO T-99 maximum density within 2 percent of optimum moisture (Berg et al., 2009).

Constructing a slope with vegetative cover can protect the reinforcing elements from ultraviolet light as per Figure 26. Face wrap is usually not required for slopes up to 1H:1V; however, if slope facing is required to prevent erosion, the reinforcement at the face is turned up and returned a minimum of 3 ft into the embankment below the next reinforcement layer. Steep slopes may also require formwork to support the face during construction. Field inspections should be performed by trained personnel to ensure that the reinforcement is not damaged and that the construction sequence and specifications are followed (Holtz et al., 1998).

Figure 26. Vegetative Cover of Geosynthetic Reinforced Steep Slope.

TRANSPORTATION AGENCY SPECIFICATIONS

In addition to the aforementioned specifications, several state transportation agencies have implemented similar requirements for construction involving geosynthetic reinforcement. Geosynthetics should be delivered to the jobsite in unopened shipping packages labeled with the supplier's name, product name, quantity, and type designation that corresponds to that required by plans (Florida DOT, 2010). They should also be accompanied by a manufacturer certified copy of test results (ASTM D4595 for geotextile or ASTM D6637 for geogrid), verifying the ultimate strength of the lots from which the rolls were obtained (Alabama DOT, 2012). Reject all rolls damaged during transport. Rolls should be protected from construction equipment, chemicals, sparks and flames, water, mud, wet cement, epoxy, and like materials (West Virginia DOT, 2010). Geosynthetics should also be protected from direct sunlight and temperatures below 0°F per Mississippi DOT (2004). Additionally, the reinforcement material must be protected from temperatures above 120°F according to Mississippi DOT (2004) or above 140°F and 160°F as per Pennsylvania DOT (2007) and California DOT (2005), respectively. Rolls should also be stored elevated from the ground and covered with a waterproof cover.

Remove all existing vegetation and unsuitable soil materials, including deleterious materials and soils, from the grade. Grade should be proof rolled with five passes of a static, smooth drum, or pneumatic tire roller with a minimum contact pressure of 120 psi as per Pennsylvania DOT (2007). However, according to Florida DOT (2010), an 8 ton vibratory or sheepsfoot roller of at least 250 psi on the tamper foot should be used. Any soft areas, as determined by the engineer, should be removed and replaced with backfill. Benching the backcut into competent soil is recommended to improve stability.

The geosynthetic should be oriented with the direction of maximum strength perpendicular to the slope face with each layer placed to form a continuous mat. Secondary reinforcement should be placed in continuous strips parallel to the slope face, and the geosynthetic must be secured and pulled taut before placing any fill. West Virginia DOT (2010) restricts operation of equipment on geosynthetic materials until 6 inch of loose backfill has been placed, although Pennsylvania DOT (2007) further limits this to 8 inch. Sudden braking and sharp turning is not allowed. Sheepsfoot or padfoot type compaction equipment is not allowed. Only place the amount of geosynthetic that can be covered in one day and slope the last level of backfill away from the slope face to allow for positive drainage.

If mechanical connectors are required, the splice mechanism must allow a minimum of 95 percent load transfer from piece to piece of geosynthetic per Florida DOT (2010). Only one joint per length of reinforcement shall be allowed, and the joint shall be made for the full width of the strip by using a similar material with similar strength that uses a connection device supplied or recommended by the manufacturer. Pennsylvania DOT (2007) does not allow for any splicing of any geosynthetic. If a geosynthetic is damaged, remove all backfill material from the area plus 4 ft in all directions beyond the limits of the damage. Patch the damaged area with the same material and overlap the undamaged patch a minimum of 3 ft in all directions. Agencies should also consider site specific installation damage testing, especially if relatively coarse, uniformly graded crushed, or otherwise angular aggregate is used as backfill, or if other relatively severe installation conditions are anticipated.

WEAK FOUNDATION SOIL

Weak foundations may be caused by sink holes, thawing ice, old stream beds, or layers of soft silt, clay, or peat as per Figure 27. Geosynthetic reinforcement may be used to reduce horizontal and vertical displacements of the foundation soil to reduce differential settlement. However, reinforcement will not reduce the magnitude of long-term consolidation or secondary settlement of the embankment. The use of geosynthetic reinforcement at the base of the embankment may allow for (Holtz et al., 1998):

- An increase in the design factor of safety.
- An increase in the height of the embankment.
- A reduction in embankment displacements during construction and a reduction in fill requirements.
- An improvement in embankment performance due to increased uniformity of post-construction settlement.

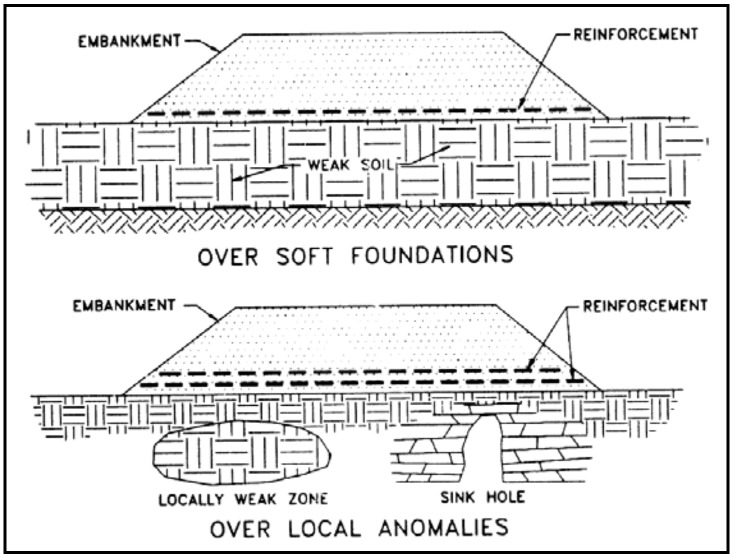


Figure 27. Reinforced Embankment Over Weak Foundation Soils (Holtz et al., 1998).

The reinforcement is typically placed with its strong direction perpendicular to the centerline of the embankment. Additional reinforcement with its strong direction oriented parallel to the centerline may be required at the ends of the embankment. Geotextiles may also be used as separators for maintaining integrity of the embankment. To improve the foundation conditions, the following project parameters should be considered: increasing the embankment width, flattening the slopes, adding toe berms, or replacing the foundation soils.

CONTRACTING METHODS

GRSS projects are typically contracted using two different approaches. The first approach is for the agency or material supplier to design and specify the system components, drainage details, erosion measures, and construction execution in the contract documents. Conversely, the second approach involves specifying the end result by only providing information regarding generic system components. The information provided also includes lines and grades noted on the drawings and geometric and design criteria. However, the actual project design occurs during the submittal process (Berg et al., 2009).

State agencies vary in method when it comes to payment. Most pay by the square yard of reinforcement used, which is consistent with current TxDOT practices. Pennsylvania DOT (2007) pays by the square foot of the reinforced slope. Most states agree that the square yard price should include all labor, materials, tools, shipping, handling, storage, protection, and connecting mechanisms for the geosynthetic material. Portions that are damaged, cut off, or overlapped are not to be paid for. Amount of fill needed should be calculated and added into the price per square yard.

SITE EVALUATION

As per FHWA recommendations, the existing topography, subsurface conditions, and soil/rock properties must be considered when evaluating a site for repair or new construction. An in-depth subsurface exploration should be performed to determine site stability, settlement potential, need for drainage, and any other items that could influence the design and stability of the structure. The subsurface exploration should be performed at the site of the construction or repair as well as in front and behind the area to better understand site conditions and overall performance behavior. The investigation will also aid in planning for conditions throughout the construction process. The engineer is responsible for the bearing resistance of the foundation materials, the allowable deformations, and the stability of the structure. The investigation should include determining the availability of the required type of reinforced fill and backfill materials. The availability of materials and site conditions will determine the cost of a new structure and minimize contractor claims for changed conditions (Berg et al., 2009).

A geotechnical engineer or an engineering geologist should perform the subsurface investigation. Existing data (topographic maps and aerial photographs) about the subsurface conditions should be considered as well as a field visit to collect data on the following:

- Limits and intervals for topographic cross sections.
- Access conditions for work forces and equipment.
- Surface drainage patterns, seepage, and vegetation characteristics.
- Surface geologic features, including rock outcrops and landforms, and existing cuts or excavations that may provide information on subsurface conditions.
- The extent, nature, and locations of existing or proposed below-grade utilities and substructures that may have an impact on the exploration or subsequent construction.
- Available right-of-way.
- Areas of potential instability such as deep deposits of weak cohesive and organic soils, slide debris, high groundwater table, bedrock, outcrops, etc.

When building a reinforced slope, several factors are considered:

- Geologic and topographic conditions.
- Environmental conditions.
- Size and nature of the structure.
- Aesthetics.
- Durability considerations.
- Performance criteria.
- Availability of materials.
- Experience with a particular system or application.
- Cost.

There are several different systems that can be put in place. A decision must be made on what kind of structure to build based on the needs and expected performance of the owner. For GRSS, there are several different factors that can be changed based on the specific application. Though addressing these factors may prove to be difficult, determining the correct design, geosynthetic reinforcement, and the treatment of the slope face can be achieved (Berg et al., 2009).

The amount to be excavated is one factor that will determine the economy of the structure. If there is a small volume to be moved, there is an economic advantage. For a larger excavation, some economic advantage is lost, but the project may still be viable. The bearing capacity of the foundation soil should always be determined. In unfavorable conditions, ground improvement techniques can be used (Elias et al., 2006):

- Excavation and removal of soft soils and replacement with a compacted structural fill.
- Use of lightweight fill materials.
- In-situ densification by dynamic compaction or improvement by use of surcharging with or without prefabricated vertical drains.

The chemical makeup of the in-situ ground affects GRSS structures. The reinforcements will deteriorate in aggressive conditions and will accelerate when exposed to deicing salts and fertilizers. Polyester reinforcements are susceptible to highly alkaline or acidic regimes and polyolefins are susceptible to highly acidic conditions. Other important factors are location and site accessibility (Elias, 1989).

The size of a GRSS structure depends on its use, but there is no limit as to how tall a structure can be built. The height of the tallest GRSS is 242 ft. Economics, soil properties, and available reinforcing materials will determine the feasibility of the structure. Making a structure taller will cost more money, but making a structure less than 10 ft to 14 ft tall is also uneconomical. Projects larger than 3000 ft^2 will usually find a 10 percent to 15 percent decrease in costs due to the economy of scale (Berg et al., 2009).

ADDITIONAL CONSIDERATIONS

Standard policies and procedures should be developed to obtain uniformity with respect to design and contracting. Many suppliers and contractors already have generic designs that may be applicable for use. The approval of such a design must depend on its comparison with systems that have been in successful use. In addition to this, the manufacturer should also submit laboratory test results pertaining to creep performance, ultimate strength, chemical and biological resistance, installation damage, joint strength, pullout resistance, and sliding resistance of the geosynthetic to be used.

A state transportation engineer warned that edge compaction is among the most common challenges faced during construction. Geocells provide an alternative approach to the facing that allows a hand compactor to be employed on the face of the earth structure, ensuring that adequate compaction levels are achieved. Care must be taken, however, when using geocells as a facing element. If fine grained sand is used, it could be displaced as water flows through the cells. Consequently, coarse grained sand, fine gravel, or cement stabilized sand is typically used for face cells.

A surveyed engineering consultant advocated that, generally, an owner is better served by a traditional design-bid-build approach. An independent designer can prepare a generic design in which multiple geosynthetic manufacturers have applicable strength products. This provides competition between geosynthetic suppliers on material costs and various earthwork contractors on installation costs while allowing the owner to have complete control over the design requirements and input soil parameters so that the owner is ensured of attaining the level of safety and reliability it desires for the reinforced slope. Another geotechnical engineer prefers to prepare generic reinforcement designs. They specify the strength, vertical spacing, and length of reinforcement required and prepare performance based specifications that specify the geosynthetic reinforcement properties. Any reinforcement product that meets the design criteria is acceptable. This design approach provides the owner with a quality design and allows the marketplace to determine the cost. Conversely, other survey respondents prefer for the manufacturer to collaborate directly with the owner during the design phase, promoting the consideration of project alternatives prior to the bid.

CHAPTER IV: PERFORMANCE MEASURES AND COST EFFECTIVENESS

GRSS can yield potential savings in material costs and construction time for new permanent embankments and recurring slope failures. However, an understanding of their performance is required to effectively use this method of mechanically stabilizing earth. Factors that lead to both successful and failed applications of geosynthetic reinforcement were documented by the research team and additional information was synthesized regarding quality control, inspections, monitoring, and lifespan.

QUALITY CONTROL

Properties of geosynthetics are classified as general, index, and performance. General properties include the polymer, mass per unit area, thickness, roll dimensions, roll weight, and specific gravity. However, index properties provide qualitative assessment through standard test procedures for utilization in product comparisons, specifications, quality control, and constructability. Index tests include uniaxial mechanical strength, multiaxial rupture strength, durability tests, and hydraulic tests. Finally, performance properties of geosynthetics include the use of soil samples for direct assessment of properties, such as in-soil stress-strain, creep, friction/adhesion, chemical resistance, and filtration. Under direction of the design engineer, performance tests are correlated to index values for use in preselecting geosynthetics for project specifications (Holtz, 2001).

Geosynthetic specifications include general requirements, specific geosynthetic properties, seams and overlaps, placement procedures, repairs, and acceptance and rejection criteria (Holtz et al., 1998). Specified general requirements include the types of geosynthetics, acceptable polymeric materials, and guidelines for the stability of the materials as well as instructions for storage and handling, roll weight, and dimensions and certification requirements. Physical, index, and performance properties are also included in the general requirements as per the specific project design. Additionally, seams and overlaps are clearly specified in all geosynthetic applications in accordance with construction requirements. Although overlaps may be increased, a minimum overlap of 1 ft is recommended for geotextile applications. However, geosynthetics are connected if overlaps will not work, and the connection material should always consist of polymeric materials that have equal or greater durability than the specified geosynthetic. Placement procedures are detailed on the construction drawings and typically include requirements for grading, ground-clearing, aggregates, lift thickness, and equipment. Repair procedures for damaged sections, acceptance and rejection criteria, and inspection procedures, including sampling and testing requirements, are also included in geosynthetic specifications to ensure successful project completion (Holtz, 2001).

FIELD INSPECTION

Methodology and tolerances dictate each step in the construction sequence of GRSS, which is relatively simple and rapid. Potential problems in the sequence can be avoided by keeping the designer, construction personnel, and inspection team aware of special construction considerations. A detailed field inspection checklist of general construction requirements for GRSS is provided in Appendix G. The table should be modified, however, to included detailed requirements based on TxDOT specifications and specific project plans.

PERFORMANCE MONITORING

Since reinforced steep slope technology is well established, Berg et al. (2009) recommends for monitoring programs to be limited to cases in which new features or materials have been incorporated in the design, post construction settlements are anticipated, or where degradation rates of reinforcements are to be monitored. The first step in planning a monitoring program is to define the purpose of the measurements. Every instrument on a project should be selected and placed to assist in answering a specific question. The characteristics of the structure as a whole must be assessed prior to developing the instrumentation program.

A limited monitoring program should observe horizontal and vertical movements of the face, vertical movements of the surface of the overall structure, local movements, or deterioration of the facing elements and performance of any structure supported by the reinforced soil. Horizontal and vertical movements can be monitored by surveying methods, using suitable measuring points on the facing elements or on the surface of the retained soil. Vertical movements should be estimated from foundation settlement analyses, and measurements of actual foundation settlement during and after construction should be made (Berg et al., 2009).

A comprehensive monitoring program may include all observations from a limited monitoring program plus the prediction of the magnitude of each parameter at working stress to establish the range of accuracy for each instrument. A comprehensive plan may include deflection monitoring, structural performance monitoring, and pullout resistance proof testing. Location of monitoring instruments must first be decided when implementing a monitoring program. Sections containing unique design features, such as sections with surcharge, must be identified. Next, two cross sections where predicted behavior is representative of behavior as a whole must be identified. Last, secondary instrumented sections must be chosen. These sections may not be representative of all points in the structure. Some instruments that may be used are tiltmeters, crack gauges, piezometers, probe extensometers, inclinometers, horizontal inclinometers, multiple types of strain gauges, pressure cells, thermocouples, thermistors, and rainfall and barometric pressure gauges. In preparing the installation plan, consideration should be given to the compatibility of the installation schedule and the construction schedule. If possible, the construction contractor should be consulted concerning details that might affect his operation or schedule. Step by step installation procedures should be prepared well in advance of scheduled installation dates for installing all instruments (Christopher et al., 1989; Dunnicliff, 1998).

Monitoring program data collected during construction must be communicated back to the engineers at all times in case immediate action needs to be taken on a certain aspect of the design. A final report is often prepared to document key aspects of the monitoring program and to support any remedial actions. The report also forms a valuable bank of experience and should be distributed to the owner and design consultant so that any lessons may be incorporated into subsequent designs.

LIFESPAN

Geotextiles have only been in use as reinforcement for embankments for a little more than 30 years and, because of this, there are some uncertainties as to their durability with respect to maintaining strength after exposure to construction stresses and exposure to soil over the design life. Berg et al. (2009) claims that potential aging depends upon the specific polymer, configuration of the reinforcements, the environment to which they are exposed, and the level of stress to which they are subjected.

The main polymers used in geotextiles and geogrids are polypropylene, polyethylene, and polyester. The final form of any of these three depends on its formulation, additives used in composition, and the methods of processing into its final form (fibers, filaments, and fabric for geotextiles or joined drawn strands for geogrids). These manufacturing methods may be a factor for durability. Polypropylene geosynthetics require antioxidants and UV inhibitors to maintain the required end-properties of the polymeric materials. Type and quantity of these additives may vary slightly between production runs. Polyethylene products also require antioxidants and UV inhibitors during manufacture. Polyester geogrids are coated with a polyvinyl chloride or an acrylic polymer to provide protection from construction damage and to ensure dimensional stability during manufacturing (Elias et al., 2009).

Geosynthetics are often degraded by a combination of environmental mechanisms. There are four steps to quantifying geosynthetic durability and making lifetime predictions based on that durability. First, identify harmful conditions or mechanisms within a particular site. Second, identify what effects these mechanisms may have on the geosynthetic. Third, identify the test data necessary. Last, evaluate the test data collected. Some potentially aggressive soil groups that may have an effect on the lifespan of a geosynthetic are salt-affected soils, acid-sulphate soils, calcareous soils, organic soils, soils containing transition metals, and modified (cement or lime-treated) soils (Horrocks, 1990).

Variables contributing to geosynthetic damage as a result of improper installation are the weight and type of construction equipment used for fill spreading, weight and type of geosynthetic, lift thickness of backfill material, and gradation and angularity of backfill. Data suggest that extreme damage is caused by coarse angular backfills spread in relatively thin lifts, compacted with heavy equipment and heavy construction traffic on top of those lifts. The effects of installation damage should be determined for each product by installation damage testing.

Test results should be compared to undamaged specimens taken preferably from the same roll (Rainey and Barksdale, 1993).

The two approaches to provide data usable in determining reduction factors against aging are excavation and retrieval of geosynthetics from construction projects and accelerated laboratory testing. Field retrievals are not good to use, for many reasons. First, the use of geosynthetics in soil slope applications has only been around for 30 years, so the sample age falls much short of the 50 to 100 year lifespan required. Second, the composition of products manufactured today is much different than 30 years ago. Third, installation damage cannot be measured unless there is an archive sample of the geosynthetic available, which is rarely the case. Accelerated laboratory aging tests are conducted in ovens at various temperatures and controlled oxygen content to model in-soil behavior (Elias et al., 2009).

FAILURE MODES

Koerner and Koerner (2012) compiled and analyzed a database of 141 failed geosynthetic reinforced structures, in which there were 34 cases of excessive deformation and 107 cases of actual collapse. Below are the main statistical findings:

- All but one were privately owned (as opposed to publicly financed).
- 72 percent were in North America.
- 49 percent were 13 ft to 26 ft high.
- 90 percent were geogrid reinforced.
- 81 percent failed in less than 4 years.
- 62 percent used silt or clay backfill in the reinforced soil zone.
- 75 percent had poor to moderate compaction.
- 98 percent were caused by improper design or construction.
- 58 percent were caused by internal or external water (the remaining 42 percent were caused by soil related issues).

The major inadequacies in these failures were a lack of proper drainage procedures and a lack of adequate placement of plumbing within the reinforced soil zone. Another inadequacy was the use of fine grained silt and clay backfill soils along with insufficient placement and compaction during construction. This led to hydraulic pressures being mobilized behind or within the reinforced soil zone, which requires the use of back and base drains so as to dissipate the pressures and properly remove the water out of the front.

Liu et al. (2012) also investigated three failures on a geogrid reinforced slope on the approaching road to Chi-Nan University in Nantou, Taiwan. The first slope failure occurred after rainfall infiltrated into the permeable gravel and was impeded by the underlying impermeable clay layer. The shear strength was reduced at the interface of the gravel and clay, initiating a slide when the toe of the slope was excavated to install reinforcement during construction. The second failure was caused by a strong earthquake, which generated stress and created a slide in the vicinity of the clay layer. The third failure occurred when abundant rainfall infiltrated into the reinforced slope during a heavy rainstorm. The infiltration was obstructed by the impermeable clay, producing transient water pressure and inducing slope failure behind the reinforced zone. Lessons learned from the study include carrying out a detailed site investigation, selecting permeable materials as backfill, installing drainage systems appropriately, and combining the design of a reinforced slope with other types of retaining structures to improve the system global stability.

COST EFFECTIVENESS

There are many site specific characteristics that contribute to the overall cost of GRSS, including cut-fill requirements, slope size and type, existing soil type, available backfill materials and facing finish as well as temporary or permanent application. Cost estimates for construction are typically provided as the price per square foot of vertical face. For reinforced slopes, the approximate costs of the principal components are as follows: reinforcement 45–65 percent, backfill 30–45 percent, and face treatment 5–10 percent (Elias et al., 2001). However, increases in structure height are typically paralleled by increases in reinforcement costs. Figure 28 illustrates how construction costs and right-of-way are influenced by different earth structures.

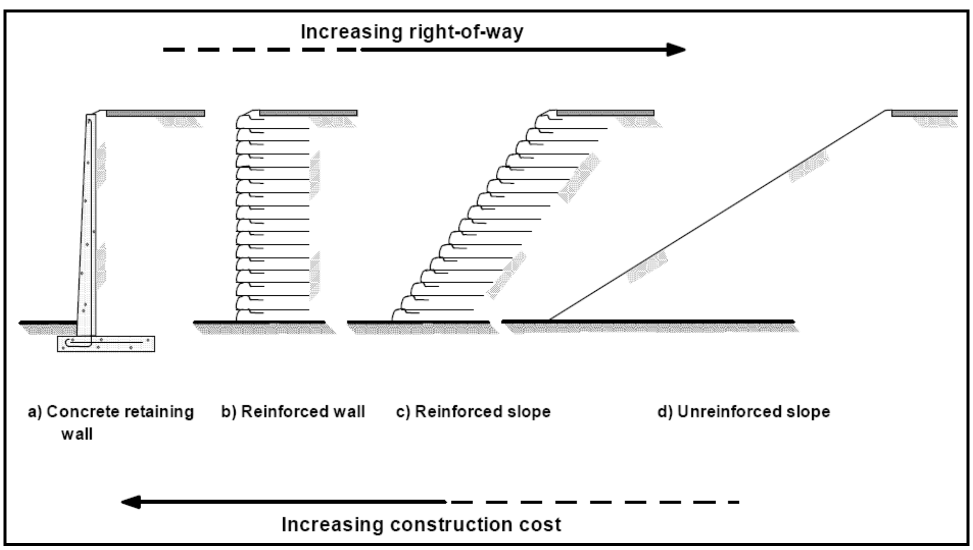


Figure 28. Construction Cost of Earth Structures (Zornberg, 2007).

When comparing reinforced and unreinforced slopes, a benefit and cost analysis is required to justify whether the cost of the GRSS is justified over the alternative flatter unreinforced slope with its increased right-of-way and material costs. Additionally, reinforced slopes can cost half as much as reinforced walls and also provide many benefits over concrete retaining walls, such as additional cost savings obtained by the ease of construction and speed of construction. The qualities of the foundation and backfill soils affect the speed of construction and must be taken into account when analyzing cost effectiveness. Other factors to consider for cost comparison include maintenance of traffic during construction, requirements for guardrails and traffic barriers, and the cost and availability of right-of-way needed (Ehrlich and Azambuja, 2003).

The unit cost information obtained from suppliers for product lines of geosynthetic reinforcement are presented in Figure 29. The costs range from \$1.35/yd^2 to \$6.48/yd^2 and correspond to tensile strengths ranging from 1875 lb/ft to 14390 lb/ft. Stronger products are also available at higher costs. Products #2 through #5 have a similar correlation between cost and tensile strength regardless of their material composition. However, Product #1 provides comparable strength at a lower cost.

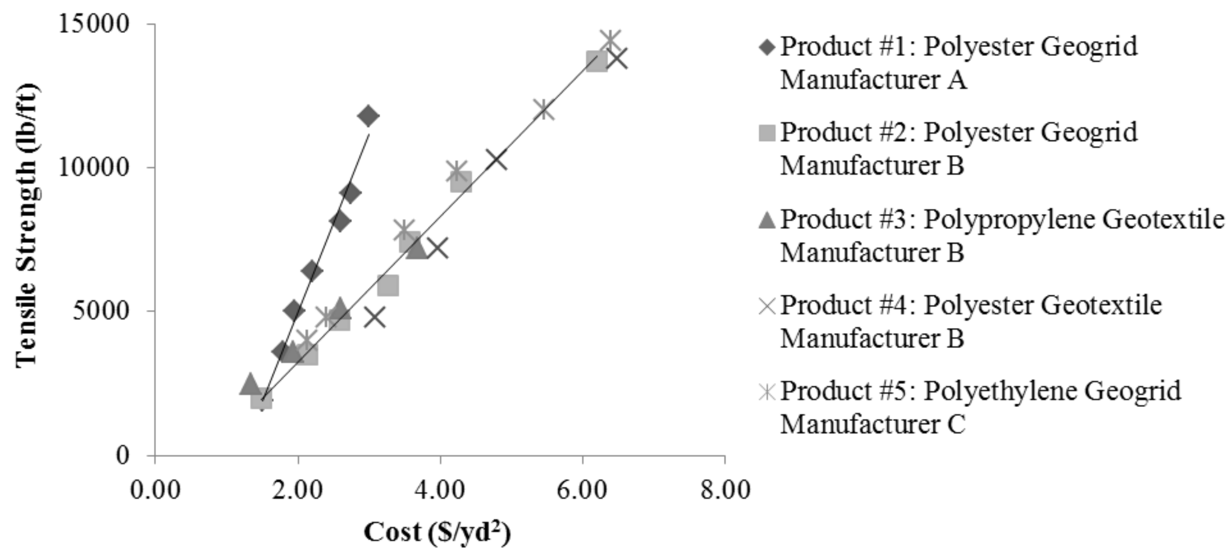


Figure 29. Cost and Tensile Strength of Geosynthetic Reinforcement Materials.

ADDITIONAL CONSIDERATIONS

A design engineer that was interviewed for the study suggested that challenges faced during construction are often due to inadequate soils or contractors underbidding the project cost. Geotechnical investigations should be conducted prior to design and construction, because assuming properties of the onsite soils can lead to unforeseen distresses. Failures are even possible if the foundation and embankment soils are unsuitable. It is also recommended that a detailed design be completed prior to the bid and for soil and reinforcing material properties to be considered in accordance with the FHWA design guidelines. Steep slopes should be inspected for movement and settlement. However, no maintenance or repair should be expected if the project is properly designed and constructed.

Another engineer claimed that a significant issue to be dealt with is the deformation behavior of such slopes, particularly if lower quality fill materials are used, such as materials containing fines in excess of 15 percent. Long-term deformation of such slopes can be problematic, specifically if the slopes support structures or pavements that cannot tolerate significant deformation. The engineer recommended use of the FHWA design guidelines with hard aggregate, such as crushed limestone or sandstone, reinforced with geotextile or geogrid. He also recommended for the owner to specify performance and for the contractor to design the project in the submittal process. However, distresses can occur if the contractor does not construct the slope with quality soil and reinforcement. Common distresses include deformation and settlement, but global failure is possible if the site has poor drainage and degraded soil quality. Soil tests should be conducted before and after delivery to verify material properties. If the proper precautions are taken into consideration, GRSS can be an economical solution for stabilizing soil. Protecting the final slope face from erosion will determine success or failure in the eyes of the public.

