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Veneer Stability Analyses for SCA Final Cover Design

Beech and Bonaparte
engineering p.c.

an affiliate of Geosyntec Consultants

CALCULATION PACKAGE COVER SHEET

Client: Honeywell **Project:** Onondaga Lake SCA Final Cover Design **Project/Proposal #:** GD5497

TITLE OF COMPUTATIONS **VENEER STABILITY ANALYSES FOR SCA FINAL COVER DESIGN**

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APPROVAL NOTES:

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Written by:	**Ray Wu / Clinton Carlson**	Date:	**09/11/15**	Reviewed by:	**Ali Ebrahimi / Jay Beech**	Date:	**09/11/15**
Client:	**Honeywell**	Project:	**Onondaga Lake SCA Final Cover Design**	Project/ Proposal No.:	**GD5497**	Task No.:	**03**

VENEER STABILITY ANALYSES FOR SCA FINAL COVER DESIGN

INTRODUCTION

This package was prepared in support of the final cover design for the Sediment Consolidation Area (SCA). This package presents the static veneer slope stability analysis for the proposed SCA final cover.

Seismic stability was not evaluated based on the requirements defined by New York State Department of Environmental Conservation (NYSDEC) Regulations Section 360-2.7(b)(7) [NYSDEC, 1988]. A detailed explanation regarding the seismic impact zone assessment was presented in Attachment 1 of the NYSDEC approved calculation package titled "*Slope Stability Analyses for SCA Design*" [Geosyntec, 2011], referred to herein as the "Slope Stability Package".

METHODOLOGY

Static Slope Stability

Slope stability of a final cover system can be analyzed by assuming infinite slope or finite slope methods. The infinite slope method considers an infinite slope length whereby driving and resisting forces occur only parallel to an interface (i.e., slip plane). The finite slope method considers a finite slope length and additionally takes into account the toe-buttressing effect. The veneer stability analyses in this package were performed using a finite slope method, using the equations proposed by Giroud et al. [1995].

$$FS = \left[\frac{\gamma_t (t - t_w) + \gamma_b t_w}{\gamma_t (t - t_w) + \gamma_{sat} t_w}\right]\frac{\tan\delta}{\tan\beta} + \frac{a / \sin\beta}{\gamma_t (t - t_w) + \gamma_{sat} t_w}$$
$$+ \left[\frac{\gamma_t (t - t^*) + \gamma_b t^*}{\gamma_t (t - t_w) + \gamma_{sat} t_w}\right]\left[\frac{\tan\phi / (2\sin\beta\cos^2\beta)}{1 - \tan\beta\tan\phi}\right]\frac{t}{h}$$
$$+ \left[\frac{1}{\gamma_t (t - t_w) + \gamma_{sat} t_w}\right]\left[\frac{1 / (\sin\beta\cos\beta)}{1 - \tan\beta\tan\phi}\right]\frac{ct}{h} \quad (1)$$

where:
- FS = factor of safety;
- δ = critical interface friction angle;
- a = critical interface adhesion intercept;
- ϕ = soil internal friction angle;
- c = soil cohesion intercept;
- γ_t = soil total unit weight;
- γ_{sat} = saturated soil unit weight;
- γ_b = buoyant soil unit weight = $\gamma_{sat} - \gamma_w$;
- γ_w = unit weight of water;
- t = depth of cover soil above critical interface;
- t_w = water depth above critical interface;
- t^* = water depth at the toe of slope;
- β = slope inclination; and
- h = vertical height of slope.

While the above equation is specifically for an interface above a geomembrane or similar layers, it can also be applied to interfaces below the geomembrane by changing the coefficient of the first term, (i.e., the coefficient of tan δ / tan β) to 1.0. The slope geometry, which is used to derive the above equation, is shown in Figure 1. It is noted that tension in the geosynthetics (T) has conservatively not been included in the above equation or analyses presented herein.

Target Factor of Safety

Target factors of safety (FSs) were selected for the veneer stability of the proposed SCA final cover using interface peak and residual shear strengths. The selected target FS values were 1.5 and 1.2 for peak and residual shear strengths, respectively, which is consistent with general engineering practice. The analyses were performed by solving the finite slope stability equation (i.e., Equation 1) for various combinations of internal/interface shear strength parameters (i.e., "δ" and "a" for above and below a geomembrane) corresponding to the target FS. By using this method, minimum acceptable internal/interface shear strength parameters for the cover system components could be established.

