August 8, 2016 123-82739.1

Mr. Scott Lockwood, PE
England-Thims & Miller, Inc.
14775 Old St. Augustine Road
Jacksonville, FL 32258

RE: CLOSURE DESIGN SUPPORT
TRAIL RIDGE LANDFILL
DUVAL COUNTY, JACKSONVILLE, FLORIDA

Dear Mr. Lockwood:

Golder Associates Inc. (Golder) has prepared the attached design calculations to document the equivalency and adequate slope stability of using the Agru Super Gripnet® with geotextile as the drainage and barrier layers for the top deck area at Trail Ridge Landfill. The calculations demonstrate equivalency for the drainage layer (previously sand drainage layer). Additionally, the calculations document adequate slope stability for the geosynthetic final cover system.

Please contact the undersigned at (904) 363-3430 should you have any questions.

Sincerely,

GOLDER ASSOCIATES INC.

Samuel F. Stafford, PE
Senior Project Engineer

Don E. Grigg, PE
Senior Engineer

Kevin S. Brown, PE
Senior Consultant and Principal

Attachments: Final Cover Slope Stability Calculation
Final Cover – Geocomposite Transmissivity Calculation

DEG/KSB/ams

FN: G:\Projects\123\123-82\123-82639\-1\Correspondence\Equivalency and Stability_sfs.docx

PROFESSIONAL ENGINEER CERTIFICATION

I certify that the veneer stability and transmissivity calculations associated with the final cover design for the top area at Trail Ridge Landfill were performed under my direction and I have checked them for completeness and accuracy. Specifically, this information includes:

1. Final Cover Slope Stability calculation (dated June 20, 2016)
2. Final Cover – Geocomposite Transmissivity calculation (dated August 24, 2013)

Samuel F. Stafford, PE
Florida Professional Engineer No. 78648
Certificate of Authorization No. 1670

8 Aug 2016

Date

SAMUEL F. STAFFORD
LICENSE
No. 78648
STATE OF
FLORIDA
PROFESSIONAL ENGINEER

ATTACHMENTS

OBJECTIVE:

1. Analyze the stability of the final cover system and determine the factor of safety during and after landfill construction .
2. Determine the stability of the landfill including seepage loading conditions

GEOMETRY:

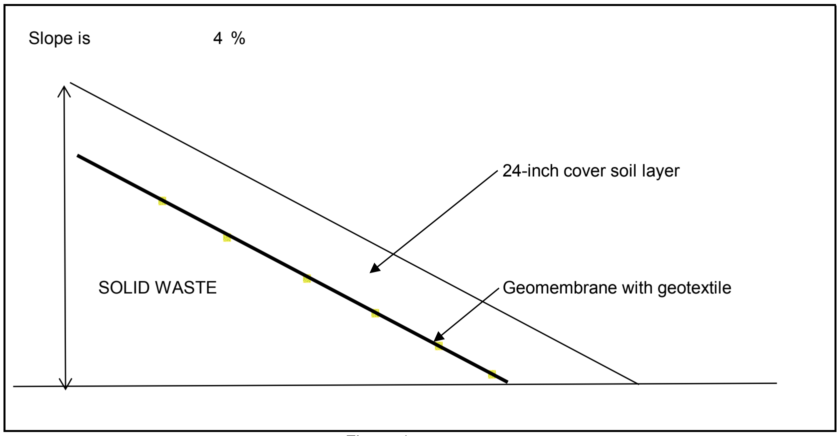


Figure-1

METHOD:

GOLDER RECOMMENDED FACTORS OF SAFETY FOR LANDFILL FINAL COVER ARE AS BELOW

Shear Strength	During Construction (Short term)	Long Term
Design	1.1	1.5, 1.1 [a]

[a] Recommended factor of safety with seepage forces included

If the calculated factors of safety exceeds the recommended factors of safety for landfill final cover, then the stability of the final cover meets the requirement.

Design Parameters:

Top Elevation of Cover: 349.00 ft
Approximate Toe Elevation : 329.00 ft

Material Properties (ref. 1)

Material	c (psf)	c_a (psf)	ϕ (°)	δ (°)	γ (pcf)	Thickness (ft)
Cover soil	0	-	38	-	103	2.00
waste/geomembrane with getotextile/cover soil	-		-	30	-	0.02

Where:
c = Cohension of the cover soil
c_a = Adhesion between cover soil of the active wedge and the geosynthetics (geomembrane and geotextile)
δ = Interface friction angle between cover soil and geosynthetics (geomembrane and geotextile)
ϕ = Friction Angle of cover soil
γ = Unit weight of the cover soil

Slope Angle = β (°) = 2.3
Slope Height = 20.00 ft (H)

CALCULATIONS:

LONG TERM VENEER STABILITY based on Koerner/Soong Method (page 487 to 490, ref. 2)

Using the Koerner/Soong Method, the factor of safety is calculated using the following equation (Eq. 13.9, ref. 2)

$$FS = \frac{-b \pm (b^2 - 4 \times a \times c)^{0.5}}{2 \times a}$$

Where:

$a = (W_a - N_a \times \cos\beta)\cos\beta$

$b = -[(W_a - N_a \times \cos\beta) \times \sin\beta \tan\phi + (N_a \times \tan\delta + C_a) \times \sin\beta \times \cos\beta + (C + W_p \times \tan\phi) \times \sin\beta]$

$c = (N_a \times \tan\delta + C_a) \times \sin^2\beta \times \tan\phi$

$W_a = \gamma \times h^2 \times (L/h - 1/\sin\beta - \tan\beta / 2)$

$N_a = W_a \times \cos\beta$

$C_a = c_a \times (L - h/\sin\beta)$

$W_p = (\gamma \times h^2) / \sin 2\beta$

$C = c \times h / \sin\beta$

Where:

- W_a = Total weight of the active wedge
- N_a = Effective force normal to the failure plane of the active wedge
- C_a = Adhesive force between cover soil of the active wedge and the GCL
- W_p = Total weight of the passive wedge
- C = Cohesive force along the failure plane of the passive wedge
- γ = Unit Weight of protective cover soil
- h = Thickness of cover soil
- β = Slope Angle
- L = Length of slope measured along the geosynthetic interface
- c = Cohension of the cover soil
- c_a = Adhesion between cover soil of the active wedge and the GCL
- δ = Interface friction angle between cover soil and GCL
- ϕ = Friction Angle of cover soil

Where:

h = Thickness of Cover (ft) = 2.00

β = Cover Slope Angle (°) = 2.3

H_{max} = Maximum height = 20.0 feet

L= 500.0 feet

Since h and L are known for **LONG-TERM Conditions,** solve for the FS:

W_a (lbs/ft) = 92,684

N_a (lbs/ft) = 92,609

C_a (lbs/ft) = 449.9600 x c_a

W_p (lbs/ft) = 5,158

C (lbs/ft) = 0

$(W_a - N_a \times \cos\beta)$ = 148

$(C + W_p \times \tan f)$ = 4030

cos β = 1.00

sin β = 0.04

sin β x tan ϕ = 0.03

$\sin^2\beta \times \tan\phi$ = 0.00

sin β x cos β = 0.04

tan ϕ = 0.78

a= 147.9

- b= 165.7 + 0.04 x $(N_a \times \tan\delta + C_a)$

c = $(N_a \times \tan\delta + C_a)$ x 0.00

Solve for FS:

δ (°)	c_a (psf)	tan δ	C_a (lbs/ft)	$(N_a \times \tan\delta + C_a)$	b	c	$(b^2 - 4ac)^{0.5}$	Factor of Safety
30.00	*0*	*0.6*	*0*	*53,468*	*-2,301*	*67*	*2292.4*	*15.5*

SHORT TERM CONDITIONS (***Dozer on the slope without acceleration)***

Veneer Stability based on Koerner/Soong Method (page 490-497, ref. 2)

$$FS = \frac{-b \pm (b^2 - 4 \times a \times c)^{0.5}}{2 \times a}$$

Where:

$a = (W_{a+e} - N_{a+e} \times \cos\beta) \cos\beta$

$b = -[(W_{a+e} - N_{a+e} \times \cos\beta) \times \sin\beta \times \tan\phi + (N_{a+e} \times \tan\delta + C_a) \times \sin\beta \times \cos\beta + (C + W_p \times \tan\phi) \times \sin\beta]$

$c = (N_{a+e} \times \tan\delta + C_a) \times \sin^2\beta \times \tan\phi)$

$W_a = \gamma \times h^2 \times (L/h - 1/\sin\beta - \tan\beta / 2)$

W_e = Equipment Weight, see below

$W_{a+e} = W_a + W_e$

$N_{a+e} = W_{a+e} \times \cos\beta$

$C_a = c_a \times (L - h/\sin\beta)$

$W_p = (\gamma \times h^2) / \sin 2\beta$

$C = c \times h / \sin\beta$

The definitions of all the parameters are as same as those in long term FS caculation except W_e, W_{a+e}, and N_{a+e}

For SHORT-Term Conditions, look at 6 inches of soil being placed up slope with a Low Ground Pressure Dozer

$L_{short\ term}$=	500.0	ft
$h_{short\ term}$=	2.00	ft
f =	38.00	degrees
c =	0.00	psf
$\gamma_{soil\ cover}$ =	103.00	pcf

Determination of W_e (See attached dozer specifications from manufacturer, ref. 3):

Width of Dozer Track =	3.00	ft
Contact Area =	32.13	sq.ft.
Ground Pressure =	9.5	psi
Influence factor (I) =	0.95	(obtained from Figure 13.7, page 493, ref. 2)
Ground Pressure at Geosynthetics =	1,304.8	psf
Length of Dozer Track =	10.7	ft
W_e=	**13,975**	**lbs/ft**

W_a+W_e (lbs/ft) =	106,658		
N_{a+e} (lbs/ft) =	106,573	W_p (lbs/ft) =	5,158
C_a (lbs/ft) =	450 x c_a	C (lbs/ft) =	0

(W_{a+e} - N_{a+e} x cos β) =	170
(C + W_p x tan f) =	4,030
cos β =	1.00
sin β =	0.04
sin β x tan ϕ =	0.03
$\sin^2$ β x tan ϕ =	0.00
sin β x cos β =	0.04
tan ϕ =	0.78

a= 170.2

- b= 166.4 + 0.04 x (N_{a+e} x tan δ + C_a)

c = (N_{a+e} x tan δ + C_a) x 0.00

Solve for FS :

δ (°)	c_a (psf)	tan δ	C_a (lbs/ft)	(N_{a+e} x tan δ + C_a)	b	c	(b^2 - 4ac)$^{0.5}$	Factor of Safety
30.00	*0.00*	*0.6*	0.00	*61,530*	*-2,624*	*77*	*2,614*	*15.4*
			x a	lbs/ft		+x tan δ + C x	+ -	x tan δ

SEEPAGE BUILT-UP CONDITIONS

Veneer Stability based on Koerner/Soong Method (page 501-508, ref. 2)

$$FS = \frac{-b \pm (b^2 - 4 \times a \times c)^{0.5}}{2 \times a}$$

Where:

$a = W_a \sin\beta \cos\beta + U_H \times (1 - \cos^2\beta)$

$b = -[W_p \times \tan\phi + W_a \times (\sin^2\beta \times \tan\phi + \cos^2\beta \times \tan\delta) -$
$U_{AN} \times \cos\beta \times \tan\delta - U_{PN} \times \tan\phi + U_H \times \sin\beta \times \cos\beta \times (\tan\phi - \tan\delta)]$

$c = (W_a \times \cos\beta - U_{AN} + U_H \times \sin\beta) \times \sin\beta \times \tan\delta \times \tan\phi)$

$U_{AN} = \gamma_w \times h_w \times (H - 0.5 \times h_w \times \cos\beta) / \tan\beta$

$U_H = 0.5 \times \gamma_w \times h_w^2$

$U_{PN} = 0.5 \times \gamma_w \times h_w^2 / \tan\beta$

$W_a = 0.5 \times [\gamma \times (h - h_w) \times (2 \times H \times \cos\beta - h - h_w) +$
$\gamma_{sat} \times h_w \times (2 \times H \times \cos\beta - h_w)] / (\sin\beta \times \cos\beta)$

$W_p = 0.5 \times [\gamma \times (h^2 - h_w^2) + \gamma_{sat} \times h_w^2] / (\sin\beta \times \cos\beta)$