According to the survey, the reinforcement material cost ranges from \$1.25/yd^2 to \$15.00/yd^2 and varies depending on quantity and material properties. One consultant claimed that project cost depends upon slope height, surcharge load, and availability of select backfill. Others suggest that cost is also highly dependent upon the tensile strength required for the geogrid, and tensile strength is dependent upon design requirements.

A state geotechnical engineer that was interviewed for the study designed slopes that have primarily been used to optimize roadway areas. Erosion was prevented by controlling the granularity of the backfill material, and there have been no signs of distress or failure. Challenges faced during construction were mitigated through sufficient communication between all parties involved. Consequently, life cycle costs have not included maintenance or repair, making reinforced slopes a cost effective solution. In Maryland, the current construction cost of a reinforced slope is in the range of \$40/ft^2 of vertical height, depending on the site conditions and project requirements. For comparison, MSE walls in Maryland cost approximately \$60/ft^2 of vertical height. These unit prices are cost estimates for facing, but the cost of backfill must also be considered. They are inflated compared to the average bid price of \$33.70/ft^2 for MSE facing in Texas. However, if the cost ratio between the two construction methods is similar, GRSS facing in Texas could cost approximately \$20/ft^2 to \$25/ft^2 of vertical height. The engineer claimed that the cost of building these structures has increased substantially in recent years due to rising material and labor costs in Maryland.

CHAPTER V: CASE STUDIES

To obtain a better understanding of GRSS projects, the research team identified 60 case studies and gathered information regarding their design and construction. Two of the case studies were based on historical data received from survey respondents, and nine were found in technical reports and journal articles. The remainder of the case studies was synthesized from information published by geosynthetic manufacturers. Project locations ranged from California to Maine within the United States, and international projects were also investigated in Canada, New Zealand, South Africa, Austria, Malaysia, Thailand, United Kingdom, Montenegro, Serbia, Germany, Taiwan, and South Korea. Appendices H and I provide a summary of published case study information and case study survey results.

PURPOSE

Geosynthetics were employed for these projects to improve soil conditions by providing tensile resistance and stability. As per Figure 30, reinforced slopes were utilized in most of the case studies as a structure for supporting roadways, bridge abutments, buildings, railways, and runways. In other cases, the construction method was also used for erosion prevention and to maximize available land.

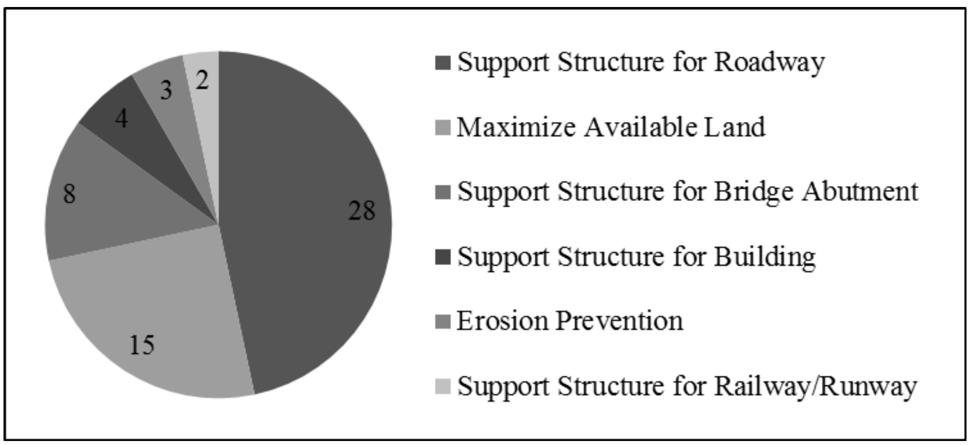


Figure 30. Purpose of Geosynthetic Reinforced Steep Slopes.

GEOSYNTHETIC MATERIAL

Reinforcing elements for the soil slopes consisted of a regular array of tensile elements that had sufficient reinforcement strength to perform their primary function. Figure 31 indicates which materials were used for reinforcement. Uniaxial polyester geogrid was used in the majority of the case studies, which consists of high tenacity polyester multifilament yarns woven in tension and finished with a polyvinyl chloride coating to provide resistance to biological degradation as well as naturally encountered chemicals, alkalis, and acids. The uniaxial polyester geogrid also has high long-term design strength to improve soil interaction and performance. Other case studies utilized uniaxial polyethylene geogrid for primary reinforcement. The high density polyethylene is manufactured with highly oriented polymer chains of hydrocarbons that maintain structural integrity and resist creep when subjected to heavy loads over time. A secondary polymer coating is not necessary, as the inert properties of polyethylene provide resistance to chemical and biological degradation. A small number of projects employed geotextiles or other geosynthetics.

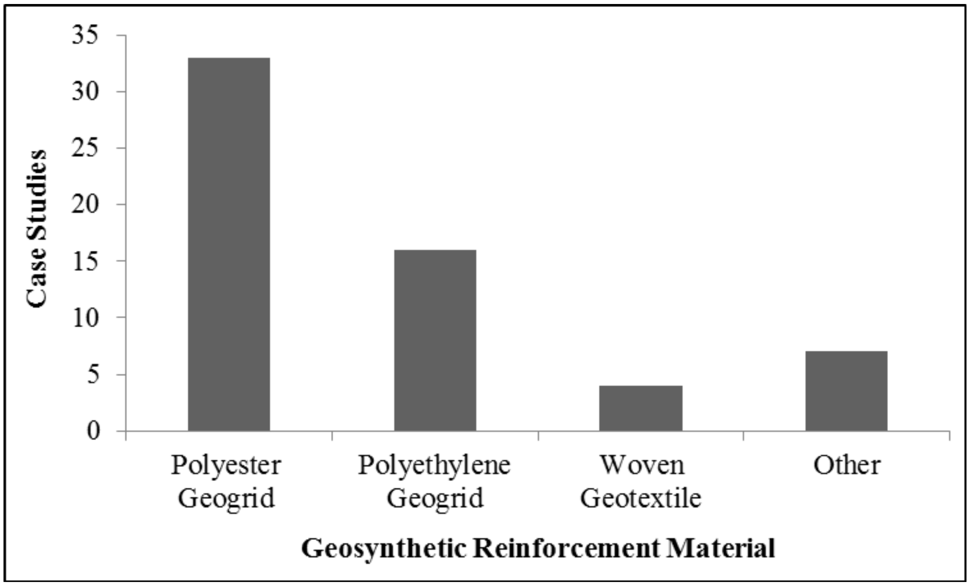


Figure 31. Geosynthetic Reinforcement Material for Steep Slopes.

Most of the case studies also supplemented the primary reinforcement with other geosynthetic materials for facing, erosion control, drainage, or separation. Popular facing elements included a variety of meshes composed of polymers or steel that allowed the faces to be vegetated after construction. Welded wire forms, gabions, and hessian bags were also used for the facade in some cases. Alternatively, biodegradable natural fiber blankets used in other projects provided a more environmentally conscious solution to slope facing.

FOUNDATION AND BACKFILL MATERIAL

Limited information was available concerning the foundation and backfill materials that were incorporated in the GRSS case studies. More detailed parameters for soil properties are available in transportation agency specifications. For example, Case Study #35 in Moscow, Maine, the reinforced backfill had to meet both Maine DOT Type E specifications and the following requirements: 0 percent to 10 percent passing the #200 sieve with maximum aggregate size of no larger than 1 in, plasticity index < 6, internal friction angle $> 34°$, free angular material, and within a pH range of 3 and 9. No shale or soft, poor-durability particles were used. Other case studies noted that conformance testing was performed for fill and reinforcement materials in accordance with project requirements. Field inspection of embedment lengths with field compaction testing was also conducted. The evaluations documented that all materials conformed to project specifications and were installed properly.

SLOPE GEOMETRY

In addition to repairing failed slopes, steep slope reinforcement was also introduced in the case studies for the construction of new embankments, the widening of existing embankments and as an alternative to retaining walls. Quantitative information regarding the slope geometry prior to construction was not available for most of the projects. However, it is possible to build reinforced slopes in many different environments provided that space constraints and site conditions allow proper access.

Slope geometry after construction was available for most of the case studies, and Figure 32 illustrates the height and angle of the GRSS. The height of the slopes ranged from 8 ft to 242 ft. Case Study #20, the reinforced slope structure that supports the runway at the Yeager Airport in Charleston, West Virginia, is considered to be among the tallest in the world. However, most of the slopes that were investigated have a height less than 50 ft. It is also worth noting that Case Study #2, the Cherry Island Landfill Expansion in Wilmington, Delaware, is 1.5 miles in length.

Since structures with inclinations over 70° are classified as walls, reinforced slopes were investigated that have inclinations less than 70°. The angle of the slopes in the case studies ranged from 27° to 70° with the most common inclinations for GRSS being 1H:1V (45°) and 1H:2V (63°). Although geosynthetic reinforcement can also be used for structures with a geometry of 1H:3V (72°) or steeper, other stabilization elements may be needed to prevent erosion of the face.

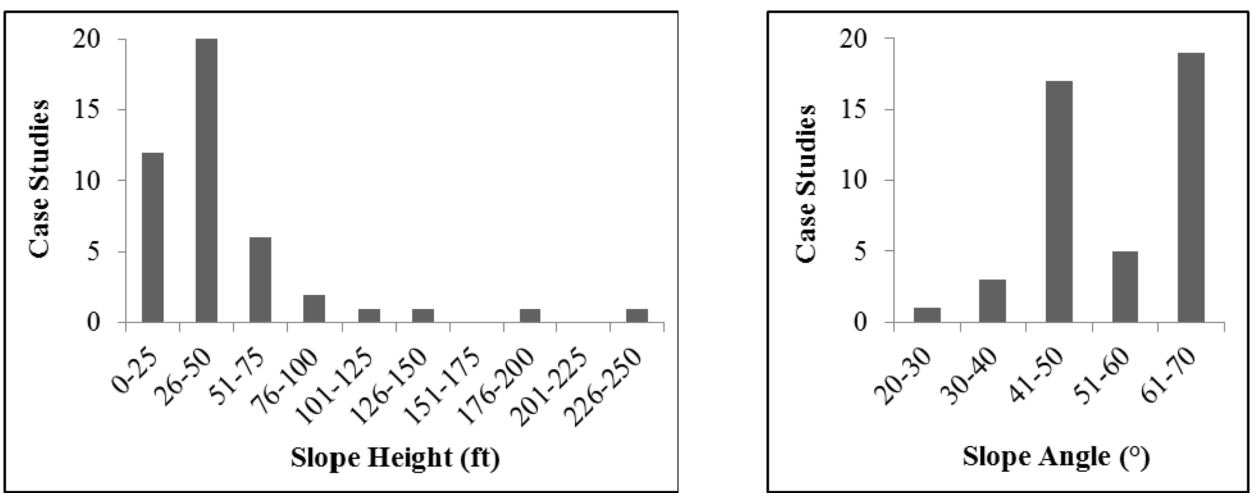


Figure 32. Height and Angle of Geosynthetic Reinforced Steep Slopes.

DESIGN METHODS

Slope stability analysis was performed utilizing the FHWA design guidelines for many of the case studies in order to evaluate the GRSS. This process is based on global safety factors and performance limits that establish the adequacy of the design features. The maximum tension that acts on each level of reinforcement is determined by considering the necessary tensile strength of reinforcement and soil shear resistance to reach local equilibrium. Considerations for the resistance of the inclined surfaces included internal stability analysis based on rotational and sliding surfaces. External stability analysis was also performed, considering deep-seated global, lateral squeeze, and bearing failure. Seismic limit-equilibrium approaches were used in some cases. Other engineers implemented a finite element analysis for designing adequate reinforcement based on the limit-state approach. Objectives were to find problem areas, investigate potential failure mechanisms, and design a safe, reliable, and economical structure. A common computational approach for designing slopes was to use analysis software. Additional information regarding design methods is provided in Chapter II.

CONSTRUCTION PRACTICES

The case study information was synthesized from projects of private and public ownership. Therefore, requirements for construction practices vary from transportation agency specifications to supplier recommendations. The following sequence was followed for typical construction of a reinforced slope:

1. Site preparation.
2. Place the first reinforcing layer.
3. Place backfill on reinforcement.
4. Compaction control.
5. Face construction.
6. Continue with additional reinforcing materials and backfill.
7. Field inspection.

Contractors were faced with numerous challenges, including adverse weather conditions, material quality, staged construction, and space constraints, but they found that production improved as they became more familiar with the handling and assembly of the geosynthetic material. Careful field layout of runoff water, reinforcing materials, and setbacks for lifts was required as well as taking care in placement of reinforcing materials and compaction of fill. Generally, slopes were seeded immediately after completion to allow grass to grow as quickly as possible. The completed slope faces were also often treated with erosion control measures to prevent erosion before permanent vegetation could be established.

PERFORMANCE

A valuable solution was found in many case studies by using GRSS as a support structure for roadways, making them more stable and improving traffic safety. When adequate materials were employed, slope performance was most satisfactory even with torrential rain, showing no damage to the structures and only minimal damage to the grass planted on the face. Occasional removal of woody vegetation and burrowing animals from the reinforced slope face was required in some cases.

Typically, minimal distress or deformation to the structures was observed due to extensive monitoring during construction. To monitor the performance of Case Study #40 in Maehongson, Thailand, a Geodetect fiber-optic strain monitoring system was incorporated into the slope with the geogrid reinforcement. The monitoring results 7 months after construction showed that horizontal strains were small, less than 1 percent. At 15 months after construction, there was negligible difference in the horizontal strains.

To achieve performance that meets expectations, many projects incorporated both geogrid for high strength reinforcement and geotextile for improved face stability. Other slopes employed welded wire forms for facing where each individual unit is laced to the adjacent units forming a monolithic structure that once complete is capable of taking up external loads including seismic forces with minimal noticeable deformation. However, natural mesh facing elements were selected in some case studies to have a lower environmental impact and a higher degree of flexibility.

Case Studies #54 and #60 provide detail regarding slope failures that have occurred in Taiwan and the United States, respectively. Observations led to the conclusion that the failures were closely related to poor embankment fill and drainage systems. Moisture migration produced adverse influences on the stability of the reinforced slope systems.

COST EFFECTIVENESS

In the case studies, constructing GRSS was determined to be the most practical and cost effective option when compared to alternative mechanically stabilized earth structures. The projects created cost savings for their owners due to reduced duration and minimal use of equipment and labor. The economic and environmental benefits of using reinforced soil rather than reinforced concrete were important in the adoption of this type of structure. Moreover, budget constraints and environmental concerns favored slope solutions that lowered costs and offered greener profiles.

Case Study #35 in Moscow, Maine, utilized geotextile for reinforced soil slopes, which resulted in cost savings of approximately $700,000. Due to the high cost of a long span bridge, the alternate option of a shorter bridge with approach embankments touching down in the lake was constructed. The environmental impact to Wyman Lake was also reduced when compared to other construction methods. The versatility of geosynthetic reinforcement allows structures to be constructed quickly and concurrent with the backfilling process. Due to the ease of constructability and the economy of reinforced slopes, many owners were able to obtain cost savings up to 50 percent over alterative systems. Construction of GRSS can play a large role in keeping projects moving forward when alternative options prove to be too costly and impractical.

CHAPTER VI: CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The purpose of the study was to provide a synthesis of GRSS construction specifications, design guidelines, and case studies. The following conclusions were made based on a comprehensive review of technical reports, journal articles, DOT specifications, and case studies as well as surveys and interviews of academic and industry professionals:

1. Reinforced slopes are a form of mechanically stabilized earth that incorporate planar reinforcing elements for the construction of sloped structures with inclinations less than 70°. To provide tensile resistance and stability, geosynthetic reinforcement has been employed for repairing failed slopes, constructing new embankments, and widening existing embankments.
2. According to the survey, following the FHWA design guidelines is the most advocated approach for designing GRSS. Other common design methods have been developed by Jewell, Leshchinsky, and Eurocode. Internal and external stability are considered, including rotational, sliding, bearing, and lateral failure. Interactive software is also available for engineers to independently design projects.
3. Geogrids and geotextiles manufactured from polyester, polypropylene, or polyethylene are commonly used for reinforcement. The material must be resistant to all naturally occurring alkaline and acidic soil conditions, resistant to heat, ultraviolet light, and to attack by bacteria and fungi in the soil.
4. An adequate subsurface investigation should be performed for the existing foundation as well as behind and in front of the structure to assess overall performance behavior. To facilitate compaction, a high quality fill meeting gradation, shear strength, and internal friction angle requirements is recommended for the embankment soil.
5. The reinforcement is placed with the principal strength direction perpendicular to the face of the slope, pulled taut, and secured with retaining pins to prevent movement during fill placement. Backfill material is placed and compacted without deforming the reinforcement, utilizing lightweight compaction equipment near the slope face to maintain alignment.
6. Performance monitoring programs are recommended for cases in which new features or materials have been incorporated in the design, post construction settlements are anticipated, or where degradation/corrosion rates of reinforcements are to be monitored.
7. Geosynthetics can be degraded by a combination of environmental mechanisms. However, none of the documented failures were due to inadequate reinforcement. All failures within the reviewed body of literature were due to improper design in the area of surface and internal water removal or the use of fine grained silt and clay backfill soils.
8. Many site specific characteristics contribute to the overall cost of GRSS, including cut-fill requirements, wall/slope size and type, existing soil type, available backfill materials,

and facing finish as well as application. The approximate costs of the principal components are as follows: reinforcement 45–65 percent, backfill 30–45 percent, and face treatment 5–10 percent.

9. In the case studies, constructing GRSS was determined to be the most practical and cost effective option when compared to alternative mechanically stabilized earth structures. Budget constraints and environmental concerns favored slope solutions that lowered costs and offered greener profiles.

RECOMMENDATIONS

The following recommendations for TxDOT were made based on the knowledge and experience gained during the present research project:

1. The research team recommends that TxDOT construct a trial GRSS project using local materials and labor. Specification compliance and construction checklists should be used, and a comprehensive performance monitoring program should also be implemented to compare the observed behavior to the intended design.
2. It is also recommended that TxDOT follow the FHWA design guidelines for GRSS. The existing topography, subsurface conditions, and soil properties must be considered when evaluating the site for construction. The investigation should include determining the availability of the required type of reinforced fill and backfill materials.
3. Geogrid or geotextile constructed of polyester, polypropylene, or polyethylene are recommended for soil slope reinforcement. The material should be resistant to heat, ultraviolet light, attack by bacteria and fungi, and all naturally occurring alkaline and acidic soil conditions.
4. Free draining backfill meeting the gradation limits of AASHTO T-27 should be used in the reinforced volume. The reinforced fill should also have a plasticity index less than 20, a pH level in the range of 5 to 10, and be reasonably free from organic or otherwise deleterious material. Soil density, cohesion, and internal friction angle should be determined and considered in design calculations.
5. Surface water runoff should be collected above the reinforced slope and channeled or piped below the base of the slope. Design of subsurface water drainage features should address flow rate, filtration, placement, and outlet details.
6. If slope facing is required to prevent erosion, the reinforcement at the face should be turned up and returned into the embankment below the next reinforcement layer. Other popular facing elements include a variety of meshes composed of polymers or steel that allows the face to be vegetated after construction.
7. The research team also recommends TxDOT incorporate the synthesized information into the geotechnical manual and construction specifications for GRSS. Consideration should be given to design methods, material specifications, and construction guidelines.

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APPENDIX A: SURVEY QUESTIONNAIRE

Texas State University respectfully requests your participation in a short survey regarding the use of geosynthetic materials for steep slope reinforcement. The survey is being conducted for TxDOT Research & Technology Implementation Project #0-6792. Findings of the present study will be used to determine the feasibility of constructing GRSS in Texas.

The following link provides access to a series of questions. We estimate that they will take approximately 5 to 10 minutes to answer. Even partial completion of the survey will be beneficial to the study.

Click to start survey: http://www.surveymonkey.com/s/Geosynthetic_Reinforced_Steep_Slopes

Your participation is greatly appreciated. Survey responses will be summarized and included in the final research project report. Please contact us if you have any questions or comments.

1. Please provide the following contact information so that we may contact you if we have further questions:

   Name:
   Organization:
   Email:
   Telephone:

2. Which category or categories best describe your organization?

   □ Transportation Agency
   □ Educational Institution
   □ Engineering Consultant
   □ Construction Contractor
   □ Material Supplier
   □ Other Category (Please Specify)

3. Has your organization designed or constructed geosynthetic reinforced steep slopes?

   □ Yes
   □ No

4. Who do you recommend that we contact regarding geosynthetic reinforced steep slopes?

   (1)
   (2)
   (3)
   (4)
   (5)

5. What design method(s) do you recommend for geosynthetic reinforced steep slopes?

   □ United States Federal Highway Administration Method
   □ Other Method (Please Specify)

6. What geosynthetic material do you recommend for reinforcing steep slopes?

   Material Description:
   Material Manufacturer:
   Product Name:
   Cost Per Square Yard:

7. Please provide any additional comments in the space provided below.

APPENDIX B: SUMMARY OF SURVEY QUESTIONNAIRE RESULTS

The survey was sent to 393 recipients, and responses were received from 52 for a response rate of 13 percent. Of those who responded, 43 have experience designing or constructing GRSS. Figure 33 shows the affiliation of the survey respondents.

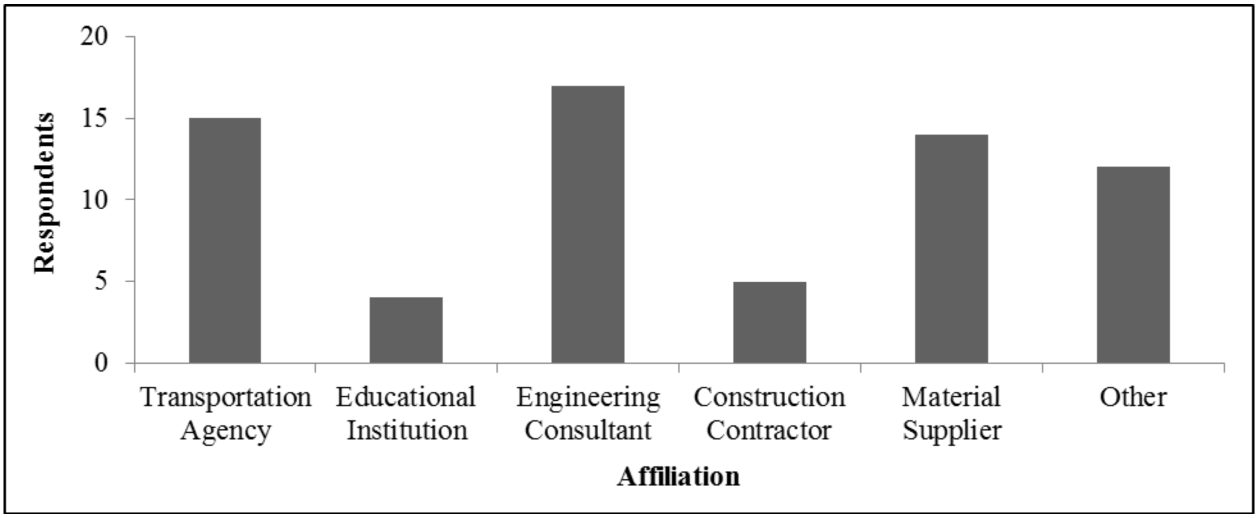


Figure 33. Affiliation of Survey Respondents.

As per Figure 34, the majority of the respondents recommend the use of the FHWA method for the design of GRSS. Eighty-eight percent of the respondents recommended the use of geogrid or a combination of geogrid and geotextile for slope reinforcement, while the others recommended independent use of geotextile. The reinforcement material cost ranges from \$1.25/yd^2 to \$15.00/yd^2 and varies depending on quantity and material properties.

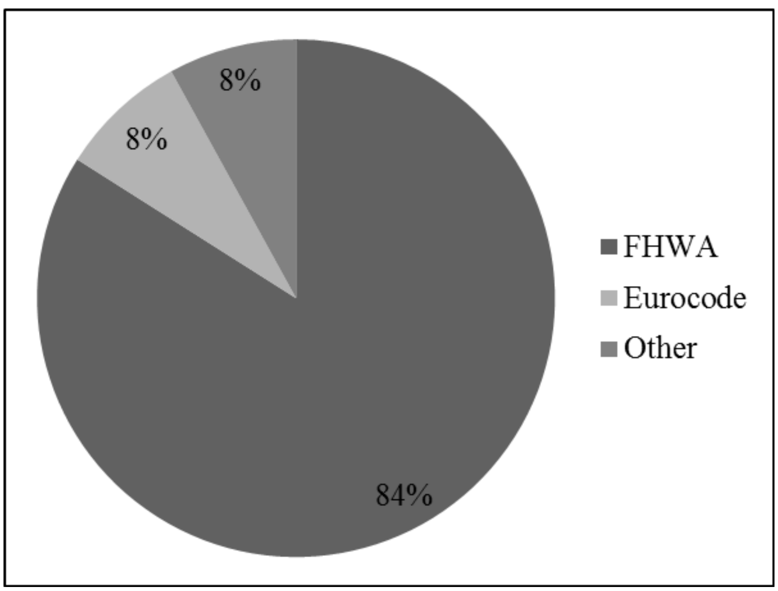


Figure 34. Recommended Design Methods.

The following additional comments were provided by the respondents:

Respondent #6
Generally, an owner is better served by a traditional design-bid-build approach. An independent designer can prepare a generic design in which multiple geosynthetic manufacturers have applicable strength products. This provides competition between geosynthetic suppliers on material costs and various earthwork contractors on the installation costs while allowing the owner to have complete control over the design requirements and input soil parameters so that the owner is ensured of attaining the level of safety and reliability it desires for the reinforced slope.

Respondent #7
Many geosynthetic and metallic reinforcing materials provided by a variety of manufacturers can be used to construct steep reinforced slopes. A significant issue to be dealt with is the deformation behavior of such slopes, particularly if lower quality fill materials are used, such as materials containing fines in excess of 15 percent. Long-term deformation of such slopes can be problematic, specifically if the slopes support structures or pavements that cannot tolerate significant deformation.

Respondent #11
Cost depends upon slope height, surcharge load, availability of select backfill, etc.

Respondent #34
I prefer high strength geotextiles over geogrids, as they provide a separation function and generally are more cost effective.

Respondent #39
Cost is highly dependent upon the tensile strength required for the geogrid. Tensile strength is dependent upon design requirements.

Respondent #44
FHWA GEC 11 is a good reference. Protecting the final slope face from erosion will determine success or failure in the eyes of the public.

Respondent #48
We prepare generic reinforcement designs. We specify the strength, vertical spacing, and length of reinforcement required. We prepare performance based specifications that specify the geosynthetic reinforcement properties. Any reinforcement product that meets the design criteria is acceptable. This design approach provides the owner with a quality design and allows the marketplace to determine the cost. Product specific design does not serve the owner and the profession well.

Respondent #51
WVDOT allows HDPE, polypropylene, and high tenacity polyester geosynthetic reinforcements in our RSS. We do not give preference for particular material types. We specify minimum requirements for strength, size, etc. and as long as the material meets the spec, we accept it.

APPENDIX C: INTERVIEW QUESTIONNAIRE

General

1. Who do you recommend that we contact to obtain additional information regarding geosynthetic reinforced steep slopes?

2. Do you have any case studies, design examples, specifications, publications, or other information that may be beneficial to the present study?

Design Methods and Material Selection

3. What equations and criteria do you recommend for designing geosynthetic reinforced steep slopes?

4. What material do you recommend for reinforcement? What alternatives have you considered?

5. What foundation and embankment soil conditions are preferred?

Construction Practices and Contracting Methods

6. What construction specifications/sequence do you recommend?

7. What challenges are faced during construction?

8. What height limitations do you recommend for geosynthetic reinforced steep slopes?

9. Which contracting method do you recommend?

Performance Measures and Cost Effectiveness

10. What measures do you use to determine project performance?

11. What are some common distresses observed in geosynthetic reinforced steep slopes?

12. What type of maintenance or repair should be expected?

13. How does the cost of geosynthetic reinforced steep slopes compare with other mechanically stabilized earth structures, and do you consider it to be a cost effective solution?

14. What is the average cost for reinforcement material per square foot?

15. What is the average cost for embankment soil per cubic yard?

APPENDIX D: SUMMARY OF INTERVIEW QUESTIONNAIRE RESULTS

Interview #1
The respondent has extensive professional experience as an engineering consultant for mechanically stabilized earth projects, including over 100 reinforced walls and slopes for private owners and state agencies. He recommends the use of geogrids and geotextiles for reinforcing steep slopes, considering it to be a cost effective solution when project parameters will allow for their construction. Challenges faced during construction are often due to inadequate soils or contractors underbidding the project cost. Geotechnical investigations should be conducted prior to design and construction, because assuming properties of the onsite soils can lead to unforeseen distresses. Wall failures are even possible if the foundation and embankment soils are unsuitable. It is also recommended that a detailed design be completed prior to the bid and for soil and reinforcing material properties to be considered in accordance with the FHWA design method. Steep slopes should be inspected for movement and settlement. However, no maintenance or repair should be expected if the project is properly designed and constructed.