SCA SIDE SLOPE GEOMETRY

Veneer stability analyses were performed for the side slopes along the main and top decks of the proposed SCA final cover. Based on the design grades of the final cover, as shown in Figure 2, the maximum side slopes of the main and top decks are 3.33 horizontal to 1 vertical (3.33H:1V or slope angle $\beta = 16.7°$) and 4H:1V (or slope angle $\beta = 14.0°$), respectively. Additionally, the slope heights for the veneer analyses in the main and top decks are approximately 30 ft and 8 ft, respectively. It is noted that the main and top decks have very gentle slopes (i.e., approximately 1.0%), therefore veneer stability of these areas was not evaluated.

MATERIAL PROPERTIES

Final Cover System along the SCA Side Slopes

The proposed final cover system along the SCA side slopes is shown in Figure 3 and consists of the following layers, from bottom to top:

- Leveling layer;
- Geotextile cushion layer;
- 40-mil textured linear low-density polyethylene (LLDPE) geomembrane (GM);
- 200-mil single-sided geocomposite (top deck side slopes) or 250-mil double-sided geocomposite (main deck side slopes) drainage layer with drainage collection pipes spaced approximately every 100 ft;
- 18-inch thick protective soil layer; and
- 6-inch thick vegetative soil layer.

The required interface shear strength properties are back-calculated to be used as part of quality control during the construction phase, therefore, the assumed type of GM is not expected to impact the veneer stability results. The protective soil and vegetative soil layers are modeled as a single 24-inch thick soil layer above the GM. This soil layer was modeled with a total and saturated unit weight of 120 pcf. The shear strength parameters of the final cover soils were modeled with a friction angle of 30 degrees and cohesion intercept of zero. These parameters are typical values used in general engineering practice and are consistent with those used in the Slope Stability Package.

Depth of Water t_w

The water depth in the drainage layer (t_w) was computed using the "Hydraulic Evaluation of Landfill Performance" (HELP) software, Version 3.07, developed by the U.S. Environmental Protection Agency [Schroeder, 1994]. More detailed information on the use of HELP is presented in the calculation package titled "Evaluation of Hydraulic Performance for SCA Final Cover Design" (hereafter referred to as the "HELP package"). The highest daily value for the average water depth (i.e., average peak daily water depth) on the main deck side slopes with a 250-mil double-sided geocomposite was calculated by HELP to be 0.14 inches (0.012 ft). The average peak daily water depth on the top deck side slopes was conservatively assumed to be approximately 0.2 inches (0.017 ft), which is equivalent to the thickness of a 200-mil geocomposite used on the 1% slope of the top deck.

RESULTS OF ANALYSES

The peak and residual interface shear strength parameters (i.e., friction angle, δ, and adhesion, *a*) for the final cover interface that meet the target FS values were calculated using an Excel spreadsheet (see Tables 1 and 2). Results of the static veneer slope stability analyses for the final cover system are presented in Tables 3 and 4 and in Figures 4 through 7. Figure 4 and Figure 5 represent various combinations of peak and residual internal/interface shear strength parameters (i.e., δ and *a*) required to achieve stability for a calculated static FS of 1.5 and 1.2, respectively, on the main deck side slopes. Figure 6 and Figure 7 represent various combinations of peak and residual internal/interface shear strength parameters (i.e., δ and *a*) required to achieve stability for a calculated static FS of 1.5 and 1.2, respectively, on the top deck side slopes. A verification of the calculation spreadsheet is included in Attachment 1. These required parameters can be achieved with commercially available textured LLDPE geomembranes.

SENSITIVITY ANALYSIS

An effective friction angle of 20 degrees with a cohesion intercept of zero for the final cover soil was also considered to evaluate the sensitivity of the back-calculated interface shear strength to the shear strength of the cover soil. As shown in Figure 8, the impact of the effective friction angle of the final cover soil on the calculated interface/internal shear strength parameters for the cover system components is minimal. Therefore, the recommendations based on the effective friction angle of 30 degrees for the cover soil are considered acceptable and practical for back calculation of the interface shear strength parameters of the final cover components. The acceptable range of interface shear strength parameters of the final cover components is included in the SCA Final Cover Project Specifications.