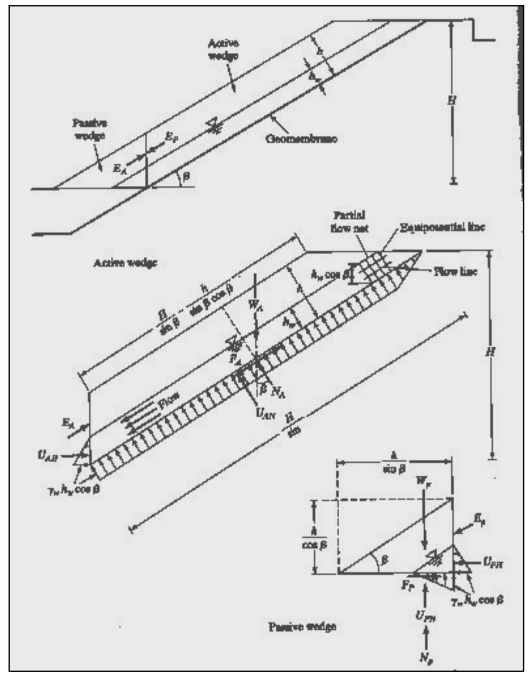


Figure -2

U_H = Resultant of the pore water pressures acting on lateral side of the active wedge or passive wedge
U_{PN} = Resultant of the pore water pressures acting on bottom of the passive wedge
U_{AN} = Resultant of the pore water pressures acting on bottom of the active wedge
h = Thickness of the soil layer
h_w = Depth of seepage water in the soil layer (perpendicular to the slope)
γ_w = Unit weight of water
γ = Moisture unit weight of the soil layer
γ_{sat} = Saturated unit weight of the soil layer

Other paramters are same as in the above calculations

γ_w =	62.4	lb/ft³	
h_w =	24.00	inches	(Conservative, assumes 100% of the soil layer is saturated).
H =	20.0	ft	
γ_{sat} =	113	lb/ft³	(Assumed)
U_{AN} =	59,282	lbs/ft	
U_H =	124.80	lbs/ft	
U_{PN} =	3,120.00	lbs/ft	
W_a =	107,431	lbs/ft	
W_p =	5,659	lbs/ft	

$W_p \times \tan\phi$ =	4421	$\sin^2\beta \times \tan\phi$ =	0.00
$U_{PN} \times \tan\phi$=	2,437.61	$\sin\beta$ =	0.04
$U_H \times \sin\beta \times \cos\beta$ =	4.9840	$\tan\phi$ =	0.78
		$\cos^2\beta$ =	1.00
		$\cos\beta$ =	1.00

a = 4291
- b= 2122 + 48,019.60 x tan δ
c = 1501.0 x tan δ

δ (°)	c_a (psf)	tan δ	b (x tan δ)	c	$(b^2 - 4ac)^{0.5}$	Factor of Safety
30.0	*0.0*	*0.577*	*-29,846*	*867*	*29,596*	*6.9*

CONCLUSION:

SUMMARY OF RESULTS

CASE ANALYZED	RECOMMENDED FACTOR OF SAFETY	ESTIMATED FACTOR OF SAFETY	MEET REQUIREMENT
Long Term using Design Shear Strength	1.5	15.5	Yes
Short Term using Design Shear Strength - with dozer on the Slope	1.1	15.4	Yes
Seepage Analysis	1.1	6.9	Yes

Therefore, the stablity of the final cover meets the recommended factors of safety.

REFERENCES:

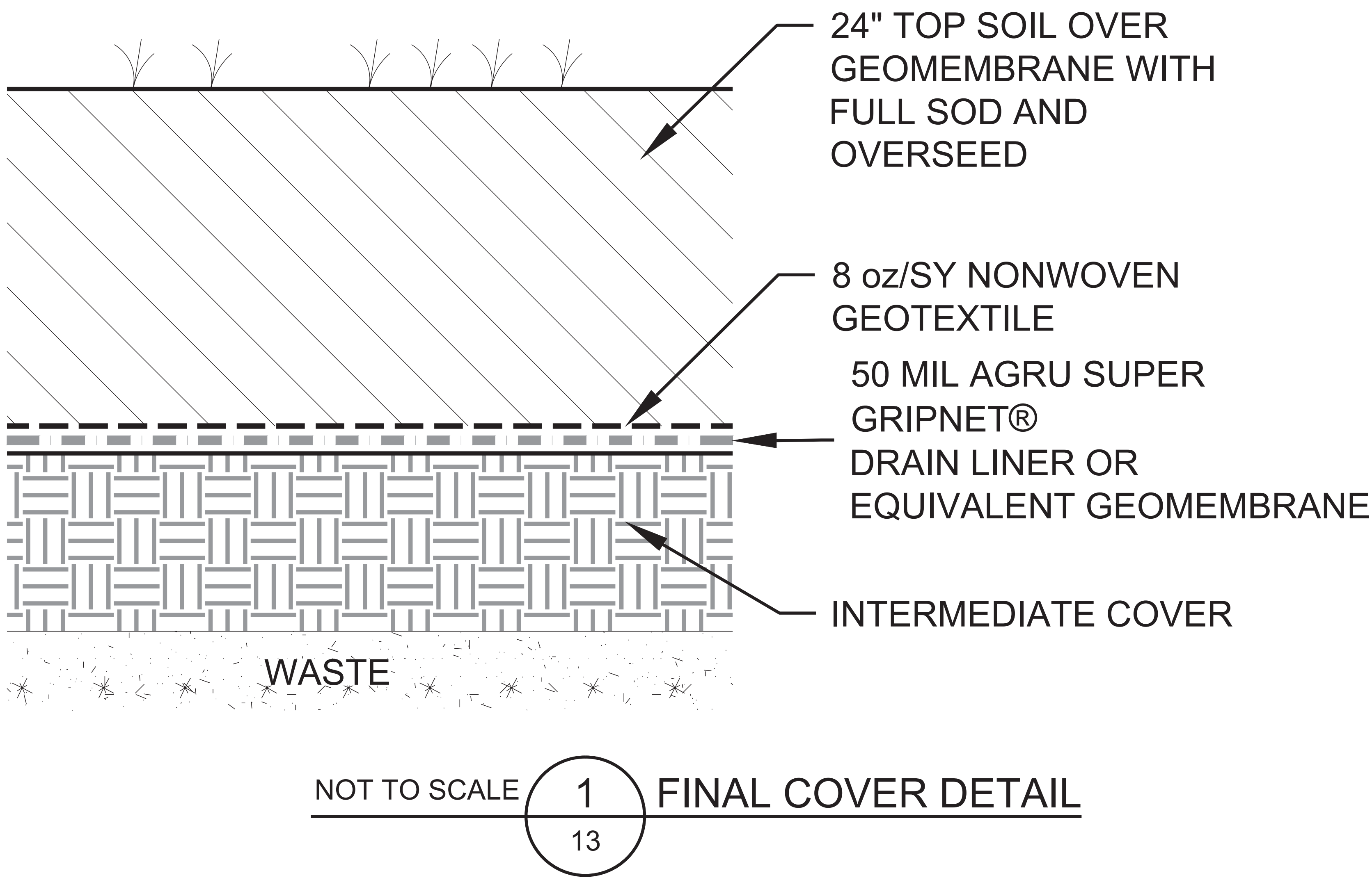
1. Material Properties - data take from ETM email dated 6/20/16.

2. Qian, X., Koerner, R. M., Gray, D. H., Geotechnical Aspects of Landfill Design and Construction, Prentice Hall, New Jersery, US, 2002.

3. Dozer Specifications from Manufacturer

4. Agru Material Manufacturer Information

<u>FIGURE 1</u>


24" TOP SOIL OVER GEOMEMBRANE WITH FULL SOD AND OVERSEED
8 oz/SY NONWOVEN GEOTEXTILE
50 MIL AGRU SUPER GRIPNET® DRAIN LINER OR EQUIVALENT GEOMEMBRANE
INTERMEDIATE COVER
WASTE
NOT TO SCALE
1
13
FINAL COVER DETAIL

REF. 2

13.4 VENEER SLOPE STABILITY ANALYSES

This section treats the standard veneer slope stability problem [as shown in Figure 13.1(a) and (b)] and then superimposes upon it a number of situations, all which tend to destabilize slopes. Included are gravitational, construction equipment, seepage and seismic forces, respectively. Each will be illustrated by a design graph and a numeric example.

13.4.1 Cover Soil (Gravitational) Forces

Figure 13.3 illustrates the common situation of a finite-length, uniformly-thick cover soil placed over a liner material at a slope angle β. It includes a passive wedge at the toe and has a tension crack on the crest. The analysis that follows is from Koerner and Soong (1998), but it is similar to Koerner and Hwu (1991). Comparable analyses are also available from Giroud and Beech (1989), McKelvey and Deutsch (1991), and others.

The symbols used in Figure 13.3 are defined a follows:

W_A = total weight of the active wedge
W_P = total weight of the passive wedge
N_A = effective force normal to the failure plane of the active wedge
N_P = effective force normal to the failure plane of the passive wedge
γ = unit weight of the cover soil
h = thickness of the cover soil
L = length of slope measured along the geomembrane
β = soil slope angle beneath the geomembrane

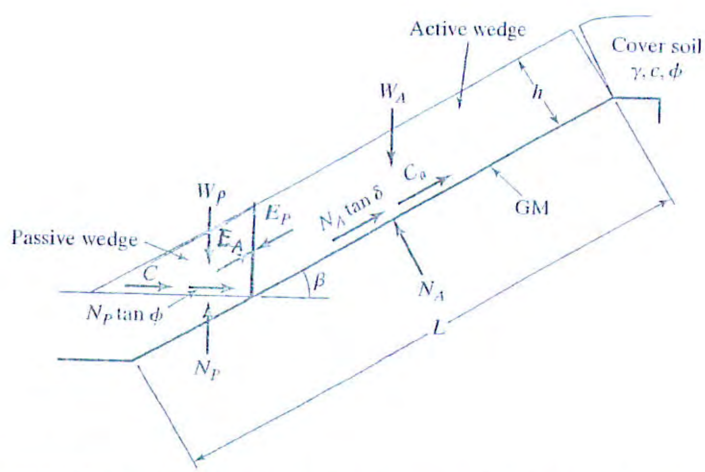


FIGURE 13.3 Limit Equilibrium Forces Involved in a Finite Length Slope Analysis for a Uniformly Thick Cover Soil

ϕ = friction angle of the cover soil
δ = interface friction angle between cover soil and geomembrane
C_a = adhesive force between cover soil of the active wedge and the geomembrane
c_a = adhesion between cover soil of the active wedge and the geomembrane
C = cohesive force along the failure plane of the passive wedge
c = cohesion of the cover soil
E_A = interwedge force acting on the active wedge from the passive wedge
E_P = interwedge force acting on the passive wedge from the active wedge
FS = factor of safety against cover soil sliding on the geomembrane.

The expression for determining the factor of safety can be derived as follows:

Considering the active wedge, the forces acting on it are

$$W_A = \gamma \cdot h^2 \cdot (L/h - 1/\sin\beta - \tan\beta/2) \tag{13.4}$$

$$N_A = W_A \cdot \cos\beta \tag{13.5}$$

$$C_a = c_a \cdot (L - h/\sin\beta) \tag{13.6}$$

By balancing the forces in the vertical direction, the following formulation results:

$$E_A \cdot \sin\beta = W_A - N_A \cdot \cos\beta - \frac{(N_A \cdot \tan\delta + C_a)}{FS}$$

Hence, the interwedge force acting on the active wedge is

$$E_A = \frac{(FS)(W_A - N_A \cdot \cos\beta) - (N_A \cdot \tan\delta + C_a) \cdot \sin\beta}{\sin\beta \cdot (FS)} \tag{13.7}$$

The passive wedge can be considered in a similar manner:

$$W_P = \frac{\gamma \cdot h^2}{\sin 2\beta}$$

$$N_P = W_P + E_P \cdot \sin\beta$$

$$C = \frac{c \cdot h}{\sin\beta} \tag{13.8}$$

By balancing the forces in the horizontal direction, the following formulation results:

$$E_P \cdot \cos\beta = \frac{C + N_P \cdot \tan\phi}{FS}$$

Hence, the interwedge force acting on the passive wedge is

$$E_P = \frac{C + W_P \cdot \tan\phi}{\cos\beta \cdot (FS) - \sin\beta \cdot \tan\phi}$$

By setting $E_A = E_P$, the resulting equation can be arranged in the form of the quadratic equation $ax^2 + bx + c = 0$, which in this case, using FS-values, results in

$$a \cdot FS^2 + b \cdot FS + c = 0$$

The resulting FS-value is then obtained from the conventional solution of the quadratic equation, which gives

$$FS = \frac{-b \pm (b^2 - 4 \cdot a \cdot c)^{0.5}}{2 \cdot a} \tag{13.9}$$

where
$$a = (W_A - N_A \cdot \cos\beta) \cdot \cos\beta$$
$$b = -[(W_A - N_A \cdot \cos\beta) \cdot \sin\beta \cdot \tan\phi + (N_A \cdot \tan\delta + C_a) \cdot \sin\beta \cdot \cos\beta + (C + W_P \cdot \tan\phi) \cdot \sin\beta]$$
$$c = (N_A \cdot \tan\delta + C_a) \cdot \sin^2\beta \cdot \tan\phi$$

When the calculated FS-value falls below 1.0, sliding of the cover soil on the geomembrane is to be anticipated. Thus, a value of greater than 1.0 must be targeted as being the minimum factor of safety. How much greater than 1.0 the FS-value should be, is a design and/or regulatory issue. Recommendations for minimum allowable FS-values under different conditions are available in Koerner and Soong (1998). In order to better illustrate the implications of Equations 13.9, typical design curves for various FS-values as a function of slope angle and interface friction angle are given in Figure 13.4. Note that the curves are developed specifically for the variables stated in the legend of the figure. Example 13.1 illustrates the use of the analytic development and the

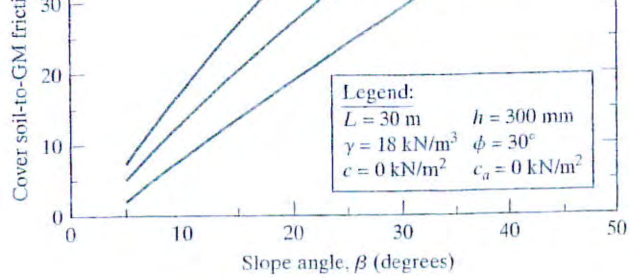


FIGURE 13.4 Design Curves for Stability of Uniform-Thickness Cohesionless Cover Soils on Linear Failure Planes for Various Global Factors of Safety

will be considered as compared.