Interview #2
The respondent assisted with development of the AASHTO design manual for reinforced slopes and has over 20 years of experience designing and evaluating reinforced earth structures. Many geosynthetic and metallic reinforcing materials provided by a variety of manufacturers can be used to construct steep reinforced slopes. A significant issue to be dealt with is the deformation behavior of such slopes, particularly if lower quality fill materials are used, such as materials containing fines in excess of 15 percent. Long-term deformation of such slopes can be problematic, specifically if the slopes support structures or pavements that cannot tolerate significant deformation. The engineer recommends use of the FHWA design method with hard aggregate, such as crushed limestone or sandstone, reinforced with geotextile or geogrid. He also recommends for the owner to specify performance and for the contractor to design the project in the submittal process. However, distresses can occur if the contractor does not construct the slope with quality soil and reinforcement. Common distresses include deformation and settlement, but global failure is possible if the site has poor drainage and degraded soil quality. Soil tests should be conducted before and after handling. If the proper precautions are taken into consideration, geosynthetic reinforced steep slopes can be an economical solution for mechanically stabilizing earth.

Interview #3
The respondent is a veteran of the construction and materials engineering field with over 15 years of experience working with designers and manufacturers. He recommends uniaxial geogrids for reinforcement of steep slopes, as they allow for less spacing and larger lifts. Further embankment of geogrids, however, is typically required when compared to geotextiles. Cost effective construction also requires a tight connection between the engineer's design and the contractor's execution. Providing backfill that is consistent with the project specifications is a major challenge faced during construction. For this reason, field inspection and quality assurance programs are critical for building successful structures. Additionally, it is preferred for the manufacturer to collaborate directly with the owner during the design phase, promoting the consideration of project alternatives prior to the bid.

Interview #4
The respondent has 15 years of experience in the geotechnical field, including over 50 reinforced steep slope projects. The slopes have primarily been used to optimize roadway areas. Erosion was prevented by controlling the granularity of the backfill material, and there have been no signs of distress or failure. Challenges faced during construction were mitigated through sufficient communication between all parties involved. Consequently, life cycle costs have not included maintenance or repair, making reinforced slopes a cost effective solution. The current construction cost of a reinforced slope is in the range of \$40/ft^2 of vertical height, depending on the site conditions and project requirements. For comparison, mechanically stabilized earth walls cost approximately \$60/ft^2 of vertical height.

Interview #5
The respondent has worked for the state transportation agency as a consulting engineer on several reinforced slope projects. He warns that edge compaction is among the most common challenges faced during construction. The engineer recommends geogrid as the primary reinforcement material, although other materials are often used for the slope facing. Geocells provide an alternative approach to the facing that allows a hand compactor to be employed on the face of the earth structure, ensuring that adequate compaction levels are achieved. Despite the fact that mechanically stabilized earth walls are easier to compact, reinforced slopes are still a cost effective construction method.

Interview #6
The respondent has over 30 years of experience as a construction contractor and materials supplier in the geosynthetics field. Since proper safety is a challenge faced during construction, he recommends for a safety plan to be implemented concerning potential hazards. The contractor also recommends geogrid for reinforcement of soil slopes and geotextile or geonet for the top. By taking adequate safety measures and utilizing sufficient materials and construction methods, there is no maintenance or repair that should be expected. Reinforced soil slopes constitute a viable solution when compared to alternatives; however, the cost of the material varies depending on the quantity and performance required.

APPENDIX E: DESIGN EXAMPLES

FHWA DESIGN GUIDELINES WITH RESSA SOFTWARE

The following example provides a step by step procedure for performing a GRSS preliminary design with ReSSA software in order to evaluate the feasibility of specific project parameters. Additional information regarding the design of GRSS is provided in Chapter 2.

Define Slope Geometry, Loading, and Performance

The first step was to establish the geometric, loading, and performance requirements for the design and input the respective values as per Figure 35. Factors of safety recommended by the FHWA were utilized for the analysis.

Geometric and Load Requirements:

Slope Height (H) = 20 ft
Slope Angle (β) = 70°
Surcharge Load (q) = 250 lb/ft^2
Crest Width (A) = 20 ft

Performance Requirements:

Internal Stability: FS = 1.5
External Stability: FS = 1.5

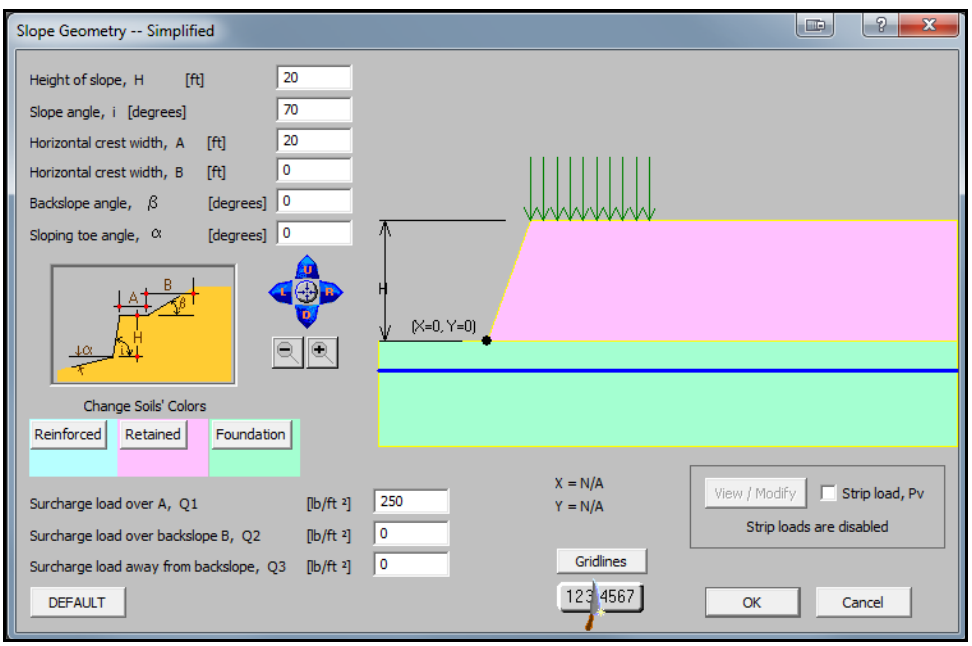


Figure 35. Slope Geometry and Surcharge Load.

Define Engineering Properties of Soils

The parameters listed below were assumed for the foundation, retained, and reinforced soils, and the respective values were input as per Figure 36. Reduction factors for cohesion and friction can also be specified; however, a value of 1.0 is recommended for conventional limit equilibrium analysis according to ADAMA Engineering. The depth of the water table was also specified as per Figure 37.

Foundation and Retained Soils:

Internal Friction Angle (ϕ_u') = 34°
Cohesion (c_u') = 0
Density (γ_u) = 125 lb/ft^3

Reinforced Soil:

Internal Friction Angle (ϕ_r') = 34°
Cohesion (c_r') = 0
Density (γ_r) = 125 lb/ft^3

Depth of Water Table (d_w) = 5 ft

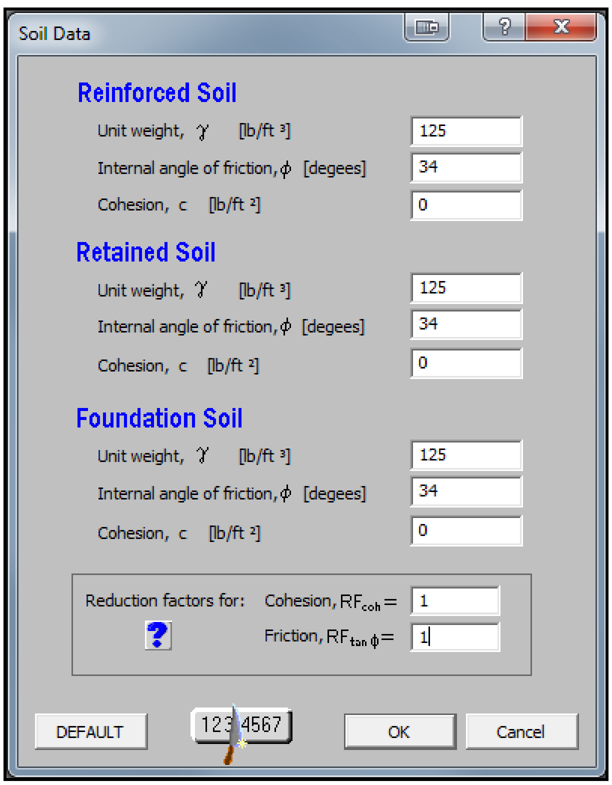


Figure 36. Engineering Properties of Foundation, Retained, and Reinforced Soils.

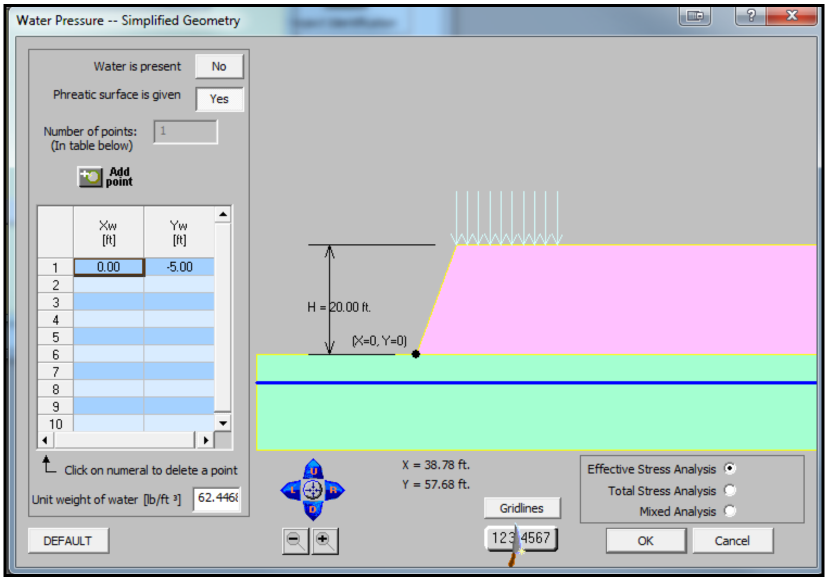


Figure 37. Depth of Water Table.

Check Unreinforced Stability

The stability of the unreinforced slope was evaluated using rotational and translational analysis. To determine the location of the critical zone, a range of upper and lower points for circular arcs were specified as per Figure 38. The AASHTO/FHWA Bishop method was selected with a relative orientation of reinforcement (ROR) equal to 1.0. Comprehensive Bishop typically utilizes ROR = 0.0. Values of this nondimensional parameter vary between 0.0 and 1.0, and FHWA guidelines specify ROR = 0.0 for discrete reinforcement with a coverage ratio (R_c) less than 1.0 and ROR = 1.0 when R_c = 1.0.

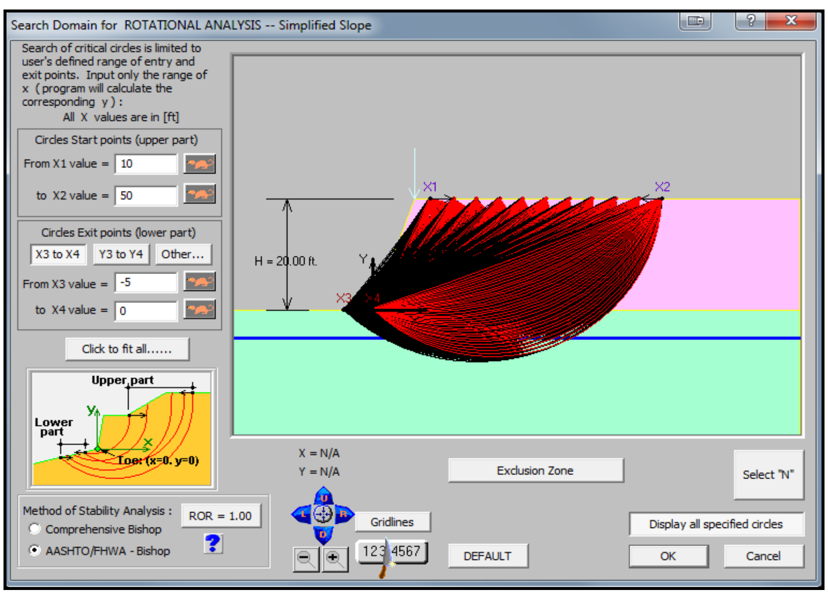
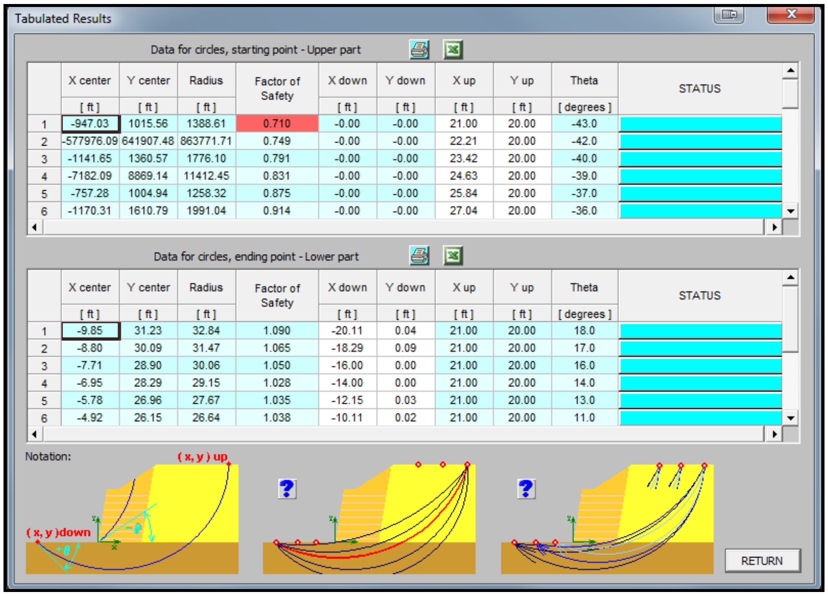


Figure 38. Upper and Lower Points of Rotational Analysis.

Tabulated results of the rotational analysis are shown in Figure 39. Upper and lower parts of the circular arc with the lowest unreinforced factor of safety (F_U) were provided along with the corresponding center of rotation, radius, and coordinate locations. As per Figure 40, the driving moment of the critical circular arc was also calculated. Using the values provided by the software, an iterative cycle was performed to calculate the maximum required tensile force per unit width of reinforcement in all reinforcement layers intersecting the failure surface.



Tabulated Results

Data for circles, starting point - Upper part

	X center [ft]	Y center [ft]	Radius [ft]	Factor of Safety	X down [ft]	Y down [ft]	X up [ft]	Y up [ft]	Theta [degrees]	STATUS
1	-947.03	1015.56	1388.61	0.710	-0.00	-0.00	21.00	20.00	-43.0	
2	-577976.09	641907.48	863771.71	0.749	-0.00	-0.00	22.21	20.00	-42.0	
3	-1141.65	1360.57	1776.10	0.791	-0.00	-0.00	23.42	20.00	-40.0	
4	-7182.09	8869.14	11412.45	0.831	-0.00	-0.00	24.63	20.00	-39.0	
5	-757.28	1004.94	1258.32	0.875	-0.00	-0.00	25.84	20.00	-37.0	
6	-1170.31	1610.79	1991.04	0.914	-0.00	-0.00	27.04	20.00	-36.0	

Data for circles, ending point - Lower part

	X center [ft]	Y center [ft]	Radius [ft]	Factor of Safety	X down [ft]	Y down [ft]	X up [ft]	Y up [ft]	Theta [degrees]	STATUS
1	-9.85	31.23	32.84	1.090	-20.11	0.04	21.00	20.00	18.0	
2	-8.80	30.09	31.47	1.065	-18.29	0.09	21.00	20.00	17.0	
3	-7.71	28.90	30.06	1.050	-16.00	0.00	21.00	20.00	16.0	
4	-6.95	28.29	29.15	1.028	-14.00	0.00	21.00	20.00	14.0	
5	-5.78	26.96	27.67	1.035	-12.15	0.03	21.00	20.00	13.0	
6	-4.92	26.15	26.64	1.038	-10.11	0.02	21.00	20.00	11.0	

Figure 39. Tabulated Results of Rotational Analysis.

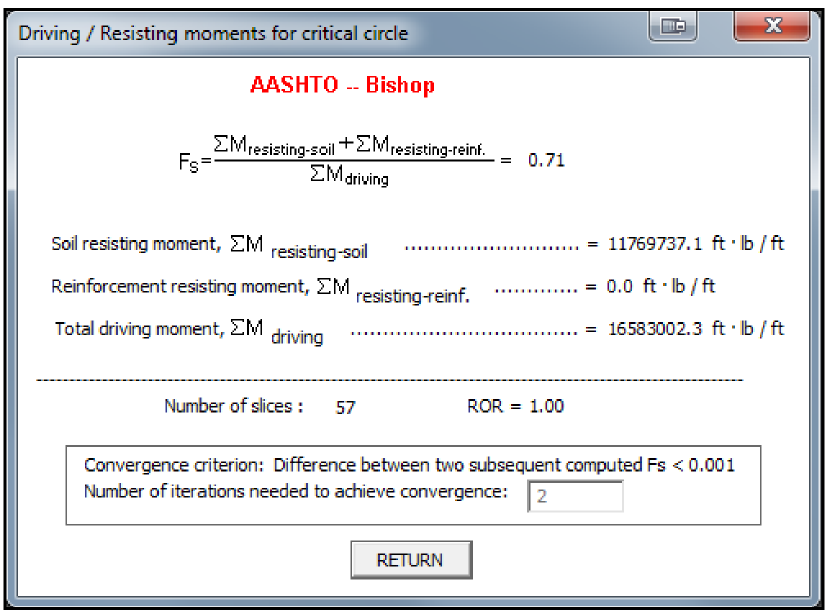


Figure 40. Driving Moment of Critical Circular Arc.

The following formula was used to calculate the total reinforcement tension per unit width of slope (T_S) that is required to obtain the required factor of safety (FS_R) for each potential failure surface in the critical zone, and the results are shown in Table 10:

$$T_S = (FS_R - FS_U) \times \left(\frac{M_D}{D}\right)$$

where:

T_S = required tensile force per unit width of reinforcement in all reinforcement layers intersecting the failure surface.

FS_R = target minimum slope factor of safety.

FS_U = unreinforced slope factor of safety.

M_D = driving moment about the center of the failure circle.

D = moment arm of T_S about the center of the failure circle.

Table 10. Determination of Critical Zone Location.

Horizontal Distance (ft)	FS_U	M_D (ft-lb/ft)	D (ft)	T_S (lb/ft)
15	0.506	2259273.5	229.38	9790
16	0.538	3351929.0	314.20	10263
17	0.573	5273061.9	461.43	10593
18	0.607	9298947.6	765.13	10853
19	0.641	21879644.6	1703.87	11031
20	0.675	11149681.7	814.22	11297
21	0.709	19880729.6	1388.61	11325
22	0.742	47139731.7	3161.55	11302
23	0.776	2681270388.9	173251.21	11205
24	0.811	18112307.8	1116.46	11178
25	0.844	23405414.0	1397.98	10983

Translational analysis of the unreinforced slope was used to confirm the location of the critical zone. This roughly defined the zone needing reinforcement. Based on the sliding wedge method, the critical zone was positioned within close proximity to that determined by the rotational analysis.

Design Slope Reinforcement

From the unreinforced stability analysis, the maximum required tensile force per unit width of reinforcement in all reinforcement layers intersecting the failure surface ($T_{S\text{-}MAX}$) was determined to be 11,325 lb/ft with the upper point of the critical zone being located at (21 ft, 20 ft) in accordance with the rotational analysis in Figure 41.

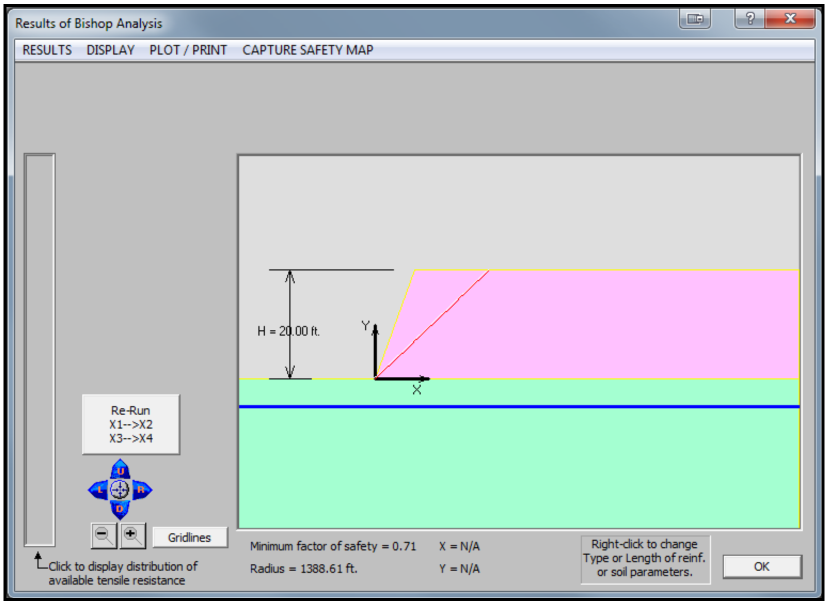


Figure 41. Critical Zone of Unreinforced Slope.

FHWA recommends for the vertical spacing of reinforcement to be no greater than 16 inch. With this consideration, the number of layers and ultimate tensile strength of the reinforcement were calculated in accordance with the following equations while also accounting for long-term strength losses by using suggested reduction factors:

$$N = \frac{H}{S_v} = \frac{20\ ft}{16\ in} = 15\ layers$$

$$T_{ult} = \left(\frac{T_{S-MAX}}{N}\right)(RF_{ID} \times RF_{CR} \times RF_D) = \left(\frac{11328\frac{lb}{ft}}{15}\right)(1.2 \times 3.0 \times 1.25) = 3398\frac{lb}{ft}$$

where:

N = number of reinforcement layers.

S_v = vertical spacing of reinforcement.

T_{ult} = ultimate tensile strength per unit width of reinforcement determined from wide strip tests as per ASTM D4595 (geotextiles) or ASTM D6637 (geogrids).

RF_{ID} = installation damage reduction factor.

RF_{CR} = creep reduction factor.

RF_D = durability reduction factor.

To accommodate the ultimate tensile strength requirement, a geogrid with T_{ult} = 3600 lb/ft was chosen for the reinforcement material and input as per Figure 42. It was also necessary to determine the length of embedment beyond the critical surface to satisfy the factor of safety for pullout. The following formula was used:

$$L_e = \frac{(FS_{PO}) \times (T_{S-MAX}/N)}{(F^* \times \alpha \times \sigma'_v \times C)} = \frac{(1.5) \times (11328\frac{lb}{ft}/15)}{\{0.67\tan 34^\circ \times 0.8 \times [200\frac{lb}{ft^2} + (128\frac{lb}{ft^3} \times 0.67 ft)] \times 2\}} = 5.5\ ft$$

where:

L_e = embedment or adherence length in the resisting zone behind the failure surface.
FS_{PO} = pullout factor of safety.
F^* = pullout resistance or friction bearing interaction factor (conservatively taken as $0.67\tan\phi$, where ϕ is the peak friction angle of the soil).
α = scale effect correction factor to account for a nonlinear stress reduction over the embedded length of highly extensible reinforcements based on laboratory data (generally 1.0 for metallic reinforcements, 0.8 for geogrids and 0.6 for geotextiles).
σ_v' = effective vertical stress at the soil reinforcement interfaces.
C = reinforcement effective unit perimeter (equal to 2 for sheets, strips, and grids).

A conservative uniform length of reinforcement was determined to be 27 ft when considering the location of the critical zone (21 ft) and the required length of embedment beyond the critical surface (5.5 ft). Figure 43 illustrates the rotational analysis of the steep slope after installing the geosynthetic reinforcement, indicating that the reinforced structure meets the specified factor of safety.

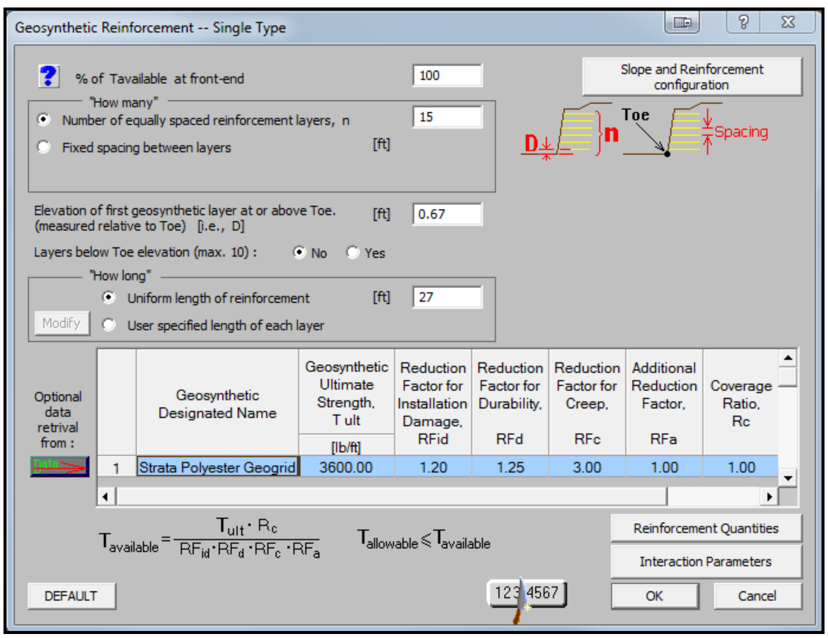


Figure 42. Strength and Reduction Factors of Geosynthetic Reinforcement.

In summary, 15 layers of geosynthetic reinforcement were required with an ultimate tensile strength of 3398 lb/ft and a uniform length of 27 ft. This is a simple structure and additional evaluation of design lengths is not required. Additional analysis of external stability, seismic stability, and runoff water control may be required depending on project requirements.

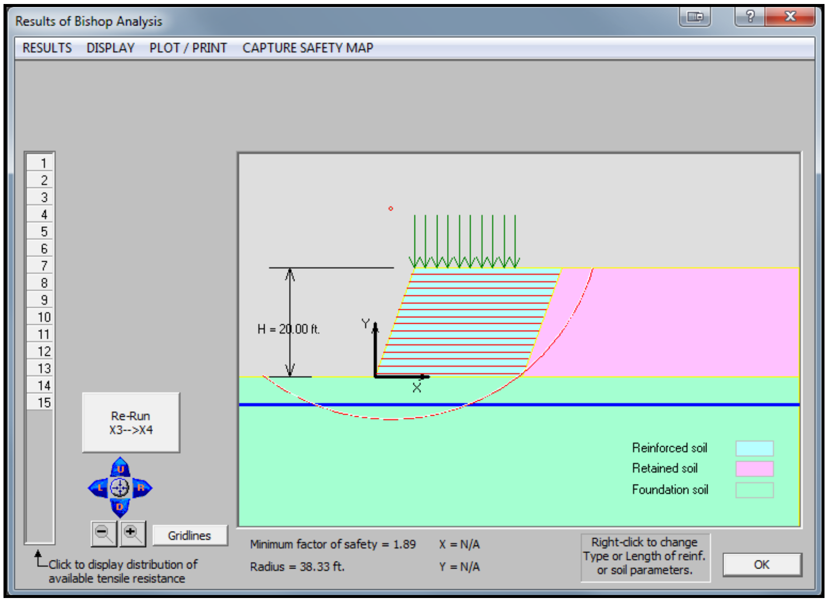


Figure 43. Rotational Analysis of Geosynthetic Reinforced Steep Slope.

FHWA DESIGN GUIDELINES WITH CHART SOLUTION

The following example provides a step by step procedure for performing a GRSS preliminary design with a chart solution in order to evaluate the feasibility of specific project parameters.

Define Slope Geometry, Loading, and Performance

The first step was to establish the geometric, loading, and performance requirements for the design. Factors of safety recommended by the FHWA were used for the analysis.

Geometric and Load Requirements:

Slope Height (H) = 20 ft
Slope Angle (β) = 70°
Surcharge Load (q) = 250 lb/ft^2
Crest Width (A) = 20 ft

Performance Requirements:

Internal Stability: FS = 1.5
External Stability: FS = 1.5

Define Engineering Properties of Soils

The parameters listed below were determined for the foundation, retained, and reinforced soils.