SUMMARY AND CONCLUSIONS

Results of the final cover system veneer slope stability analysis indicated that a combination of peak internal/interface shear strength of δ and *a* as shown in Figure 4 and Figure 6, and a combination of residual internal/interface shear strength of δ and *a* as shown in Figure 5 and Figure 7 are required to maintain a calculated FS of 1.5 and 1.2, respectively. These required properties correspond to an effective normal stress of approximately 240 psf for the top and main decks at the interface of geosynthetic components of the final cover due to the weight of the protective soil and vegetative soil layers.

The minimum requirements for internal/interface shear strength parameters for the final cover in Figures 4 through 7 can be achieved with commercially available textured LLDPE geomembranes. Prior to construction of the final cover system, the internal/interface shear strength properties of the soil and geosynthetic materials selected for use should be verified by performing site-specific interface shear strength testing and approved by the Design Engineer.

REFERENCES

Geosyntec Consultants, "Appendix G: *Slope Stability Analyses for SCA Design*," Onondaga Lake Sediment Consolidation Area Final Design, April 2011.

Giroud, J.P., Bachus, R.C., and Bonaparte, R., "Influence of Water Flow on the Stability of Geosynthetic-Soil Layered Systems on Slopes," Geosynthetics International, Vol. 2, No. 6, 1995, pp. 1149-1180.

New York State Department of Environmental Conservation (NYSDEC). "Landfill Construction Requirements, Subpart 360-2.7(b)(7)," Effective Date December 31, 1988.

Schroeder, P.R., et al. *"The Hydrologic Evaluation of Landfill Performance (HELP) Model: Engineering Documentation for Version 3"*, EPA/600/9-94/xxx, U.S. EPA Risk Reduction Engineering Laboratory, Cincinnati, OH, 1994.

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Tables

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Table 1. Sample Back Calculation of Peak Interface Strength (zero cohesion) of SCA Final Cover System on the Main Deck Side Slopes with FS = 1.5

Onondaga Lake SCA Final Design		
Finite Slope Equation [Giroud et. al., 1995]		
FS Above GEOMEMBRANE		
Input Parameters:		
γ_t (Moist soil unit weight):	120	pcf
γ_{sat} (Saturated soil unit weight):	120	pcf
γ_w (Unit wt of water):	62.4	pcf
γ_b (Buoyant unit wt of soil):	57.6	pcf
t_w (water depth above critical interface):	0.012	ft
t* (water depth at slope toe):	0.012	ft
δ (interface friction angle):	***23.0***	deg
ϕ (soil internal friction angle):	30	deg
a (interface adhesion intercept):	***0.0***	psf
c (soil cohesion intercept):	0	psf
h (vertical height of slope):	30	ft
t (depth of cover soil above critical interface):	2.0	ft
β (slope inclination):	16.7	deg
FS:	**1.50**	
FS Below GEOMEMBRANE		
Input Parameters:		
γ_t (Moist soil unit weight):	120	pcf
γ_{sat} (Saturated soil unit weight):	120	pcf
γ_w (Unit wt of water):	62.4	pcf
γ_b (Buoyant unit wt of soil):	57.6	pcf
t_w (water depth above critical interface):	0.012	ft
t* (water depth at slope toe):	0.012	ft
δ (interface friction angle):	***23.0***	deg
ϕ (soil internal friction angle):	30	deg
a (interface adhesion intercept):	***0.0***	psf
c (soil cohesion intercept):	0	psf
h (vertical height of slope):	30	ft
t (depth of cover soil above critical interface):	2.0	ft
β (slope inclination):	16.7	deg
FS:	**1.50**	

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Table 2. Sample Back Calculation of Residual Interface Strength (zero cohesion) of SCA Final Cover System on the Main Deck Side Slopes with FS = 1.2

Onondaga Lake SCA Final Design
Finite Slope Equation [Giroud et. al., 1995]

FS Above GEOMEMBRANE

Input Parameters:		
γ_t (Moist soil unit weight):	120	pcf
γ_{sat} (Saturated soil unit weight):	120	pcf
γ_w (Unit wt of water):	62.4	pcf
γ_b (Buoyant unit wt of soil):	57.6	pcf
t_w (water depth above critical interface):	0.012	ft
t* (water depth at slope toe):	0.012	ft
δ (interface friction angle):	***18.5***	deg
ϕ (soil internal friction angle):	30	deg
a (interface adhesion intercept):	***0.0***	psf
c (soil cohesion intercept):	0	psf
h (vertical height of slope):	30	ft
t (depth of cover soil above critical interface):	2.0	ft
β (slope inclination):	16.7	deg
FS:	**1.20**	