EXAMPLE 13.1

The following are given: a 30-m slope with a uniformly thick 300-mm-deep cover soil at a unit weight of 18 kN/m^3. The soil has a friction angle of 30° and zero cohesion (i.e., it is a sand). The cover soil is placed directly on a geomembrane as shown in Figure 13.3. Direct shear testing has resulted in an interface friction angle between the cover soil and geomembrane of 22° with zero adhesion. What is the *FS*-value at a slope angle of 3(H)-to-1(V) (i.e., 18.4°)?

Solution Using Equation 13.9 to solve for the *FS*-value results in a value of 1.25, which is seen to be in agreement with the curves of Figure 13.4:

$$a = 14.7 \text{ kN/m}$$
$$b = -21.3 \text{ kN/m}$$
$$c = 3.5 \text{ kN/m}$$

Thus, $FS = 1.25$

This value can be confirmed using Figure 13.4.

Comment In general, this is too low of a value for a final cover soil factor-of-safety and a redesign is necessary. There are many possible options to increase the value (e.g., changing the geometry of the situation, the use of toe berms, tapered cover soil thickness, and veneer reinforcement, see Koerner and Soong, 1998). Nevertheless, this general problem will be used throughout this section for comparison with other cover soil slope stability situations.

13.4.2 Tracked Construction Equipment Forces

The placement of cover soil on a slope with a relatively low shear strength interface (like a geomembrane) should always start at the toe and move upward to the crest. Figure 13.5(a) shows the recommended method. In doing so, the gravitational forces of the cover soil and live load of the construction equipment are compacting previously placed soil and working with an ever-present passive wedge and a stable lower portion beneath the active wedge. While it is necessary to specify low ground pressure equipment to place the soil, the reduction in the *FS*-value for this situation of equipment working up the slope will be seen to be relatively small.

For soil placement down the slope, however, a stability analysis cannot rely on toe buttressing and also a dynamic stress should be included in the calculation. These conditions decrease the *FS*-value—in some cases, to a great extent. Figure 13.5(b) shows this procedure. Unless absolutely necessary, it is not recommended that cover soil be placed on a slope in this manner. If it is necessary, the design must consider the unsupported soil mass and the possible dynamic force of the specific type of construction equipment and its manner of operation.

For the *first case* of a bulldozer pushing cover soil up from the toe of the slope to the crest, the analysis uses the free body diagram of Figure 13.6(a). The analysis uses a

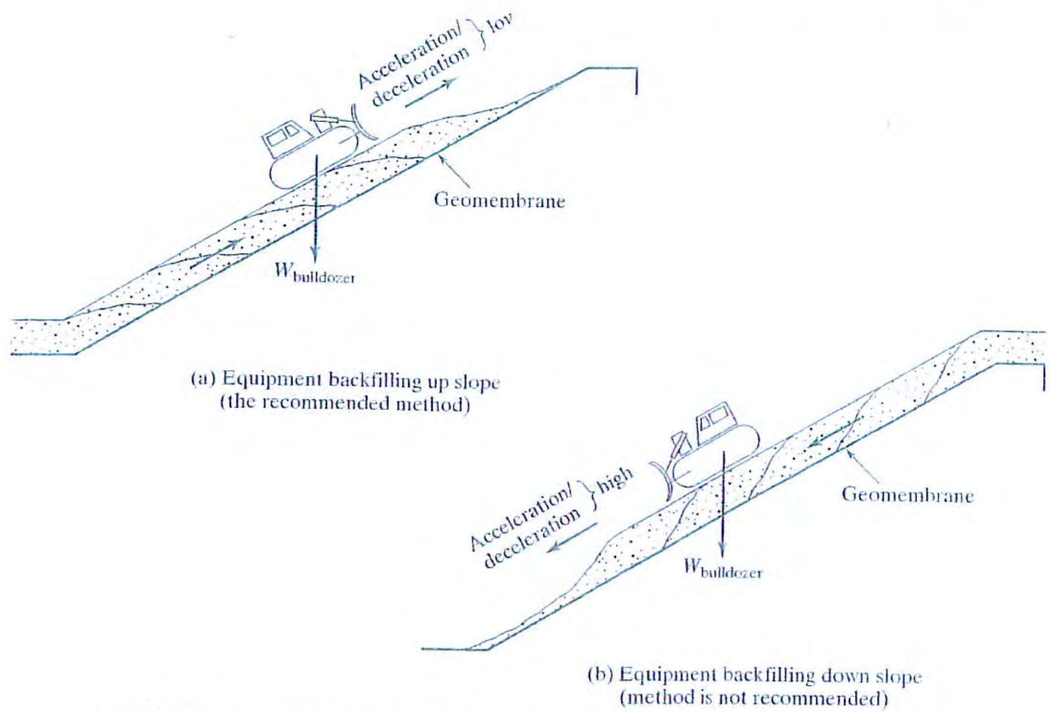


FIGURE 13.5 Construction Equipment Placing Cover Soil on Slopes Containing Geosynthetics

known type of construction equipment (such as a bulldozer characterized by its ground contact pressure) and dissipates this force or stress through the cover soil thickness to the surface of the geomembrane. A Boussinesq analysis is used (see Poulos and Davis, 1974). This results in an equipment force per unit width of

$$W_e = q \cdot w \cdot I \tag{13.10}$$

where W_e = equivalent equipment force per unit width at the geomembrane interface;
$q = W_b/(2 \cdot w \cdot b)$;
W_b = actual weight of equipment (e.g., a bulldozer);
w = length of equipment track;
b = width of equipment track;
I = influence factor at the geomembrane interface (see Figure 13.7).

Upon determining the additional equipment force at the cover soil-to-geomembrane interface, the analysis proceeds as described in Section 13.3.1 for gravitational forces only. In essence, the equipment moving up the slope adds an additional term (W_e) to the W_A-force in Equation 13.4. Note, however, that this involves the generation of a resisting force as well. Thus, the net effect of

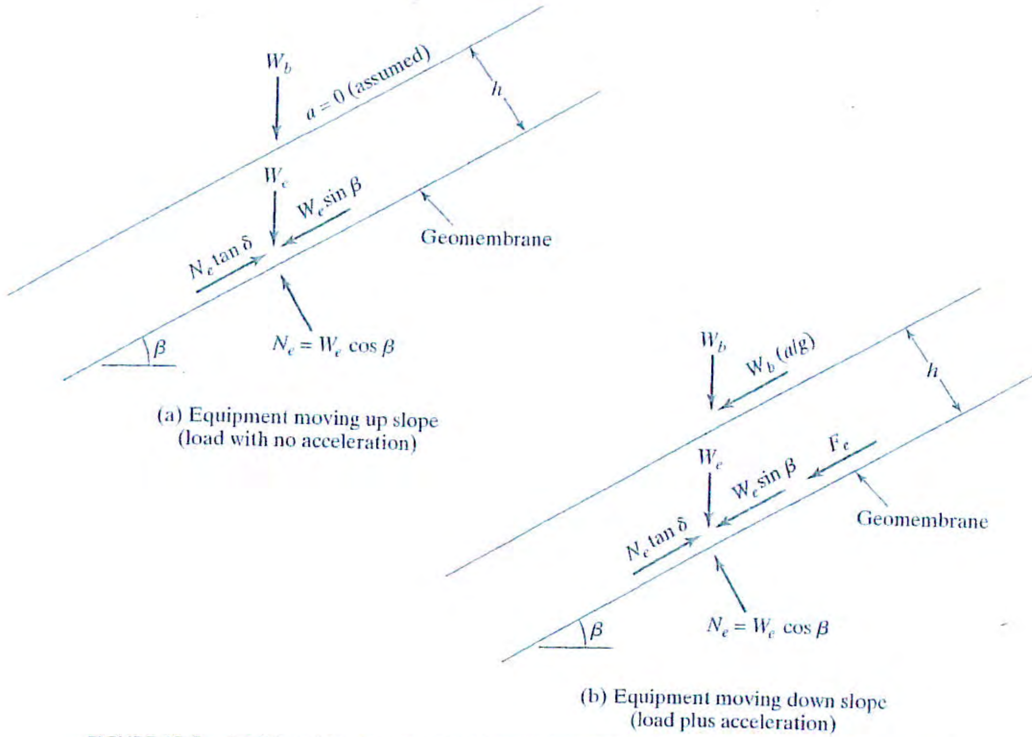


FIGURE 13.6 Additional (to Gravitational Forces) Limit Equilibrium Forces due to Construction Equipment Moving on Cover Soil (see Figure 13.3 for the gravitational soil force to which the above forces are added).

concerned. It should also be noted that no acceleration/deceleration forces are included in this analysis, which is somewhat idealistic. Using these concepts (the same equations used in Section 13.3.1 are used here), typical design curves for various *FS*-values as a function of equivalent ground contact equipment pressures and cover soil thicknesses are given in Figure 13.8. Note that the curves are developed specifically for the variables stated in the legend. Example 13.2 illustrates the use of the formulation.

EXAMPLE 13.2

The following are given: a 30-m-long slope with uniform cover soil of 300 mm thickness at a unit weight of 18 kN/m^3. The soil has a friction angle of 30° and zero cohesion (i.e., it is a sand). It is placed on the slope using a bulldozer moving from the toe of the slope up to the crest. The bulldozer has a ground pressure of 30 kN/m^2 and tracks that are 3.0 m long and 0.6 m wide. The cover soil to geomembrane friction angle is 22° with zero adhesion. What is the *FS*-value at a slope angle 3(H)-to-1(V)(i.e., 18.4°)?

Solution This problem follows Example 13.1 exactly except for the addition of the bulldozer moving up the slope. Using the additional equipment load, Equation 13.10 substituted into Equation 13.9 results in the following:

$$a = 73.1 \text{ kN/m}$$
$$b = -104.3 \text{ kN/m}$$
$$c = 17.0 \text{ kN/m}$$

Thus, $FS = 1.24$

This value can be confirmed using Figure 13.8.

Comment While the resulting *FS*-value is still low, the result is important to assess by comparing it with Example 13.1 (i.e., the same problem except without the bulldozer). It is seen that the *FS*-value has only decreased from 1.25 to 1.24. Thus, in general, a low ground contact pressure bulldozer placing cover soil up the slope with negligible acceleration/deceleration forces does not significantly decrease the factor-of-safety.

