TECHNICAL NOTE

GEOSYNTHETIC REINFORCEMENT IN WASTE CONTAINMENT APPLICATIONS

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GEOSYNTHETIC SYSTEMS

Applications of Reinforced Soil Layer Systems

Construction of soil and aggregate layers on steep slopes or over potential voids is becoming more common in many areas of the country. This is because the construction of new waste containment and liquid impoundment facilities and the expansion or closing of old waste facilities has become environmentally necessary to assure protection of groundwater supplies. Often these facilities must be designed to maximize storage volume, creating steep slopes, or to overcome inadequate foundation conditions, including foundation voids, while incorporating the best available containment technology. Thus designers are commonly faced with assuring the integrity and stability of sophisticated containment systems constructed on steep slopes and over void-prone foundations.

To assure optimal performance, state-of-the-art waste containment systems commonly include both conventional soil materials as well as geosynthetics. Yet, system instability or damage may result when soil - geosynthetic layers are placed on a steep slope or over a void. Reinforcing these soil layers provides a cost effective means to achieve long-term stability of soil - geosynthetic lining systems. *Figure* 1 illustrates some typical landfill applications of reinforced soil layers.

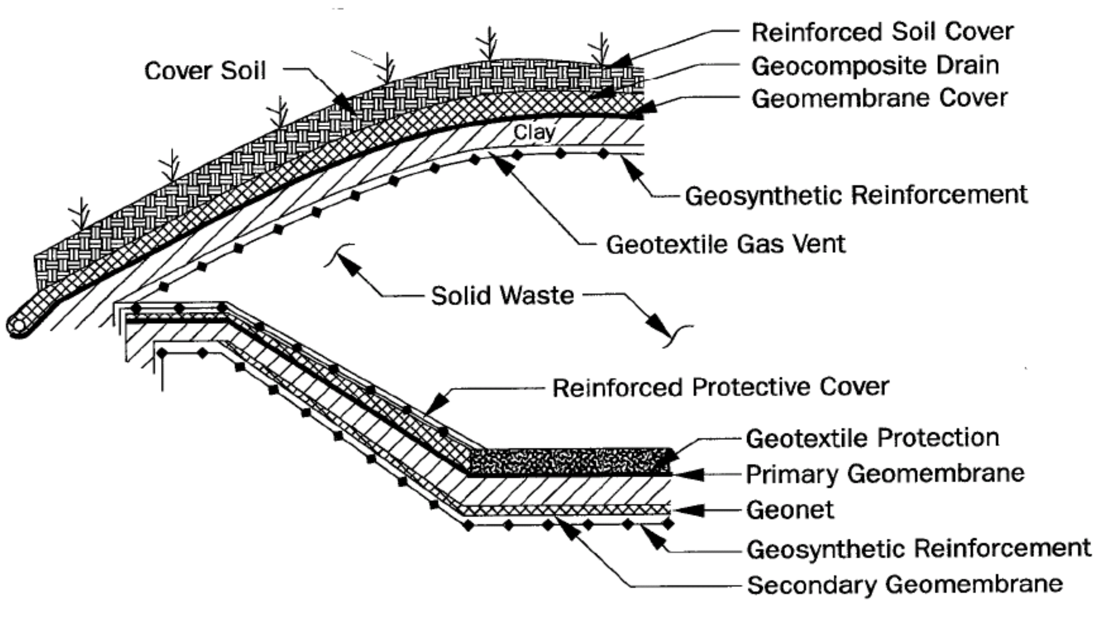


FIGURE 1: Applications Using Reinforced Soil Layers

Details of a Soil Layer - Geosynthetic System

Overview: Geosynthetic reinforced soil layers are relatively thin layers of soil which incorporate a high strength geosynthetic. The reinforced soil layer may provide only tension to the system or, in combination with the soil, provide composite action which combines geosynthetic membrane tension with soil arching.

Tension is required to stabilize or prevent the slippage between lining system components on steep slopes. This is sometimes referred to as cover soil reinforcement. Composite action involving both soil arching and the geosynthetic as a tensioned membrane is necessary to stabilize, or support, out of plane forces such as a supporting layer over a void. These stabilizing forces are shown graphically in *Figure* 2.

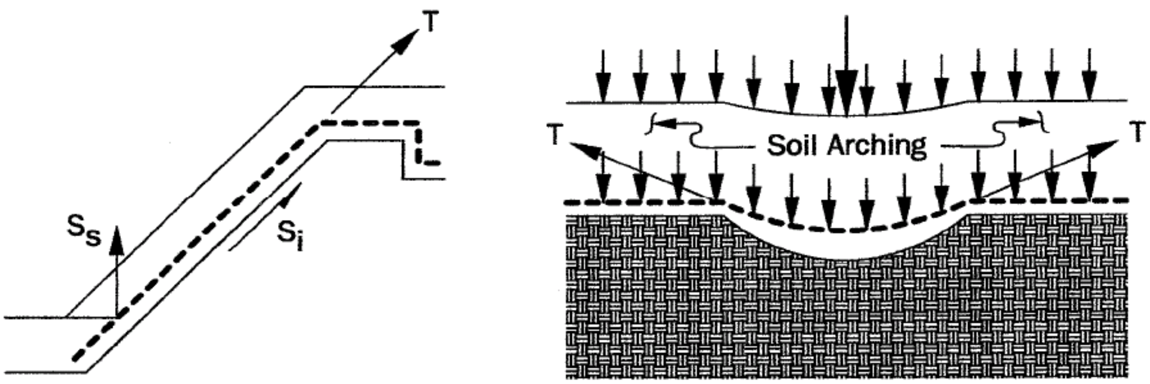


FIGURE 2: Cover Soil Reinforcement vs. Reinforced Support Layer

System Components: Like conventional soil layers, reinforced soil layers are constructed by compacting soil in layers. Yet, geosynthetic reinforcing elements are incorporated into the soil layers to assure the stability of the overall system or structure. Following are the detailed components of a geosynthetic reinforced soil layer system:

Foundation - Soil and geosynthetic layers upon which the system to be stabilized is constructed.

Bedding Layer - The soil which is placed adjacent to an unstable interface and which incorporates a layer(s) of reinforcing to create a composite layer. This may be a cover soil or an intermediate soil layer.

Reinforcement - Geosynthetic, either geogrid or geotextile with sufficient strength and soil compatible modulus, placed adjacent to or within a soil layer to provide tensile forces to resist instability or deformation.

Surcharge - Overlying soil, waste, or liquid mass which exerts a destabilizing force on the reinforced soil layer and the foundation. *Figure* 3 shows the components of a reinforced soil layer system and their relative locations.