Foundation and Retained Soils:

Internal Friction Angle (ϕ_u') = 34°
Cohesion (c_u') = 0
Density (γ_u) = 125 lb/ft^3

Reinforced Soil:

Internal Friction Angle (ϕ_r') = 34°
Cohesion (c_r') = 0
Density (γ_r) = 125 lb/ft^3

Depth of Water Table (d_w) = 5 ft

Determine the Geogrid Force Coefficient and Total Design Tension

$\phi_f = [\tan^{-1} \times (\tan\phi_r / FS)] = [\tan^{-1} \times (\tan 34° / 1.5)] = 24.2°$

K = 0.34 as per Figure 19 Chart

$T_{S\text{-}MAX} = [0.5 \times K \times \gamma_r \times (H')^2] = \{0.5 \times 0.34 \times 125 \times [20 + (250 / 125)]^2\} = 10285$ lb/ft

Determine the Reinforcement Vertical Spacing and Design Tension per Reinforcement Layer

S_v = 16 in (1.33 ft)

$$\begin{aligned} T_{MAX} &= [(T_{S\text{-}MAX} \times S_v) / H)] \times (RF_{ID} \times RF_{CR} \times RF_D) \\ &= [(10285 \times 1.33) / 20)] \times (1.2 \times 3.0 \times 1.25) \\ &= 3078 \text{ lb/ft} \end{aligned}$$

Determine Length of Reinforcement

L/H′ = 0.8 as per Figure 19 Chart

$L = (L/H') \times H' = 0.8 \times [20 + (250 / 125)] = 17.6$ ft

JEWELL METHOD

The following example provides a step by step procedure for performing a GRSS preliminary design using the Jewell Method in order to evaluate the feasibility of specific project parameters.

Consider a slope with the following parameters:

H	= 20 ft	(height)
β	= 70°	(slope angle)

q	$= 210\ lb/ft^2$	(surcharge load)
c	$= 0$	(soil cohesion)
ϕ	$= 32°$	(soil internal friction angle)
γ	$= 127\ lb/ft^3$	(soil unit weight)
FS_{design}	$= 1.30$	(design factor of safety)
FS_{grid}	$= 2.75$	(geogrid factor of safety)
T_{ult}	$= 4500\ lb/ft$	(geogrid tensile strength)
r_u	$= 0.25$	(pore water pressure coefficient)

1) Calculate the allowable tensile strength (T_{allow}) and design tensile strength (P).

   $T_{allow} = (T_{ult} / FS_{grid}) = (4500 / 2.75) = 1636$ lb/ft

   $P = (T_{allow} / FS_{design}) = (1636 / 1.30) = 1258$ lb/ft

2) Based on the pore water pressure coefficient, determine the coefficient of earth pressure (K) and the ratios of reinforcement length to embankment height $(L/H)_{overall}$ and $(L/H)_{sliding}$ using the charts in Chapter 2 Figure 7, then calculate the reinforcement length.

   $K = 0.30$
   $(L/H)_{overall} = 0.65$
   $(L/H)_{sliding} = 0.60$

   $H' = [H + (q / \gamma)] = [20 + (210 / 127)] = 21.7$ ft

   $L = [H' \times (L/H)_{overall}] = (21.7 \times 0.65) = 14.1$ ft

3) Define the spacing constant (Q) for the slope in terms of the minimum spacing (v) to be used.

   $v = 1$ ft

   $Q = [P / (K \times \gamma \times v)] = [1258 / (0.30 \times 127 \times 1)] = 33$

4) Define the zones for reinforcement layers spaced equally at $v_1, v_2, v_3 \ldots v_n$.

i	Spacing (Sv_i)	Depth (Z_i)	Thickness (s_i)
1	1v = 1 ft	$Q / (Q / 2) = 33 / (33 / 2) = 2$ ft	$H' - (Q / 2) = 21.7 - (33 / 2) = 5.2$ ft
2	2v = 2 ft	$(Q / 2) / (Q / 3) = (33 / 2) / (33 / 3) = 1.5$ ft	$(Q / 2) - (Q / 3) = (33 / 2) - (33 / 3) = 5.5$ ft
3	3v = 3 ft	$(Q / 3) / (W_s / \gamma) = (33/3) / (210 / 127) = 6.7$ ft	$(Q / 3) - (W_s / \gamma) = (33/3) - (210 / 127) = 6.7$ ft

5) Calculate the number and position of the required reinforcement layers. The number of grids in a zone (N) is rounded down to the nearest whole number.

i	s_i'/Sv_i	Number of Grids (N_i)	Remaining Thickness ($R_i = s_{i-1} - (Sv_i \times N_i)$)	$s_{i+1}' = s_{i+1} + R_i$
0			$R_0 = 0.0$ ft	$s_1' = 5.2 + 0 = 5.2$ ft
1	$5.2 / 1 = 5.2$	5	$R_1 = 5.2 - (1 \times 5) = 0.2$ ft	$s_2' = 5.5 + 0.2 = 5.7$ ft
2	$5.7 / 2 = 2.9$	2	$R_2 = 5.7 - (2 \times 2) = 1.7$ ft	$s_3' = 6.7 + 1.7 = 8.4$ ft
3	$8.4 / 3 = 2.8$	2	$R_3 = 8.4 - (3 \times 2) = 2.4$ ft	

If the top layer of reinforcement is more than 2 ft below the slope crest, it is prudent to add an additional layer. Therefore, although $N_{total} = 9$, a 10^{th} reinforcement layer spaced 2 ft near the crest of the slope should be added.

6) Calculate the gross horizontal force for equilibrium and check the geogrid tensile force.

$$T = [0.5 \times K \times \gamma \times (H')^2] = [0.5 \times 0.30 \times 127 \times (21.7)^2] = 8970 \text{ lb/ft}$$

$$T / N_{total} = 8970 / 10 = 897 \text{ lb/ft}$$

$$T / N_{total} \leq P$$

APPENDIX F: SUMMARY OF TRANSPORTATION AGENCY SPECIFICATIONS

Geosynthetic Material Specifications

Texas DOT (2004)	• Geogrid shall have greater than or equal to 50% open area as per Tex-621-J. • The long-term design allowable strength shall be greater than or equal to 1300 lb/ft according to the manufacturer's certification that the material has been tested in accordance with GRI GG-4.
Alabama DOT (2012)	• The geosynthetic reinforcement (either geogrid or geotextile) shall be constructed of polyester, polypropylene, or polyethylene, resistant to all naturally occurring alkaline and acidic soil conditions, resistant to heat, ultraviolet light, and to attack by bacteria and fungi in the soil. • Reinforcement for soil slopes shall be any geosynthetic whose strength in the machine direction equals or exceeds the values provided in the specification.
California DOT (2005)	• Only one type of geosynthetic reinforcement material shall be used for an entire embankment, except as shown on the plans. • Geosynthetic reinforcement shall be configured as either a geogrid or geotextile. • The percentage of the open area for geogrids shall range from 50% to 90% of the total projection of a section of the material. • Geotextiles shall have an irregular or regular open area with the spacing of open areas being less than 6.3 mm in any direction. • Geosynthetic reinforcement material shall be resistant to naturally occurring alkaline and acidic soil conditions and to attack by bacteria. • Long Term Design Strength (LTDS) for geosynthetic reinforcement shall be determined by GRI standard practices. • Geosynthetic reinforcement shall consist of high density polyethylene, polypropylene, high density polypropylene sheets, high tenacity polyester yarn, or polyaramide.
Florida DOT (2010)	• Use primary and secondary reinforcing elements consisting of a regular array of tensile elements that have sufficient reinforcement strength to perform the prime functions of reinforcement and which are listed on Design Standards Index #501.
Mississippi DOT (2004)	• The geogrid shall be mildew resistant and inert to biological degradation and naturally encountered chemicals, alkalis, and acids. • The geogrid shall contain stabilizers and/or inhibitors, or a resistance finish or covering to make it resistant to deterioration from sunlight, UV rays, and heat.
Pennsylvania DOT (2007)	• Material shall consist of either a geogrid or geotextile. Use geotextiles of woven or nonwoven construction. Do not use woven slit films. • Furnish geosynthetic consisting of either a polypropylene, polyester, or high density polyethylene polymer. • Wire mesh forms shall consist of galvanized welded wire mesh and galvanized wire support struts.
West Virginia DOT (2010)	• Geosynthetics shall be made of polypropylene, high density polyethylene or high tenacity polyester fibers having cross sections sufficient to permit significant mechanical interlock with the soil. • Geosynthetics shall have a high tensile modulus in relation to the soil and shall

	have a high resistance to deformation under sustained long-term design loads while in service and resistant to ultraviolet degradation, to damage under normal construction practices and to all forms of biological or chemical degradation normally encountered in the material being reinforced. • Geosynthetics shall be capable of withstanding 150 hours of testing as per ASTM D4355 with no measurable reduction in the ultimate tensile strength or deterioration of the coating. • The allowable tensile strength shall not exceed 25% of the ultimate tensile strength of the reinforcement used. • The LTDS of geosynthetic reinforcement shall be calculated using the method described in FHWA SA-93-025.

Embankment Soil Specifications

California DOT (2005)	• Material shall be free from organic material and substantially free from shale or other soft, poor durability particles; shall not contain recycled materials such as glass, shredded tires, portland cement concrete rubble, asphaltic concrete rubble or other unsuitable materials. • Embankment material shall have a pH of 5 to 9, a sand equivalent of 10 minimum and a plasticity index of 10 maximum.
Florida DOT (2010)	• Use only free draining backfill materials in the reinforced volume as shown in the plans meeting the gradation limits as determined in accordance with AASHTO T-27 and FM 1-T 011. • Do not use backfill material containing more than 2% by weight of organic material as determined by FM 1-T 267. • Use backfill with a maximum plasticity index of 6 as determined by AASHTO T-90 and a maximum liquid limit of 15 as determined by AASHTO T-89. • Use backfill materials with a pH between 4.5 and 10.
Pennsylvania DOT (2007)	• 100% of the embankment material shall pass a 2″ sieve. • Provide fill that meets the minimum required shear strength parameters. Use peak shear strength parameters. Determine parameters using direct shear or consolidated-drained triaxial tests. • If no minimum shear strength parameters are indicated, then provide material with a minimum angle of internal friction of 32°. • Provide material with a pH between 3 and 9 when using PVC coated polyester geosynthetics. Provide material with a pH > 3 when using polypropylene or high density polyethylene geosynthetics.
West Virginia DOT (2010)	• All backfill material used in the structure volume shall be reasonably free from organic or otherwise deleterious materials and shall conform to the gradation limits as determined by AASHTO T-27. • The Plasticity Index of the backfill material shall be less than or equal to 20 as per AASHTO T-90. • The contractor, prior to incorporating the soil into the RSS, shall perform one pH test in each soil type each day of operation and the pH of the soil shall be within the allowable limits of the design for the geosynthetic material used.

Material Storage and Handling Specifications

Alabama DOT (2012)	• Delivered material shall be accompanied by a manufacturer certified copy of test results (ASTM D4595 for Geotextiles or ASTM D6637 for Geogrids) verifying the ultimate strength of the lot(s) from which delivered rolls of reinforcement were obtained.
California DOT (2005)	• Geosynthetic reinforcement shall be furnished in an appropriate protective cover, which shall protect it from ultraviolet radiation and from abrasion during shipping and handling. • Geosynthetic rolls shall be protected from construction equipment, chemicals, sparks and flames, temperatures in excess of 160°F, and any other environmental conditions that may degrade physical properties. • To prevent geosynthetic material from being saturated, if stored outdoors, the rolls shall be elevated from the ground surface or placed on a sacrificial sheet of plastic in an area where water will not accumulate. Geogrids, except extruded grids, shall be protected with an opaque waterproof cover.
Florida DOT (2010)	• Deliver geosynthetic materials (including facing and drainage elements) to the job site in unopened shipping packages labeled with the supplier's name and product name. • During shipping and storage, protect the geosynthetic from physical damage, debris, and from temperatures greater than 140°F.
Mississippi DOT (2004)	• Each roll or container of geogrid shall be visibly labeled with the name of the manufacturer, trade name of the product, lot number, and quantity of material. In addition, each roll or container shall be clearly tagged to show the type designation that corresponds to that required by the plans. • During shipment and storage the geogrid shall be protected from direct sunlight and temperatures above 120°F or below 0°F. • The geogrid shall either be wrapped and maintained in a heavy duty protective covering or stored in a safe enclosed area to protect from damage during prolonged storage.
Pennsylvania DOT (2007)	• Protect the geosynthetics from temperatures greater than 140°F and from debris that may damage the material. • Protect all geosynthetic materials from sunlight. • Reject all geosynthetics with defects, tears, punctures, flaws, deterioration, or damage incurred during installation, manufacture, transportation, or storage.
West Virginia DOT (2010)	• Store geosynthetics in conditions above 20°F and not greater than 140°F. • Prevent mud, wet cement, epoxy, and like materials from coming into contact with and affixing to the geosynthetic material. • Rolled geosynthetic may be laid flat or stood on end for storage. • Cover the geosynthetic and protect from sunlight prior to placement.

Site Preparation Specifications

Texas DOT (2004)	• Prepare subgrade.
Florida DOT (2010)	• Remove all existing vegetation and all unsuitable foundation materials. • Proof roll the graded area with a vibratory roller weighing a minimum of 8 tons or a sheepsfoot roller, where appropriate, exerting a compression of at least 250 psi on the tamper foot for at least five passes. • Remove and replace any soft or loose foundation subsoils that are, in the opinion of the engineer, incapable of sustaining the required proof rolling.
Mississippi DOT (2004)	• The embankment site shall be cleared and graded to establish a relatively smooth surface. • Trees and stumps are to be cut off at the ground line and sawdust or sand placed over these areas to provide a cushion for the geogrid. • A design soil or subgrade which is to receive geogrid shall be shaped and compacted to the required density thus providing a smooth finish, free of loose material, and sharp objects.
Pennsylvania DOT (2007)	• Prepare foundation free of deleterious or unsuitable soils. • Proof roll the foundation with 5 passes of a static, smooth drum, or pneumatic tire roller, with a minimum contact pressure of 120 psi, to provide a uniform and firm surface. • Proof roll in a systematic manner, ensuring complete coverage of the foundation surface. Operate roller at a speed between 3 and 5 mph. • Excavate and replace any unstable areas with suitable materials as directed by the representative.
West Virginia DOT (2010)	• All areas immediately beneath the installation area for the geosynthetic reinforcement shall be properly prepared for a width equal to the length of reinforcement elements plus 3 ft or as detailed on the plans or as directed by the engineer. • The surface shall be level, free from deleterious materials, loose or otherwise unsuitable soils. • Prior to placement of geosynthetic reinforcement, foundation shall be proof rolled to provide a uniform and firm surface. • Any soft areas, as determined by the engineer, shall be removed and replaced with backfill. • Benching the backcut into competent soil is recommended to improve stability, and the backslope shall not be steeper than 1.5:1.

Material Installation Specifications

Texas DOT (2004)	• Install geogrid in accordance with lines and grades shown on the plans. • Orient the geogrid such that the strong direction runs perpendicular to the face of the embankment. Place geogrid adjacent to successive placements with no laps or splices in the geogrid treatment perpendicular to the face of the embankment. • Cut geogrid as necessary to maintain complete coverage around corners. Use installation methods that keep the geogrid taut throughout the backfilling section. Use anchor pins as necessary to secure the geogrid. • Excessive deformation or damage during installation will not be accepted. • Place fill material in lift thicknesses and to the compaction requirements shown on the plans. • A minimum fill cover of 6 inch is required to operate tracked construction equipment on the geogrid. If the underlying material can support the loads and if approved by the engineer, operation of rubber tired equipment directly on the geogrid is allowed as long as the speed is limited to less than 5 mph. Turn equipment gradually to avoid damage to the geogrid. • All geogrid sections damaged by construction activity will be replaced at the contractor's expense. Lap all repaired sections a minimum of 3 ft in all directions.
Florida DOT (2010)	• Place the geosynthetics used for slope stabilization such that its primary direction of tensile strength is perpendicular to the plan face of the slope. • Pull the material tight and secure it as necessary to lay flat against the soil prior to fill placement. • Place only that amount of geosynthetic material, including facing and drainage material, which will be covered in a single day's production.
Mississippi DOT (2004)	• Geogrid shall be placed coincidently with the compacted lift nearest the design elevation shown on the plans. No partial or half-lift thicknesses are required; however, at no time shall the placement elevation deviate by more than 1 ft from the design grade.
Pennsylvania DOT (2007)	• Place the geosynthetic within the layers of the compacted fill as indicated. • Use wire mesh forms to establish a stepped face to the slope and dimensions indicated. Internally brace wire forms to maintain verticality of step faces. • Place primary geosynthetic of the minimum lengths indicated in continuous strips in the primary direction of stabilization perpendicular to the slope face. Minimum length of grid type reinforcement is measured beginning and ending at primary transverse ribs. Maximum allowable vertical spacing of primary geosynthetics is 1.5 ft. Place secondary reinforcement, in continuous strips parallel to the slope face. Maximum allowable vertical spacing of secondary geosynthetic is 0.5 ft. Minimum length of secondary reinforcement is 7 ft. Overlap adjacent sections of primary and secondary reinforcements a minimum of 6″ along parallel roll edges. • All geosynthetics must be backfilled before the end of the workday. • Place geosynthetic to lay flat, pulled tight and anchored in place until backfill is placed. Place geosynthetic within 2″ of the design elevations and to the minimum length indicated.

	• Do not dump fill directly onto exposed geosynthetics. Place fill on previously spread fill and blade out. • No vehicles are permitted on the geosynthetic until 8″ of loose backfill has been placed. Sudden braking or sharp turning of any vehicle on reinforced fill is prohibited. • Sheepsfoot/padfoot type compaction equipment is not permitted for the compaction of reinforced fill. • Grade the surface of the fill only as necessary to facilitate surface drainage. Seal surface with a smooth drum roller at the end of each workday.
West Virginia DOT (2010)	• Geosynthetic reinforcement shall be placed horizontally unless otherwise shown in the plans. • Backfill placement shall closely follow the installation of each geosynthetic reinforcement layer. • Backfill shall be placed in such a manner as to minimize the development of wrinkles in and/or movement of the geosynthetic material. • A minimum thickness of 6″ is required prior to the operation of tracked vehicles over the geosynthetic reinforcement. • Turning of vehicles should be kept to a minimum to prevent tracks from displacing the fill and damaging the geosynthetic. Rubber tired equipment may pass over the geosynthetic reinforcement at low speeds provided that no sharp turns are made. • The maximum lift thickness after compaction shall not exceed 6″, and the contractor shall decrease this lift thickness, if necessary to obtain the specified density. • The moisture content of the backfill material prior to and during compaction shall be uniformly distributed throughout each layer. • At the end of each day's operation, the contractor shall slope the last level of the backfill away from the slope to rapidly direct runoff away from the slope face and construction area, and the contractor shall not allow surface runoff from adjacent areas to enter the reinforced soil slope construction site.

Geosynthetic Material Splicing and Repair Specifications

California DOT (2005)	• For geotextiles, no splicing joints parallel to slope alignment shall be allowed. • Geogrid reinforcement may be joined with mechanical connectors. Joints shall not be placed vertically within 2 meters of the slope face, within 2 meters of the slope top, nor horizontally or vertically adjacent (within 1.2 meters) to another joint. Only one joint per length of geogrid shall be allowed. • If the geosynthetic reinforcement is damaged during construction operations, the damaged sections shall be repaired at the contractor's expense by placing additional geosynthetic reinforcement to cover the damaged area and meeting the overlap requirements.
Florida DOT (2010)	• When splices in the primary direction are approved, make splices full width of the geosynthetic strip by using a similar material with similar strength. • Use a splice mechanism that allows a minimum of 95% load transfer from piece to piece of geosynthetic. • Make only one splice per length of geosynthetic. • Do not place splices within 6 ft of the slope face, within 6 ft below top of slope or horizontally adjacent to another splice. • Remove all backfill material from the damaged area of the reinforcement geosynthetic plus an additional 4 ft in all directions beyond the limits of damage. Place a patch consisting of the same material as the reinforcement geosynthetic over the damaged area. Overlap the undamaged reinforcement geosynthetic with the patch a minimum of 3 ft in all directions.
Mississippi DOT (2004)	• If the contractor is unable to complete a required length with a continuous length of geogrid, a joint may be made with the engineer's approval. • No end joints will be allowed in any two adjacent strips or within 10 ft of the face of the embankment or, in the case of a spill through slope, in front of the abutment.
Pennsylvania DOT (2007)	• Splicing of any primary or secondary geosynthetic, including seams or connections, is prohibited. • Slit secondary reinforcement a length only as necessary to permit installation between wire struts.
West Virginia DOT (2010)	• Cutting of geosynthetic reinforcement longitudinal to the slope face or at vertical obstacles shall not be permitted. • End to end splicing of geosynthetic material will not be permitted.

Basis of Payment Specifications

Texas DOT (2004)	• Geogrid will be measured by the square yard of each layer in its final position. No measurement will be made for lapping of material, ties and grid anchor pins. • The work performed and materials furnished will be paid for at the unit price bid for geogrid reinforcement for embankment. • This price is full compensation for furnishing all labor, materials, freight, tools, equipment and incidentals, and for doing all the work involved in placement of the grid, complete in place.
California DOT (2005)	• Geosynthetic reinforcement will be measured and paid for by the square meter for the total area of geosynthetic reinforcement as shown on the plans and for any additional area as directed by the engineer. • Payment shall not include additional reinforcement required for overlaps. • Embankment fill (geosynthetic reinforced embankment) will be measured and paid for by the cubic meter.
Mississippi DOT (2004)	• Geogrid will be measured by the square yard of surface area covered. Any overwidth of geogrid installed and additional material required for laps or damage repairs will not be measured. • No separate payment shall be made for shipping, handling, storage, protection, fabrication, securing pins or installation, the cost of which shall be included in the contract price for geogrid. • Geogrid will be paid for at the contract unit price per square yard, which shall be compensation for furnishing and placing the geogrid, pins, lapping, joints, repairs, maintaining the geogrid until covered and satisfactorily completing the work.
Pennsylvania DOT (2007)	• Measurement and payment of the geosynthetic reinforced slope systems shall be by vertical square foot of the reinforced slope. • All materials and construction of reinforced slope system, including required and discretionary laboratory tests, foundation preparation, all geosynthetics, wire forms, all fill materials, turf reinforcement mat, seeding and soil supplements and all drainage.
West Virginia DOT (2010)	• The pay items shall be measured in square yards of geosynthetic reinforcement as determined by the dimensions in the plans. • No adjustment of pay quantity shall be allowed for changes in design to facilitate the contractor's methods of construction or geosynthetic type used. • Any adjustment to the required amount of embankment backfill due to the particular geosynthetic reinforcement proposed by the contractor shall be considered incidental to the project. • No separate payment shall be made for increased embankment backfill requirements. • The contractor shall be responsible for any of the cost of changes in waste, borrow or earthwork quantities from the shown in the plans caused by the requirements of the geosynthetic reinforcement.

APPENDIX G: SPECIFICATION COMPLIANCE AND CONSTRUCTION CHECKLISTS

Specification Compliance Checklist

YES	NO	N/A	
			DOCUMENTS
			Have you thoroughly reviewed the specifications?
			Is there a set of specifications in the field trailer?
			Are standard specifications or special provisions required in addition to the project specifications? Do you have a copy?
			PRECONSTRUCTION QUALIFYING OF MATERIALS
			Has the contractor submitted preconstruction qualification test results (showing that it meets the gradation, density, electrochemical and other soil property requirements) for:
			Reinforced soil
			Retained soil
			Facing soil (if applicable)
			Drainage aggregate
			Graded granular filters (if applicable)
			Has the contractor or manufacturer submitted preconstruction qualification test results and/or certificate of compliance demonstrating that the facing materials comply with the applicable sections of the specifications including:
			Facing unit and connections
			Horizontal facing joint bearing pads
			Geotextile filter for facing joint
			Has the contractor or manufacturer submitted preconstruction qualification test results and/or certificate of compliance demonstrating that the reinforcing materials comply with the applicable sections of the specifications?
			Has the contractor or manufacturer submitted preconstruction qualification test results and/or certificate of compliance demonstrating that the drainage materials comply with the applicable sections of the specifications including:
			Geotextile filters (type, AOS, permittivity, strength)
			Prefabricated drains (geotextile filter and core)
			Drainage pipe (material, type, ASTM designation and schedule)
			Has approval of the soil sources been officially granted for:
			Reinforced soil
			Retained soil
			Facing soil
			Drainage aggregate
			Has approval of the facing material sources been officially granted?
			Has approval of the reinforcing material sources been officially granted?

			FOUNDATION PREPARATION
			Has temporary shoring been designed and approved?
			DRAINAGE
			Is the contractor or manufacturer submitting QC test results at the specified frequency demonstrating that the drainage materials comply with the applicable sections of the specifications?
			Do the drainage materials delivered to the site correspond to the approved shop drawings?
			Do the identification labeling/markings on the geotextile filters and/or prefabricated drainage materials delivered to the site correspond to the preconstruction and QC submittals (date of manufacturing, lot number, roll numbers, etc.)?
			Have the drainage materials been inspected for damage due to transport, handling or storage activities?
			Are the drainage materials properly stored to prevent damage, exposure to UV light and contamination?
			If any drainage materials were found damaged, have they been set aside, rejected or repaired in accordance with the specifications?
			Has QA sampling of the drainage materials been performed at the required frequency?
			Does the QA lab know exactly which tests to run and the required test parameters?
			Do the QA test results for the drainage materials meet the specified property values?
			FACING
			Is the contractor or manufacturer submitting QC test results at the specified frequency demonstrating that the facing materials comply with the applicable sections of the specifications?
			Do the facing components delivered to the site correspond to the approved shop drawings including:
			Facing unit (shape, dimensions, reinforcement connections, overall quantity)
			Horizontal facing joint bearing pads (materials type, hardness, modulus)
			Geotextile filter for facing joint (type, AOS, permittivity, strength)
			Do the identification labeling/markings on the facing units and components delivered to the site correspond to the preconstruction qualification and QC submittals (date of manufacturing, batch number, lot number, etc.)?
			Have the facing units and components been inspected for damage due to transport, handling or storage activities?
			Are the facing units and components properly stored to prevent damage?
			If any facing units and components were found damaged, have they been rejected or repaired in accordance with the specifications?
			Has QA sampling of the facing units and component materials been

			performed at the required frequency?
			Does the QA lab know exactly which tests to run and the required test parameters?
			Do the QA test results for the facing unit and component materials meet the specified property values?
			REINFORCING
			Is the contractor or manufacturer submitting QC test results at the specified frequency demonstrating that the reinforcing materials comply with the applicable sections of the specifications?
			Do the reinforcing materials delivered to the site correspond to the approved shop drawings (strength, dimensions, overall quantity)?
			Do the identification labeling/markings on the reinforcing materials delivered to the site correspond to the preconstruction and QC submittals (date of manufacturing, lot number, roll numbers, etc.)?
			Have the reinforcing materials been inspected for damage due to transport, handling or storage activities?
			Are the reinforcing materials properly stored to prevent damage, exposure to UV light or corrosion?
			If any reinforcing materials were found damaged, have they been set aside, rejected or repaired in accordance with the specifications?
			Has QA sampling of the reinforcing materials been performed at the required frequency?
			Does the QA lab know exactly which tests to run and the required test parameters?
			If pullout or interface shear testing is required, does the QA lab have enough of the applicable soil and the compaction criteria (in addition to the reinforcing materials)?
			Do the QA test results for the reinforcing materials meet the specified property values?
			BACKFILL
			Is the contractor submitting QC test results at the specified frequency for:
			Reinforced soil
			Retained soil
			Facing soil
			Does the QA lab know exactly which tests to run and the required test parameters?
			Do the QA test results for the various materials meet the specified property values:
			Reinforced soil
			Retained soil
			Facing soil
			ANCILLARY ITEMS
			Do any ancillary materials delivered to the site correspond to the approved shop drawings (prefabricated copings, cap blocks and

			attachment glue, if required, catch basins, pipe, guardrail, etc.)?
			Do the identification labeling/markings on the ancillary materials delivered to the site correspond to the QC submittals (date of manufacturing, batch number, etc.)?
			Have the ancillary materials been inspected for damage due to transport, handling or storage activities?
			Are the ancillary materials properly stored to prevent damage?
			If any ancillary materials were found damaged, have they been set aside, rejected or repaired in accordance with the specifications?
			Have all requirements to sample/test any aspect of the work product after assembly, installation and compaction been met?