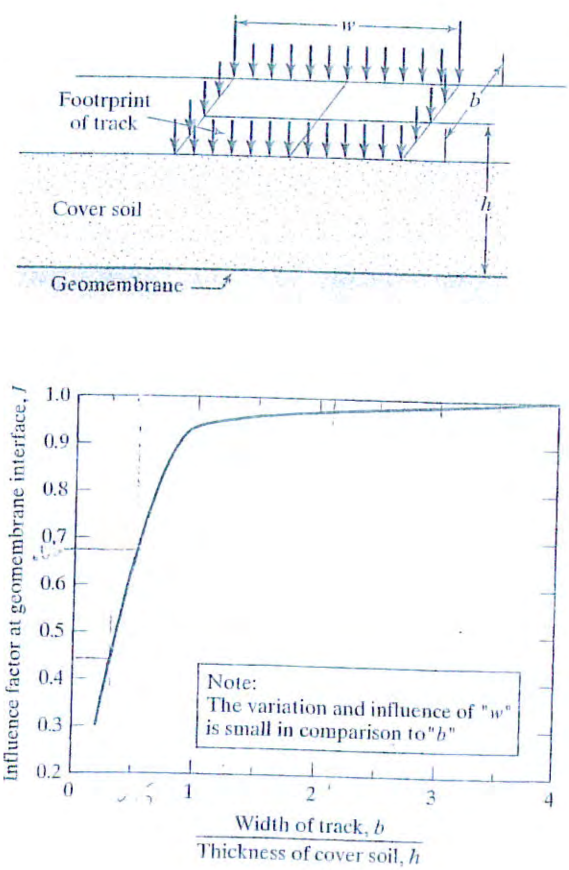


FIGURE 13.7 Values of Influence Factor, "I", for Use in Equation 13.10 to Dissipate Surface Force through the Cover Soil to the Geomembrane Interface (after Soong and Koerner, 1996)

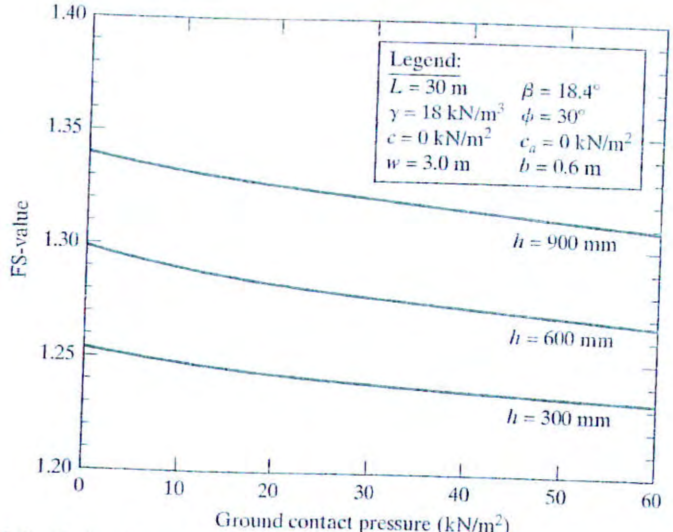


FIGURE 13.8 Design Curves for Stability of Different Thickness of Cover Soil for Various Construction Equipment Ground Contact Pressure

For the *second case* of a bulldozer pushing cover soil down from the crest of the slope to the toe as shown in Figure 13.5b, the analysis uses the force diagram of Figure 13.6(b). While the weight of the equipment is treated as just described, the lack of a passive wedge along with an additional force due to acceleration (or deceleration) of the equipment significantly decreases the resulting *FS*-values. This analysis again uses a specific piece of construction equipment operated in a specific manner. It produces a force parallel to the slope equivalent to $W_b \cdot (a/g)$, where W_b = the weight of the bulldozer, a = acceleration of the bulldozer, and g = acceleration due to gravity. Its magnitude is equipment operator dependent and related to both the equipment speed and time to reach such a speed (see Figure 13.9).

The acceleration of the bulldozer, coupled with an influence factor I from Figure 13.7, results in the dynamic force per unit width at the cover soil to geomembrane interface F_e. The relationship is given by

$$F_e = W_e \cdot (a/g) \qquad (13.11)$$

where F_e = dynamic force per unit width parallel to the slope at the geomembrane interface;
W_e = equivalent equipment (e.g., bulldozer) force per unit width at geomembrane interface, recall Equation 13.10;
β = soil slope angle beneath geomembrane;
a = acceleration of the construction equipment;
g = acceleration due to gravity.

Using these concepts, the new force parallel to the cover soil surface is dissipated through the thickness of the cover soil to the interface of the geomembrane. Again, a

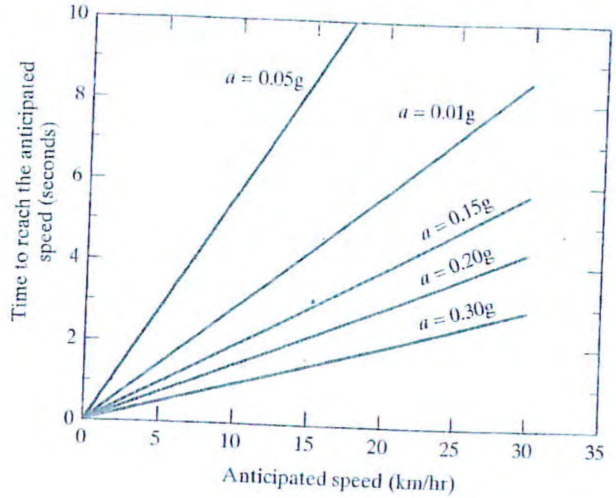


FIGURE 13.9 Graphic Relationship of Construction Equipment Speed and Rise Time to Obtain Equipment Acceleration.

Boussinesq analysis is used (see Poulos and Davis, 1974). The expression for determining the FS-value is derived next.

Considering the active wedge and balancing the forces in the direction parallel to the slope, the resulting formulation is

$$E_A + \frac{(N_e + N_A)\cdot\tan\delta + C_a}{FS} = (W_A + W_e)\cdot\sin\beta + F_e$$

where

N_e = effective equipment force normal to the failure plane of the active wedge.

$$N_e = W_E\cdot\cos\beta \qquad (13.12)$$

Note that all the other symbols have been previously defined.

The interwedge force acting on the active wedge can now be expressed as

$$E_A = \frac{(FS)[(W_A + W_e)\cdot\sin\beta + F_e]}{FS} - \frac{[(N_A + N_e)\cdot\tan\delta + C_a]}{FS}$$

The passive wedge can be treated in a similar manner. The following formulation of the interwedge force acting on the passive wedge results:

$$E_P = \frac{C + W_P\cdot\tan\phi}{\cos\beta\cdot(FS) - \sin\beta\cdot\tan\phi}$$

By setting $E_A = E_P$, the resulting equation can be arranged in the form of the quadratic equation $ax^2 + bx + c = 0$ which in this case, using FS-values, is

$$a\cdot FS^2 + b\cdot FS + c = 0$$

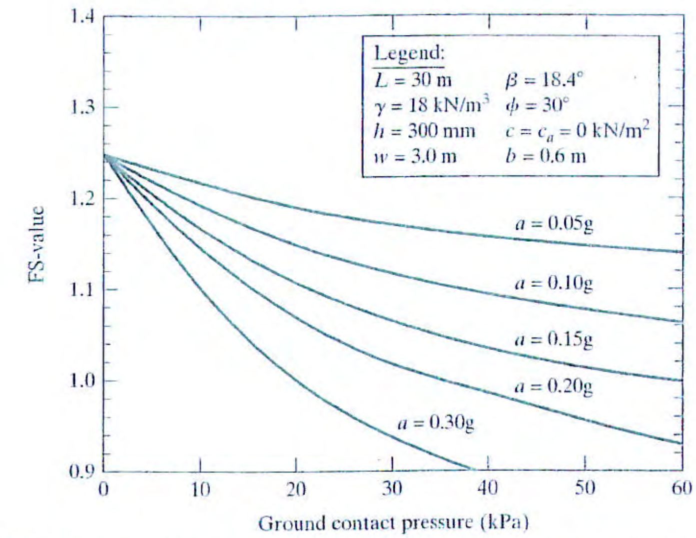


FIGURE 13.10 Design Curves for Stability of Different Construction Equipment Ground Contact Pressure for Various Equipment Accelerations

The resulting *FS*-value is then obtained from the conventional solution of the quadratic equation

$$FS = \frac{-b \pm (b^2 - 4 \cdot a \cdot c)^{0.5}}{2 \cdot a} \tag{13.13}$$

where
$$a = [(W_A + W_e) \cdot \sin\beta + F_e] \cdot \cos\beta$$
$$b = -\{[(N_A + N_e) \cdot \tan\delta + C_a] \cdot \cos\beta + [(W_A + W_e) \cdot \sin\beta + F_e] \cdot \sin\beta \cdot \tan\phi + (C + W_P \cdot \tan\phi)\}$$
$$c = [(N_A + N_e) \cdot \tan\delta + C_a] \cdot \sin\beta \cdot \tan\phi$$

Using these concepts, typical design curves for various *FS*-values as a function of equipment ground contact pressure and equipment acceleration can be developed (see Figure 13.10). Note that the curves are developed specifically for the variables stated in the legend. Example 13.3 illustrates the use of the formulation.

EXAMPLE 13.3

The following are given: a 30-m-long slope with uniform cover soil of 300-mm thickness at a unit weight of 18 kN/m³. The soil has a friction angle of 30° and zero cohesion (i.e., it is a sand). It is placed on the slope using a bulldozer moving from the crest of the slope down to the toe. The bulldozer has a ground contact pressure of 30 kN/m² and tracks that are 3.0 m long and 0.6 m wide. The estimated equipment speed is 20 km/hr, and the time to reach this speed is 3.0 seconds. The cover soil to geomembrane friction angle is 22 degrees with zero adhesion. What is the *FS*-value at a slope angle of 3(H)-to-1(V) (i.e., 18.4°)?

Solution Using the design curves of Figure 13.10 along with Equation 13.13, the solution can be obtained.

- From Figure 13.9, at 20 km/hr and 3.0 seconds, the bulldozer's acceleration is 0.19g.
- From Equation 13.13,

$$a = 88.8 \text{ kN/m}$$
$$b = -107.3 \text{ kN/m}$$
$$c = 17.0 \text{ kN/m}$$

Thus, $FS = 1.03$

This value can be confirmed using Figure 13.10.

Comment This problem solution can now be compared with those of the previous two examples:

Example 13.1.	Cover soil along with no bulldozer loading:	$FS = 1.25$
Example 13.2.	Cover soil plus bulldozer moving up slope:	$FS = 1.24$
Example 13.3.	Cover soil plus bulldozer moving down slope:	$FS = 1.03$

The inherent danger of a bulldozer moving down the slope is readily apparent. Note, that the same result comes about by the bulldozer decelerating instead of accelerating. The sharp breaking action of the bulldozer is arguably the more severe condition, due to the extremely short times involved when stopping forward motion. Clearly, only in unavoidable situations should the cover soil placement equipment be allowed to work down the slope. If it is unavoidable, an analysis should be made of the specific stability situation and the construction specifications should reflect the precise conditions made in the design. The maximum weight and ground contact pressure of the equipment should be stated along with suggested operator movement of the cover soil placement operations. Truck traffic on the slopes can also give stresses as high or even higher than illustrated here and should be avoided in all circumstances.

13.4.3 Inclusion of Seepage Forces

The previous sections presented the general problem of slope stability analysis of cover soils placed on slopes under different conditions. The tacit assumption throughout was that either permeable soil or a drainage layer was placed above the barrier layer with adequate flow capacity to efficiently and safely remove permeating water away from the cross section. The amount of water to be removed is obviously a site-specific situation. Note that, in extremely arid areas, or with very low permeability cover soils, drainage may not be required, although this is generally the exception.

Unfortunately, adequate drainage of final covers has sometimes not been available and seepage-induced slope stability problems have occurred. Figure 13.11 shows a final cover slope failure during a heavy raining. The following situations have resulted in seepage-induced slides:

- Drainage soils with hydraulic conductivity (permeability) too low for site-specific conditions.
- Inadequate drainage capacity at the toe of long slopes, where seepage quantities accumulate and are at their

FIGURE 13.11 Final Cover Slope Failure during a Heavy Raining

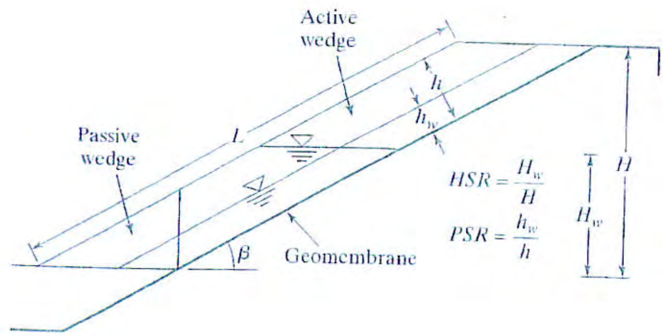
- Fine, cohesionless, cover soil particles migrating through the filter (if one is present) either clogging the drainage layer, or accumulating at the toe of the slope, thereby decreasing the as-constructed outlet permeability over time.
- Freezing of the outlet drainage at the toe of the slope, while the top of the slope thaws, thereby mobilizing seepage forces against the ice wedge at the toe.

If seepage forces of the types described occur, a variation in slope stability design methodology is required. Such an analysis is the focus of this subsection. (See Koerner and Soong, 1998; and Qian, 1997; also, Thiel and Stewart, 1993; and Soong and Koerner, 1996.)