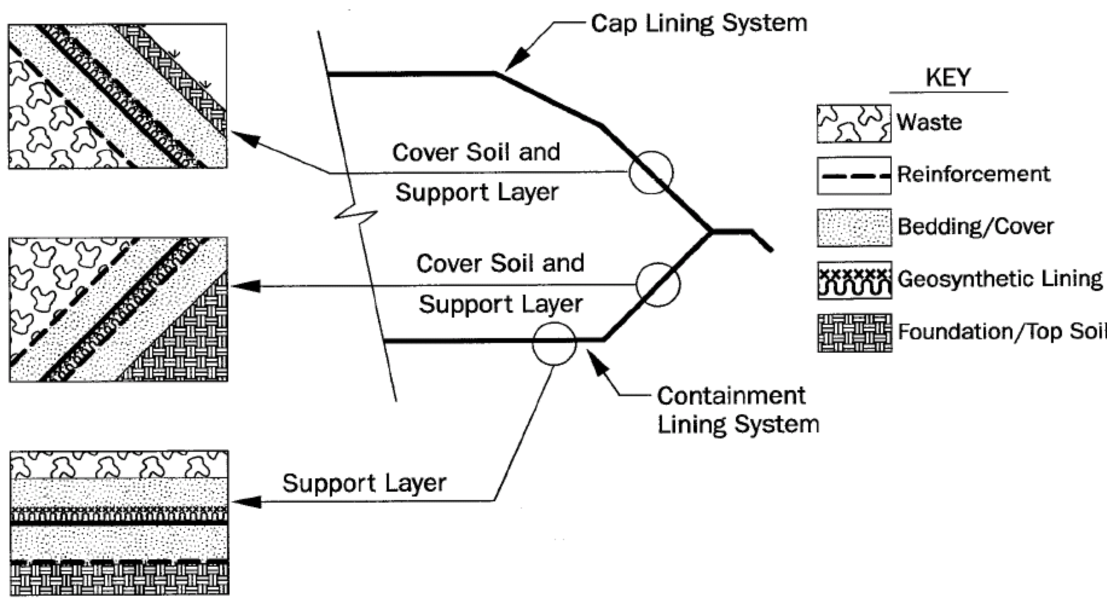


FIGURE 3: Components of Reinforced Soil Layer Systems

Site Specific Design Considerations

Site Geometry: The grade or steepness of slopes as well as their height may vary along the slope alignment requiring the designer to select reasonably spaced, representative cross-sections for reinforced soil layer design.

Foundation Conditions: The designer must assess the foundation conditions in the proximity of a proposed reinforced soil layer to determine the critical failure condition. This should include expected settlement, surface cracking and void development. Soil test borings can be made to determine subsurface conditions including the assessment of material properties, the location of geologic features, and the identification of ground water conditions which might lead to void formation.

Lining System Components: The specific soil and geosynthetic components of the proposed lining system must be identified. This identification must include the tensile strength properties of each component as well as the interface friction relationship between each component and those adjacent components. Interface friction relationships are determined using a laboratory direct shear box and should be correlated to expected surcharge and overburden loads.

Surcharge Loading: The critical destabilizing load which will be exerted on the reinforced soil layer must be determined. This critical load may occur during construction or may not occur until the facility is in full operation. It is important to note that the interface friction force between lining system components will vary with the magnitude of the surcharge loading and the presence of water at the

interface. Therefore, it is important to run laboratory friction tests at normal load levels corresponding to the expected critical loading condition.

Other External Loading: Other externally applied loading such as point loads or seismic loads are beyond the scope of this document.

Soil Layer and Geosynthetic Reinforcement Properties

Material Selection: Each prospective type of soil will develop unique strength and reinforcement interaction properties under the expected compaction and soil moisture conditions. Therefore, the cost-effectiveness of a reinforced soil layer can be affected by the soil and corresponding reinforcement type selected. A thorough evaluation of potential soil and reinforcement materials is necessary to identify the best combination.

Soil Properties: The critical equilibrium for reinforced soil layers may be governed by short- or long-term stability conditions. The soil strength used in any stability analysis must therefore correspond to the expected stability condition. For long-term, i.e. drained, stability conditions, the soil is commonly described in terms of its moist unit weight, γ_{max}, effective friction angle, ϕ'_f and effective cohesion, c'. Short-term, i.e. un-drained, stability conditions may require the use of total stress parameters. These properties are used to determine the stability of soil layers under design loadings.

Table 1 outlines some typical soil types and ranges of associated soil properties. This information is for general groups of soils and should be used only as a guide. Specific soil properties for the foundation fill and embankment soils on a given project should be determined from field and laboratory testing.

As noted earlier, the soil properties used in the design of reinforced soil layers must reflect the expected *in-situ* conditions. Cohesion in the soil is often neglected which pro vides additional conservatism to the design. When controlled placement of the soil, surface water management, and moderate flexibility in the finished structure are assured, drained, large strain conditions are generally appropriate for design. The soil strength is therefore properly described by either a large strain or a factored peak effective soil friction angle, ϕ'_f. The factored soil friction angle is calculated using *Equation* 1.

$$\phi'_f = \tan^{-1}\left[\tan\frac{\phi'}{FS}\right] \quad \text{(Eqn. 1)}$$

Geosynthetic Reinforcement: The geosynthetic reinforcement, i.e. geogrids or geotextiles, used in soil layers must satisfy both strength and soil interaction requirements. The strength requirements focus on the tensile modulus and the limit equilibrium Long Term Design Strength (LTDS) of the reinforcement. Soil interaction properties include soil - geosynthetic interface friction.

Table 1: Typical Soil Properties [2]

Soil Description	Classification[1]	ϕ'	MDD[2] Standard Compaction (pcf)	Optimum Moisture Content (%)
Well Graded Sand-Gravel	GW	>38	125 – 135	8 – 11
Poorly Graded Sand-Gravel	GP	>37	115 – 125	11 – 14
Silty Gravels	GM	>34	120 – 135	8 – 12
Clayey Gravels	GC	>31	115 - 130	9 – 14
Well Graded Sands	SW	38	110 - 130	9 – 16
Poorly Graded Sands	SP	37	100 - 120	12 – 21
Silty Sands	SM	34	110 - 125	11 – 16
Clayey Sands	SC	31	105 - 124	11 – 19
Sandy Silts, Low Plasticity Silts	ML	32	95 - 120	12 – 24
Silty Clays, Low Plasticity Clays	CL	28	95 – 120	12 – 24
Clayey Silts, Elastic Silts	MH	25	70 – 95	12 – 40
Fat Clays, High Plasticity Clays	CH	19	75 - 105	20 – 50

[1] Unified Soil Classification System
[2] MDD = Maximum Dry Density

Modulus: The tensile modulus describes the geosynthetic strain level corresponding to a given strength level. For reinforced soil structures it is important for the reinforcement to be "compatible" with the soil. This means that the design strength of the reinforcement should occur at a strain level (elastic & creep) corresponding to the strain in the soil that leads to peak soil strength. For most soils the strain level at peak soil strength is between 3 and 10 percent and is easily determined by laboratory testing. As a result, a total strain level not to exceed 10 percent is often used *for* reinforced cover soils, though a smaller limiting strain may be necessary to limit strains in adjacent geosynthetic membranes or strain sensitive soils.