Construction Checklist

YES	NO	N/A	
			DOCUMENTS & PLANS
			Has the contractor furnished a copy of the installation plans or instructions from the geosynthetic materials supplier?
			Have the installation plans or instructions been approved by the designer and/or construction division manager?
			Have stockpile and staging areas been discussed and approved?
			Have access routes and temporary haul roads been discussed and approved?
			LAYOUT
			Has the contractor staked out sufficient horizontal and vertical control points, including points required for stepped foundations?
			Has the contractor accounted for the slope angle when staking the base of the structure?
			Have drainage features and all utilities been located and marked?
			Have erosion and sedimentation controls been installed?
			FOUNDATION PREPARATION
			Has the GRSS foundation area been excavated to the proper elevation?
			Has the foundation subgrade been inspected and proof rolled as required by the specifications?
			Has all soft or loose material been compacted or unsuitable materials been removed or replaced?
			DRAINAGE
			Is the drainage being installed in the correct location?
			Are drainage aggregates being kept free of fine materials?
			Are all holes, rips and punctures in geotextiles being repaired in accordance with the specifications?
			Do all collection and outlet pipes have a positive slope?
			FACING
			Is the contractor using the correct facing (size, shape, color, connections) for the applicable location and elevation?

			Have secondary reinforcing layers and vegetated matting been properly placed where applicable? Are they setback correctly to result in the designed slope angle?
			Is the vertical elevation and horizontal alignment being checked periodically and adjusted as needed?
			Is the spacing correct between overlaps of reinforcement?
			REINFORCEMENT
			Is the reinforcement being properly connected (connections tight and all of the slack in the reinforcing layers removed)?
			Is the reinforcement in the proper alignment?
			Is the reinforcement the right type?
			Is the reinforcement the correct length?
			Is the reinforcement being placed at the correct spacing and location?
			Is the fill being brought up to 2″ above the soil reinforcement elevation before the reinforcement is connected?
			Is construction equipment being kept from operating directly on the reinforcement until adequate soil cover is placed?
			BACKFILL
			At the end of each day's operation, is the contractor grading the upper surface of reinforced and retained soil to ensure runoff of storm water away from the GRSS face or providing a positive means of controlling runoff away from the construction area?
			Where applicable, has the contractor backfilled in front of the GRSS?
			Is the contractor placing the reinforced soil in lifts that are thin enough to ensure good compaction, but thick enough not to damage the reinforcement?
			If the contractor is using water to adjust the moisture of the reinforced, retained or facing soil, does it meet the requirements set forth in the specifications?
			Is the reinforced soil being placed to prevent damage to the reinforcement?
			Are the lifts being spread to prevent excessive tension or excess slack in the reinforcement?
			Is the fill being compacted using the correct equipment and in the correct pattern?
			Is the soil moisture content within the specified range?
			Is the soil compaction (dry density) within the specified range?
			Is large compaction equipment being kept at least 3′ from the face?
			ANCILLARY ITEMS & FINISHED PRODUCT
			Could installation of ancillary components affect the reinforcing or facing components already installed?
			Have ancillary items been installed in accordance with the drawings and specifications?
			Are ancillary items being installed at the proper locations?

			Are diversion ditches, collection ditches or slope drains installed in accordance with the drawings and specifications?
			Is permanent or temporary erosion blanket installed at the required locations and using the details shown on the drawings?
			Are there any visible signs of the GRSS tilting, bulging or deflecting?
			Has the vertical and horizontal alignment been confirmed by survey?
			Is there a need to confirm the vertical or horizontal alignment at a future time to evaluate whether movement is occurring?
			Are there any signs of distress to the facing components?

APPENDIX H: CASE STUDY SURVEY

A technical objective of the present research project is to identify case studies where GRSS have been constructed. The information will provide TxDOT with a better understanding of current practices and will be used to determine the feasibility of constructing GRSS in Texas. Primary applications of interest include side slopes for roadways and bridge approaches that do not have adequate space for a gentle slope.

Please provide the following information regarding the design and construction of a GRSS project. It is preferred for you to complete as much of the template as possible, but questions may be skipped if the information is not available.

General Information

Project Name:
Location:
Owner:
Engineer:
Contractor:
Start Date:
Completion Date:
Project Purpose:
Slope Classification:

Design Methods and Material Selection

- What equations and criteria were used to design the GRSS (e.g., FHWA Method)?
- What material was used for reinforcement (e.g., geotextile, geogrid)?
- Who manufactured the reinforcement material, and what was the product name/number?
- What were the *foundation* soil conditions? Shear cohesion? Friction angle? Dry unit weight?
- What were the *embankment* soil conditions? Shear cohesion? Friction angle? Dry unit weight?
- What was the maximum settlement of the loading slab?
- What was the geometry of the slope *before* construction? Height? H:V? Area? Surface type?
- What was the geometry of the slope *after* construction? Height? H:V? Area? Surface type?

Construction Practices and Contracting Methods

- Did the owner specify the system components in the contract documents or did the project design occur during the submittal process?
- What construction specifications were followed?
- What was the construction sequence?
- What were the soil compaction requirements?
- What type of material was used to finish the slope face?
- What challenges were faced during construction of the GRSS?

Performance Measures and Cost Effectiveness

- What measures were used to determine project performance (e.g., soil testing, material testing, field inspection)?
- What was the outcome of the project performance evaluation?
- What type of maintenance or repair is expected?
- Were there any problems with erosion or slope failure?
- What was the total construction cost of the GRSS?
- What was the quantity and unit cost of the reinforcement material?
- What was the quantity and unit cost of the embankment soil?

Supplementary Information

- Are current GRSS specifications adequate to produce a quality product?
- What does a *good* GRSS contractor do that is important?
- What does a *poor* GRSS contractor do that is harmful?
- If there is anything that you would like to add that was not covered in this questionnaire which you feel would benefit this study, please write your comments below.
- Please insert below or attach any project plans, specifications, or pictures that are available.

APPENDIX I: SUMMARY OF PUBLISHED CASE STUDY INFORMATION AND CASE STUDY SURVEY RESULTS

#	Project	Location	Purpose
1	Samsung Y Project Phase 2	South Korea	Support Structure for Roadway
2	Cherry Island Landfill Expansion	Delaware	Maximize Available Land
3	Bennington Bypass Bridge	Vermont	Support Structure for Bridge Abutment
4	Niagara Escarpment Residence	Canada	Erosion Prevention
5	Bridge 60A Abutment	New Zealand	Support Structure for Bridge Abutment
6	Bryants Bridge Abutment Dropout Repair	New Zealand	Support Structure for Roadway
7	SH60 Eureka Bend Slope Reinstatement	New Zealand	Support Structure for Roadway
8	Speights Garden Subdivision	New Zealand	Maximize Available Land
9	Hill Road in Hawks Bay	New Zealand	Support Structure for Roadway
10	Sandy Bay Road Slip Repair	New Zealand	Support Structure for Roadway
11	Kapiti Views Subdivision	New Zealand	Support Structure for Buildings
12	Kawakawa Bay Landslide	New Zealand	Erosion Prevention
13	Kerikeri Heritage Bypass	New Zealand	Support Structure for Bridge Abutment
14	Morning Star Subdivision	New Zealand	Support Structure for Roadway
15	SH4 Realignment	New Zealand	Support Structure for Bridge Abutment
16	Westgate Reinforced Slope	New Zealand	Maximize Available Land
17	SH2 Kaitoke	New Zealand	Support Structure for Roadway
18	Ohiwa Harbor Road Slip	New Zealand	Support Structure for Building
19	Castleberry Community Reinforced Slope	Georgia	Maximize Available Land
20	Yeager Airport Runway	West Virginia	Support Structure for Runway
21	Crystal Cove Slope Reinforcement	California	Support Structure for Buildings
22	Anthony Henday Freeway	Canada	Support Structure for Roadway
23	Hampton Township Home Depot	Pennsylvania	Maximize Available Land
24	I-495 Marston Street Northbound Ramp	Massachusetts	Support Structure for Roadway
25	Kraugh Landslide Repair	Minnesota	Support Structure for Building
26	Wal-Mart Distribution Center	Maine	Maximize Available Land
27	Mississippi River Landslide Repair	Minnesota	Support Structure for Roadway
28	Canal Quarry Reinforced Slope	California	Maximize Available Land
29	Clemson Road Bridge	South Carolina	Support Structure for Bridge Abutment
30	Statesville Home Depot	North Carolina	Maximize Available Land
31	Donzi Landfill Expansion	Georgia	Maximize Available Land
32	Widening I-695 @ I-83S	Maryland	Support Structure for Roadway
33	Sycamore Ranch Slope Reinforcement	California	Maximize Available Land
34	Hirini Road Loggin Storage Underpass	New Zealand	Support Structure for Roadway
35	US Route 201 Carney Brook Bridge	Maine	Support Structure for Roadway
36	Russell Road Slip Repair	New Zealand	Support Structure for Roadway
37	Umhlanga Rocks Drive	South Africa	Support Structure for Roadway
38	Rodlauer Bridge Road Realignment	Austria	Support Structure for Roadway
39	Langkawi Landslide Restoration	Malaysia	Support Structure for Roadway
40	Maehongson Slope Restoration	Thailand	Support Structure for Roadway
41	Srivichai Road Widening	Thailand	Support Structure for Roadway
42	Diasbach Avalanche Protection Barrier	Austria	Erosion Prevention
43	A3 Hindhead Highway Earthworks Widening	United Kingdom	Maximize Available Land
44	Hamilton Railway Embankment Widening	Canada	Support Structure for Railway
45	The Village at Clagett Farm	Maryland	Maximize Available Land
46	North Island Slope Repair	New Zealand	Support Structure for Roadway
47	County Road 46A Terraced Vegetated Slope	Florida	Support Structure for Roadway
48	Port Mann Bridge	Canada	Support Structure for Bridge Abutment
49	M21 (E673) Ring Road	Montenegro	Support Structure for Roadway
50	Zeleznik Ring Road Viaduct	Serbia	Support Structure for Bridge Abutment
51	Pancevo-Vrsac Bridge	Serbia	Support Structure for Bridge Abutment
52	Berlin A9 Motorway	Germany	Maximize Available Land
53	Old Town of Idstein	Germany	Maximize Available Land
54	Three Failures of a Steep Reinforced Slope	Taiwan	Maximize Available Land
55	Dickey Lake Roadway Grade Improvement	Montana	Support Structure for Roadway
56	Lost Trail Roadway Widening	Idaho	Support Structure for Roadway
57	Cannon Creek Alternate Embankment	Arkansas	Support Structure for Roadway
58	SR 54 Roadway Repair	Pennsylvania	Support Structure for Roadway
59	Raleigh Street Reinforced Embankment	Florida	Support Structure for Roadway
60	Reinforced Slope Failure & Reconstruction	New Mexico	Support Structure for Roadway

Case Study #1: Samsung Y Project Phase 2

Location: Cheoin-Gu, Yongin-Si, Gyeonggi-Do, South Korea
Owner: Samsung Everland
Engineer: E&S Engineering
Contractor: Samsung Engineering & Construction Group
Purpose: Support Structure for Roadway
Duration: 11/23/2010 to 01/20/2011

Geosynthetic Material:
- Reinforcement: Polyester Geogrid
- Facing: Polyethylene Geocells

Foundation Soil:

	Unit Weight (γ, lb/ft^3)	Cohesion (c, lb/ft^2)	Friction Angle (ϕ,°)
Sedimentary Layer	108	104	28
Weathered Soil	115	209	30
Weathered Rock	127	627	33
Soft Rock	159	3,133	35

Embankment Soil:

	Unit Weight (γ, lb/ft^3)	Cohesion (c, lb/ft^2)	Friction Angle (ϕ,°)
Reinforced Fill	134	-	33
Replaced Fill	121	313	25

Slope Height: 11 ft to 69 ft
Slope Face Area: 12,900 ft^2
Slope Angle: 2.1H:1V to 0.9H:1V

Design Method: Federal Highway Administration

Construction Sequence:
- Preparation and ground excavation.
- Installation of geocell facing.
- Geocell infill and compaction with 10 ton vibrating roller.
- Placement and compaction of reinforced fill.
- Installation of geogrid and repeat steps to planned height.

Performance: Soil density was tested as per KS F 2312 standard test method for soil compaction using a rammer and KS F 2311 standard test method for density of soil in place by the sand cone method. Direct shear test was used to measure soil strength, and plate load test determined degree of compaction.

Case Study #1: Samsung Y Project Phase 2 (Continued)

Material Cost:

	Unit	Quantity	Unit Cost ($)	Total Cost ($)
Geogrid (5500 lb/ft)	ft^2	37,975	0.55	20,886
Geogrid (7000 lb/ft)	ft^2	69,115	0.63	53,542
Geogrid (10000 lb/ft)	ft^2	171,006	0.75	128,254
Compacted Fill	yd^3	31,286	2.56	80,092

Total Construction Cost: $522,000

Case Study #2: Cherry Island Landfill Expansion

Location: Wilmington, Delaware
Owner: Delaware Solid Waste Authority
Engineer: Geosyntec Consultants
Contractor: Stevenson Environmental Services
Purpose: Maximize Available Land
Duration: 09/2006 to 05/2011

Geosynthetic Material:

- Reinforcement: Polyester Geogrid & Geotextile

Foundation & Embankment Soil:

	Unit Weight (γ, lb/ft^3)	Cohesion (c, lb/ft^2)	Friction Angle (ϕ,°)
Foundation Soil	56	0.29	0
Embankment Soil	90	0	29

Maximum Settlement of Loading Slab: 14 ft

Slope Height: 70 ft
Slope Length: 7920 ft
Slope Angle: 1H:3V

Design Method: Finite Element Analysis

Construction Sequence:

- Install foundation improvements and geotechnical instrumentation.
- Construct reinforced slope in horizontal lifts with facing materials and reinforced fill.
- Minimum 95% of standard proctor for all embankment fill.
- Geogrid with vegetation was constructed for the facing.
- Careful field layout of reinforcing materials and setbacks for lifts was required as well as taking care in placement of reinforcing materials and compaction of fill.
- Runoff was directed away from the reinforced slope and quality topsoil was used to finish the vegetated faces.

Performance: Full time field oversight was required. Conformance testing was performed for fill and reinforcement materials. Field inspection of embedment lengths with field compaction testing was also conducted. The evaluation documented that all materials conformed to project requirements and were installed properly. Occasional removal of woody vegetation and burrowing animals from the reinforced slope face is required.

Total Construction Cost: $52,000,000

Case Study #3: Bennington Bypass Bridge

Location: Bennington, Vermont
Owner: Vermont Agency of Transportation
Engineer: GZA GeoEnvironmental
Contractor: J. A. McDonald
Purpose: Support Structure for Bridge Abutment

Geosynthetic Material:

- Primary Reinforcement: Polyester Geogrid (27415 lb/ft)
- Secondary Reinforcement: Polyester Geogrid (2000 lb/ft)
- Drainage & Slope Face: Polypropylene Nonwoven Geotextile

Foundation Soil: Medium Dense Soil
Embankment Soil: Granular Borrow from Onsite

Slope Height: 55 ft

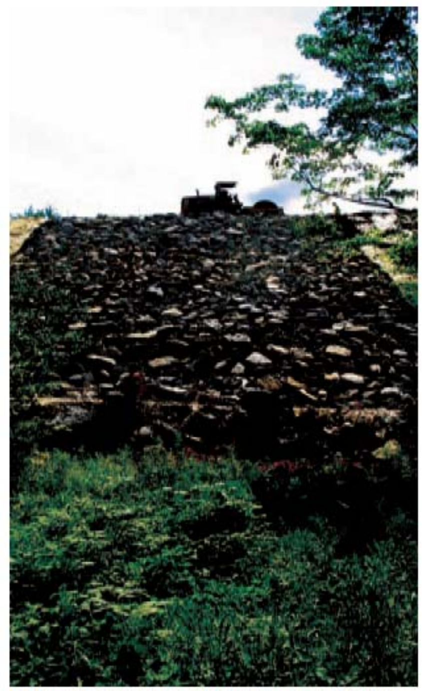
Construction Specifications: Vermont Agency of Transportation

Construction Sequence:

- Excavated and compacted the base elevation for support pad.
- Installed perimeter drain.
- Installed primary reinforcement with embedment length of 112 ft.
- Spread soil to thickness of 8 inch and compacted with CAT 563 vibrator/compactor to 95% maximum density.
- Installed secondary reinforcement with embedment length of 6 ft at 16 ft.
- Process continued in four stages with embedment lengths of 112 ft, 76 ft, 48 ft and 32 ft with 18 panels in each stage.
- Covered face with riprap and vegetated side slopes.

Cost Effectiveness: Project created cost savings for Vermont DOT due to reduced duration and the use of minimal equipment and labor.

First layer of Miragrid® 24XT placed at base elevation.



Facing of slope using onsite rip rap and vegetation.

BELOW: Final elevation of support pad for west abutment.

Case Study #4: Niagara Escarpment Residence

Location: Burlington, Ontario, Canada
Owner: J. Smithson
Engineer: InterSol Engineering
Contractor: Norseman Steel Fabricator
Purpose: Erosion Prevention

Geosynthetic Material:

- Reinforcement: Polyester Geogrid (3500 lb/ft)
- Separation: Polypropylene Geotextile
- Slope Face: Polypropylene Geotextile

Slope Height: 10 ft
Slope Length: 200 ft
Wall Batter: 3°
Layer Set Back: 8 inch

Design Method: Slope stability analysis was performed to determine the reinforcement requirements.

Construction Sequence:

- Construction commenced after excavating an 8 ft bench for the wall.
- The wall was constructed with 4 ft × 3 ft × 10 ft pregalvanized 6 gauge 20 in high baskets. Each basket was overlapped 4 inch and wired together.
- Wire struts that provided alignment and wall batter were installed at 20 in centers.
- Next, geogrid was placed to the front face of the wall. It was determined that an embedment of 8 ft with spacing at 20 inch would satisfy project requirements.
- The geotextile was then installed at the front face along with the wire struts. To separate the topsoil and granular reinforced zone, a nonwoven geotextile was used.
- To collect any water seeping from the slope, a 4 inch perforated pipe was installed parallel to the wall face to provide drainage.
- Before placing the topsoil at the face, it was mixed with a grass seed mixture.
- Both the topsoil and granular backfill were compacted in 8 inch lifts using a jumping jack and diesel plate tamper.

Performance: The post construction inspection indicated that the French drain intercepted the underground water course and the slope started to stabilize.

Cost Effectiveness: Project created cost savings due to reduced duration and the use of minimal equipment and labor.


A welded wire wall is constructed with Miragrid® 3XT, Mirafi® 160N, and Miramesh® GR.


Miramesh® GR is selected as the face wrap to protect the vegetation from erosion.


Each basket overlapped 100mm (4in.) Miragrid® 3XT was placed to the front face, then Miramesh® GR was installed along the wire struts.


Mirafi® 160N seperates the topsoil and granular reinforced zone.

Case Study #5: Bridge 60A Abutment

Location: Auckland, New Zealand
Owner: Ontrack New Zealand
Engineer: Fraser Geologics
Contractor: Rogers Civil Limited
Purpose: Support Structure for Bridge Abutment

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Slope Face: Prefilled Gabions with Ballast Stones

Embankment Soil: Scoria Fill

Slope Height: 23 ft
Slope Angle: 1H:1V

Design Method: Considerations included internal, compound, global, and wedge stability analysis.

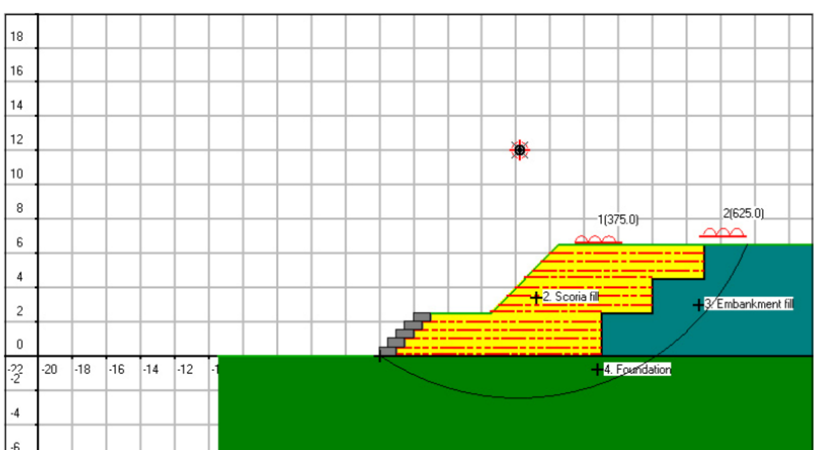
Construction Sequence:
- Gabions were prefilled so that they were not within the critical path of the project installation schedule.
- The gabions were mechanically placed to form the steeper face for the lower 8 ft within the design flood zone, and a 45° slope constructed on top provided a platform sufficiently wide for a 300 tonne crane to be positioned and operate. The placement of the gabions provided a rapid method of front face construction.
- A highly frictional and free draining scoria fill along with the geogrid reinforcement ensured that construction could continue in a range of weather conditions with minimal interruption to the construction program.

Performance: No deformations or distress to the structure was observed during the critical phase of placement of the bridge elements.


Site prior to construction Date: Oct 2007


Lower prefilled gabion section Date: Nov 2007

Placement of geogrid & fill Date: Nov 2007



Section showing a typical circular analysis for crane loads Date: October 2007

Case Study #6: Bryants Bridge Abutment Dropout Repair

Location: Palmerston North, New Zealand
Owner: New Zealand Transport Authority
Engineer: MWH New Zealand Limited
Contractor: Higgins Contractors
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Slope Face: Wire Mesh

Embankment Soil: AP40 Granular Backfill

Slope Height: 36 ft
Slope Length: 82 ft

Construction Specifications: New Zealand Transport Authority

Construction Sequence:
- The design considered a mix of geogrid grades located at each 2 ft vertical lift of the facing units.
- A geocomposite drain was used up against the cut face at the rear of the reinforced soil zone to cut off the path of groundwater.
- Subsoil collector drains located at the base of the cut slope ensured any excess groundwater collected by the drain was quickly removed away from the structure.
- After receiving onsite training, the contractor was able to develop a construction methodology, which included the use of two pneumatic lacing tools.

Performance: Traffic disruption was kept to a minimum, providing a great result to the client and road users.

Cost Effectiveness: The solution for this site was cost effective, quick, and easy to construct.


Site prior to Construction


Construction of Green Terramesh Structure


Completed Green Terramesh Structure at Bryants Bridge

Case Study #7: SH60 Eureka Bend Slope Reinstatement

Location: Golden Bay, New Zealand
Owner: New Zealand Transport Authority
Engineer: GHD Limited
Contractor: Fulton Hogan
Purpose: Support Structure for Roadway

Geosynthetic Material:

- Reinforcement: Polyethylene Geogrid
- Slope Face: Wire Mesh

Foundation Soil: Collovium/Fractured Rock Layer

Slope Height: 39 ft
Slope Angle: 65° to 70°
Slope Face Area: 10,700 ft^2

Design Method: Static and seismic slope stability analysis.

Construction Specifications: New Zealand Transport Authority

Construction Sequence:

- The final solution incorporated an in-situ stabilization method using soil nailing to maintain surface stability of the cut face and to facilitate the construction of the structure while keeping one lane open.
- Soil nails were installed at various lengths from top down, concurrent with the excavation.
- Wire mesh was used at the face between nail heads and the cut slope profile. This type of facing option is considered as flexible structural facing according to CIRIA report C637.
- The entire structure was completed with a construction period of less than two months.

Cost Effectiveness: A gentler profile was discounted as it would have resulted in an even higher structure along with a huge increase in earthworks volumes, time, and associated costs. The overall project was completed ahead of time and under the allocated budget.


Slip before repair


Soil nailing work in progress


Construction of Green Terramesh structure


Completed Green Terramesh structure

Case Study #8: Speights Garden Subdivision

Location: Queenstown, New Zealand
Owner: Empire Trust
Engineer: GDM Consultants
Contractor: BMT Contracting
Purpose: Maximize Available Land

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Slope Face: Wire Mesh & Biodegradable Mesh

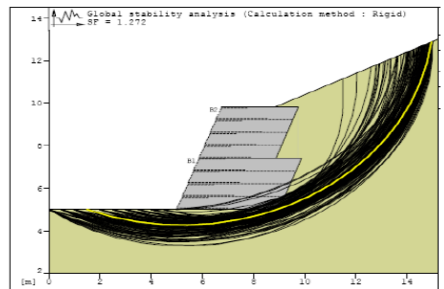
Slope Height: 16 ft
Slope Angle: 1H:2V

Design Method: Static and seismic slope stability analysis.

Construction Sequence:
- The manufacturer was able to present information on the product and installation process including installation guidelines.
- This support contributed to the contractor taking less than 4 weeks to complete the project.
- The contractor found that construction became quicker as they became familiar with the handling and assembly of the product.

Performance: The structure was selected due to it having a lower environmental impact and a higher degree of flexibility in design than conventional retaining walls.

Vegetation starting to grow prior to hydroseeding



Stability Analysis using MacStars

Overall view of Green Terramesh slope

Case Study #9: Hill Road in Hawkes Bay

Location: Napier, New Zealand
Owner: Napier City Council
Engineer: Opus Consultants
Contractor: Higgins Contractors
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Facing: Wire Mesh & Biodegradable Mesh
- Drainage: Polyester Geotextile

Slope Angle: 70°

Construction Sequence:
- Construction of the 5 layer high system was achieved with 4 staff, a 20 tonne digger, a roller, and light plate compactor used for area close to the face.
- A geocomposite drainage blanket was installed between the cut slope and the new reinforced fill to limit ingress of groundwater into the reinforced structure, minimizing the development of pore pressures within the reinforced fill zone.
- Ease of construction with the preformed units set at 70° enabled completion of the structure within 2 weeks.

Performance: Like gabions each individual unit is laced to the adjacent units forming a monolithic structure that once complete is capable of taking up external loads including the seismic forces considered for this site with minimal noticeable deformation.

Cost Effectiveness: Wire mesh is a cost effective alternative to gabions, where the availability of a suitable gabion rock is an issue.

Initial Hill Rd site May 2009

Green Terramesh Units being assembled May 2009

Completed Green Terramesh Structure May 2009

Case Study #10: Sandy Bay Road Slip Repair

Location: Nelson, New Zealand
Owner: Tasman District Council
Engineer: MWH Nelson
Contractor: Colin Thompson Contracting
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Facing: Wire Mesh
- Erosion Control: Polyamide Mat
- Separation: Polyester Geotextile

Design Method: Static and seismic slope stability analysis.

Construction Sequence:
- The installation of wire mesh was found to be straightforward. This ensured that the construction tolerances required for the face were easily met and the work was completed within the tight construction period.
- Polyamide matting was used a surface erosion control blanket at the toe of the slope and geotextile was used as a separator between the rock facing and the reinforced backfill.

Cost Effectiveness: This was an innovative technique that combined the use of geogrids for reinforcement and a modular front face system for facing stability and face construction. The system was cost effective through improvements in construction tolerances and savings in construction time.


Before construction Date: Oct 2004


During Construction Date: December 2004


After Construction Date: December 2004

Case Study #11: Kapiti Views Subdivision

Location: Waikanae, New Zealand
Owner: Kapiti Views Trust
Engineer: Cuttriss Consultants Kapiti Coast, Tonkin & Taylor
Contractor: Mills Albert
Purpose: Support Structure for Buildings

Geosynthetic Material:

- Reinforcement: Polyester Geogrid
- Erosion Protection: Biodegradable Mat
- Drainage: Polyester Geotextile

Slope Angle: 60°

Construction Sequence:

- The design required the placement of primary geogrid layers at every 2 ft and a short intermediate secondary geogrid layer midway between the primary layers to assist with facing stability.
- A 7.5 tonne digger with 4 staff was used for the construction of the reinforced slopes, which included the placement of free draining backfill, incorporation of drainage at the rear of the structure, and placement of each layer of geogrid including the wrap around facing.
- Approximately 260 ft at 3 ft high could be constructed weekly.
- Lightweight, easy to handle and place, subsoil drains, geotextile, and sheet drainage were comprehensively used on the site to cope with the vast quantities of water coming from the springs in the hillside.
- The contractor used different facing techniques for the slopes including the use of hessian bags filled with top soil.
- Once completed, the slope was then hydroseeded using seed indigenous to the area.

Cost Effectiveness: As the slope had numerous springs, the drainage system was used to intercept the flow and collect the water, minimizing entry into the reinforced soil slopes and segmental wall. The use of these geosynthetic products enabled the engineers to cost effectively reduce the geotechnical risks associated with this site.