FS Below GEOMEMBRANE

Input Parameters:		
γ_t (Moist soil unit weight):	120	pcf
γ_{sat} (Saturated soil unit weight):	120	pcf
γ_w (Unit wt of water):	62.4	pcf
γ_b (Buoyant unit wt of soil):	57.6	pcf
t_w (water depth above critical interface):	0.012	ft
t* (water depth at slope toe):	0.012	ft
δ (interface friction angle):	***18.5***	deg
ϕ (soil internal friction angle):	30	deg
a (interface adhesion intercept):	***0.0***	psf
c (soil cohesion intercept):	0	psf
h (vertical height of slope):	30	ft
t (depth of cover soil above critical interface):	2.0	ft
β (slope inclination):	16.7	deg
FS:	**1.20**	

Table 3. Minimum Required Peak and Residual Interface Shear Strength for the Final Cover System on the Main Deck Side Slopes

Peak		**Residual**	
Friction Angle δ (°)	Adhesion *a* (psf)	Friction Angle δ (°)	Adhesion *a* (psf)
23	0	19	0
12	49	10	36
0	98	0	77

Note:

Additional combinations of friction angle and adhesion may be used as shown in Figures 4 and 5 for peak and residual shear strengths, respectively.

Table 4. Minimum Required Peak and Residual Interface Shear Strength for the Final Cover System on the Top Deck Side Slopes

Peak		**Residual**	
Friction Angle δ (°)	Adhesion *a* (psf)	Friction Angle δ (°)	Adhesion *a* (psf)
16	0	12	0
8	33	6	24
0	66	0	49

Note:

Additional combinations of friction angle and adhesion may be used as shown in Figures 6 and 7 for peak and residual shear strengths, respectively.

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Figures

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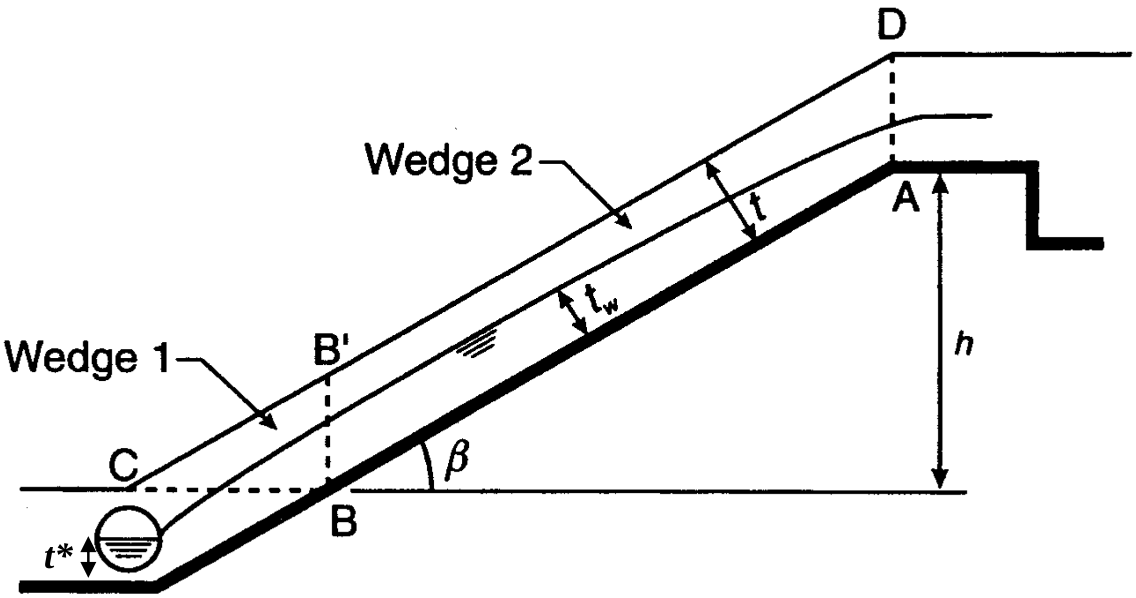

Figure 1. Slope Geometry used to derive Veneer Finite Slope Stability Equation [Giroud et al, 1995]