LTDS: The Long Term Design Strength of geosynthetic reinforcement is determined by applying partial factors of safety to the ultimate tensile strength of the reinforcement to account for creep, chemical and biological degradation and installation damage. *Equation* 2 is used to calculate LTDS. *Table* 2 provides LTDS values in the primary strength direction for selected polyester reinforcement geosynthetics.

$$LTDS = T_{ULT} / (FS_{CR} * RF_D * RF_{ID}) \qquad \text{(Eqn. 2)}$$

Where: T_{ULT} = Ultimate Wide Width Tensile Strength,
RF_{CR} = Reduction Factor for Creep,
RF_D = Reduction Factor for Durability,
RF_{ID} = Reduction Factor for Installation Damage.

Table 2: LTDS for Selected Mirafi Geosynthetics

GEOSYNTHETIC	**LTDS @ 10% Total Strain in Sand, Silt, Clay (lb/ft)**	**LTDS @ 5% Total Strain in Sand, Silt, Clay (lb/ft)**
Geogrids		
Miragrid 2XT	1096	608
Miragrid 3XT	1918	1063
Miragrid 5XT	2575	1428
Miragrid 7XT	3233	1792
Miragrid 8XT	4055	2248
Miragrid 10XT	5206	2886
Miragrid 20XT	7510	4163
Miragrid 22XT	11266	6246
Miragrid 24XT	15023	8328
Geotextiles		
HS400	2272	1139
HS600	3408	1709
HS800	4544	2279
HS1150	6532	3276
HS1715	10185	5107
PET 400	13566	6803
PET 600	20349	10205
PET 800	27132	13606
PET 1000	33915	17008

Interface Friction: Interface friction is a measure of the interaction between geosynthetic-soil or geosynthetic-geosynthetic interface and is determined by laboratory testing. The shear resistance is used in stability calculations involving sliding at the interface of a geosynthetic layer. *Equations* 3a and *3b* are used to calculate the shear resistance offered by the (a) soil itself and (b) the soil/geosynthetic interface. *Table* 3 provides efficiency values for selected geosynthetic/soil interfaces.

$$s_u = c + \sigma_n \tan \phi \qquad \text{(Eqn. 3a)}$$

$$\tau_f = c_a + \sigma_n \tan \delta \qquad \text{(Eqn. 3b)}$$

Table 3: Interface Friction Efficiencies for Selected Geosynthetics

Geosynthetic	Soil Type	Efficiency (τ/s)
Miragrid	Sand	>0.90
	Silt	>0.80
	Clay	>0.70
High Strength Geotextile	Sand	>0.90
	Silt	>0.80
	Clay	>0.70

REINFORCED COVER SOILS ON LINED SLOPES

Overview: As designers attempt to maximize the capacity of containment facilities, slope stability becomes an important criterion. Though internal and overall stability of the sloping soil mass is beyond the scope of this document, the following sections provide guidance in the use of reinforced soil layer systems as an effective way of assuring the stability of geosynthetic lining and capping systems placed on steep slopes. *Figure* 4 illustrates some typical cover soil configurations involving lined side slopes. From *Figures 4b* and *4d* it is clear that numerous interfaces can be involved in an assessment of stability.

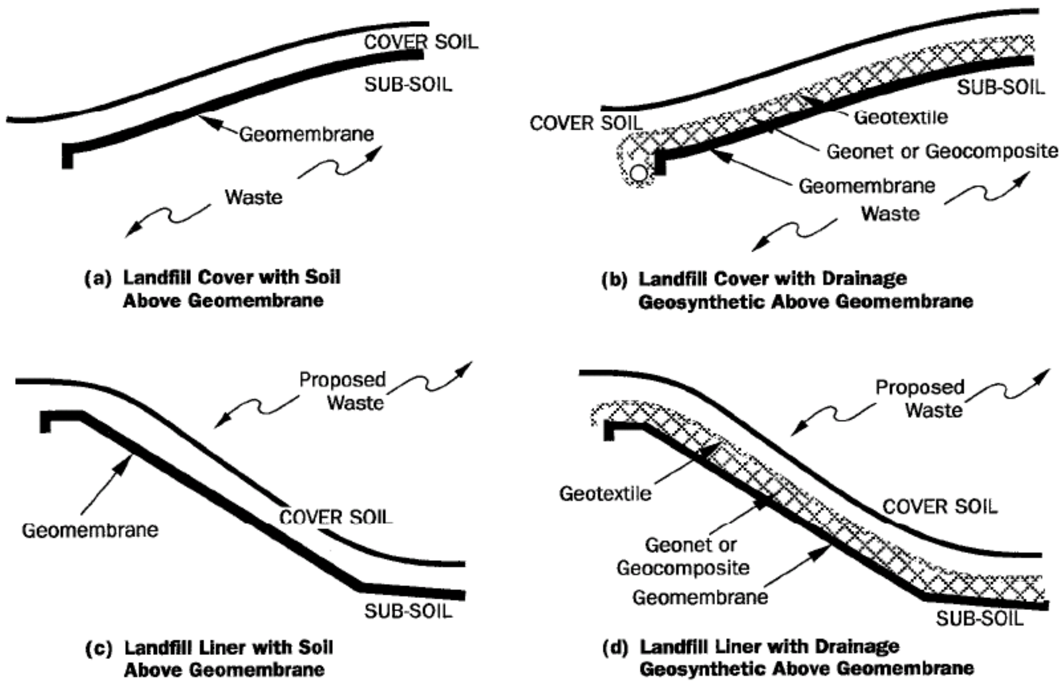


FIGURE 4: Various Solid Waste Caps and Liners Involving Cover Soils and Geosynthetics (after 5)

<u>Cover Soil Stability and Reinforcement</u>: Placing a protective soil cover over a geosynthetic lining system can lead to instability. Several methods have been proposed to assess the stability of cover soils and to design geosynthetic reinforced cover soils to achieve desired factors of safety [3, 5]

The proposed design methods are very straight forward and are based on static conditions. *Figure* 5 shows a segment of subsoil, geomembrane and a cover soil which has a uniform thickness. For this set of conditions, summing the down slope forces along the slope angle β leads to an equation for the factor of safety against failure:

$$FS = \text{Resisting Forces} / \text{Driving Forces}$$
$$= F/W\sin\beta = N\tan\delta / W\sin\beta = W\cos\beta\tan\delta/W\sin\beta$$

$$FS = \tan\delta/\tan\beta \qquad \text{(Eqn. 4)}$$

Where: β = slope angle
δ = friction angle between the liner and cover soil

Since the slope angle and the desired safety factor are usually known, the type of membrane and the quality of the cover soil remain to be selected to provide a sufficient interface friction angle to achieve stability. *Figure 6* gives design curves that can be generated for any slope angle and factor of safety [7].