Hessian bag face with layers of Miragrid February 2008


Prefabricated formwork used for construction April 2008


Enkadrain SL behind segmental block wall April 2008


Reinforced soil slope near completion July 2008

Case Study #12: Kawakawa Bay Landslide

Location: Auckland, New Zealand
Owner: Manukau City Council
Engineer: Tonkin & Taylor
Contractor: Downer Edi Works
Purpose: Erosion Prevention

Geosynthetic Material:

- Reinforcement: Polyester Geogrid
- Facing: Polyester Geotextile & Biodegradable Mat

Construction Sequence:

- 130,000 yd^3 of earth was removed to unload the top of the landslide thus reducing the driving force.
- A geogrid reinforced soil buttress was built at the base of the landslide, and a drainage system was installed to lower the ground water pressures beneath the potential landslide region.
- Ground anchors were used to restrain movement of the landslide.
- By utilizing the biodegradable mat in the front face of the wrap around buttress structure, a green finish was achieved, restoring the hill as close as possible to its original state.

Performance: The drainage has yielded significant volumes of water with a measurable effect on reducing and limiting the pore pressures in the rock. No further movement of the landslide has been detected as a result of rainfall events.

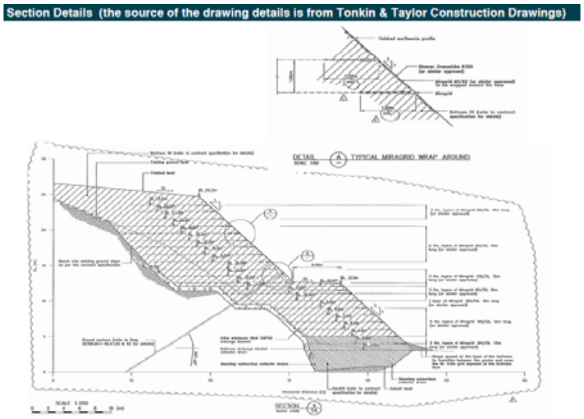
Cost Effectiveness: The wide roll widths of 17 ft enabled the contractor to save time and money with a decrease in installation time.


The initial site before construction


Building of the reinforced soil slope


Greening of the reinforced soil slope


Completed Miragrid & Grasstrike reinforced steep soil slope

Section Details (the source of the drawing details is from Tonkin & Taylor Construction Drawings)


Case Study #13: Kerikeri Heritage Bypass

Location: Kerikeri, New Zealand
Owner: Far North District Council
Engineer: GHD Limited Auckland
Contractor: HEB Construction Whangarei
Purpose: Support Structure for Bridge Abutment

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Facing: Wire Mesh
- Drainage: Polyester Geotextile

Construction Sequence:
- The bridge abutment had to have high resistance to flood damage with any repair/maintenance work (if required) being at minimal cost.
- The incorporation of a stone facing in the mesh units satisfied the erosion protection requirements as well as making it aesthetically pleasing.

Performance: System provided a monolithic structure having a high degree of flexibility should settlement occur without losing its structural integrity, a critical requirement for this hydraulic application.

Cost Effectiveness: The structure provided a cost effective and easy to construct solution for this site with the system already passing its first test of extensive flooding soon after construction.

Bridge abutment commencement Date: March 2007

Project completion Date: June 2008

Completion of bridge abutment Date: Feb 2008

Case Study #14: Morning Star Subdivision

Location: Queenstown, New Zealand
Owner: Paterson Pitts & Partners
Engineer: Tonkin & Taylor
Contractor: Fulton Hogan Limited
Purpose: Support Structure for Roadway

Geosynthetic Material:

- Reinforcement: Polyethylene Geogrid
- Facing: Wire Mesh & Biodegradable Mat

Slope Height: 33 ft
Slope Angle: 60°

Design Method: Static and seismic slope stability analysis, including checks on the internal stability taking into account the long-term reinforcement contribution of both the mesh units and geogrids. Additional checks for sliding and external global stability were also carried out. A seismic PGA of 0.2g was considered for this site.

Performance: A 60° front face angle for the structure was chosen for this site by the engineers as the best balance between gain in usable level ground and the ability of the slope to capture both rainfall and sunlight to sustain long-term vegetation growth.

Cost Effectiveness: GRSS was chosen for this site as the best option for establishing a vegetated structure that is both cost effective and easy to construct.


Before construction Date: July 2007


During Construction Date: October 2007


After Construction Date: November 2007

Case Study #15: SH4 Realignment

Location: Okura, New Zealand
Owner: New Zealand Transport Agency (Wangnui)
Engineer: MWH New Zealand Limited
Contractor: Concrete Structures New Zealand Limited
Purpose: Support Structure for Bridge Abutment


Bridge prior to construction with piers installed Date: Feb 2009

Geosynthetic Material:

- Reinforcement: Polyester & Polyethylene Geogrid
- Facing: Wire Mesh

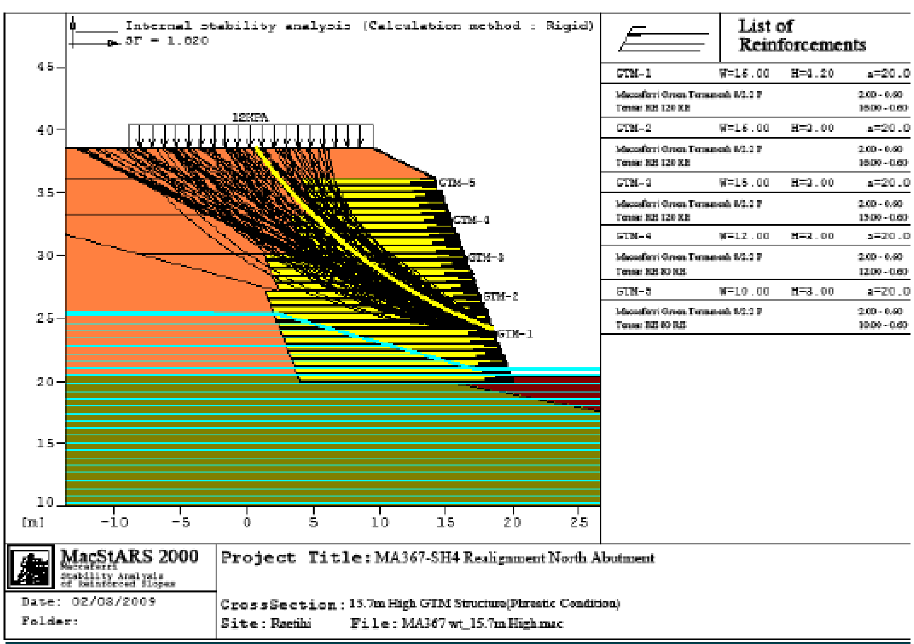
Design Method: Static and seismic slope stability analysis. Full PGA horizontal load was applied in the design and analysis of the structure since it was associated with a bridge abutment. The design also considered a rapid draw down case for a 100-year flood event on the static case.

Construction Sequence:

- The project required a base geogrid reinforcement length of 52 ft.
- In addition, some geogrid wrap around structure was constructed behind the existing piers to relieve the lateral soil thrust.
- The contractor completed the structure for the southern abutment (3550 ft^2) and for the northern abutment (6460 ft^2) expediently.


Completed Green Terramesh abutment structure Date: April 2009

Cost Effectiveness: The versatility of geogrid reinforcement when laid around the two existing bridge piers allowed the structure to be constructed quickly and concurrent with the backfilling process. The alternative option was a conventional concrete retaining wall, which proved to be too costly and impractical to construct.



Typical Cross Section Drawing

Case Study #16: Westgate Reinforced Slope

Location: West Auckland, New Zealand
Owner: Placemakers Westgate
Engineer: Soil & Rock Consultants
Contractor: Vuksich & Borich
Purpose: Maximize Available Land

Geosynthetic Material:

- Reinforcement: Polyester Geogrid
- Facing: Biodegradable Mat

Slope Height: 20 ft
Slope Angle: 1H:1V

Design Method: The internal stability in terms of tensile rupture and pullout failure as well as block sliding was checked. Global stability as well as potential failure surface extending back into the unreinforced embankment fill was also checked.

Construction Sequence:

- Geogrid placement was fast and efficient using the 12 ft wide rolls of polyester geogrid, which are light, flexible, and easy to handle. This enabled the contractor to complete the fill operation before the winter period.
- A biodegradable mat was placed on the front face to prevent erosion and provide a weed-free and protected habitat for shrubbery plantings.

Site prior to construction Date: 1998

Wide viewof slope after 7 years of growth

Side view of vegetated slope Date: Feb 2007

Case Study #17: SH2 Kaitoke

Location: Upper Hutt, New Zealand
Owner: Connell Wagner
Engineer: Opus International Consultants
Contractor: Higgins Contractors
Purpose: Support Structure for Roadway

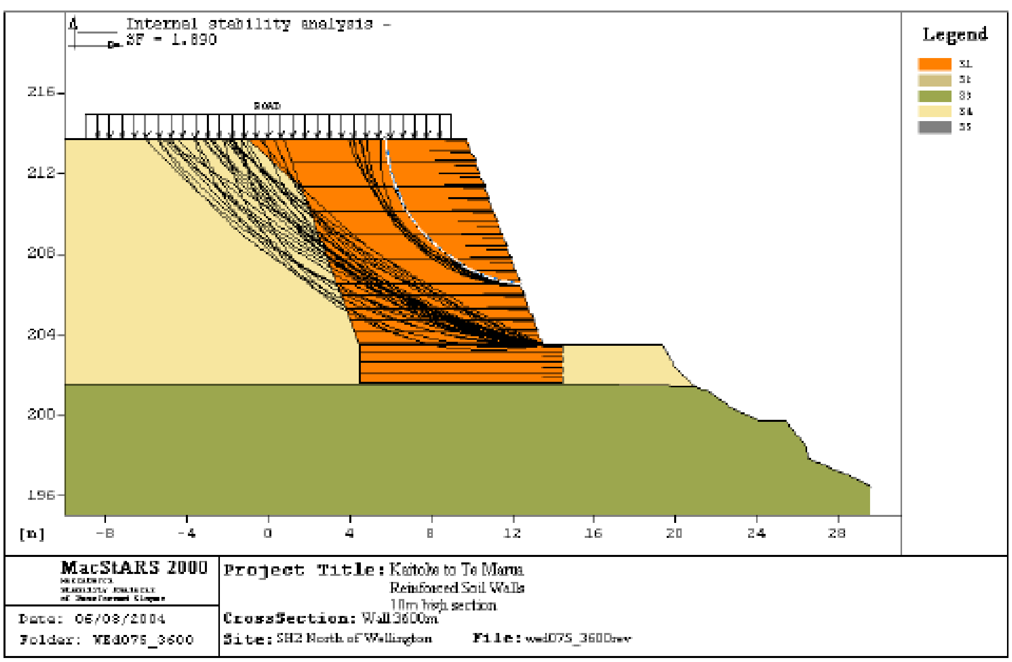
Geosynthetic Material:

- Reinforcement: Polyethylene Geogrid
- Facing: Wire Mesh
- Drainage: Geocomposite

Construction Sequence:

- The placement and lacing up of the wire mesh units using a pneumatic lacing gun was a straight forward process along with the laying of the geogrid.
- In addition, the placement of the rear drainage using a geocomposite was found to be a lot easier to construct than the more traditional gravel or sand chimney drains.

Cost Effectiveness: The manufacturer worked closely with Higgins Contractors and the engineers in developing a cost effective solution that met the environmental requirements of the site for one of the major wall sections from chainage 3530 to 3560.



Green Terramesh Analysis Date: February 2003

Case Study #18: 338 Ohiwa Harbor Road Slip

Location: Opotiki, New Zealand
Owner: Private Owner
Engineer: Opotiki District Council
Contractor: Tracks Concrete Limited
Purpose: Support Structure for Building

Geosynthetic Material:

- Reinforcement: Polyester Geogrid
- Facing: Wire Mesh
- Drainage: Geocomposite

Slope Angle: 70°

Design Method: Static and seismic slope stability analysis was performed. The analysis included internal stability of the reinforced soil block, global and sliding stability.

Construction Sequence:

- Geogrid were laid between the wire mesh units to provide long-term internal and external stability to the new structure.
- The construction of this new slope created a sufficiently wide platform for the construction of a 1:1 geogrid reinforced slope above.
- A geocomposite was used up the cut face to intercept groundwater and channel it down to collector drains, which in turn discharge the water away from the slip area.

Overall view of GTM structure under construction

GTM structure under construction

Completed GTM structure

Case Study #19: Castleberry Community Reinforced Slope

Location: Cumming, Georgia
Owner: Villages at Castleberry
Engineer: Soil Reinforcement Design
Contractor: ECM
Purpose: Maximize Available Land

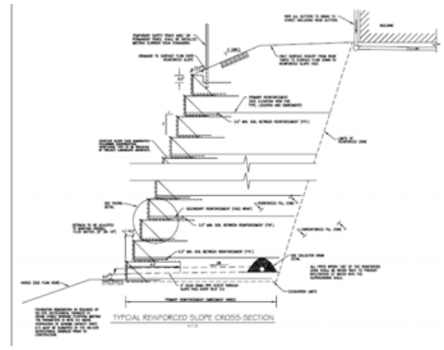
Geosynthetic Material:
- Reinforcement: Geocomposite
- Facing: Polypropylene Mesh

Slope Height: 30 ft
Slope Face: 71,000 ft^2

Construction Sequence:
- The base was a well compacted subgrade and geosynthetics were installed as primary reinforcement.
- Geotextile was placed inside the 3 ft welded wire baskets to provide a stable platform for hydroseeding.
- The embedment lengths varied, but were around 15 ft to 20 ft.
- The wall was seeded immediately after completion to allow grass to grow as quickly as possible.
- The project installation lasted approximately 10 months.

Performance: The wall has been completed for several months and the grass has taken to the wall very well. The condominiums and homes are being constructed and the project seems to be moving forward with no problems.

Cost Effectiveness: The main purpose of the slope was to provide more build space for condominiums and residential homes used an economical solution. A vegetated slope was determined to be the most cost effective.



To complete this reinforced slope, 44,733m² (53,500yd²) of the HS400PP and 48,495m² (58,000yd²) of the HS800PP were installed as primary reinforcement.

Mirafi® MMESH biaxial geogrid is specifically designed for secondary reinforcement and erosion protection in steepened slopes.

Above: The HS400PP and HS800PP high strength geotextiles were embedded between 4.5-6m (15-20ft) in length.

Case Study #20: Yeager Airport Runway

Location: Charleston, West Virginia
Owner: Yeager Airport
Engineer: Triad Engineering
Contractor: Cast & Baker
Purpose: Support Structure for Airport Runway

Geosynthetic Material:
- Reinforcement: Polyester Geogrid (9500 lb/ft & 13700 lb/ft)
- Facing: Polypropylene Mesh
- Drainage: Polypropylene Geotextile

Foundation & Embankment Soil: The onsite geomorphology consisted of weathered sandstone underlain by sandstone and some shale. Testing of the weathered sandstone soil showed it to have a maximum dry density of 127 lb/ft^3 and a peak friction angle of 39°. The compressive strength of the rock foundation varied from 4350 psi to 13750 psi.

Slope Height: 242 ft
Slope Angle: 1H:1V

Design Method: Limit Equilibrium Analysis

Construction Sequence:
- The existing ground was excavated to the required level to provide a stable platform for the reinforced slope.
- The geogrids were installed as horizontal reinforcing elements into the slope in conjunction with the backfill material.
- Embedment lengths of the geogrid were on the order of 195 ft in length.
- A drainage composite was installed along the back of the excavation to intercept and drain seepage water from the existing mountain side away from the reinforced mass.
- Mesh was installed on the face of the slope at 2 ft vertical intervals, with 3 ft embedded into the slope face and 2.5 ft down the face for facial stability and erosion protection.

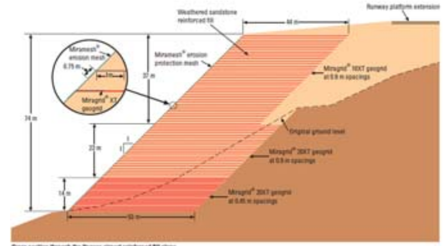
Performance: The reinforced slope was successfully completed and is performing as expected. Geogrids provided the high strengths required for a structure of this size, and the mesh allowed for facing stability and quick germination of surficial vegetation for improved stability.

Cost Effectiveness: Construction options for extending the runway past the existing hillside included evaluation of bridge structures, retaining walls, and reinforced slopes. Engineering evaluation indicated the reinforced slope provided the most cost effective and easiest constructed option of the structures considered.


Early construction at the bottom of the slope.


Completed 242 foot slope with good vegetation cover.


Aerial photo of slope during construction, approximately 80% complete.


Cross section through the Yeager airport reinforced fill slope

Case Study #21: Crystal Cove Slope Reinforcement

Location: Newport Coast, California
Owner: Irvine Company
Engineer: Leighton Associates
Contractor: Sukut Construction
Purpose: Support Structure for Buildings

Geosynthetic Material:
- Reinforcement: Polyester Geogrid
  (9500 lb/ft, 13700 lb/ft & 20500 lb/ft)

Slope Height: 200 ft
Slope Length: 500 ft

Construction Sequence:
- The contractor placed the large rolls of geogrid on a spool and unrolled the geogrid at the face of the slope, then moved the spool into position for the next cut.
- The contractor was able to install over 5,000 yd^2 of geogrids a day.
- The geogrid was placed at 1 ft intervals and was imbedded up to 200 ft.
- The contractor placed 250,000 yd^2 of 20500 lb/ft, 98,000 yd^2 of 13700 lb/ft and over 45,000 yd^2 of 9500 lb/ft.

Performance: The geogrids are all functioning as designed.

Cost Effectiveness: The expense of building this slope was significantly less than the value of the premium view lots atop the reinforced slope.


Over 400,000 yds^2 of Miragrid® geogrids were used to reinforce this development.


The contractor was able to install 5,000 yds2 of Miragrid® geogrids a day.


These premium lots were considered unbuildable. Miragrid® geogrids made it possible to develop this valu able property.

Case Study #22: Anthony Henday Freeway

Location: Edmonton, Alberta, Canada
Owner: Alberta Transportation
Engineer: Thurber Engineering Edmonton
Contractor: Kiewit
Purpose: Support Structure for Roadway

Geosynthetic Material:

- Reinforcement: Polyester Geogrid
- Erosion Control: Geocells

Slope Height: 36 ft
Slope Angle: 1H:1V to 3H:1V

Construction Sequence:

- Construction on the reinforced slopes started in the spring 2004 and was completed by the fall 2005.
- It was determined for the 1H:1V and 2H:1V slope areas that 9500 lb/ft high tenacity polyester geogrid, with an embedment of 69 ft spaced at 39 inch was required.
- For slopes included between 2H:1V to 3H:1V, the 9500 lb/ft geogrid was spaced at 39 in intervals by 49 ft long.
- For all slope configurations, 2000 lb/ft geogrid 6 ft long was used for the secondary reinforcement, spaced at 20 in intervals.
- On all the slopes, a 4 inch large geocell system was used for erosion control.
- The contractor was faced with numerous challenges, those including staged construction of the slopes (maximum 39 inch thick soil lifts per week), fill soils that were above optimum moisture content and a summer with above normal precipitation.

Performance: Extensive monitoring during construction confirmed that the slopes were performing as designed.

Cost Effectiveness: Due to the ease in constructability and the economy of the reinforced slopes, the owners were able to see a 50% cost savings over the alternative MSE wall system.

Above: 10cm (4in) Geocell material being installed.

Pre-cut lengths of 21m (69ft) Miragrid® 10XT geogrid ready to be rolled out.

5m (49ft) and 21m (69ft) lengths of Mirafi® Miragrid® installed and reac or backfill.

Installing stakes to keep geogrid positioned.

Case Study #23: Hampton Township Home Depot

Location: Hampton Township, Pennsylvania
Owner: Home Depot
Engineer: Construction Engineering Consultants
Contractor: CKS Environmental
Purpose: Maximize Available Land

Geosynthetic Material:
- Reinforcement: Polyester Geogrid
- Drainage: Geocomposite

Slope Height: 30 ft
Slope Length: 600 ft
Slope Angle: 0.5H:1V

Construction Sequence:
- Composite drains were installed vertically on the existing slope, covering 70% of the height and 33% of the total area.
- The composite was connected to a 6 inch perforated pipe that measured the distance of the existing slope. The pipe had bleeder drains every 40 ft, which daylighted beyond the face of the reinforced slope.
- The slope was designed using primary geogrids every 3 ft of vertical height and a secondary geogrid every 18 inch.
- High-galvanized face baskets were used to allow for better compaction at the face and to make the slope as aesthetically pleasing as possible.
- A narrow 4 ft × 4 ft rock toe was designed not to infringe on the county road or utility pole at the base of the slope.

Performance: During the installation, two major rain events occurred, producing no slope failures.

Case Study #24: I-495 Marston Street Northbound Ramp

Location: Lawrence, Massachusetts
Owner: Massachusetts Highway Department
Engineer: Fay Spofford & Thorndike
Contractor: SPS New England
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyester Geogrid (2000 lb/ft & 7400 lb/ft)
- Drainage: Geocomposite

Slope Angle: 1H:1V

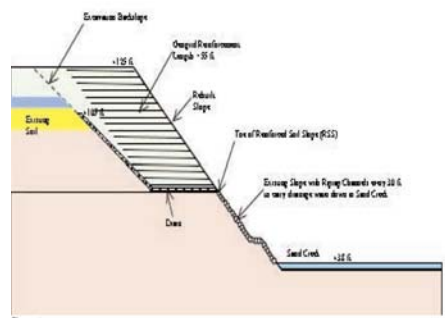
Construction Specifications: Massachusetts Highway Department

Construction Sequence:
- The lower portion of the slope contained 6 layers of 7400 lb/ft geogrid as the primary reinforcement spaced 2 ft vertically with a 3 ft embedment length.
- The upper portion of the slope used 7400 lb/ft geogrid 3 ft vertically with a 26 ft embedment length.
- 2000 lb/ft geogrid was used as an intermediate, spaced 2 ft vertically with an embedment length of 6 ft and placed in the upper portion of the slope in between the other layers.
- The drainage composite was installed at the back of the slope against the native soil and up 1/3 of the slope height.
- The slope face was loamed, seeded, and covered with a synthetic permanent erosion control mat.

Performance: The I-495 MSE slope and relocated northbound ramp has been in use for approximately one year, and the 1:1 slope is fully vegetated and performing as expected.

Miragrid® 8XT, used as the primary reinforcement, is installed in 0.9 m (3.0 ft) embedment lengths.

The 2:1 MSE slope at Marston Street was steepened to 1:1.

Case Study #25: Kraugh Landslide Repair	
Location: Jordan, Minnesota **Owner:** Dr. Lyle and Esther Kraugh **Engineer:** Gale-Tec Engineering **Contractor:** Rachel Contracting **Purpose:** Support Structure for Building **Geosynthetic Material:** • Reinforcement: Polyester Geogrid (4700 lb/ft & 7400 lb/ft) • Drainage: Polypropylene Geotextile **Slope Angle:** 1H:1V **Construction Sequence:** • The lower slope was cut/graded to a consistent slope angle while trying to minimize any changes to the existing angle of the slope. • Then it was stabilized by placing a layer of 4 inch cellular confinement over the entire surface. • The 4 inch cellular confinement was filled with topsoil borrow, seeded, and covered with a category 4 erosion control blanket. • The upper slope was subcut (benched) up to 25 ft from the top of the slope, and then it was built back with successive 8 inch horizontal layers of cellular confinement with geogrid reinforcement. • The cellular confinement was backfilled with granular borrow, and the face was backfilled with a mixture of topsoil, compost, and seed. • At the base of the upper slope was a coarse/rock layer to facilitate within the slope repair. This rock layer was relieved by 6 inch PE drain daylighted to the bottom of the slope and into the creek. **Performance:** The slope has been permanently restored and is performing as expected without any further erosion to date.	  

Case Study #26: Wal-Mart Distribution Center

Location: Lewiston, Maine
Owner: Wal-Mart
Engineer: Carter- Burgess & S.W. Cole
Contractor: H.E. Sargent
Purpose: Maximize Available Land

Geosynthetic Material:
- Primary Reinforcement: Polyester Geogrid (4700–7400 lb/ft)
- Secondary Reinforcement: Polyester Geogrid (2000 lb/ft)
- Erosion Control: Polypropylene Geotextile

Slope Angle: 1.5H:1V

Construction Sequence:
- The design consisted of slopes at a 1.5H:1V angle and called for geogrid to be placed at 4 ft height vertical spacing as the primary reinforcement with embedment lengths from 45 ft to 60 ft.
- Secondary reinforcement and was centered between the primary grid with 12 ft embedment lengths.
- To protect the slope from erosion, geotextile was placed on the slope face and covered with rip rap.
- Construction of the reinforced slopes began in the second week of November. Using an excavator, dozer, loader, roller and small crew, the slope were completed in the second week of January.

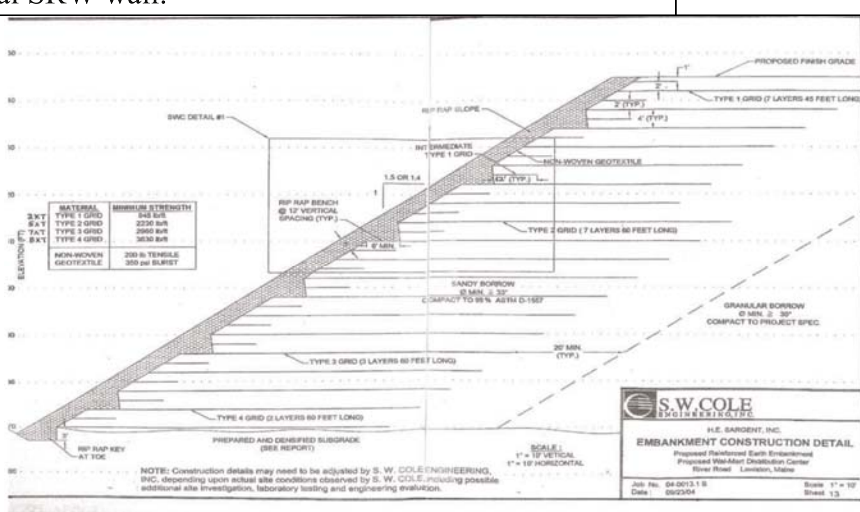
Performance: According to the contractor, the polyester geogrids outperformed HDPE geogrids they had previously used in similar weather conditions.

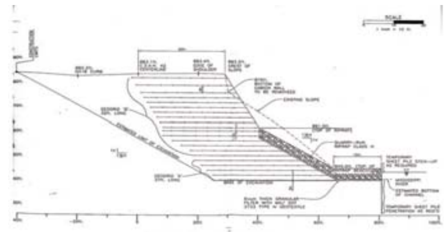
Cost Effectiveness: The steepened slope alternative played a big part in keeping the project moving forward and the design saved approximately 30% versus the original SRW wall.

ABOVE: The finished Miragrid® reinforced slopes.

BELOW: The Miragrid® reinforced slope saved approximately 30% compared to the original SRW design.

Mirafi® 180N was placed on the slope face and covered with riprap to protect the slope from erosion.



Case Study #27: Mississippi River Landslide Repair	
Location: Otsego, Minnesota **Owner:** Wright County **Engineer:** Gale-Tec Engineering **Contractor:** Veit Company **Purpose:** Support Structure for Roadway **Geosynthetic Material:** • Reinforcement: Polyester Geogrid (4700 lb/ft & 7400 lb/ft) • Erosion Control: Polypropylene Geotextile **Slope Height:** 50 ft **Slope Angle:** 1H:1V **Design Method:** Limit Equilibrium Analysis **Construction Sequence:** • The geogrid chosen consists of high tenacity, high molecular weight polyester fibers capable of tensile reinforcement between 2200 lb/ft and 4300 lb/ft long-term allowable design strength. • Embedment lengths of nearly 40 ft were determined based on limit equilibrium analysis. • The contractor initially began his excavation below normal Mississippi River water elevation in order to establish a necessary base for construction. Construction then proceeded up in 1 ft lifts. • A special seed mix consisting of a deep-rooted prairie perennial grass was used within a 6 inch high cellular confinement system web with a green face.	 