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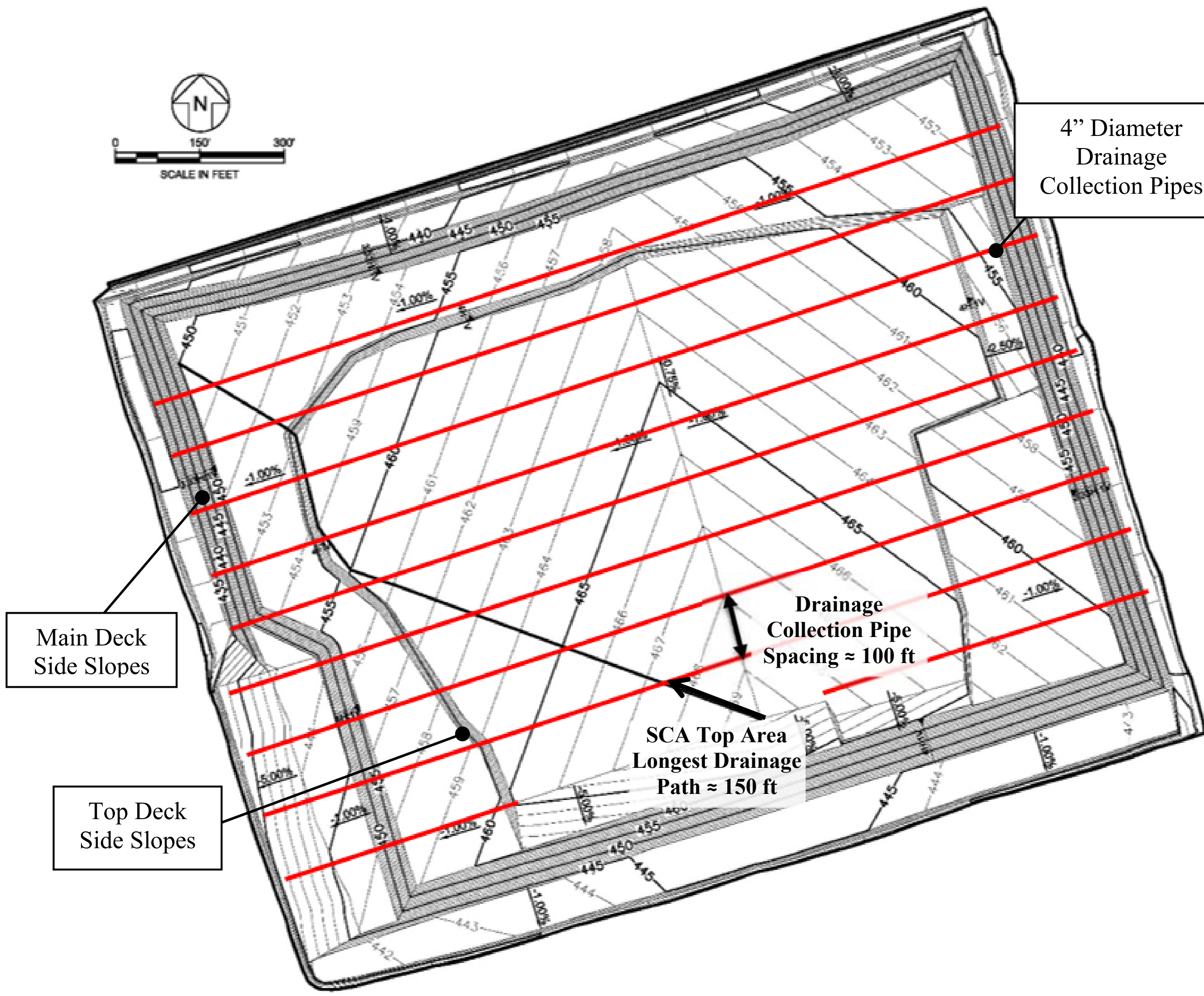

Figure 2. Design Grading Plan for the SCA Final Cover with Drainage Collection Pipe Layout

Note: The grading plan shown here is based on a topographic survey of the SCA conducted December 7, 2014.