Consider a cover soil of uniform thickness placed directly above a geomembrane at a slope angle of β, as shown in Figure 13.12. What is different from previous examples, however, is that within the cover soil there can exist a saturated soil zone for part or all of the thickness. The saturated boundary is shown as two possibly different phreatic surface orientations. This is because seepage can be built up in the cover soil in two different ways: a horizontal buildup from the toe upward, or a parallel-to-slope buildup outward. These two hypotheses are defined and quantified as a horizontal submergence ratio (HSR) and a parallel submergence ratio (PSR). The dimensional definitions of both ratios are given in Figure 13.12.

When analyzing the stability of slopes using the limit equilibrium method, free-body diagrams of the passive and active wedges are taken with the appropriate forces

FIGURE 13.12 Cross Section of a Uniform Thickness Cover Soil on a Geomembrane Illustrating Different Submergence Assumptions and Related Definitions (Soong and Koerner, 1996)



being applied (now including pore water pressures). The formulation for the resulting factor of safety for horizontal seepage buildup and also for parallel-to-slope seepage buildup is described next.

13.4.3.1 The Case of the Horizontal Seepage Buildup. Figure 13.13 shows the free-body diagram of both the active and passive wedge assuming horizontal seepage building. Horizontal seepage buildup can occur when toe blockage occurs due to inadequate outlet capacity, contamination or physical blocking of outlets, or freezing conditions at the outlets.

All symbols used in Figure 13.13 were previously defined except the following:

γ_{sat} = saturated unit weight of the cover soil
γ_t = dry unit weight of the cover soil
γ_w = unit weight of water
H = vertical height of the slope measured from the toe
H_w = vertical height of the free water surface measured from the toe
U_h = resultant of the pore pressures acting on the interwedge surfaces
U_n = resultant of the pore pressures acting perpendicular to the slope
U_v = resultant of the vertical pore pressures acting on the passive wedge

The expression for determining the factor of safety can be derived as follows:

Considering the active wedge,

$$W_A = \frac{\gamma_{sat} \cdot h \cdot (2 \cdot H_w \cdot \cos\beta - h)}{\sin 2\beta} + \frac{\gamma_{dry} \cdot h \cdot (H - H_w)}{\sin\beta} \quad (13.14)$$

$$U_n = \frac{\gamma_w \cdot h \cdot \cos\beta \cdot (2 \cdot H_w \cdot \cos\beta - h)}{\sin 2\beta} \quad (13.15)$$

$$U_h = 0.5 \cdot \gamma_w \cdot h^2 \quad (13.16)$$

$$N_A = W_A \cdot \cos\beta + U_h \cdot \sin\beta - U_n \quad (13.17)$$

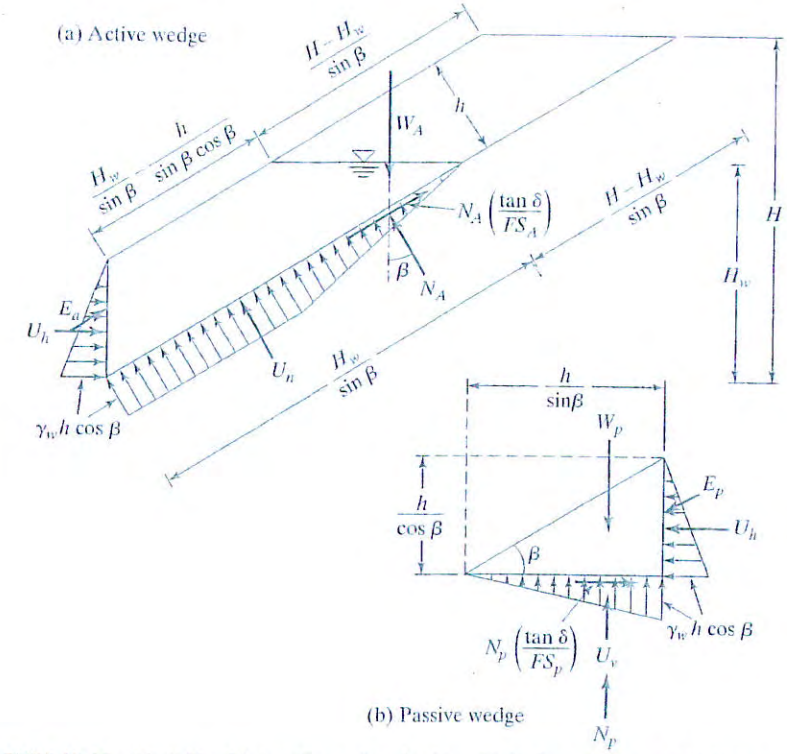


FIGURE 13.13 Limit Equilibrium Forces Involved in a Finite Length Slope of Uniform Cover Soil with Horizontal Seepage Buildup

The interwedge force acting on the active wedge can then be expressed as

$$E_A = W_A \cdot \sin\beta + U_h \cdot \cos\beta - \frac{N_A \cdot \tan\delta}{FS}$$

The passive wedge can be considered in a similar manner and the following expressions result:

$$W_P = \frac{\gamma_{sat} \cdot h^2}{\sin 2\beta} \tag{13.18}$$

$$U_v = U_h \cdot \cot\beta \tag{13.19}$$

The interwedge force acting on the passive wedge can then be expressed as

$$E_P = \frac{U_h \cdot (FS) - (W_P - U_v) \cdot \tan\phi}{\sin\beta \cdot \tan\phi - \cos\beta \cdot (FS)}$$

By setting $E_A = E_P$, the following equation can be arranged in the form of $ax^2 + bx + c = 0$, which in this case is

$$a \cdot FS^2 + b \cdot FS + c = 0$$

The resulting FS-value is then obtained from the conventional solution of the quadratic equation as

$$FS = \frac{-b \pm (b^2 - 4 \cdot a \cdot c)^{0.5}}{2 \cdot a} \tag{13.20}$$

where
$a = W_A \cdot \sin\beta \cdot \cos\beta - U_h \cdot \cos^2\beta + U_h$
$b = -W_A \cdot \sin^2\beta \cdot \tan\phi + U_h \cdot \sin\beta \cdot \cos\beta \cdot \tan\phi - N_A \cdot \cos\beta \cdot \tan\delta - (W_P - U_v) \cdot \tan\phi$
$c = N_A \cdot \sin\beta \cdot \tan\delta \cdot \tan\phi$

13.4.3.2 The Case of Parallel-to-Slope Seepage Buildup. Figure 13.14 shows the free body diagrams of both the active and passive wedges with seepage buildup in the direction parallel to the slope. Parallel seepage buildup can occur when soils placed above a geomembrane are initially too low in their hydraulic conductivity, or become too low due to long-term clogging from overlying soils that are not filtered. The individual forces, friction angles, and slope angles involved in Figure 13.14 are listed as follows:

W_A = weight of the active wedge (area times unit weight), lb/ft or kN/m;
W_P = weight of the passive wedge (area times unit weight), lb/ft or kN/m;
β = angle of the slope, degree;
H = height of the cover soil slope from the toe of the cover soil to the top of the slope (see Figure 13.14), ft or m;
h = thickness of the soil layer (perpendicular to the slope), ft or m;
h_w = depth of seepage water in the soil layer (perpendicular to the slope), ft or m;
γ = moisture unit weight of the soil layer, lb/ft^3 or kN/m^3;
γ_{sat} = saturated unit weight of the soil layer, lb/ft^3 or kN/m^3;
γ_w = unit weight of water, 62.4 lb/ft^3 or 9.81 kN/m^3;
ϕ = friction angle of the cover soil, degree;
δ = interface friction angle between the soil layer and geomembrane, degree;
N_A = normal force acting on bottom of the active wedge, lb/ft or kN/m;
F_A = frictional force acting on bottom of the active wedge, lb/ft;
U_{AN} = resultant of the pore water pressures acting on bottom of the active wedge (perpendicular to the slope), lb/ft or kN/m;
U_{AH} = resultant of the pore water pressures acting on lower lateral side of the active wedge (perpendicular to the interface between the active and passive wedges), lb/ft or kN/m;
E_A = force from passive wedge acting on active wedge (unknown in magnitude but assumed direction parallel to the slope), lb/ft or kN/m;
N_P = normal force acting on the bottom of passive wedge, lb/ft or kN/m;
F_P = frictional force acting on the bottom of passive wedge, lb/ft ...

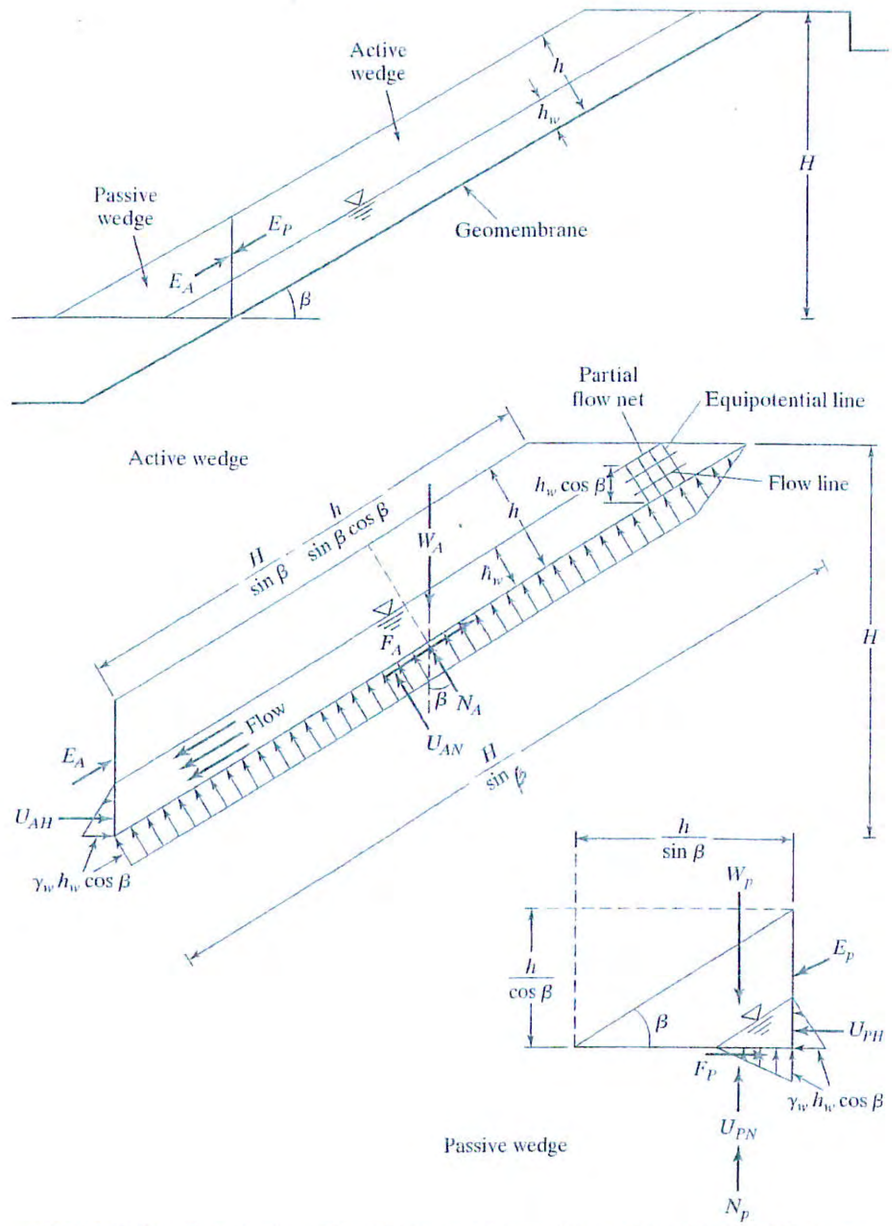


FIGURE 13.14 Cross Section of Sand Layer over Geomembrane on Side Slope with Seepage Parallel to Slope.

U_H = resultant of the pore water pressures acting on lateral side of the active wedge or passive wedge (perpendicular to the lateral side), lb/ft or kN/m. $U_H = U_{AH} = U_{PH}$;

U_{PN} = resultant of the pore water pressures acting on bottom of the passive wedge (perpendicular to bottom of the passive wedge), lb/ft or kN/m;

E_P = force from active wedge acting on passive wedge (unknown in magnitude but assumed direction parallel to the slope), lb/ft or kN/m, $E_A = E_P$;

FS = factor of safety for stability of the cover soil mass.