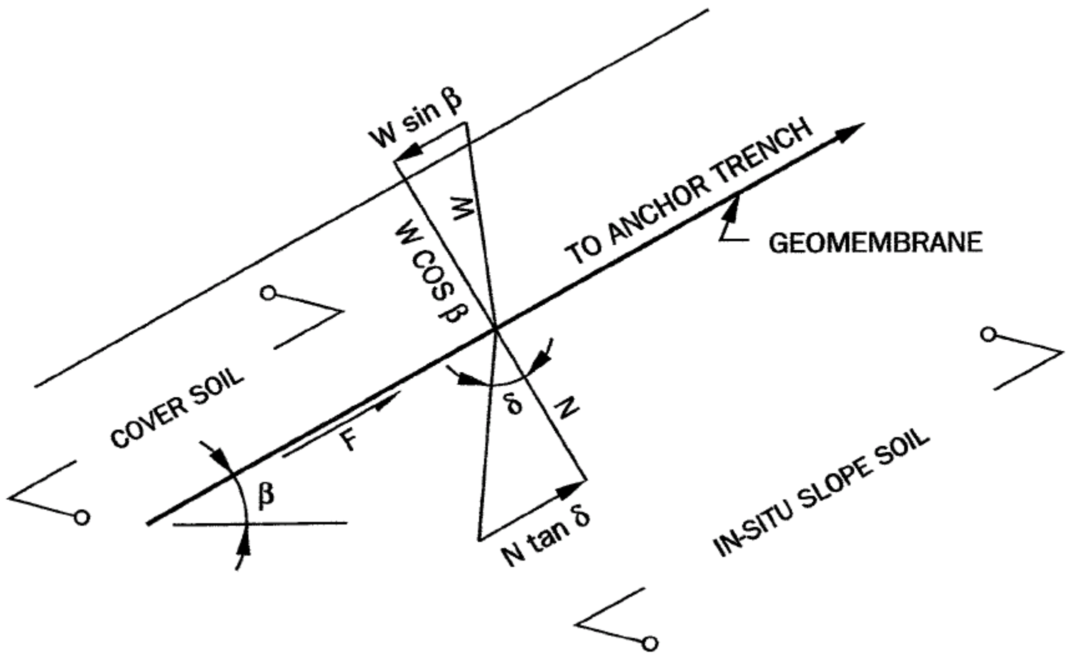


FIGURE 5: Schematic Diagram for Force Involved with Cover Soils on Geomembrane Lined Slopes with Uniform Depth Cover Soil[7]

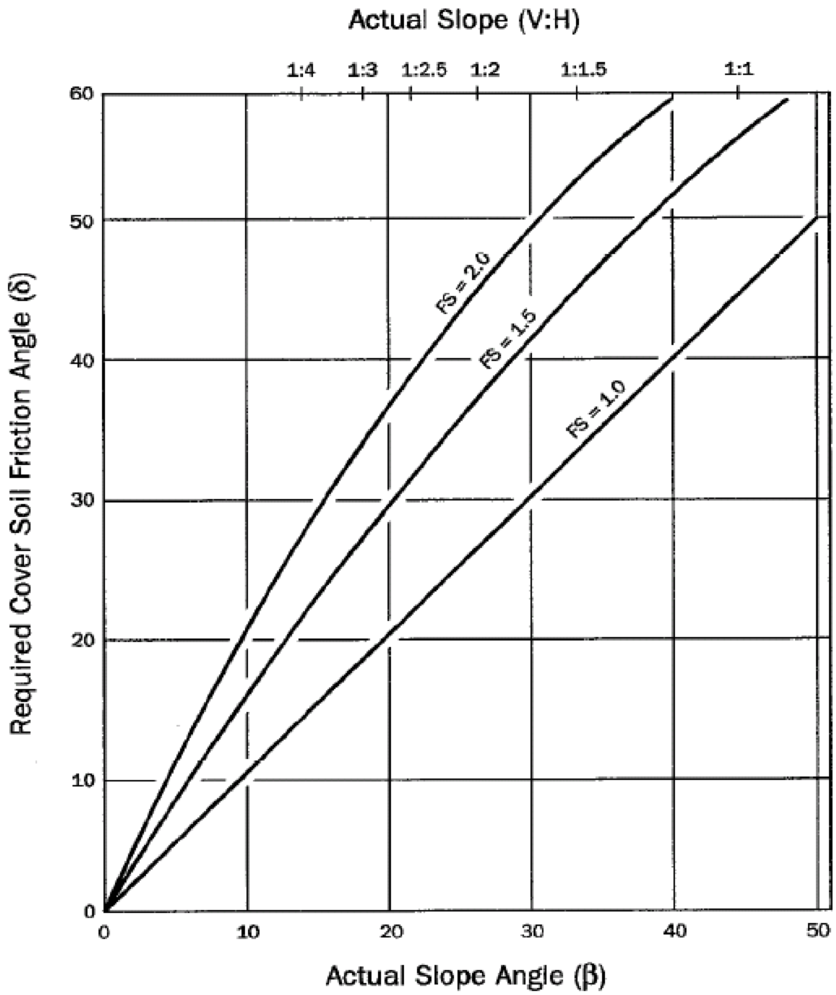


FIGURE 6: Design Curves for Uniform Thickness Cover Soils in Geomembrane Lined Slopes(7)

The design methods commonly used can be expanded to account for geosynthetic anchorage, interface sliding resistance and buttressing at the toe of the slope. These methods can be used to determine the maximum height to which an unreinforced protective soil cover can be placed or the factor of safety against instability of a given cover soil and configuration. If the design slope height is greater than the maximum stable cover soil height, then it is necessary to anchor the protective soil cover with geosynthetic reinforcement [5]. *Figure* 7 shows the placement of reinforcement in capping and lining systems.