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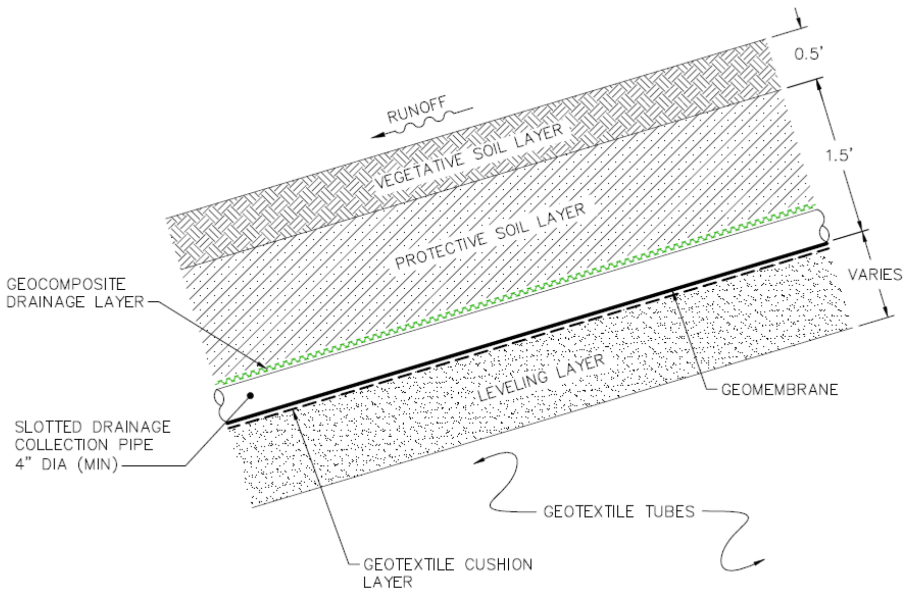

Figure 3. SCA Final Cover System Components of the SCA Side Slopes

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MINIMUM REQUIRED PEAK INTERFACE / INTERNAL SHEAR STRENGTH FOR COVER SYSTEM GEOSYNTHETICS