Considering the force equilibrium of the active wedge (Figure 13.14), we obtain

$\Sigma F_Y = 0$:

$$N_A + U_{AN} = W_A \cdot \cos\beta + U_{AH} \cdot \sin\beta$$

$$N_A = W_A \cdot \cos\beta - U_{AN} + U_{AH} \cdot \sin\beta \tag{13.21}$$

$\Sigma F_X = 0$:

$$F_A + E_A + U_{AH} \cdot \cos\beta = W_A \cdot \sin\beta$$

$$E_A = W_A \cdot \sin\beta - U_{AH} \cdot \cos\beta - F_A \tag{13.22}$$

$$F_A = N_A \cdot \tan\delta / FS \tag{13.23}$$

Substituting Equation 13.21 into Equation 13.23 gives

$$F_A = (W_A \cdot \cos\beta - U_A + U_{AH} \cdot \sin\beta) \cdot \tan\delta / FS \tag{13.24}$$

Substituting Equation 13.24 into Equation 13.22 gives

$$E_A = W_A \cdot \sin\beta - U_{AH} \cdot \cos\beta - (W_A \cdot \cos\beta - U_A + U_{AH} \cdot \sin\beta) \cdot \tan\delta / FS \tag{13.25}$$

Considering the force equilibrium of the passive wedge (Figure 13.14) yields

$$E_P = E_A \tag{13.26}$$

$\Sigma F_Y = 0$:

$$N_P + U_{PN} = W_P + E_P \cdot \sin\beta \tag{13.27}$$

Substituting Equation 13.26 into Equation 13.27 gives

$$N_P = W_P + E_A \cdot \sin\beta - U_{PN} \tag{13.28}$$

Substituting Equation 13.25 into Equation 13.28 gives

$$N_P = W_P - U_{PN} + [W_A \cdot \sin\beta - U_{AH} \cdot \cos\beta - (W_A \cdot \cos\beta - U_A + U_{AH} \cdot \sin\beta) \cdot \tan\delta / FS] \cdot \sin\beta$$

$$N_P = W_P - U_{PN} + W_A \cdot \sin^2\beta - U_{AH} \cdot \sin\beta \cdot \cos\beta - (W_A \cdot \cos\beta - U_A + U_{AH} \cdot \sin\beta) \cdot \sin\beta \cdot \tan\delta / FS \tag{13.29}$$

$\Sigma F_X = 0$:

$$F_P = U_{PH} + E_P \cdot \cos\beta \tag{13.30}$$

Substituting Equation 13.26 into Equation 13.30 gives

$$F_P = U_{PH} + E_A \cdot \cos\beta \tag{13.31}$$

Substituting Equation 13.25 into Equation 13.31 gives

$$F_P = U_{PH} + W_A \cdot \sin\beta \cdot \cos\beta - U_{AH} \cdot \cos^2\beta - (W_A \cdot \cos\beta - U_{AN}$$

$$FS = \frac{N_P \cdot \tan\phi}{F_P} \tag{13.33}$$

Substituting Equations 13.29 and 13.32 into Equation 13.33 gives

$$FS = \frac{(W_P - U_{PN} + W_A \cdot \sin^2\beta - U_{AH} \cdot \sin\beta \cdot \cos\beta) \cdot \tan\phi - (W_A \cdot \cos\beta - U_A + U_{AH} \cdot \sin\beta) \cdot \sin\beta \cdot \tan\delta \cdot \tan\phi / FS}{U_{PH} + W_A \cdot \sin\beta \cdot \cos\beta - U_{AH} \cdot \cos^2\beta - (W_A \cdot \cos\beta - U_{AN} + U_{AH} \cdot \sin\beta) \cdot \cos\beta \cdot \tan\delta / FS}$$

$$(U_{PH} + W_A \cdot \sin\beta \cdot \cos\beta - U_{AH} \cdot \cos^2\beta) \cdot FS - (W_A \cdot \cos\beta - U_{AN} + U_{AH} \cdot \sin\beta) \cdot \cos\beta \cdot \tan\delta = (W_P - U_{PN} + W_A \cdot \sin^2\beta - U_{AH} \cdot \sin\beta \cdot \cos\beta) \cdot \tan\phi - (W_A \cdot \cos\beta - U_A + U_{AH} \cdot \sin\beta) \cdot \sin\beta \cdot \tan\delta \cdot \tan\phi / FS$$

$$(W_A \cdot \sin\beta \cdot \cos\beta + U_{PH} - U_{AH} \cdot \cos^2\beta) \cdot FS^2 - (W_A \cdot \cos\beta - U_{AN} + U_{AH} \cdot \sin\beta) \cdot \cos\beta \cdot \tan\delta \cdot FS = (W_P - U_{PN} + W_A \cdot \sin^2\beta - U_{AH} \cdot \sin\beta \cdot \cos\beta) \cdot \tan\phi \cdot FS - (W_A \cdot \cos\beta - U_A + U_{AH} \cdot \sin\beta) \cdot \sin\beta \cdot \tan\delta \cdot \tan\phi$$

$$(W_A \cdot \sin\beta \cdot \cos\beta + U_{PH} - U_{AH} \cdot \cos^2\beta) \cdot FS^2 - [W_P \cdot \tan\phi + W_A \cdot (\sin^2\beta \cdot \tan\phi + \cos^2\beta \cdot \tan\delta) - U_{AN} \cdot \cos\beta \cdot \tan\delta - U_{PN} \cdot \tan\phi + U_{AH} \cdot \sin\beta \cdot \cos\beta \cdot (\tan\phi - \tan\delta)] \cdot FS + (W_A \cdot \cos\beta - U_A + U_{AH} \cdot \sin\beta) \cdot \sin\beta \cdot \tan\delta \cdot \tan\phi = 0 \tag{13.34}$$

Because $U_H = U_{PH} = U_{AH}$,

$$[W_A \cdot \sin\beta \cdot \cos\beta + U_H \cdot (1 - \cos^2\beta)] \cdot FS^2 - [W_P \cdot \tan\phi + W_A \cdot (\sin^2\beta \cdot \tan\phi + \cos^2\beta \cdot \tan\delta) - U_{AN} \cdot \cos\beta \cdot \tan\delta - U_{PN} \cdot \tan\phi + U_H \cdot \sin\beta \cdot \cos\beta \cdot (\tan\phi - \tan\delta)] \cdot FS + (W_A \cdot \cos\beta - U_{AN} + U_H \cdot \sin\beta) \cdot \sin\beta \cdot \tan\delta \cdot \tan\phi = 0 \tag{13.35}$$

Using $a \cdot x^2 + b \cdot x + c = 0$

The resulting FS can be expressed as

$$FS = \frac{-b \pm (b^2 - 4 \cdot a \cdot c)^{0.5}}{2 \cdot a} \tag{13.36}$$

where

$$a = W_A \cdot \sin\beta \cdot \cos\beta + U_H \cdot (1 - \cos^2\beta)$$

$$b = -[W_P \cdot \tan\phi + W_A \cdot (\sin^2\beta \cdot \tan\phi + \cos^2\beta \cdot \tan\delta) - U_{AN} \cdot \cos\beta \cdot \tan\delta - U_{PN} \cdot \tan\phi + U_H \cdot \sin\beta \cdot \cos\beta \cdot (\tan\phi - \tan\delta)]$$

$$c = (W_A \cdot \cos\beta - U_{AN} + U_H \cdot \sin\beta) \cdot \sin\beta \cdot \tan\delta \cdot \tan\phi$$

$$U_{AN} = \gamma_w \cdot h_w \cdot (H - 0.5\, h_w \cdot \cos\beta)/\tan\beta \tag{13.37}$$

$$U_H = 0.5 \cdot \gamma_w \cdot h_w^2 \tag{13.38}$$

$$U_{PN} = 0.5 \cdot \gamma_w \cdot h_w^2/\tan\beta \tag{13.39}$$

$$W_A = 0.5 \cdot [\gamma \cdot (h - h_w)(2 \cdot H \cdot \cos\beta - h - h_w) + \gamma_{sat} \cdot h_w \cdot (2 \cdot H \cdot \cos\beta - h_w)]/(\sin\beta \cdot \cos\beta) \tag{13.40}$$

$$W_P = 0.5 \cdot [\gamma \cdot (h^2 - h_w^2) + \gamma_{sat} \cdot h_w^2]/(\sin\beta \cdot \cos\beta) \tag{13.41}$$

EXAMPLE 13.4

A 44-ft (13.2-m) high and 3(H):1(V) slope has cover sand with a uniform thickness of 2 ft (0.6 m) at a unit weight of 110 lb/ft^3 (17.3 kN/m^3). The cover sand has a friction angle of 32 degrees and zero cohesion. Seepage occurs parallel to the slope and the seepage water head in the sand layer is 6 inches (0.15 m). The saturated unit weight of sand is 115 lb/ft^3 (18 kN/m^3). The interface friction angle between sand drainage layer and geomembrane is 22 degrees and zero adhesion. What is the factor of safety at a slope of 3(H)-to-1(V)?

Solution The side slope angle is at 18.4° for a 3(H):1(V) slope. Hence,

$\sin\beta = \sin(18.4°) = 0.316,\ \cos\beta = \cos(18.4°) = 0.949,\ \tan\beta = \tan(18.4°) = 0.333.$

$H = 44$ ft (13.2 m), $h = 2$ ft (0.6 m), $h_w = 0.5$ ft (0.15 m), $\gamma = 110$ lb/ft^3 (17.3 kN/m^3),

$\gamma_{sat} = 115$ lb/ft^3 (18 kN/m^3), $\gamma_w = 62.4$ lb/ft^3 (9.81 kN/m^3), $\phi = 32°$, $\delta = 22°$.

$\tan\phi = \tan(32°) = 0.625,\ \tan\delta = \tan(22°) = 0.404.$

$$U_{AN} = \gamma_w \cdot h_w \cdot (H - 0.5\, h_w \cdot \cos\beta)/\tan\beta \qquad (13.37)$$
$$= (62.4)(0.5)[44 - (0.5)(0.5)(0.949)]/(0.333) = 4{,}100.3 \text{ lb/ft } (58.02 \text{ kN/m})$$

$$U_H = 0.5 \cdot \gamma_w \cdot h_w^2 \qquad (13.38)$$
$$= (0.5)(62.4)(0.5)^2 = 7.8 \text{ lb/ft } (0.11 \text{ kN/m})$$

$$U_{PN} = 0.5 \cdot \gamma_w \cdot h_w^2/\tan\beta \qquad (13.39)$$
$$= (0.5)(62.4)(0.5)^2/(0.333) = 23.4 \text{ lb/ft } (0.33 \text{ kN/m})$$

$$W_A = 0.5 \cdot [\gamma \cdot (h - h_w)(2 \cdot H \cdot \cos\beta - h - h_w) + \gamma_{sat} \cdot h_w \cdot (2 \cdot H \cdot \cos\beta - h_w)]/(\sin\beta \cdot \cos\beta) \qquad (13.40)$$
$$= (0.5)\{(110)(2 - 0.5)[(2)(44)(0.949) - 2 - 0.5] + (115)(0.5)[(2)(44)(0.949) - 0.5]\}/[(0.316)(0.949)]$$
$$= (0.5)(13{,}366.98 + 4{,}773.19)/[(0.316)(0.949)] = 30{,}245.3 \text{ lb/ft } (427.6 \text{ kN/m})$$

$$W_P = 0.5 \cdot [\gamma \cdot (h^2 - h_w^2) + \gamma_{sat} \cdot h_w^2]/(\sin\beta \cdot \cos\beta) \qquad (13.41)$$
$$= (0.5)\{(110)[(2)^2 - (0.5)^2] + (115)(0.5)^2\}/[(0.316)(0.949)] = 735.7 \text{ lb/ft } (10.4 \text{ kN/m})$$