Case Study #28: Canal Quarry Reinforced Slope

Location: Point Richmond, California
Owner: East Bay Regional Parks
Engineer: Gilpin Geo Sciences
Contractor: North Bay Construction
Purpose: Maximize Available Land

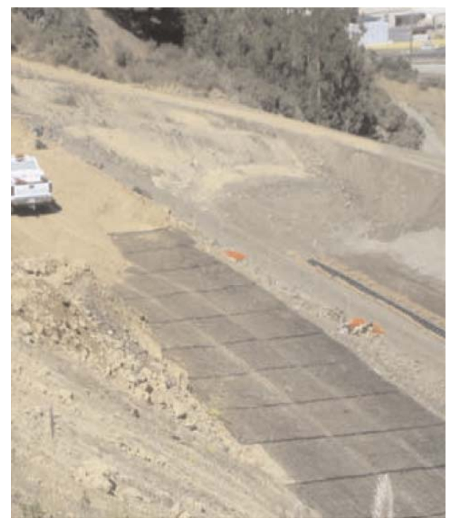
Geosynthetic Material:
- Primary Reinforcement: Polyester Geogrid (5900 lb/ft & 7400 lb/ft)
- Secondary Reinforcement: Polyester Geogrid (2000 lb/ft)

Slope Height: 60 ft to 70 ft
Slope Angle: 1H:1V

Construction Sequence:
- The reinforced steepened slope design required the placement of geogrid reinforcement horizontally within layers of compacted fill.
- To attain an acceptable slope stability factor of safety, primary geogrid reinforcement with long-term design strengths of 3000 lb/ft and 3700 lb/ft were required.
- The design also required a biaxial geogrid for secondary (surfacial) reinforcement of 1000 lb/ft.
- The completed slope faces were treated with erosion control measures to prevent surfacial erosion of the slope faces before permanent vegetation could be established.

Performance: Over 50,000 yd^2 of geogrids are performing perfectly to support the reinforced slope.

Cost Effectiveness: Using geogrids to construct the reinforced slope proved to be the most economical way of putting the quarry back into a more natural state.



Case Study #29: Clemson Road Bridge

Location: Columbia, South Carolina
Owner: South Carolina Department of Transportation
Engineer: South Carolina Department of Transportation
Contractor: C. Ray Miles Construction
Purpose: Support Structure for Bridge Abutment

Geosynthetic Material:

- Reinforcement: Polyester Geogrid (3600 lb/ft)
- Facing: Welded Wire Forms

Foundation Soil: Silty-Sand

Slope Height: 26 ft
Slope Angle: 1H:1V

Construction Specifications: South Carolina DOT

Construction Sequence:

- The slope design required primary geogrid reinforcement to be placed at 2 ft vertical spacing for the bottom third of the slope and 6 ft vertical spacing in the upper third of the slope.
- The geogrid embedment lengths required to satisfy overall slope stability were 40 ft for the bottom three geogrid layers and 30 ft at the top of the slope.
- The slope face was constructed using prefabricated welded wire forms bents to the specified slope batter of 45°.
- A secondary reinforcement and a seven ounce non-woven geotextile were place in each wire form prior to primary geogrid placement and compacted soil.
- The secondary reinforcement provided surficial slope stability and a minimum 6 ft top and bottom embedment specified by SCDOT.

Cost Effectiveness: The reinforced slope eliminated the costly need for lengthening the bridge span or constructing a structural wall and provided the additional right-of-way required for the access road.

Fill is placed atop StrataGRID in the Reinforced Structured Slope.

Construction of the StrataSLOPE for the Clemson Road project.

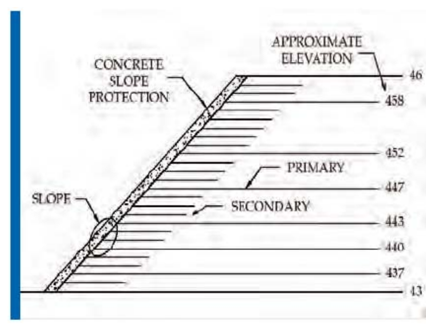


Figure 1: Typical cross-section for a reinforced StrataSLOPE.

The completed Clemson Road bridge abutment.

Case Study #30: Statesville Home Depot	
Location: Statesville, North Carolina **Owner:** Home Depot **Engineer:** Thomas Rainey **Contractor:** Earth Structures **Purpose:** Maximize Available Land **Geosynthetic Material:** • Reinforcement: Polyester Geogrid (3500-7400 lb/ft) • Facing: Wire Basket Forms • Drainage: 4 inch Perforated Plastic Pipe • Erosion Control: Polyamide Mat **Slope Height:** 36 ft **Slope Length:** 600 ft **Slope Face Area:** 16,000 ft^2 **Slope Angle:** 0.5H:1V **Construction Sequence:** • The reinforced soil slope incorporated geogrid reinforcement with the maximum anchor length of 36 ft, used in a wrapped face system with 90° wire basket forms and an erosion control matting to create the face. • Geogrids were installed at 18 inch vertical spacing with a 4 ft tail draped over the front on the wire form, soil compacted, then the tail wrapped back over the fill. • A standard 139 inch width flat back three-dimensional permanent erosion geomat was installed behind the geogrids at the wire basket face to retain the soil at the face and provide long-term erosion protection. • To protect from potential water problems, 4 inch perforated plastic pipe was installed perpendicular to the slope face, penetrating the wire forms to provide positive drainage in the reinforced zone. • In addition to Earth Structures' two D-5 dozers and 84 inch compactor, the onsite grading contractor, Hoffman Grading, provided additional dozers and compaction equipment, which allowed the placement and compaction of over 1,500 yd^3 of fill dirt per day. • The construction of the slope was completed in 28 days. **Performance:** The slope has been in place since late September 2000 and is functioning well.	   

Case Study #31: Donzi Landfill Expansion

Location: Atlanta, Georgia
Owner: APAC Southeast
Engineer: Hodges, Harbin, Newberry & Tribble
Contractor: APAC Construction
Purpose: Maximize Available Land

Geosynthetic Material:

- Primary Reinforcement: Polyester Geogrid (6400 lb/ft & 8100 lb/ft)
- Secondary Reinforcement: Polyester Geogrid (1900 lb/ft)
- Facing: Welded Wire Baskets

Slope Height: 40 ft
Slope Angle: 0.5H:1V

Design Method: Analysis was performed for internal stability, compound stability, direct sliding, and deep seated analysis. Seismic stability analysis was also performed, completing the geotechnical analysis of the site structures.

Construction Sequence:

- The primary reinforcement layers consisted of geogrid with maximum embedment lengths of 26 ft.
- The vertical spacing for the initial 6 ft of slope construction was 1.5 ft, while 3 ft vertical spacing was utilized for the remainder of the slope up to the maximum vertical height of 40 ft.
- The facing detail utilized secondary reinforcement and 90° welded wire baskets for facing support.
- Since aesthetics was not an issue and the owner did not want to maintain a vegetated slope, the baskets were filled with stone. This facing detail also provided long-term erosion control.

Cost Effectiveness: A geogrid reinforced steep slope with wire basket facing was selected to increase the landfill volume and provide the most cost effective solution to this site.

Case Study #32: Widening I-695 @ I-83S

Location: Baltimore, Maryland
Owner: Maryland State Highway Administration
Engineer: Soil Reinforcement Design
Contractor: Facchina Construction Company
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyester Geogrid
- Erosion Control: Polypropylene Geotextile

Construction Sequence:
- In widening I-695 at I-83S, the owner required the slope adjacent to an off ramp to be steeper than 2:1 due to the delineated environmental impact at the toe of the slope.
- The required slope face angle meant that geosynthetic reinforcement was needed to build the structure and the face also needed to be protected against erosion both short term, prior to vegetation, and long term.
- The design called for the slope to be reinforced with a uniaxial geogrid and the face of the slope to be reinforced with biaxial geogrid erosion control blanket combination.

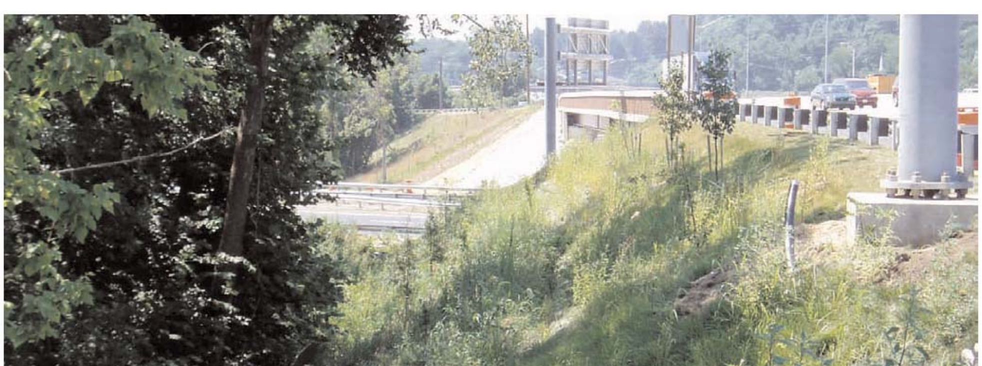

Preparing the drainage fabric behind the slope.


Above: Overlap required between primary reinforcement and face wrap.

Below: Compaction of soil at the face of the slope for vegetation.



Slope nearing the finished grade.


Completed slope with vegetation.

Case Study #33: Sycamore Ranch Slope Reinforcement

Location: Murrieta, California
Owner: Sycamore Ranch
Engineer: Petra Geotechnical
Contractor: Kemmis Equipment
Purpose: Maximize Available Land

Geosynthetic Material:
- Reinforcement: Polyester Geogrid (2700 lb/ft)

Slope Height: 20 ft
Slope Angle: 1H:1V

Construction Sequence:
- The contractor excavated the keyway and encountered standing water about 1 ft deep. Geogrid was rolled out and an 8 inch lift of native material was placed on top.
- The bottom of the keyway solidified and allowed the grading operation to commence.
- Geogrid was placed in 3 ft intervals for a total slope of 20 ft.

Cost Effectiveness: The geogrid was easily installed and saved the contractor time and the owner money.

Enkagrid® PRO is placed in 3 foot intervals for a total slope of 20 feet.

Enkagrid PRO was used to stabilize the slope under the water level.

Case Study #34: Hirini Road Logging Storage Underpass

Location: Gisborne, New Zealand
Owner: Gisborne District Council
Engineer: Opus Consultants Gisborne
Contractor: Quality Roading & Services
Purpose: Support Structure for Roadway

Geosynthetic Material:

- Reinforcement: Polyethylene Geogrid
- Facing: Hessian Bags & Polyester Geotextile

Slope Angle: 70°

Construction Sequence:

- Construction was undertaken on a 5 day per week basis, using a total of 6 staff. A light plate compactor, a 2 tonne roller and a 12 tonne digger were used.
- Hessian bags were initially used with the geosynthetic wrap around. This enabled good compaction and evenness of each layer.
- The thickness of each layer was 0.5 ft, with 4 lifts required for each geogrid wrapped layer at 2 ft centers.
- A secondary layer of geogrid was placed midway between the layers to improve face stability.
- Approximately 2,600 ft^2 of reinforced slope was constructed per week.
- The 70° slope was hydroseeded at the completion of the work.


New underpass Date: November 2007


Typical logging truck Date: February 2008


Wrapped slope with hessian bags Date: December 2007

Case Study #35: US Route 201 Carney Brook Bridge

Location: Moscow, Maine
Owner: Maine Department of Transportation
Engineer: Maine Department of Transportation
Contractor: Bridge Corporation
Purpose: Support Structure for Roadway

Geosynthetic Material:

- Reinforcement: Polyester Geotextile (4800 lb/ft)

Embankment Soil: The reinforced backfill had to meet both MEDOT Type E specifications and the following requirements: 0% to 10% passing the #200 sieve with maximum aggregate size of no larger than 1 inch, plasticity index < 6, internal friction angle > 34°, free angular material and within a pH range of 3 and 9. No shale or soft, poor-durability particles were used.

Slope Height: 10 ft to 30 ft
Slope Length: 425 ft
Slope Angle: 1H:1V

Construction Specifications: Maine Department of Transportation

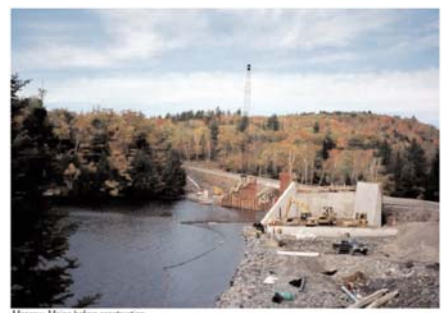
Construction Sequence:

- The contractor built temporary forms to aid in the construction of the 1H:1V slope and up to 25 layers of geotextile with embedment lengths of up to 25 ft were used with select backfill.
- The contractor was able to spread the reinforced soil and compact to 95% of standard Proctor effort.
- The lower zone reinforcing fabric was spaced at 1 ft and the second and third zone at 2 ft. On the second and third zones, a secondary compaction aid geotextile was used.
- Each lift was stepped back approximately 1 ft. Each step was then filled with a specific soil mix designed by MEDOT, seeded, and then covered with a turf reinforcement mat.

Performance: The completed project met the National Scenic Byway requirements while also resulting in a safer alignment than previously configured.

Cost Effectiveness: By using geotextile for the reinforced soil slopes, the wetland impacts to Wyman Lake were reduced by 50% over other construction methods. This option resulted in a cost savings of approximately $700,000. Due to the high cost of a long span bridge, the alternate option of a shorter bridge with approach embankments touching down in the lake was constructed.

Moscow, Maine



Moscow, Maine before construction.

Moscow, Maine during construction.

Case Study #36: Russell Road Slip Repair

Location: Whangarei, New Zealand
Owner: Whangarei District Council
Engineer: Opus Consultants
Contractor: Fulton Hogan
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Facing: Polyester Geotextile & Biodegradable Mat

Slope Height: 39 ft

Construction Sequence:
- Opus Consultants with input from Fulton Hogan and technical assistance from the manufacturer came up with a combination tie back piling system at the base of the slip with a geogrid reinforced slope.
- A combination of hydroseeding and biodegradable matting were used to green up the front face of the slope. Geotextile was used on top of the slope under the new carriage way pavement construction.

Cost Effectiveness: This design combination proved very effective in relation to cost, speed of construction, and a long-term solution.

Helena Bay Road Slip

Laying Bidim, Biomac and Tensar

Vegetated bank

Case Study #37: Umhlanga Rocks Drive

Location: Durban, South Africa
Owner: Borough of Umhlanga Rocks
Engineer: BCP
Contractor: Afrocon Construction
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyester Geotextile

Slope Angle: 60°

Construction Sequence:
- Geotextile was placed in 1 ft lifts with tie-back lengths of 8 ft.
- The front face was protected using the wraparound construction technique.

Performance: The results have been most satisfactory, with the wall standing up to the torrential rains in October 1999, showing no damage to the structure itself, and only minimal damage to the grass sods planted on the face.

Cost Effectiveness: A number of alternatives were investigated to find the most cost effective and environmentally pleasing solution. The geotextile reinforced embankment alternative met these two criteria.

Case Study #38: Rodlauer Bridge Road Realignment

Location: Styria, Austria
Owner: Steiermarkische
Engineer: Buro Eisner
Contractor: Lang & Menhofer
Purpose: Support Structure for Roadway

Geosynthetic Material:

- Reinforcement: Polyester Geogrid (7500 lb/ft & 13700 lb/ft)

Slope Height: 112 ft
Slope Angle: 1H:2V

Design Method: Limit Equilibrium Analysis

Construction Sequence:

- At the toe of the steep slope, it was not possible to provide a graded earth foundation base, so a concrete foundation block was constructed into the rock stratum.
- Layers of geogrid reinforcement, having ultimate tensile strengths of 13,700 lb/ft and 7,500 lb/ft, were used throughout.
- To form a smooth surface at the slope face, a steel mesh was bent to the required 1H:2V face angle and consisted of units 2 ft high, which coincided with the vertical spacing between the geogrid reinforcement layers.
- Inside the steel mesh facing, an erosion protection grid made of glass fibers was installed. The role of this glass grid is to protect the soil face from surface erosion until surface vegetation growth has been established.

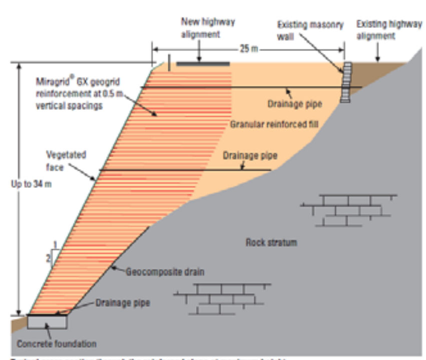
Performance: A value solution was found by using a geosynthetic reinforced steep slope to realign the highway, making it more stable, and improving traffic safety.

Cost Effectiveness: The value of this reinforced slope has proven to be very good, with its cost being around 50% of the cost of the originally proposed bridge solution.

Existing highway and proposed new highway alignment

Steel mesh facing used to form a smooth slope face which aids in vegetation growth and aesthetics

Reinforced fill slope 2 years after construction



Typical cross section through the reinforced slope at maximum height

Case Study #39: Langkawi Landslide Restoration

Location: Kedah, Malaysia
Owner: Kuala Lumpur Public Works Department
Engineer: KGA Consultants
Contractor: Protab Construction
Purpose: Support Structure for Roadway

Geosynthetic Material:

- Reinforcement: Geocomposite
- Drainage: Polypropylene Geotextile

Embankment Soil: Sandy Soil

Slope Height: 79 ft
Slope Angle: 1H:1.2V

Construction Sequence:

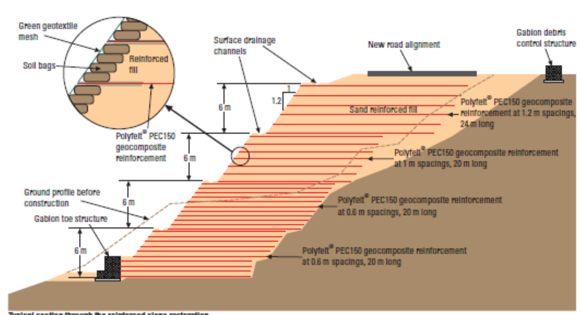
- The landslide debris was removed from the site to clear the road and provide an adequate zone for the new reinforced slope.
- At the rear of the excavated zone, a subsurface drainage layer was provided behind the reinforced soil zone to intercept ground water seepage from the natural strata.
- At the toe of the slope, a low gabion structure is incorporated to enhance toe stiffness.
- The geocomposite reinforcement has a tensile strength of 10,280 lb/ft, and the length was maintained at a constant 66 ft throughout the height of the slope for construction simplicity, except for the upper tier where the reinforcement length was 79 ft.
- The vertical reinforcement spacing varied between 2 ft and 4 ft depending on the vertical location in the slope.
- Soil-filled bags were used as forms to shape the steep slope profile and enable the compactor to work close to the slope face for good compaction of the reinforced fill.
- Sandy soil from a nearby borrow area was used as the reinforced fill, and this was placed in lifts and compacted using a 10 tonne roller to achieve a minimum of 90% of standard Proctor density.
- A green colored geotextile mesh was used as a wraparound on the slope surface.


Installing the gabion toe of the reinforced slope


Compacting the reinforced fill


Reinforced slope partially completed


Completed reinforced slope with vegetation being established



Typical section through the reinforced slope restoration

Case Study #40: Maehongson Slope Restoration

Location: Maehongson, Thailand
Owner: Chiangmai Bureau of Highways
Engineer: Chiangmai Bureau of Highways
Contractor: Phatthananuphap
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyester Geogrid
- Drainage: Polypropylene Geotextile

Slope Height: 43 ft
Slope Angle: 1H:2V

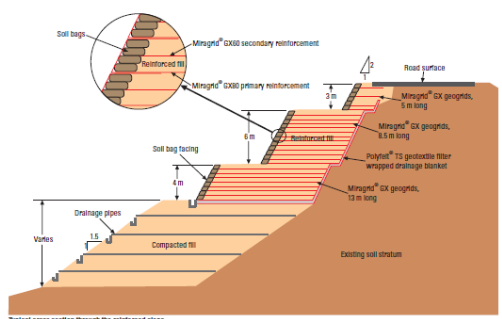
Construction Sequence:
- The lower part was rebuilt at a shallow slope angle of 1.5H:1V with compacted residual soil benched into the existing good ground.
- This was done such that a 49 ft wide platform would be created for the construction of the 43 ft high upper part of the slope consisting of reinforced fill.
- Within the fill in the lower part of the slope, horizontal drainage pipes were installed to drain out any accumulating groundwater at the rear of the compacted fill zone.
- At the base of the reinforced fill slope, a horizontal drainage blanket was constructed using single sized aggregate sandwiched between two layers of a geotextile filter.
- The upper part of the restored slope consists of 3 benched tiers of reinforced fill, each having a slope face angle of 1H:2V.
- At the face of the reinforced slope, the geogrid reinforcements are wrapped around soil bags and tucked back into the slope at the next reinforcement level.

Performance: To monitor the performance of the reinforced slope, the Geodetect fiber-optic strain monitoring system was incorporated into the slope with the geogrid reinforcement. The monitoring results 7 months after construction showed that horizontal strains were small, less than 1%. At 15 months after construction, there was negligible difference in the horizontal strains.

Installation of the drainage blanket at the base of the reinforced slope

Spreading locally obtained reinforced fill over Miragrid® GX geogrid reinforcement

Completed reinforced slope with vegetation growth on the face



Typical cross section through the reinforced slope

Case Study #41: Srivichai Road Widening

Location: Chiangmai, Thailand
Owner: Thailand Department of Highways
Engineer: Thailand Department of Highways
Contractor: Jirangkorn
Purpose: Support Structure for Roadway

Geosynthetic Material:

- Reinforcement: Polyester Geogrid
- Erosion Control: Polypropylene Mat
- Drainage: Polypropylene Geotextile

Slope Height: 16 ft
Slope Angle: 1H:2V

Construction Sequence:

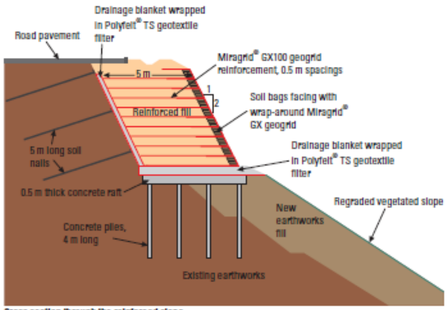
- So as not to jeopardize the integrity of the existing road, soil nails were installed in a 5 ft square grid pattern to provide stability to the steep excavations necessary for the reinforced fill structure to be constructed.
- To prevent differential settlements between the fill and the cut ground from damaging the reinforced soil structure, the designed decided to provide a piled foundation support.
- Precast square piles were driven 13 ft into the ground and capped with a reinforced concrete raft prior to constructing the reinforced soil structure.
- Above the concrete raft, a drainage blanket was installed consisting of single-size stone wrapped with a geotextile filter. This drainage blanket was continued up the rear of the reinforced slope to intercept groundwater flows emanating from the existing slope.
- Geogrid reinforcement, composed of high modulus polyester yarns within a robust polymer coating, was used at 2 ft vertical spacings and has an initial tensile strength of 6850 lb/ft.
- Soil bags were used to form the face of the reinforced fill slope.

Cost Effectiveness: The geogrid reinforced fill slope option was determined to be the most practical and cost effective as well as taking the least time for construction.

Placement of stone drainage blanket with Polyfelt® TS geotextile filter on top

Placing reinforced fill in the reinforced slope

Reinforced slope nearing completion



Cross section through the reinforced slope

Case Study #42: Diasbach Avalanche Protection Barrier

Location: Tyrol, Austria
Owner: WLV
Engineer: Geotechnik Henzinger
Contractor: Streng Bau
Purpose: Erosion Prevention

Geosynthetic Material:
- Reinforcement: Polyester Geogrid
- Facing: Steel Mesh Units
- Erosion Control: Glass Fiber Grid

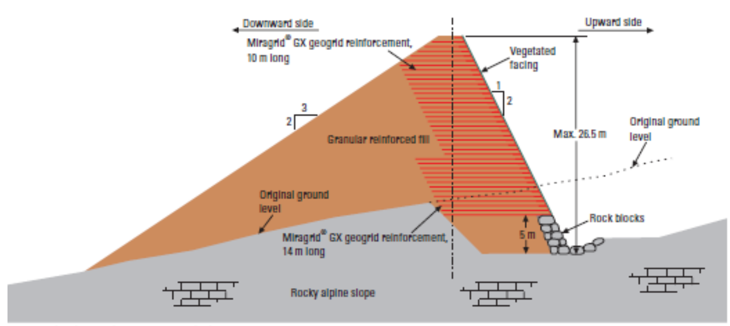
Slope Height: 87 ft
Slope Length: 2133 ft
Slope Angle: 1H:2V

Construction Sequence:
- The construction of the barrier was carried out during the summer months only over a 4 year period.
- The first 16 ft in height of the barrier was constructed using rock blocks in order to provide a stable foundation and adequate resistance and hydraulic conductivity for the large flows emanating from the snow melt and passing along the barrier during the spring thaw seasons.
- The reinforced soil system used on the upward side of the avalanche protection barrier above the rock block platform consisted of 2 ft high steel mesh facing units angled at 1H:2V with layers of geogrid reinforcement at 2 ft vertical spacings.
- In the lower part of the slope, the geogrid extended 46 ft into the slope, while in the upper part the geogrid extended 33 ft into the slope.
- Inside the steel mesh facing, an erosion protection grid made of glass fibers was installed to provide long-term local stability to the slope face.
- Immediately behind the steel mesh and glass grid facing, good quality top soil was placed to enable vegetation growth, followed by the placement and compaction of the granular reinforced fill.


Miragrid® GX geogrid reinforcement being placed in the reinforced slope


Wire mesh facing on the reinforced slope face with vegetation applied to the lower part of the slope


Avalanche protection barrier almost completed



Cross section through the avalanche protection barrier

Case Study #43: A3 Hindhead Highway Earthworks Widening

Location: Surrey, United Kingdom
Owner: United Kingdom Highways Agency
Engineer: Atkins Consultants
Contractor: Balfour Beatty Civil Engineering
Purpose: Maximize Available Land

Geosynthetic Material:
- Reinforcement: Polyester Geogrid
- Facing: Geocell & Hessian Bags

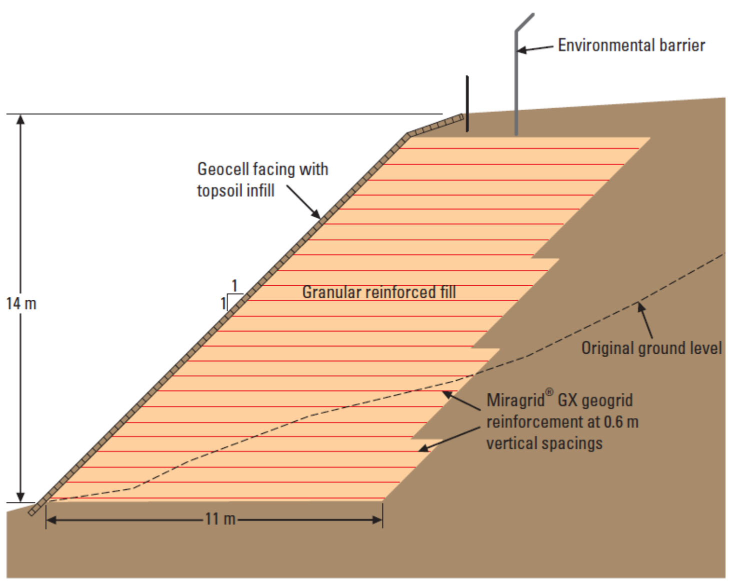
Slope Height: 49 ft
Slope Angle: 1.5H:1V to 1H:1V

Construction Sequence:
- The foundations for the reinforced fill slopes were prepared by top soil stripping, excavation, and proof rolling. Any soft spots were removed and replaced with compacted general fill.
- The geogrid reinforcement was placed at 2 ft vertical spacings in the reinforced fill extending from the rear of the reinforced fill to the slope face where it was truncated. Depending on the height of the reinforced slopes, up to four different strengths of geogrid was used.
- The slope facing consisted of 8 inch deep geocell containing topsoil infill. The geocell was placed down the slope face and fixed to the reinforced soil slope surface by means of galvanized steel anchor pins of 30 in in length.
- Some slopes used layers of geogrid wrapped around hessian bags fill with seeded topsoil for the facing.