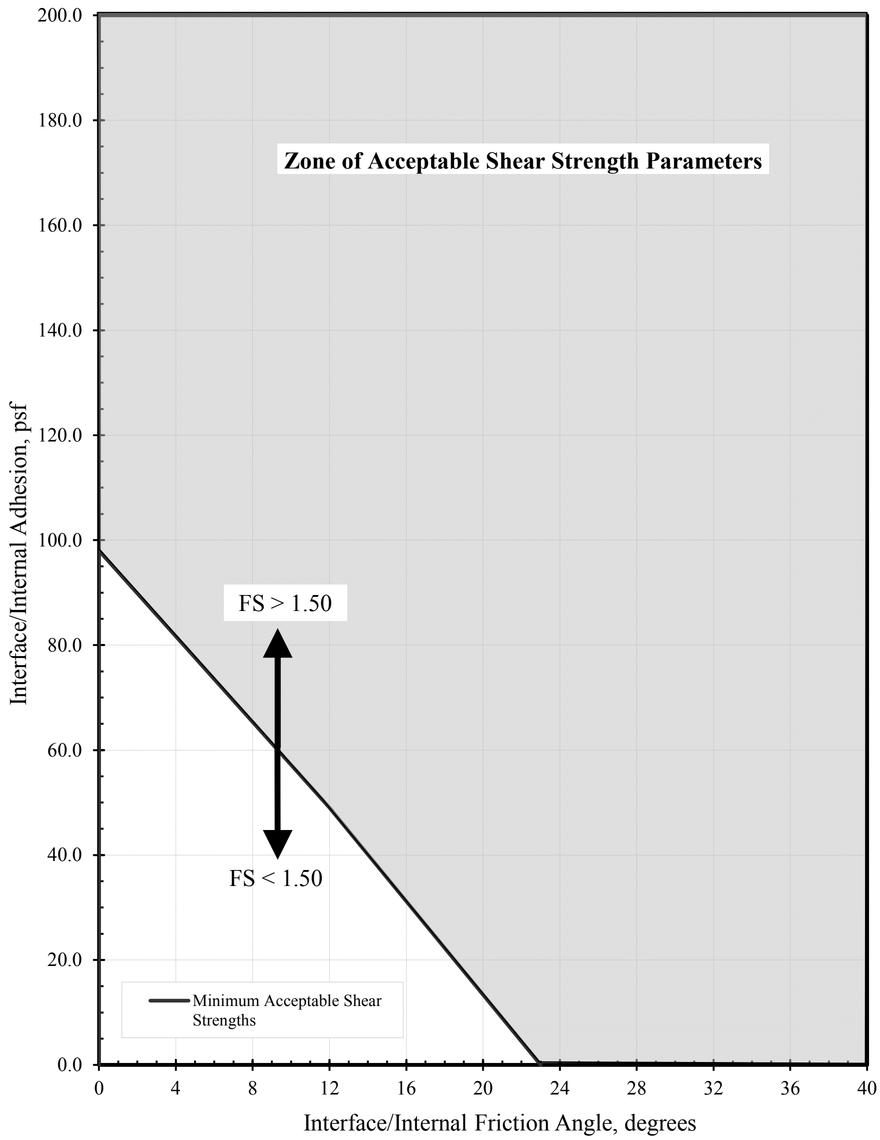

Figure 4. Acceptable Zone of Peak Interface/Internal Shear Strength Parameters for Final Cover System Components on Main Deck Side Slopes
(Effective friction angle of 30° was assumed for the final cover soil)

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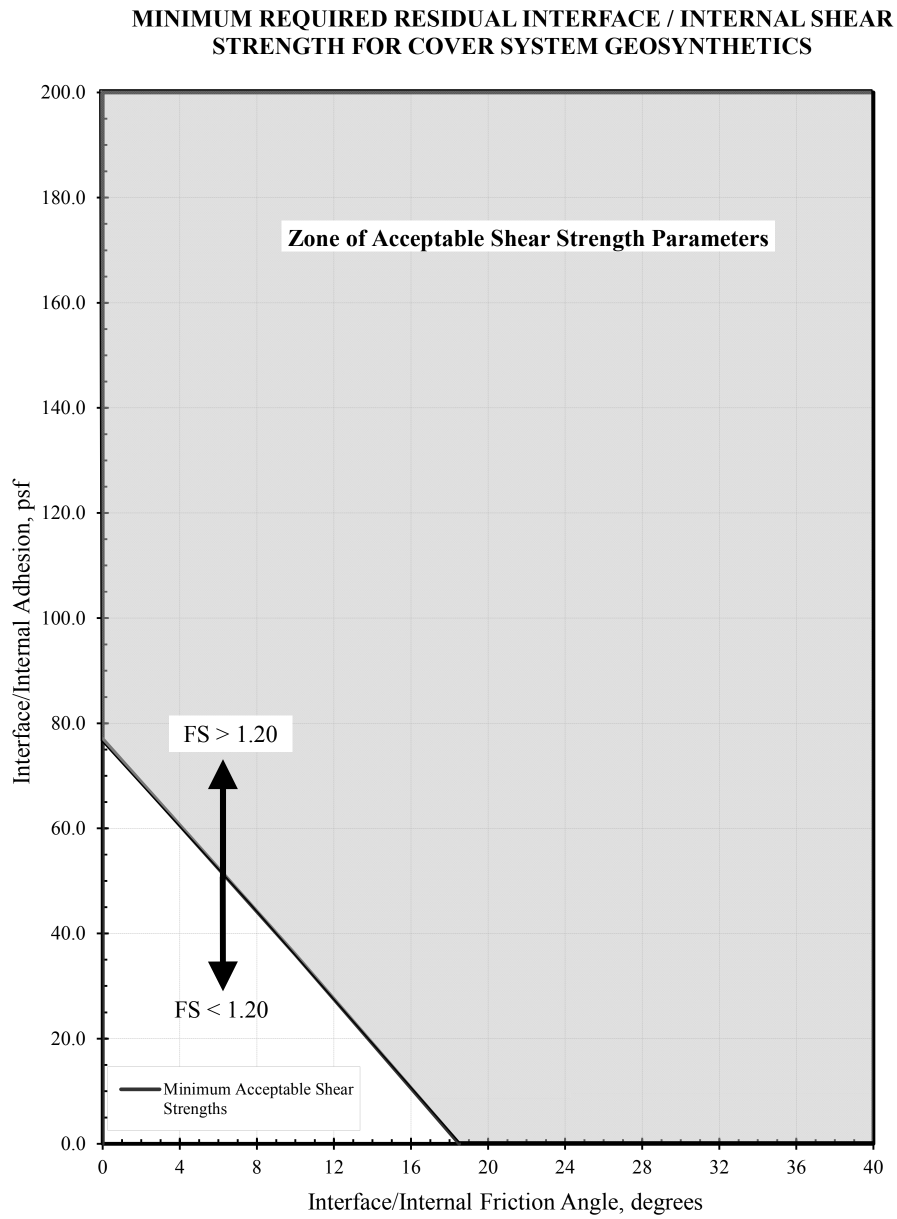