Using Equation 13.36,

$$a = W_A \cdot \sin\beta \cdot \cos\beta + U_H \cdot (1 - \cos^2\beta)$$
$$= (30{,}245.3)(0.316)(0.949) + (7.8)[1 - (0.949)^2] = 9{,}071 \text{ (128 for SI units)}$$

$$b = -[W_P \cdot \tan\phi + W_A \cdot (\sin^2\beta \cdot \tan\phi + \cos^2\beta \cdot \tan\delta) - U_{AN} \cdot \cos\beta \cdot \tan\delta - U_{PN} \cdot \tan\phi + U_H \cdot \sin\beta \cdot \cos\beta \cdot (\tan\phi - \tan\delta)]$$
$$= -\{(735.7)(0.625) + (30{,}245.3)[(0.316)^2(0.625) + (0.949)^2(0.104)] - (4{,}100.3)(0.949)(0.404) - (23.4)(0.625) + (7.8)(0.316)(0.949)(0.625 - 0.404)\}$$
$$= -(459.8 + 12{,}892.1 - 1{,}572.0 - 14.6 + 0.5) = -11{,}766 \text{ } (-166 \text{ for SI units})$$

$$c = (W_A \cdot \cos\beta - U_{AN} + U_H \cdot \sin\beta) \cdot \sin\beta \cdot \tan\delta \cdot \tan\phi$$
$$= [(30{,}245.3)(0.949) - 4{,}100.3 + (7.8)(0.316)](0.316)(0.625)(0.404) = 1{,}963 \text{ (28 for SI units)}$$

$$FS = \frac{-b \pm (b^2 - 4 \cdot a \cdot c)^{0.5}}{2 \cdot a} \qquad (13.36)$$

$$11{,}766 \pm [(-11{,}766)^2 - (4)(9{,}071)(1{,}963)]^{0.5}$$

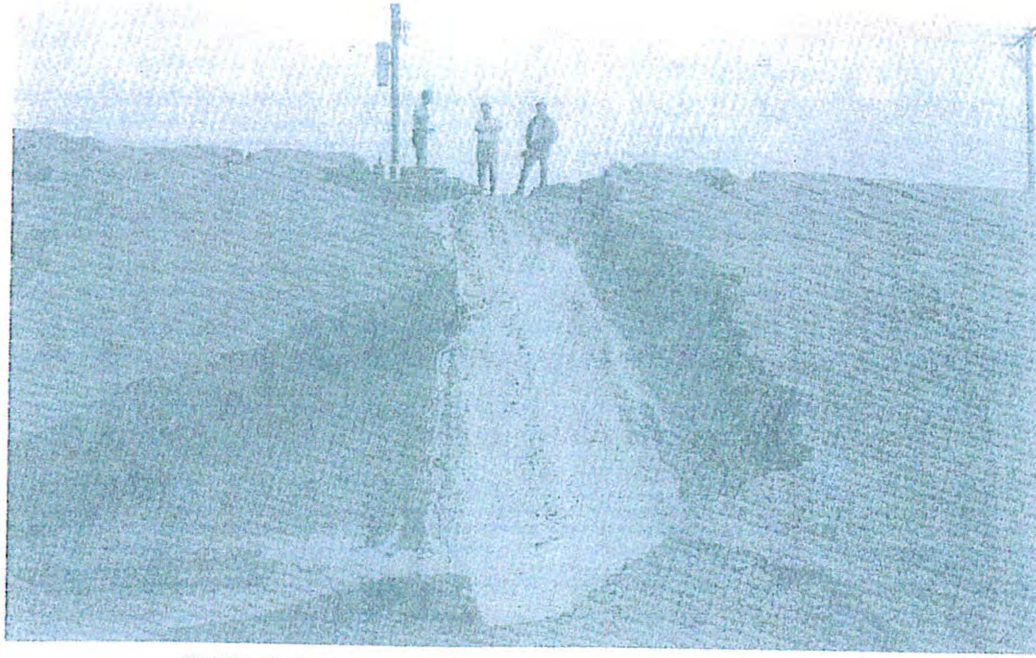


FIGURE 13.15 Sand Layer Failure along Sideslope Caused by Seepage Force

$$= \frac{11{,}766 + 8{,}198}{(2)(9{,}071)}$$
$$= 1.10$$

Comment The seriousness of seepage forces in a slope of this type is immediately obvious. Had the saturation been 100% of the drainage layer thickness, the FS-value would have been still lower. Furthermore, the result using a horizontal assumption of saturated cover soil with the same saturation ratio will give essentially identical low *FS*-values. Clearly, the teaching of this example problem is that adequate long-term drainage above the barrier layer in cover soil slopes must be provided to avoid seepage forces from occurring. Figure 13.15 shows a sand layer sliding failure along sideslope caused by seepage force.

An incremental placement method should be implemented for sideslopes higher than the maximum height that can be built in a single lift with a minimum required factor of safety, such as the previous example. Based on the incremental placement method, the first step is to place the sand drainage layer on the sideslope to the maximum unsupported height. As waste is filled against the sideslope to approximately 2 feet (0.6 m) below the protective layer, the next lift of the layer can proceed. This procedure that is illustrated in Figure 13.16 should be continued until the protective layer reaches the top of the sideslope. The heights of the following lifts of the sand drainage layer should not be higher than the calculated maximum unsupported height minus 2

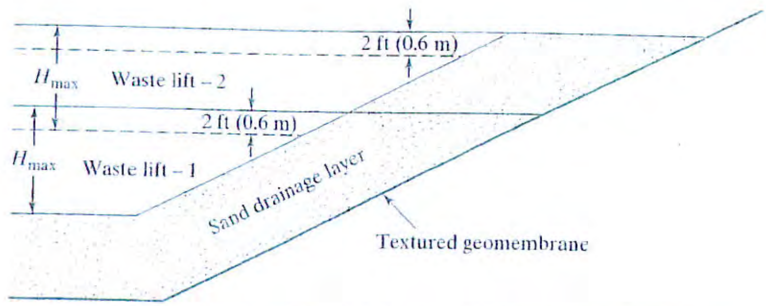


FIGURE 13.16 Incremental Placement of Soil Drainage Layer on Sideslope

feet (0.6 m). The height of the first lift of sand placement can be calculated as shown in the equations that follow (Qian, 1997):

In U.S. units,

$$H = (H_{total} - 2)/n + 2 \tag{13.42}$$

In SI units,

$$H = (H_{total} - 0.6)/n + 0.6 \tag{13.43}$$

where H = height of the first step of sand placement on the sideslope (see Figure 13.14), ft or m;
H_{total} = total height of the cover sand slope from the toe of the cover sand to the top of the slope (see Figure 13.16), ft or m;
n = number of the placement steps.

EXAMPLE 13.5

Continue the calculations of Example 13.4 and use the incremental method to achieve a factor of safety no less than 1.2 for the cover sand resting on the sideslope?

Solution Use the incremental method to place drainage sand on the side slope to achieve a minimum factor of safety of 1.2. Try three steps of sand placement (n = 3) on the sideslope.

$$H = (H_{total} - 2)/n + 2 \tag{13.42}$$
$$= (44 - 2)/3 + 2 = 14 + 2 = 16 \text{ ft } (4.8 \text{ m})$$

So,

H = 16 ft (4.8 m), h = 2 ft (0.6 m), h_w = 0.5 ft (0.15 m), γ = 110 lb/ft^3 (17.3 kN/m^3),

γ_{sat} = 115 lb/ft^3 (18 kN/m^3), γ_w = 62.4 lb/ft^3 (9.81 kN/m^3), ϕ = 32°, δ = 22°.

$\tan\phi = \tan(32°) = 0.625$, $\tan\delta = \tan(22°) = 0.404$,

$$U_{AN} = \gamma_w \cdot h_w \cdot (H - 0.5\ h_w \cdot \cos\beta)/\tan\beta \tag{13.37}$$

$$= (62.4)(0.5)[16 - (0.5)(0.5)(0.949)]/(0.333) = 1{,}476.9\ \text{lb/ft}\ (20.90\ \text{kN/m})$$

$$U_H = 0.5 \cdot \gamma_w \cdot h_w^{\ 2} \tag{13.38}$$

$$= (0.5)(62.4)(0.5)^2 = 7.8\ \text{lb/ft}\ (0.11\ \text{kN/m})$$

$$U_{PN} = 0.5 \cdot \gamma_w \cdot h_w^{\ 2}/\tan\beta \tag{13.39}$$

$$= (0.5)(62.4)(0.5)^2/(0.333) = 23.4\ \text{lb/ft}\ (0.33\ \text{kN/m})$$

$$W_A = 0.5 \cdot [\gamma \cdot (h - h_w)(2 \cdot H \cdot \cos\beta - h - h_w) + \gamma_{sat} \cdot h_w \cdot (2 \cdot H \cdot \cos\beta - h_w)]/(\sin\beta \cdot \cos\beta) \tag{13.40}$$

$$= (0.5)\{(110)(2 - 0.5)[(2)(16)(0.949) - 2 - 0.5] + (115)(0.5)[(2)(16)(0.949) - 0.5]\}/[(0.316)(0.949)]$$

$$= (0.5)(4{,}598.22 + 1{,}717.41)/[(0.316)(0.949)] = 10{,}530.1\ \text{lb/ft}\ (148.9\ \text{kN/m})$$

$$W_P = 0.5 \cdot [\gamma \cdot (h^2 - h_w^{\ 2}) + \gamma_{sat} \cdot h_w^2]/(\sin\beta \cdot \cos\beta) \tag{13.41}$$

$$= (0.5)\{(110)[(2)^2 - (0.5)^2] + (115)(0.5)^2\}/[(0.316)(0.949)] = 735.7\ \text{lb/ft}\ (10.4\ \text{kN/m})$$

Equation 13.36 yields

$$a = W_A \cdot \sin\beta \cdot \cos\beta + U_H \cdot (1 - \cos^2\beta)$$

$$= (10{,}530.1)(0.316)(0.949) + (7.8)[1 - (0.949)^2] = 3{,}159\ (45\ \text{for SI units})$$

$$b = -[W_P \cdot \tan\phi + W_A \cdot (\sin^2\beta \cdot \tan\phi + \cos^2\beta \cdot \tan\delta) - U_{AN} \cdot \cos\beta \cdot \tan\delta - U_{PN} \cdot \tan\phi + U_H \cdot \sin\beta \cdot \cos\beta \cdot (\tan\phi - \tan\delta)]$$

$$= -\{(735.7)(0.625) + (10{,}530.1)[(0.316)^2(0.625) + (0.949)^2(0.404)] - (1{,}476.9)(0.949)(0.404) - (23.4)(0.625) + (7.8)(0.316)(0.949)(0.625 - 0.404)\}$$

$$= -(459.8 + 4{,}488.5 - 566.2 - 14.6 + 0.5) = -4{,}368\ (-62\ \text{for SI units})$$

$$c = (W_A \cdot \cos\beta - U_{AN} + U_H \cdot \sin\beta) \cdot \sin\beta \cdot \tan\delta \cdot \tan\phi$$

$$= [(10{,}530.1)(0.949) - 1{,}476.9 + (7.8)(0.316)](0.316)(0.625)(0.404) = 680\ (10\ \text{for SI units})$$

$$FS = \frac{-b \pm (b^2 - 4 \cdot a \cdot c)^{0.5}}{2 \cdot a} \tag{13.36}$$

$$= \frac{4{,}368 + [(-4{,}368)^2 - (4)(3{,}159)(680)]^{0.5}}{(2)(3{,}159)}$$

$$= \frac{4{,}368 + 3{,}238}{(2)(3{,}159)}$$

$$= 1.20$$

Thus, based on the above calculation, the first step is to place the drainage sand on the sideslope to a height of 16 feet (4.8 m). As waste is filled against the sideslope to approximately 2 feet (0.6 m) below the protective layer, the next lift of 14 feet (4.2 m) can be placed. This procedure should be continued until the protective layer reaches the top of the sideslope.

13.4.4 Inclusion of Seismic Forces

In areas of anticipated earthquake activity, the slope stability analysis of a final cover soil over an engineered landfill, abandoned dump, or remediated site must consider seismic forces. In the United States, the Environmental Protection Agency (EPA)

Reference 3

Dozer Specifications from Manufacturer

D5C LGP	
1 kW	90 HP
00 kg	19,800 lb
—	
3204	
2400	
4	
4 mm	4.5"
7 mm	5"
;.2 L	318 in³
6	
;0 mm	26"
.14 m	7'0.4"
83 m²	4389 in²
.72 m	5'8"
.75 m	5'9.2"
.72 m	8'11"
.07 m	13'4"
.99 m	9'9.8"
—	
:.38 m	7'10"
1.4 mm	14.2"
—	
—	
3.26 m	10'8"
2.95 m	9'8"
167 L	44 U.S. gal