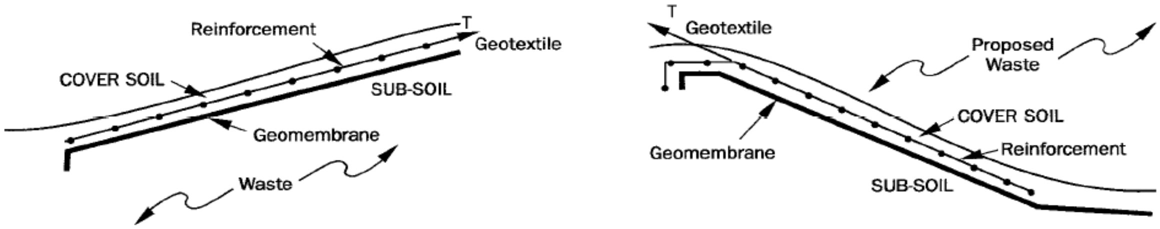


FIGURE 7: Cover Soil Reinforcement in Solid Waste Containment (a)above waste; (b) beneath waste(after 5)

<u>Design Models</u>: Two analyses of side slope stability are provided in *Equations* 5-8 along with *Figures* 8 and 9. *Equations* 5 and 6 and *Figure* 8 present the design model developed by Giroud and Beech [3] which assumes no cohesion. In *Equations* 7 and 8 and *Figure* 9, Koerner and Hwu [5] propose a model which accommodates cohesive soils. Both models assume uniform cover soil thickness and drained conditions.

Giroud and Beech [3] (neglects cohesion)

- **Unreinforced:**

$$H_{max}/t_c = {}^{1}/_{2}\cos\beta[\,1 + \sin\varphi\cos\delta/\cos(\beta + \varphi)\,\sin(\beta - \delta)] \qquad \text{(Eqn. 5)}$$

- **With reinforcement:** $T_{req'd}$ =

$$\frac{\gamma t_c^2}{\sin 2\beta}\left[\frac{\left(\frac{2H\cos\beta}{t_c} - 1\right)\frac{\sin(\beta-\delta)}{\cos\delta} - \sin\phi}{\cos(\beta+\phi)}\right] \qquad \text{(Eqn. 6)}$$

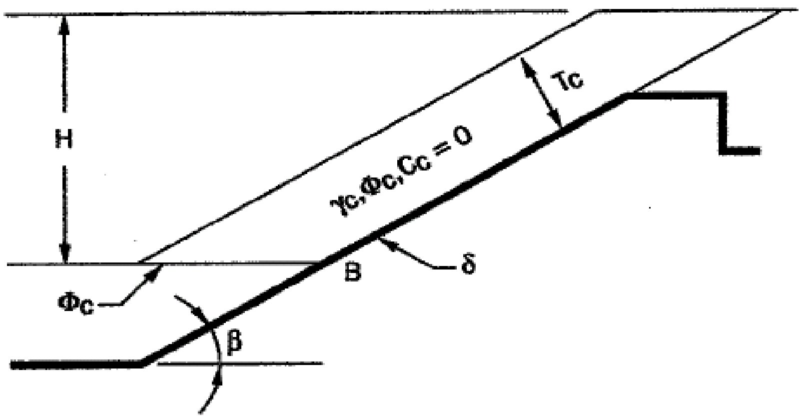


FIGURE 8: Side Slope Stability Model for Lining and Capping Systems, Assuming no Cohesion (3)

Koerner and Hwu [5] (includes cohesion)

- **Unreinforced**

FS = [-b+/-(b^2-4ac)$^{1/2}$] / 2a (Eqn. 7)

Where: a = 0.5γLtcsin22β
b = -[γLtccos2βtanδsin(2b) + caLcosβsin(2β) + …
…+ Ltc sin2β tanφsin(2β) + 2ctccosβ+ γtc2tanφ]
c = (γLtccosβtanδ + caL) (tanφsinβsin(2β))

- **With Reinforcement:** $T_{req'd}$ =

$$\frac{\gamma L_c t_c \sin(\beta-\delta)}{\cos\delta} - c_a L - \frac{\cos\phi\left[\dfrac{c t_c}{\sin\beta + \left(\dfrac{\gamma t_c^2}{\sin 2\beta}\right)\tan\phi}\right]}{\cos(\phi+\beta)}$$ (Eqn. 8)

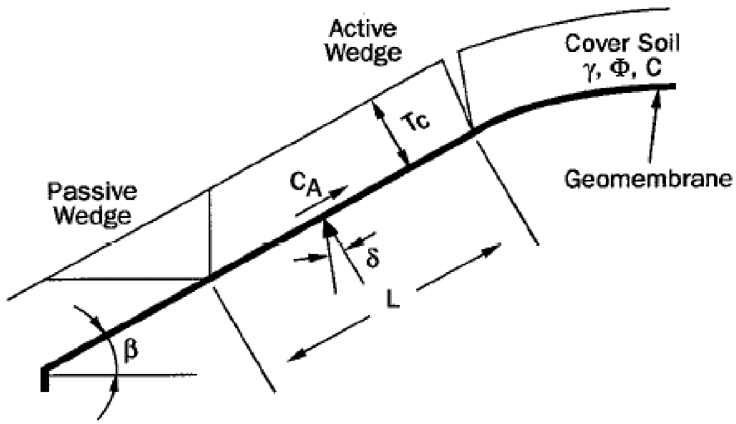


FIGURE 9: Side Slope Stability Model for Lining and Capping Systems, Including Cohesive Soils[5]

Factors of Safety: The equations presented do not include any factors of safety. Yet, designers should use prudent safety factors when using these equations. One method of incorporating a factor of safety is to use mobilized friction angles, ϕ_{cm} and ϕ_{im} instead of the actual friction angles, ϕ_c and ϕ_i. The mobilized friction angles are defined as follows:

$$\tan\phi_{cm} = \tan\phi \; / \; FS \qquad \& \qquad \tan\phi_{im} = \tan\delta \; / \; FS \qquad \text{(Eqn. 9)}$$

Other Design Considerations

Tapered Cover Soils: The equations presented herein for cover soil stability assume uniform cover soil thickness, yet additional stability can be achieved by increasing the cover soil thickness at the bottom of the slope. Though beyond the scope of this document, Martin and Koerner [7] provide a detailed procedure for using a graphical procedure to assess the stability of tapered cover soils.

Seepage Forces: Proper design and selection of drainage systems and cover soils should assure drained conditions are maintained in the cover soil, yet if saturated conditions are unavoidable, seepage forces should be considered in the stability analysis. Martin and Koerner [7] provide guidance in quantifying the additional destabilizing force due to seepage.

Design Procedures

1. **Define the Problem:** Define slope and cover soil geometry. Determine soil properties and interface friction values by laboratory testing.

2. **Determine the Unreinforced Cover Soil Stability:** Calculate the unreinforced factor of safety using *Equation* 7 or the maximum unreinforced cover soil height using *Equation 5*.