Use of timber shutter system to align the face for the steep reinforced slope sections


One of the steep reinforced slopes nearing completion


Placing geocell facing with topsoil infill for one of the shallow reinforced slopes



Typical cross section through the shallow reinforced slopes

Case Study #44: Hamilton Railway Embankment Widening

Location: Hamilton, Ontario, Canada
Owner: GO Transit
Engineer: Isherwood Geotechnical Engineers
Contractor: Birmingham Construction
Purpose: Support Structure for Railway

Geosynthetic Material:

- Primary Reinforcement: Polyester Geogrid (5900 lb/ft)
- Secondary Reinforcement: Polyester Geogrid (2000 lb/ft)
- Erosion Control: Polypropylene Geotextile

Slope Height: 36 ft
Slope Angle: 1.4H:1V

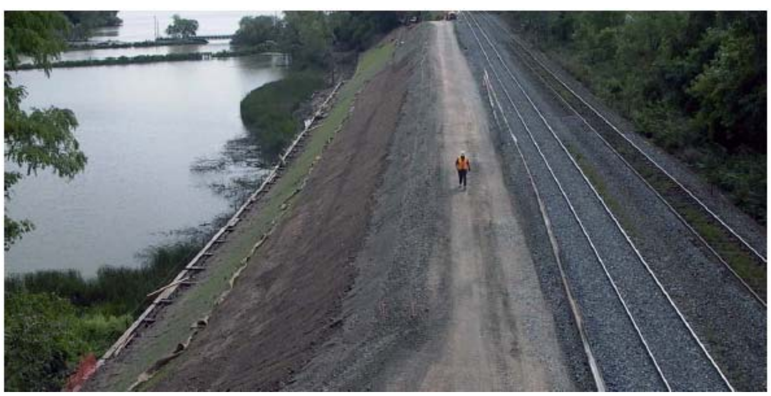
Construction Sequence:

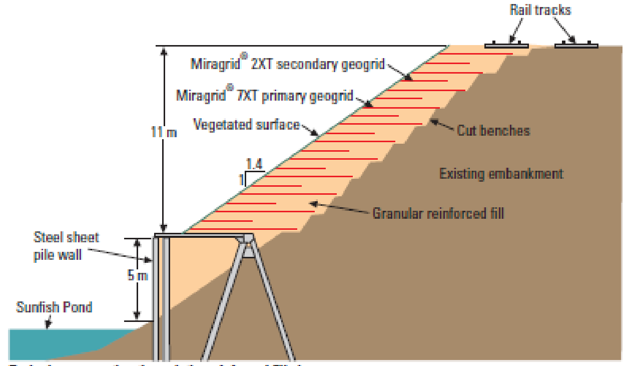
- After evaluating a number of options, the solution chosen was a combined steel sheet pile wall with a vegetated geogrid reinforced slope on top.
- The slope consisted of compacted granular fill with layers of 5900 lb/ft geogrid as the primary reinforcement placed at 3 ft vertical spacings, extending 20 ft into the slope.
- 2000 lb/ft geogrid was used as the secondary reinforcement to provide local slope face stability, and these were installed at 3 ft vertical spacings intermediately between the primary geogrid layers and extended 7 ft into the slope face.
- The geogrid reinforcements are composed of high strength, high stiffness, polyester yarns encased within a robust polymer coating.
- After completion of the structural portion of the reinforced fill slope, the slope surface was covered with 4 inch of topsoil and then hydroseeded with a mix of grasses. The slope surface was then covered with a geotextile erosion protection layer to prevent erosion of the topsoil while vegetation was established and to provide reinforcement for the vegetation's root matrix.


Clearing of vegetation from the existing embankment slope


Placing reinforced fill over Miragrid® XT geogrid reinforcement


Completed reinforced fill slope with vegetated surface





Typical cross section through the reinforced fill slope

Case Study #45: The Village at Clagett Farm

Location: Clagett Farm, Maryland
Owner: Toll Brothers
Engineer: Tensar
Contractor: Hardscapes Construction
Purpose: Maximize Available Land

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Facing: Welded Wire Baskets & Reinforcement Mat

Slope Height: 23 ft
Slope Length: 673 ft
Slope Face Area: 6,100 ft^2
Slope Angle: 1H:3V

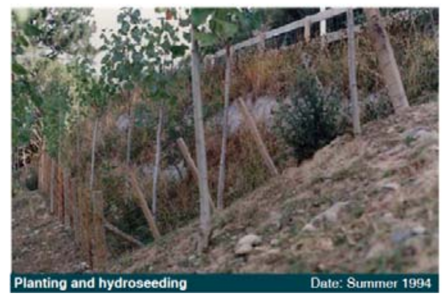
Construction Sequence:
- The wall was constructed with ungalvanized welded wire form baskets, reinforced with UV-stabilized geogrid, and lined with a permanent reinforcement mat.
- Ensuring that the accelerated construction schedule was met, the reinforcement system provided the idea solution since it has minimal, lightweight components that are easy to transport.
- The system is simple to install and requires no specialized equipment.
- Since the vegetated wall could be reinforced quickly and easily, the contractor was able to install the wall ahead of schedule, allowing for the construction of the model homes to begin much sooner than originally planned.
- Once the slope was reinforced, the contractor added a winter seed mix to the face in order to facilitate vegetation.

Case Study #46: North Island Slope Repair

Location: Ashhurst, New Zealand
Owner: Palmerston North
Engineer: Palmerston North
Contractor: Brownell Contracting
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyester Geogrid
- Facing: Biodegradable Mat

Construction Sequence:
- To achieve long-term facing protection for wrap around slope construction, it is commonly recommended to use a 1 ft to 2 ft zone of a loam type soil in the front face that is able to hold moisture and nutrients for sustained plant growth.
- This can be created using a false formwork system with a biodegradable mat or hessian bags filled with topsoil. The topsoil can be preseeded or the face can be hydroseeded.
- Additional plantings are recommended to ensure a recovery of the ecosystem. Over time, a range of plant species will develop.



Case Study #47: County Road 46A Terraced Vegetated Slope

Location: Sanford, Florida
Owner: Seminole County
Engineer: SRDI
Contractor: Gibbs & Register
Purpose: Support Structure for Roadway

Geosynthetic Material:

- Reinforcement: Polyester Geogrid (3500 lb/ft)
- Facing: Polypropylene Geotextile

Slope Height: 8 ft
Slope Length: 400 ft

Construction Sequence:

- The design called for a fairly open high tenacity monofilament polypropylene product and a polyester geogrid product that provides excellent reinforcement for slopes and has low creep values.
- The installation was started in June 2007 and completed a month later by Gibbs & Register. The project manager led the installation team on the project and had never installed a wire slope system before.

Cost Effectiveness: A terraced vegetated slope was chosen in lieu of sheet piling or modular block wall. The installation of the system was easy, economical, and aesthetically pleasing.

Case Study #48: Port Mann Bridge

Location: Vancouver, British Columbia, Canada
Owner: British Columbia Ministry of Transportation and Infrastructure
Engineer: Western Canada
Contractor: Kiewit/Flatiron General Partnership
Purpose: Support Structure for Bridge Abutment

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Facing: Welded Wire Units
- Erosion Control: Geocomposite

Slope Height: 30 ft
Slope Angle: 69°

Design Method: Finite Element Analysis

Construction Sequence:
- A series of stone support columns were first installed at a depth of 66 ft, then the area was topped with a level granular surface.
- The system's welded wire facing units were stepped from the granular foundation up and lined with biaxial geogrid.
- The soil was reinforced with the primary placement of uniaxial geogrid.
- The geogrid-reinforced zone required a 14,387 yd^3 of compacted granular or sand backfill.
- Permanent erosion control blankets were used to vegetate the slope.
- To promote internal drainage, a trench was installed within the slope, and drain gravel was placed within its lower portion.

Cost Effectiveness: Budget constraints and environmental concerns favored slope solutions that were more cost efficient and offered greener profiles.

Nearly two dozen Sierra Slopes were installed as part of the Port Mann Bridge Project. The bridge will double existing lanes from five to ten and will sustain Vancouver's traffic growth over the next two decades.

Case Study #49: M21 (E673) Ring Road

Location: Bijelo Polje, Montenegro
Owner: Bijelo Polje
Engineer: Urbis Doo
Contractor: Putevi Uzice
Purpose: Support Structure for Roadway

Geosynthetic Material:

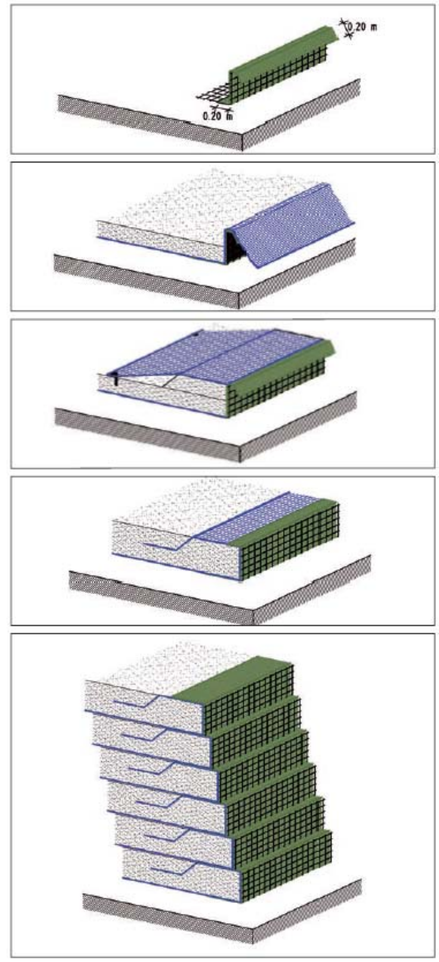
- Reinforcement: Polyester Geogrid
- Facing: Polymer Mesh

Slope Height: 15 ft to 20 ft
Slope Length: 1640 ft

Construction Sequence:

- The design specified a wraparound faced, geogrid reinforced structure, with a lost steel facing system, which acts as a temporary formwork during construction as well as a permanent protection facing in the long term.
- The construction process involves the use of a geogrid laid in horizontal layers at 2 ft lifts, with a finer green mesh product used to retain the soil behind the front face.
- A high quality granular backfill was used in the soil block immediately behind the front face to ensure that the alignment was maintained during the construction process.

Cost Effectiveness: The additional economic and environmental benefits of using reinforced soil rather than reinforced concrete was also an important benefit in the adoption of this type of structure.



Case Study #50: Zeleznik Ring Road Viaduct

Location: Belgrade, Serbia
Owner: Belgrade Highway Institute
Engineer: Belgrade Highway Institute
Contractor: Planum
Purpose: Support Structure for Bridge Abutment

Geosynthetic Material:

- Reinforcement: Polyester Geogrid
- Facing: Polymer Mesh

Slope Height: 31 ft
Slope Length: 394 ft
Slope Angle: 68°

Construction Sequence:

- The reinforced soil slope was formed using geogrid with a wraparound face in 2 ft vertical lifts with a fine green mesh used to retain the soil behind the front face.
- Permanent lost formwork of angled steel mesh panels were used to form the front face and assist in keeping the correct geometry and alignment along the slope face.
- The slope angle was formed at 68° with small horizontal setbacks between each 2 ft lift. This assists in allowing the infiltration of rain water into the vegetated front face of the structure.
- Topsoil was placed immediately inside the front face of the wraparound to ensure the successful vegetation of the structure.
- The overall construction period was around 10 weeks.

Case Study #51: Pancevo-Vrsac Bridge

Location: Pancevo-Vrsac, Serbia
Owner: Belgrade Highway Institute
Engineer: Belgrade Highway Institute
Contractor: Vojvodinaput Pancevo
Purpose: Support Structure for Bridge Abutment

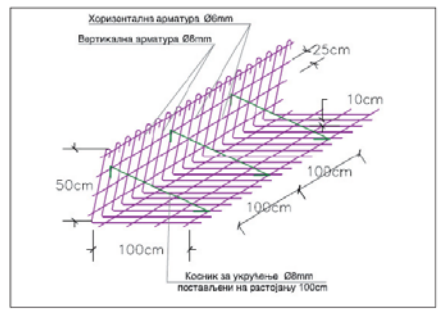
Geosynthetic Material:

- Reinforcement: Polyester Geogrid
- Facing: Steel Mesh Angled Panels

Slope Height: 20 ft
Slope Angle: 45°

Construction Sequence:

- A geogrid reinforced soil structure was adopted as the solution, using geogrids as the main reinforcement elements.
- The structure was approximately 20 ft high with the slope faces formed at 45° to ensure that future vegetation would establish and grow after completion.
- The external faces were formed from a wraparound geogrid face with a non-woven geotextile placed between the geogrid and the steel mesh angled panels, which formed the lost permanent formwork and ensured an accurate geometric alignment to the abutments.
- The slopes were subsequently planted with grass to ensure a green vegetated structure was created.



Case Study #52: Berlin A9 Motorway

Location: Berlin, Germany
Purpose: Maximize Available Land

Geosynthetic Material:
- Reinforcement: Geogrid
- Facing: Steel Mesh

Slope Height: 20 ft to 49 ft
Slope Length: 860 ft
Slope Angle: 60°

Construction Sequence: Part of the A9 motorway runs parallel to inclined terrain. To reduce the necessary slope length, a geogrid reinforced slope was built in 1998. This solution prevented an ecologically valuable forest area from being cut down. The inclination of the reinforced slope was 60°. The height varied from 20 ft to 49 ft, and the overall length was 860 ft. On top of the reinforced slope, a 26 ft high road embankment with an inclination of 33.7° was built.

Cost Effectiveness: Originally, two concepts for building a supporting structure were suggested. The first was a stiff concrete construction, which would have been built as an angular retaining wall or a retaining wall built on piles. Because of the varying subsoil conditions and the different heights of the total construction, a stiff construction built as a concrete retaining wall was rejected. The second concept was a geogrid reinforced slope, which was regarded as being more flexible and thus less sensitive to settlement than a solid construction. The geogrids were installed in layers of 2 ft using the wrap around method in conjunction with steel mesh facing elements.

Case Study #53: Old Town of Idstein

Location: Idstein, Germany
Purpose: Maximize Available Land

Geosynthetic Material:
- Reinforcement: Geosynthetic
- Facing: Geosynthetic & Steel Grid

Slope Height: 18 ft
Slope Length: 525 ft
Slope Angle: 60°

Construction Sequence: To sustain a large population of old trees, a geosynthetic reinforced slope was built adjacent to the historical Old Town of Idstein, near Frankfurt in 2001. Using longitudinal inclination of 12%, an altitude difference of 65 ft was achieved over a length of approximately 525 ft. The maximum inclination of the slope was 60°, and the average height of the slope was 18 ft. Between the soil facing and the steel grid cladding, a green dyed separator and nonwoven filter was laid, which prevented erosion of the soil and provided an acceptable facing in the transition period until an overall vegetated situation is reached. Flatter slope inclinations were built using a construction of berms, which at the same time prevented surface water from running off too quickly.

Cost Effectiveness: Compared to the angular retaining wall, which was considered in the preliminary planning, the final solution was 50% cheaper.

Case Study #54: Three Failures of a Steep Reinforced Slope

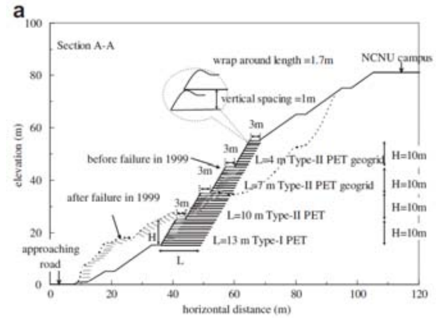
Location: Nantou, Taiwan
Purpose: Maximize Available Land

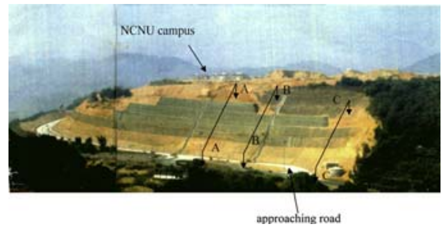
Geosynthetic Material:
- Reinforcement: Polyester Geogrid (3200-17800 lb/ft)
- Facing: Polyester Geogrid

Slope Height: 131 ft
Slope Length: 1411 ft
Slope Angle: 63°

Construction Sequence:
- Construction began in 1994 and finished in the spring 1996.
- An approach road was constructed to connect Tai-21 and the Chi-Nan University campus by excavating along a relatively gently natural slope of 28°.
- The backfill materials was taken from the field and compacted in each 3 ft lift.
- The surface of the reinforced slope was designed to be vegetated and flexible by using geogrid wrapped around the compacted backfill layers. The wraparound length was 6 ft.
- Drainage channels were constructed along the slope to route the surface water collected by the drainage channels installed across the offset between the tiers of reinforced zone. There was no subdrainage medium (such as geosynthetics or coarse gravels) installed within or at the boundary of the reinforced zone.

Performance: Three failures have occurred on this reinforced slope. The first slope failure occurred during construction in 1994 after a heavy rainfall season. The sliding plane was along the interface of laterite gravel and underneath stiff brown-yellowish clay. It is evident that the failure was closely related to the clay layer. The disastrous 7.3 Chi-Chi earthquake in 1999 resulted in a massive second failure of the reinforced slope. Since the earthquake, the construction regulated value of design ground acceleration has been increased to 330 gals in central Taiwan. The rehabilitation of this failure began in 2002 and was finished in the spring 2004. The third slope collapse happened in 2004 when Typhoon Ming-Du-Li passed over Taiwan. A maximum hourly rainfall intensity of 6.5 inch and one day rainfall accumulation of 20 inch was recorded. Moisturized brown-yellowish clay was also observed along the sliding plane. These observations led to the conclusion that this failure was closely related to rainfall and the clay layer. Cohesion reduction due to moisture migration produced adverse influences on the stability of the reinforced slope system.





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Case Study #55: Dickey Lake Roadway Grade Improvement

Location: Dickey Lake, Montana
Owner: Montana Department of Transportation
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Geogrid (6850 lb/ft)
- Facing: Biaxial Geogrid
- Erosion Control: Welded Wire Forms & Organic Blanket

Embankment Soil: Glacial Till

Slope Height: 30 ft to 60 ft
Slope Angle: 1.5H:1V to 0.84H:1V

Design Method: Global Stability Analysis with Safety Factors

Construction Specifications: Montana Department of Transportation

Construction Sequence:
- Reconstruction of a portion of US 93 around the shore of Dickey Lake required the use of an earth retention system to maintain grade and alignment.
- The design called for primary reinforcing geogrid 15 ft to 60 ft long and spaced 2 ft to 4 ft vertically throughout the reinforced embankment.
- Intermediate reinforcement consisting of lower strength, biaxial geogrids was provided in lengths of 5 ft with a vertical spacing of 1 ft at the face of slopes 1H:1V or flatter.
- The design also incorporated geocomposite fabricated drains placed along the backslope, draining into a french drain at the toe of the backslope.

Performance: The project has been periodically monitored by visual inspection and slope inclinometers. The embankment performance has been satisfactory with no major problems observed. Some minor problems have been reported with respect to the erosion control measured and some minor differential movement in one of the lower sections of the embankment.

Cost Effectiveness: The project was constructed in 1989 at a cost of approximately $\$17/ft^2$ of vertical face.

Case Study #56: Lost Trail Roadway Widening

Location: Salmon, Idaho
Engineer: Federal Highway Administration
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Geotextile (1370 lb/ft & 6850 lb/ft)
- Facing: Vegetated

Embankment Soil: Decomposed Granite

Slope Height: 50 ft
Slope Length: 565 ft
Slope Angle: 45°

Design Method: Federal Highway Administration

Construction Specifications: Federal Highway Administration

Construction Sequence:
- Widening of the original road was achieved by turning the original 2H:1V unreinforced slope into a 1H:1V reinforced slope.
- Geotextile reinforcements with an in-plane transmissivity were selected to evaluate the potential of modifying the seepage regime in the slope.
- Field tests were used to reduce the reduction factor for construction damage from the assumed value of 2.0 to the test value of 1.1 at a substantial savings to the project (40% reduction in reinforcement).

Performance: The structure was constructed as an experimental features project and was instrumented with inclinometers within the reinforced zone, extensometers on the reinforcement, and piezometers within and at the back of the reinforced section. Survey monitoring was also performed during construction. Total lateral displacements recorded during construction were on the order of 0.1% to 0.2% of the height of the slope with maximum strains in the reinforcement measured at only 0.2%. Pose construction movement has not been observed within the accuracy of the instruments. These measurements indicate the excellent performance of the structure as well as the conservative nature of the design.

Cost Effectiveness: The steepened slope was constructed at a faster rate and proved more economical than the other retaining structures constructed along the same alignment. The constructed cost of the reinforced slope section was on the order of \$15/ft^2 of vertical face. Metallic grid reinforced MSE wall costs in other areas of the site were on the order of \$22/ft^2 of vertical face for similar or lower heights.

Case Study #57: Cannon Creek Alternate Embankment

Location: Cannon Creek, Arkansas
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid (6850 lb/ft)

Slope Height: 75 ft
Slope Area: 100,000 yd^3
Slope Angle: 2H:1V

Construction Sequence:
- A large embankment was planned to carry Arkansas State Highway 16 over Cannon Creek.
- A cast-in-place concrete box culvert was first constructed to carry the creek under the embankment.
- Embankment construction commenced but was halted quickly when several small slope failures occurred. It then became apparent that the embankment fill could not be safely constructed at 2H:1V.
- 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 the on-site soil could be used with geosynthetic reinforcement.
- Both options were bid as alternatives and the geosynthetic option was selected for construction.

Cost Effectiveness: The geogrid reinforcement option was estimated to be $200,000 less expensive than the gravelly soil fill option.

Case Study #58: SR 54 Roadway Repair

Location: State Route 54, Pennsylvania
Owner: Pennsylvania Department of Transportation
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polypropylene Geotextile (1100 lb/ft)

Embankment Soil: Sandy Clay

Slope Height: 50 ft
Slope Angle: 1.5H:1V

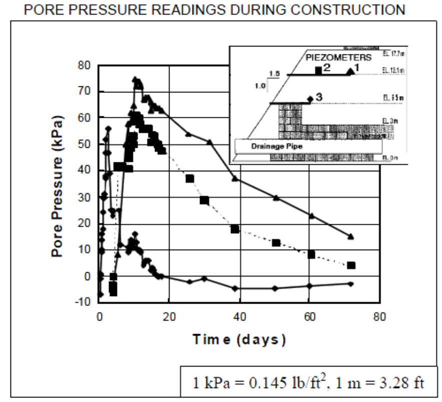
Construction Specifications: Pennsylvania DOT

Construction Sequence:
- During the winter of 1993, a sinkhole formed in a section of State Route 54 in Pennsylvania. Further investigation revealed that an abandoned railroad tunnel had collapsed.
- The traditional repair would have involved the removal and replacement of the embankment.
- Due to the high cost of replacement materials, PennDOT decided to use geosynthetics to provide drainage of the native soil and reinforce the side slopes.
- With the geotextile placed at a compacted lift spacing of 1 ft, full pore pressure dissipation was achieved within approximately 4 days as compared with a minimum dissipation (approximately 25%) without the geosynthetic during the same time period.
- By placing the geotextile at 1 ft lift intervals, the effective drainage path was reduced from the full height of the slope by a factor of over 100.
- This meant that consolidation of the embankment would essentially be completed by the end of construction as opposed to waiting almost a year for completion of the settlement without the geosynthetic.

Performance: Piezometers at the base and middle of the slope during construction confirmed the test pad results. Deformations of the geotextile in the side slope were also monitored and found to be less than the precision of the gages (± 1% strain).

Cost Effectiveness: The cost of the geotextile was approximately \$1/yd^2. In-place costs of the geotextile, along with the on-site fill averaged just over \$3/yd^3 for a total cost of \$70,000, resulting in a savings of approximately \$200,000 over the select-fill alternative. Additional savings resulted from not having to remove the on-site soils from the project site.

PORE PRESSURE READINGS DURING CONSTRUCTION



Case Study #59: Raleigh Street Reinforced Embankment

Location: Winter Park, Florida
Purpose: Support Structure for Roadway

Geosynthetic Material:
- Reinforcement: Polyethylene Geogrid
- Facing: Polyethylene Geogrid

Slope Height: 40 ft
Slope Angle: 1H:2V

Construction Sequence:
- The Raleigh Street reinforced earth embankment was the first of its kind in central Florida and is also one of the highest reinforced embankments that has been successfully constructed in the southeast United States.
- The existing street lies about 40 ft above the surface of a small lake, and conventional solutions of providing a large grade separation between the roadway and the lake were rejected because of the curve geometry, future development considerations, and cost constraints.
- The emerging concept of soil reinforcement was applied to create the needed grade separation.
- The slope required 15 layers of high strength geogrid placed horizontally, and lower strength geogrid was wrapped around sod to hold the facing in place.

Performance: Because earth reinforcement was a new technique in central Florida, the construction of Raleigh Street embankment was closely monitored. Survey control was a major issue during the construction of the steepest portion of the embankment.

Cost Effectiveness: The construction cost for the geogrid reinforced slope was less than other conventional alternatives such as filling the lake at a flatter slope or constructing a retaining wall. The embankment was completed in two months at a cost of $200,000. Alternative methods of construction would have ranged from 50% to 100% higher than the costs associated with the method used.

Figure 1. Vicinity map of Raleigh Street embankment.

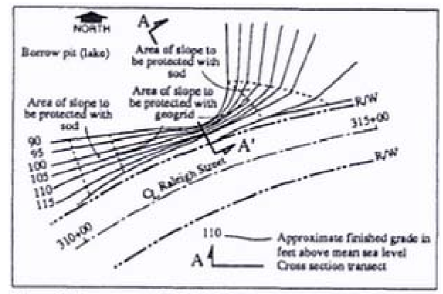


Figure 2. Contour map of Raleigh Street embankment.

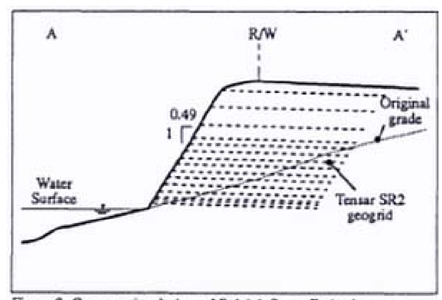


Figure 3. Cross sectional view of Raleigh Street Embankment.

Case Study #60: Reinforced Slope Failure & Reconstruction

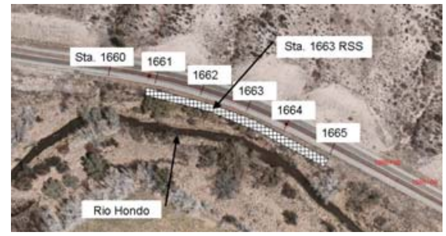
Location: Hondo Valley, New Mexico
Owner: New Mexico Department of Transportation
Engineer: Kleinfelder
Contractor: Sierra Blanca Constructors
Purpose: Support Structure for Roadway

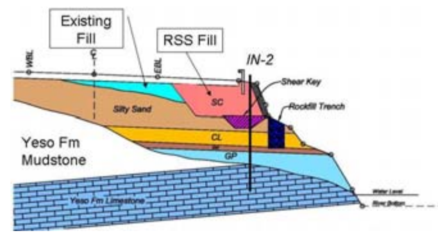
Geosynthetic Material:
- Reinforcement: Geogrid

Slope Height: 25 ft
Slope Angle: 1H:2V

Construction Specifications: New Mexico DOT

Construction Sequence:
- The geotechnical investigation consisted of drilling two soil borings adjacent to the deepest parts of the roadway fill. The investigation indicated that the geology in the area was terrace deposits and alluvium overlying Yeso formation mudstone.
- Groundwater was not encountered in the borings drilled at the site, and no signs of slope instability were noted during the site reconnaissance.
- A major geotechnical slope failure occurred a year after construction due to movement associated with severe rain storms. The project team excavated a test trench through the roadway to evaluate the conditions at the cracked area, and noted vertical cracks observed at the surface were about 2 inch deep and were located directly behind the top layer of geogrid.
- Additional field exploration activities began as the team drilled seven additional borings below the roadway. The borings were used to establish a detailed stratigraphic log of the subsurface conditions at the GRSS and to collect soil samples for laboratory testing.
- The maximum cumulative displacement measured at the top of the inclinometers was approximately 3.5 inch, and a clear failure surface was apparent just beneath the bottom geogrid.
- The analysis concluded that the distress was the result of peak flows and saturation during heavy and prolonged rainfall that developed excess water pressure at the rear of the slope.
- The contractor excavated about 20 ft long segments to remove unsuitable material below the embankment. The back and sides of the excavation were lined with filter fabric to reduce the potential for piping of fines from the native materials into the rock fill.
- On the back of the excavation, geocomposite drain fabric was placed that extended vertically from just below the existing pavement down to the smaller rock layer.





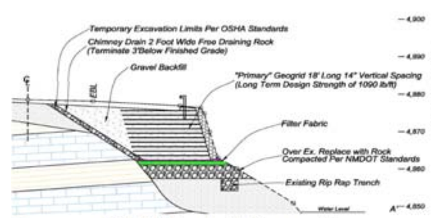


FIG 5: RSS Reconstruction Recommendations