ator. D3C LGP Series II

MODEL	D4H LGP Series III		D5H LGP Series II		D6D LGP		D6H LGP Series II	
Flywheel Power	86 kW	116 HP	97 kW	130 HP	104 kW	140 HP	127 kW	170 HP
Operating Weight*								
(Power Shift)	12 196 kg	26,830 lb	15 337 kg	33,818 lb	17 373 kg	38,300 lb	19 814 kg	43,590 lb
(Direct Drive)	12 356 kg	27,180 lb	15 419 kg	33,999 lb	—		19 969 kg	43,976 lb
(Power Shift Differential Steer)	—		—		—		20 060 kg	44,131 lb
Engine Model	3304		3304		3306		3306	
Rated Engine RPM	2200		2200		1900		1900	
No. of Cylinders	4		4		6		6	
Bore	121 mm	4.75"	121 mm	4.75"	121 mm	4.75"	121 mm	4.75"
Stroke	152 mm	6"	152 mm	6"	152 mm	6"	152 mm	6"
Displacement	7 L	425 in³	7 L	425 in³	10.5 L	638 in³	10.5 L	638 in³
Track Rollers (Each Side)	7		8		7		8	
Width of Standard Track Shoe	760 mm	30"	860 mm	34"	910 mm	36"	915 mm	36"
Length of Track on Ground	2.62 m	8'7"	3.12 m	10'3"	2.87 m	9'5"	3.27 m	10'8.5"
Ground Contact Area (W/Std. Shoe)	3.98 m²	6170 in²	5.37 m²	8320 in²	5.25 m²	8136 in²	5.97 m²	9254 in²
Track Gauge	2.00 m	6'6"	2.16 m	7'1"	2.11 m	6'9"	2.23 m	7'3"
GENERAL DIMENSIONS:								
Height (Stripped Top)**	2.20 m	7'3"	2.30 m	7'6.5"	2.05 m	6'8"	2.32 m	7'7"
Height (To Top of ROPS Canopy)	3.63 m	9'11.4"	3.12 m	10'3"	2.92 m	9'7.5"	3.16 m	10'5"
Height (To Top of Cab ROPS)	—		3.18 m	10'5"	—		3.16 m	10'5"
Overall Length (With P Blade)	4.77 m	15'8"	5.30 m	17'6.3"	—		5.18 m	17'0"
(Without Blade)	—		4.13 m	13'7"	—		4.49 m	14'9"
Overall Length (With S Blade)	—		—		5.16 m	16'11"	—	
(Without Blade)	—		—		3.94 m	12'11"	—	
Width (Over Trunnion)	—		3.26 m	10'8.4"	—		3.43 m	11'3"
Width (W/O Trunnion — Std. Shoe)	2.76 m	9'1"	3.02 m	9'11"	—		3.14 m	10'3.6"
Width (With Standard Shoe)	—		—		3.02 m	9'11"	—	
Ground Clearance	363 mm	14.3"	529 mm	20.8"	310 mm	12.2"	382 mm	15"
Blade Types and Widths:								
Straight	3.26 m	10'8.2"	3.65 m	12'0"	3.71 m	12'2"	3.99 m	13'1"
Angle	—		—		—		—	
Power Angle & Tilt	—		3.98 m	13'0.1"	—		—	
"P" Straight	3.26 m	10'8.2"	—		—		—	
Angled	3.00 m	9'10.1"	3.66 m	11'11.9"	—		—	
Fuel Tank Refill Capacity	200 L	52 U.S. gal	246 L	65 U.S. gal	295 L	78 U.S. gal	337 L	89 U.S. gal

*Operating Weight includes lubricants, coolant, full fuel tank, straight bulldozer, hydraulic controls and fluid, ROPS canopy and operator and rigid drawbar. D5H Series II with P-blade.

**Height (stripped top) — without ROPS canopy, exhaust, seat back or other easily removed encumbrances.

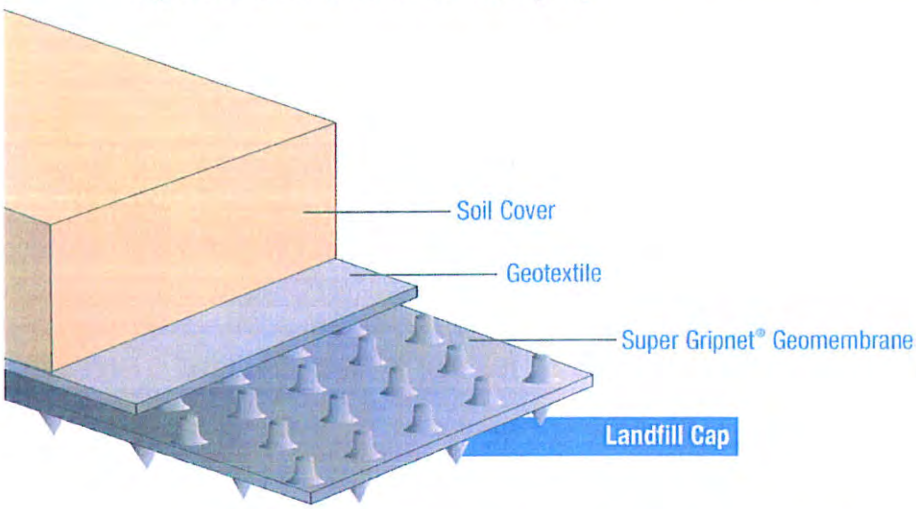
Note: D4H LGP Series III has P-blade.

REF 4

Super Gripnet® Geomembrane

Applications for HDPE and LLDPE Agru Super Gripnet® include projects where drainage and high interface friction as well as cost savings are critical i.e. landfill caps, landfill slopes and mining reclamation projects. Recent bids for installations have indicated cost savings of over $3,000.00 per acre with the use of Super Gripnet® as a replacement for traditional geocomposite overlying a textured geomembrane.

Agru America's structured geomembranes are manufactured on state-of-the-art manufacturing equipment using a flat cast extrusion manufacturing process as opposed to blown film extrusion. Agru America uses only the highest grade of HDPE and LLDPE resins manufactured in North America. The structured geomembrane is manufactured by a continuous horizontal flat die extrusion into profile rollers. The machined rollers give the product the final structured surface with drainage studs and spikes which are an integral (homogenous) part of the liner and have a smooth edge for on site welding. This process provides a consistent core thickness resulting in higher sheet tensile strength, consistent high profile texturing resulting in higher interface friction capabilities as well as consistent drain capacity.



Interface Shear – Cap Loading Conditions ASTM D 5321

Soil/Grip Liner Surface	P	LD
Coarse Sand	35°	31°
Glacial Till	38°	34°
Silty Sand	28°	26°
Non Woven GT	31°	26°

Soil/Drain Liner Surface with GT		
Coarse Sand	30°	φ= 30°

Note: The above values are representative friction angles only. It is recommended that site specific conformance testing be carried out using the actual soils, geosynthetics and loading conditions for a specific project.

P = Maximum or Peak Interface Shear Value in degrees
LD = Large Displacement Interface Shear Value in degrees
GT = Geotextile

Super Gripnet® Geomembrane

- Combines Drainage with Shear Resistance
- High Water Flow Rate on Top Side
- Spike/Texture Bottom
- Consistent Drain and Structure Pattern
- Combine with Smooth
- Combine with Fabric

US Patent - No. 5.258.217

The machine rollers provide the final structured surface with a 3.6 mm (0.145 in.) high studded drain surface on the top side and 4.4 mm (0.175 in.) high spiked friction surface on the bottom side. The 7 m (23 ft.) wide rolls of finished product include a smooth edge on both sides of the roll for ease of thermal welding in the field. Due to the molded structure, core thickness does not vary as with blown film textured sheet, thus mechanical properties of the sheet are not affected. In addition, the consistent high profile texture insures optimum interface friction characteristics at any point on the sheet surface.

The top surface integral drain structure consists of 3.2 mm (0.13 in.) diameter studs 3.6 mm (0.145 in.) in height and spaced on a diamond pattern of 12.5 mm (0.5 in.) spacing. A filter/protection geotextile is required to be placed on the drain profile. The geotextile is heat set on one side (placed against the drain structure) to reduce intrusion into the drain. Large-scale flow rate testing with this configuration, overlying soils and expected normal loads resulted in high planar flow rates.

The bottom spiked friction surface with 4.4 mm (0.175 in.) high spikes and patterned texture provides maximum interface friction and high factor of safety against sliding.

Thus, the Super Gripnet® Liner is a synthetic drainage media which has decided advantages over conventional geocomposites:

- ***Cost Savings*** – The drain media and liner are one and installed as one panel
  – No waste due to fitting of geocomposite sections or discarding roll ends
- ***Improved Planar Flow*** – Less reduction for chemical/biological clogging considerations
- ***Consistent Material*** – Studs and spikes (drainage and friction) totally integrated with the geomembrane
- ***High Interface Shear*** –Exceptional shear resistance between soil & geotextile components allows flexibility and stability during protective cover material placement
- ***Meets/exceeds Project Requirements*** – Excellent fluid barrier
  – Excellent drainage medium
  – Excellent friction characteristics

Agru's Super Gripnet® geomembrane is a high performance liner system with integrated top surface drainage supplying the functional needs for any project with the added benefit of substantial cost savings.

Why specify or use anything else!

Agru has over 20 years experience with Geomembranes and 50 years experience with Thermoplastic Extrusion Agru offers a wide range of concrete protective liners (Sure Grip), pipe fittings and semi-finished materials.

Executive Offices: 500 Garrison Road, Georgetown, SC 29440 843-546-0600 800-321-1379 Fax: 843-546-0516
Sales Office: 700 Rockmead, Suite 150, Kingwood, TX 77339 281-358-4741 800-373-2478 Fax: 281-358-5297
email: salesmkg@agruamerica.com www.agruamerica.com

Golder Associates

CALCULATIONS

Date:	July 24, 2013	**Prepared by:**	S. Stafford
Project No.:	123-82639	**Checked by:**	HRC 8/5/2013
Subject:	ETM/TRLF Final Cover Geosynthetics/FL	**Reviewed by:**	DGM 3/18/2015
Project Short Title:	**FINAL COVER - GEOCOMPOSITE TRANSMISSIVITY TRAIL RIDGE LANDFILL**		

OBJECTIVE

Determine the required transmissivity of geocomposite for final cover based on the designed drainage layer of 1.0 feet (30 cm) of sand with a hydraulic conductivity of 1.0×10^{-3} cm/sec.

REFERENCES

1. "Designing with Geosynthetics"; Koerner, 4th Edition
2. "Design of Lateral Drainage Systems for Landfills", Giroud, Richardson, & Zhao, 2000.
3. "Determination of the Allowable Flow Rate of a Drainage Geocomposite", GRI Standard GC8
4. "The Myth of Hydraulic Transmissivity Equivalency Between Geosynthetic and Granular Liquid Collection Layers", Giroud et. al., 2000

METHOD AND CALCULATIONS

TRANSMISSIVITY OF NATURAL DRAINAGE LAYER (SAND)

The transmissivity of the designed sand drainage layer is calculated using the following equation:

$$\theta_{SAND} = k \cdot t$$

Where:

θ_{SAND}= Transmissivity of sand layer, m^2/sec

k = sand hydraulic conductivity = 1.0×10^{-3} cm/sec = 1.0×10^{-5} m/sec

t = thickness of drainage layer = 1 foot = 30 cm = 0.3 m

Therefore, the transmissivity of the sand drainage layer (θ_{SAND}) is 3.0×10^{-6} m^2/sec.

Using a drainage factor of safety of 2 for the sand drainage layer, the allowable transmissivity ($\theta_{ALLOW\ SAND}$) of the natural drainage layer is 6.0×10^{-6} m^2/sec.

EQUIVALENCY OF GEOSYNTHETIC AND NATURAL DRAINS

Equivalency between the natural sand drainage layer and a drainage geocomposite must take into consideration the flow gradients and flow depths. The thicker natural drainage layer can support larger gradients and flow depth, therefore the minimum transmissivity of the drainage geocomposite must be greater than the transmissivity of the natural drainage layer by an equivalence factor (E).

The equivalence factor (E) for a natural drainage layer having a maximum flow depth of 30 cm (1ft) is calculated using the following equation (Giroud, et. al.):

$$E \cong \frac{1}{0.88}\left[1 + \left(\frac{1}{0.88 * L}\right)\left(\frac{\cos\beta}{\tan\beta}\right)\right]$$

Where:

L = Slope length = 575 ft = 175 m

β = Slope of drainage layers = 4.0% = 2.3°

Therefore, the equivalence factor (E) is 1.32.

The required transmissivity of the geocomposite is therefore calculated as:

$$\theta_{REQ\ GEO} = \theta_{ALLOW\ SAND} * E$$

$\theta_{REQ\ GEO}$ = 7.9x10^{-6} m^2/sec

The allowable transmissivity ($\theta_{GEO\ ALLOW}$) of the geocomposite can be calculated from the following equation:

$$\theta_{GEO\ ALLOW} = \theta_{GEO\ REQ} \cdot FS_D \cdot RF_{CR} \cdot RF_{IN} \cdot RF_{CC} \cdot RF_{BC}$$

Where:

$\theta_{GEO\ ALLOW}$ = Allowable Geocomposite Transmissivity, m^2/sec

$\theta_{GEO\ REQ}$ = Required Geocomposite Transmissivity = 7.9x10^{-6} m^2/sec

FS_D = Drainage Factor of Safety = 2.0

RF_{CR} = Reduction factor of long-term creep = 1.4

RF_{IN} = Reduction factor of intrusion = 1.2

RF_{CC} = Reduction factor for chemical clogging = 1.5

RF_{BC} = Reduction factor for biological clogging = 1.2

Therefore the allowable transmissivity ($\theta_{GEO\ ALLOW}$) is 4.8x10^{-5} m^2/sec.

The specified transmissivity of the geocomposite (or geosynthetic drainage layer) should be set equal to or greater than the allowable transmissivity. Agru 50-mil LLDPE Super Gripnet Liner with 8 oz. non-woven geotextile has an estimated transmissivity ranging from 1.2x10^{-3} to 9.8x10^{-4} m^2/sec.

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