3. **Determine the Reinforced Cover Soil Stability:** Calculate the tensile force "T" required to stabilize the cover soil using *Equations 6* or *8*.

4. **Develop the Factored Geosynthetic Tensile Strength:** If friction angles used in the design equations have not been factored to include a safety factor, multiply the required tensile force by an appropriate safety factor to determine the required geosynthetic tensile strength.

EXAMPLE PROBLEM

Given:

Cover soil slope, β = 18.4° (i.e. 3 to 1) — cover soil unit weight, 'Y = 115 pcf
thickness, t_c = 3 ft — cover soil friction angle = 32°
cohesion, c = 300 pcf (neglect) — cover soil is free draining
slope length, L = 150 ft
cover soil/liner interface friction angle, δ = 14°

Determine: 1. Unreinforced factor of safety; 2. Required reinforcement

Solution:

- **Calculate the unreinforced factor of safety using *Equation* 7:**
  a = 0.5 (1.1.5) (300) (3) sin2(36.8) = 1.8569 lb/ft
  b = - [(115) (300) (3) $\cos^2$(18.4) tan(14) sin(36.8) + 0 +
  (115) (300) (3) $\sin^2$(18.4) tan(32) sin(36.8) +
  2(0) (3) cos(18.4) + 115 (9) tan(32)]
  = - [13918 + 0 + 3860 + 0 + 647] = -1.8425 lb/ft
  c = [(115) (300) (3) cos(18.4) tan(14) + 0] x
  [tan(32) sin(18.4) sin(36.8)] = [24486] [0.118] = 2893 lb/ft
  FS = 18425 + $[(-18425)^2$ - 4(18569) $(2893)]^{1/2}$ / (2) (18569);
  FS = 0.80 < 1 therefore, the slope is unstable.

- **Calculate T using *Equation* 6:**
  T = [(115) (9) / sin(2) (18.4)] [(2) (47) cos(1.8.4)/3] – 1]
  x [sin(4.4) / cos(14)] - [sin(32) / cos(50.4)]]
  T = 2479 lb/ft

- **Calculate the required geosynthetic tensile strength:**
  $T_{req'd}$ = T x FS = 2479 lb/ft x 1.5
  $T_{req'd}$ = 3718 lb/ft

- **Select Geosynthetic Reinforcement:**
  Choose Miragrid 20XT if 5% total strain limit is required.
  Otherwise, choose Miragrid 8XT for a 10% total strain limit.

Note: Refer to *Table* 2 to select geosynthetic layer(s) with LTDS exceeding $T_{req'd}$.

REINFORCED SOIL SUPPORT LAYERS FOR SPANNING VOIDS

Overview: Giroud, et al [4] presented a design methodology for spanning voids with soil layer-geosynthetic systems. Voids can be defined as tension cracks, sinkholes, dissolution cavities and depressions in foundation soils resulting from differential settlements or localized subsidence. This design methodology was developed by combining tensioned membrane theory (for the geosynthetic) with arching theory (for the soil layer), thereby providing a more complete design approach than one that considers tensioned membrane theory only. The relevant design equations, tables, and charts are reintroduced herein.

Support Layer Stability and Reinforcement: Failure of roads, foundations, and other earthen facilities can result from unexpected loss of subgrade support caused by subsurface voids. For a number of years, engineers have been considering the suitability of supporting these soil structures over voids using geosynthetic reinforced soil layers. The design challenge has been to verify that a reinforced soil layer can span a void and support the loads applied by the overlying soil, waste, or liquid without failing or undergoing excessive deflection.

Voids: Voids can be characterized as either infinitely long (plane-strain) with width b or circular (axi-symmetric) with a diameter of 2r. The modeling of infinitely long voids would apply to cracks or depressions associated with trenches or faults. A circular void model is appropriate for karstic sinkholes, dissolution cavities, municipal solid waste settlement, lens settlement, soil surface depressions and ground subsidence.

In many landfill capping problems, a theoretical rusted refrigerator creating a six foot diameter void within the waste is assumed for design. This is modeled as a circular void with a radius of 3 feet.

Support Mechanism: When a reinforced soil layer spans a subsurface void, the soil layer - geosynthetic system deflects under the applied loads. As the layer deflects, the soil component bends and the underlying geosynthetic stretches. The bending of the soil generates arching inside the soil which transfers part of the applied load away from the void area. Stretching the geosynthetic mobilizes a portion of the geosynthetic's strength. In carrying this load, applied normal to the surface of the geosynthetic, it acts as a "tensioned membrane". In a solid waste facility, the waste itself has been assumed to experience soil arching and therefore it is often considered along with the bedding layer in reinforcement calculations.

Design Model

The design models presented by Giroud, et al [4] apply to infinitely long and circular voids, respectively. The equations, tables, and charts make it possible to solve problems such as:

- selecting the required geosynthetic mechanical properties when geometric parameters and loading conditions are known;

- determining the required thickness of the soil layer associated with a given geosynthetic over a given void and subjected to a given loading condition;

- determining the void size that a given geosynthetic may bridge when the associated soil layer is subjected to given loading conditions; and

- determining the maximum load which can be carried by a given soil - geosynthetic system over a given void.

Only the first type of problem listed above will be addressed in this document. Equations, tables and charts are available in the reference that specifically address the other problems.

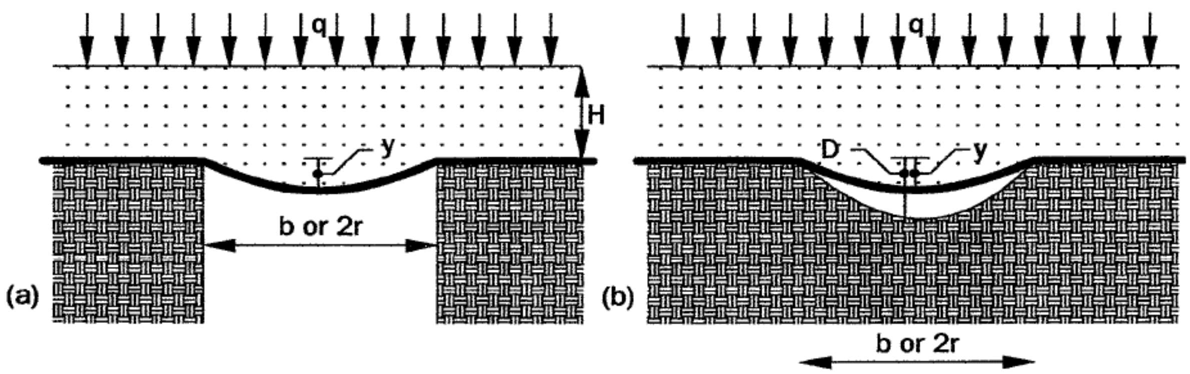


FIGURE 10: Schematic Cross Section for Theoretical Analysis (a) bottomless void, (b) void with bottom & y < D[4]

Figure 10 shows schematic diagrams of the design models for reinforced soil support layers over infinitely long and circular voids. The equations for solving the problems out-lined above are based on *Equation 10,* for soil arching, and *Equation* 11, for tension membrane action.

$$p = 2\gamma b\ (1 - e^{-0.5H/b}) + qe^{-0.5H/b} \qquad \text{(Eqn. 10)}$$

Where: p = pressure on the geosynthetic
γ = unit weight of layer of thickness, H

$$\alpha = pb\Omega \qquad \text{(Eqn. 11)}$$

Where: α = tension in geosynthetic
Ω = dimensionless factor

The relevant soil properties are the unit weight γ, the friction angle ϕ and the cohesion c, though the cohesion is neglected for this analysis. Additionally, the friction angle ϕ does not have a significant influence on the analysis results if it is equal to or greater than 20°.

The relevant geosynthetic properties are wide-width tension and corresponding strain. The solution to problems involving reinforced support layers depends on the allowable geosynthetic strain. The allowable strain should be the lesser of the maximum design strain for the considered geosynthetic and the strain beyond which the soil layer would be unacceptably deformed or cracked.

There is a unique relationship between the geosynthetic strain and its deflection relative to the width of the void. *Table 4* provides values for the dimensionless factor Ω as a function of strain and deflection for use in calculating the tension in the geosynthetic as described in *Equation* 11.

Table 4: Values for Ω as a Function of Deflection or Strain(4)

y/b or	ε (%)	Ω	y/b or	ε (%)	Ω
0.000	0.000	∞	0.123	4.00	1.08
0.010	0.027	12.51	0.130	4.45	1.03
0.020	0.107	6.26	0.138	5.00	0.97
0.030	0.240	4.18	0.140	5.15	0.96
0.040	0.425	3.15	0.150	5.90	0.91
0.050	0.663	2.53	0.151	6.00	0.90
0.060	0.960	2.11	0.160	6.69	0.86
0.061	1.000	2.07	0.164	7.00	0.84
0.070	1.30	1.82	0.170	7.54	0.82
0.080	1.70	1.60	0.175	8.00	0.80
0.087	2.00	1.47	0.180	8.43	0.78
0.090	2.15	1.43	0.186	9.00	0.76
0.100	2.65	1.30	0.190	9.36	0.75
0.107	3.00	1.23	0.197	10.00	0.73
0.110	3.20	1.19	0.200	10.35	0.72
0.120	3.80	1.10	0.210	11.37	0.70

Determining the Required Tensile Force: The relevant equation for an infinitely long void is:

$$\alpha/\Omega = pb = 2\gamma b^2 (1 - e^{-0.5H/b}) + qbe^{-0.5H/b} \qquad \text{(Eqn. 12)}$$

Equation 12 can be used for a circular void if b is replaced by r. *Equation* 12 can be solved for the required tensile force α by multiplying by the appropriate Ω from *Table 4*.

Factors of Safety: Appropriate factors of safety should be used when designing with the above equations and table. The factor of safety can be applied to the geosynthetic tension or the applied loads, with application to the geosynthetic tension being more common. The factor of safety should not be applied to the soil shear strength (as is commonly the case in geotechnical problems) due to the insensitivity of the arching theory results *(Equation 10)* to the soil shear strength.

Required Geosynthetic Tensile Strength: The tensile strength required in the geosynthetic must correspond to the design model used. For reinforced support layers spanning infinitely long voids, the value $T_{req'd}$ from the calculations is the tensile strength in the direction of the width of the void for the considered design strain. However, some strength is required length-wise in places where the actual situation departs from a pure plane-strain situation (i.e. at the end of the void).

In the case of a circular void, the tensioned membrane equation *(Equation* 12) is valid only if the geosynthetic has isotropic tensile characteristics. For woven geotextiles and geogrids that have different tensile characteristics in the two principal directions, two cases can be considered depending on the ratio between the geosynthetic tensions at the design strain in the weak and the strong directions: (i) if the ratio is more than 0.5, α should be taken equal to the tension in the weak direction; and (ii) if the ratio is less than 0.5, α should be taken equal to half the tension in the strong direction [4]

Therefore, it is recommended that for voids which can be modeled as circular, one of the following solutions can be adopted: (i) use two perpendicularly orientated layers of the same anisotropic geosynthetic; or (ii) model a void *larger* than the *circular* void by replacing the circular void by an infinitely long void with a width, b, equal to the diameter, 2r of the circular void. This would require using one layer of geosynthetic which has twice the required strength as for the design of a circular void.

Design Procedures

Problem Definition: Refer to *Figure 11* and define the geometry (including void size), loading and material properties of the design cross section.

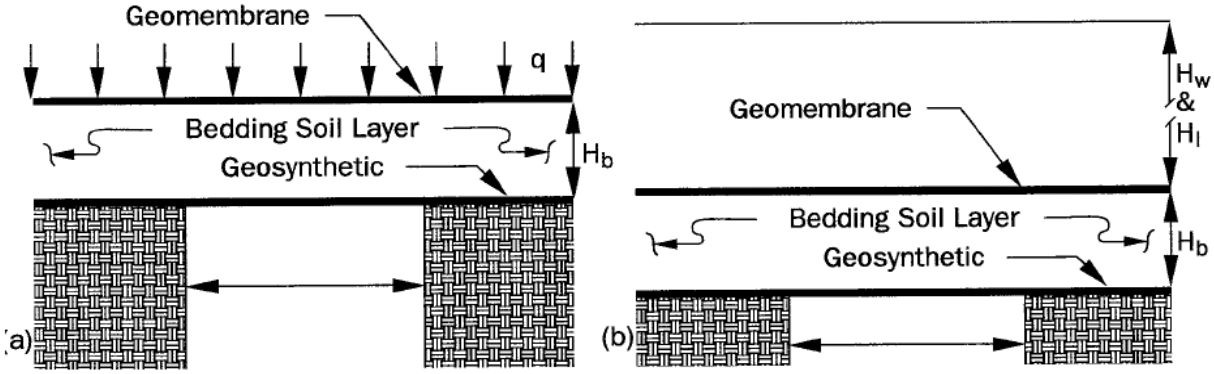


FIGURE 11: Design Cross Sections with (a) liquid or equipment surcharge, q, and (b) soil or waste surcharge

Determine the Allowable Geosynthetic Strain: The allowable strain for the reinforcement should be the lesser of the elastic + creep limit strain for the geosynthetic and the limit strain for the soil. Generally, this will be less than 10 percent.

Calculation of Appropriate Unit Weight: The pressure on the geosynthetic is directly related to the unit weight(s) of the overlying soil or waste layer(s), therefore it is important to accurately quantify the unit weight to be used in reinforcement calculations. The reinforcement may support a bedding layer, H_b, a soil layer within the lining system, H_l, and a waste layer, H_w.

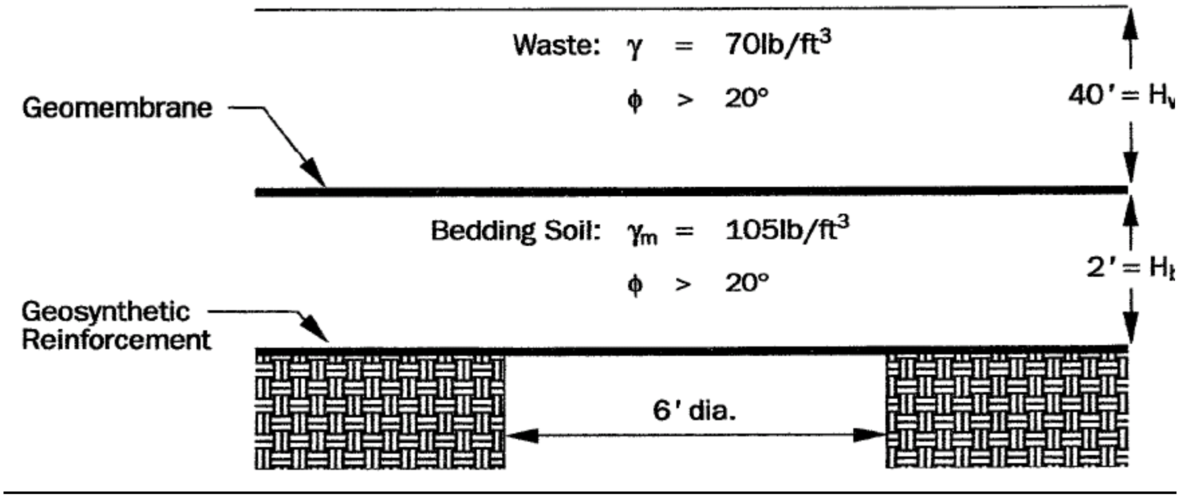
It has been shown that the vertical stress on reinforcement overlying a void tends toward zero-due to cohesionless soil arching, as the ratio of soil thickness to void diameter approaches 3 to 4 [1]. Therefore, it is reasonable to use a weighted average moist unit weight based on all layers overlying the geosynthetic reinforcement up to a distance of three to four times the depression diameter or width.

Determination of Required Tensile Force: Determine the tensile force required at the allowable strain using *Equation 12*. *Equation 12* can be solved for the required tensile force α by multiplying by the appropriate Ω from *Table 4*.

Required Geosynthetic Tensile Strength and Selection: The required tensile force is multiplied by an appropriate safety factor to determine the required strength. A geosynthetic is then selected based on cost and constructability associated with the necessary number and orientation of reinforcement layers.

EXAMPLE PROBLEM

Given:



Determine: Required geosynthetic tensile strength.

Solution:

- **Determine allowable geosynthetic strain:**

  The limit strain for the geosynthetic at the LTDS is 10 percent. This is considered acceptable for both the soil strain and other components of the lining system.

- **Calculate Average Unit Weight: (based on 3 times void diameter):**

  γ_{avg} = [(2 x 105) + (16 x 70)] /18 = 74 lb/ft^3

- **Calculate required tensile force:**

  Using *Equation*.12...

  $\alpha/\Omega = 2(74)\ (9)\ (1\text{-}e^{-0.5(42/3)}) + 0 = 1331$ lb/ft

  From *Table 4*, Ω = 0.73 for 10% strain limit, therefore…

  α = 1331 x 0.73 = 972 lb/ft

  From *Table 4*, Ω = 0.97 for 5% strain limit, therefore…

  α = 1331 x 0.97 = 1291lb/ft

- **Calculate required geosynthetic tensile strength:**

  Applying an overall FS = 1.5...

  $T_{req'd}$ = 972 x 1.5 = 1458 lb/ft for 10% strain limit

  $T_{req'd}$ = 1291 x 1.5 = 1937 lb/ft for 5% strain limit

  $T_{req'd}$ is the minimum strength required in both principle directions.
  2 $T_{req'd}$ is the minimum strength required in the main principal direction if modeling the circular void as an infinitely long void.

- **Select Geosvnthetic Reinforcement (Refer to *Table* 2)**

  Circular Void Design (requiring 2 layers placed in mutually perpendicular directions):

  Choose Miragrid 3XT or HS400 for 10% strain limit.

  Choose Miragrid 8XT or HS800 for 5% strain limit.

  Infinitely Long Void (requiring 1 layer with twice the strength requirement):

  Choose Miragrid 7XT or HS600 for 10% strain limit.

  Choose Miragrid 22XT or HS1715 for 5% strain limit.

References

1. Bonaparte, R. and R. R. Berg (1987). "The Use of Geosynthetics to Support Roadways over Sinkhole Prone Areas." Proceedings of the 2nd Multidisciplinary Conference on Sinkholes and the Environmental Impacts of Karsts, Orlando, FL. pp.437-445.
2. Carter, M. and S.P. Bentley (1991). "Correlations of Soil Properties." Pentech Press, London. pp. 46, 90-91.
3. Giroud, J. P. and J. F. Beech (1989). "Stability of Soil Layers on Geosynthetic Lining Systems." Proceedings of Geosynthetics '89, San Diego, IFAI. pp. 35-48.
4. Giroud, J. P., R. Bonaparte, J. F. Beech and B. A. Gross (1990). "Design of Soil Layer - Geosynthetic Systems Overlying Voids." Geotextiles and Geomembranes. Vol. 9, No.1, pp. 11-50.
5. Koerner, R. M. and B-L. Hwu (1991). "Stability and Tension Considerations Regarding Cover Soils on Geomembrane Lined Slopes." Geotextiles and Geomembranes. Vol. 10, No.4, pp. 335-355.
6. Koutsourais, M. M., C. J. Sprague and R. C. Pucetas (1991). "Interfacial Friction Study of Cap and Liner Components for Landfill Design." Geotextiles and Geomembranes. Vol. 10, No. 5-6, pp. 531-548.
7. Martin, J. P. and R. M. Koerner (1985). "Geotechnical Design Considerations for Geomembrane Lined Slopes: Slope Stability." Geotextiles and Geomembranes. Vol. 2, No.4, pp. 299-321.