Figure 5. Acceptable Zone of Residual Interface/Internal Shear Strength Parameters for Final Cover System Components on Main Deck Side Slopes
(Effective friction angle of 30° was assumed for the final cover soil)

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MINIMUM REQUIRED PEAK INTERFACE / INTERNAL SHEAR STRENGTH FOR COVER SYSTEM GEOSYNTHETICS

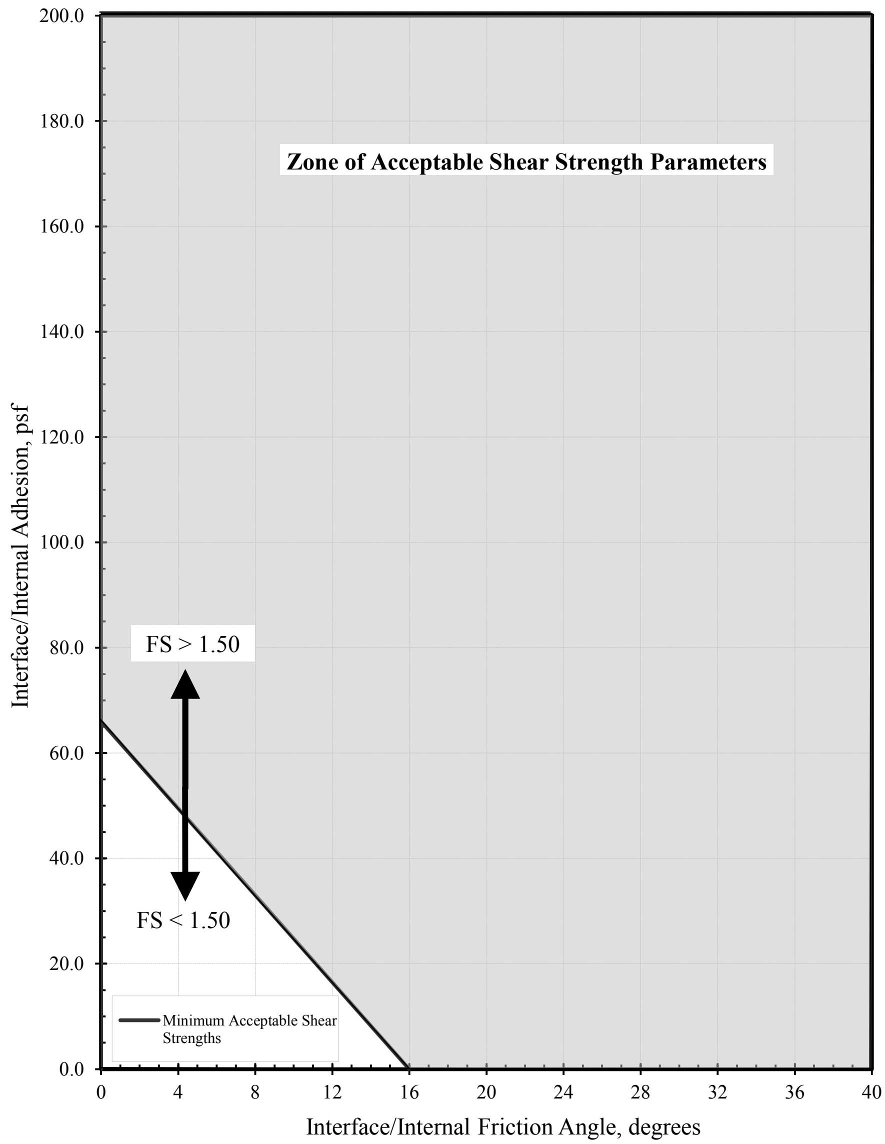

Figure 6. Acceptable Zone of Peak Interface/Internal Shear Strength Parameters for Final Cover System Components on Top Deck Side Slopes
(Effective friction angle of 30° was assumed for the final cover soil)

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MINIMUM REQUIRED RESIDUAL INTERFACE / INTERNAL SHEAR STRENGTH FOR COVER SYSTEM GEOSYNTHETICS

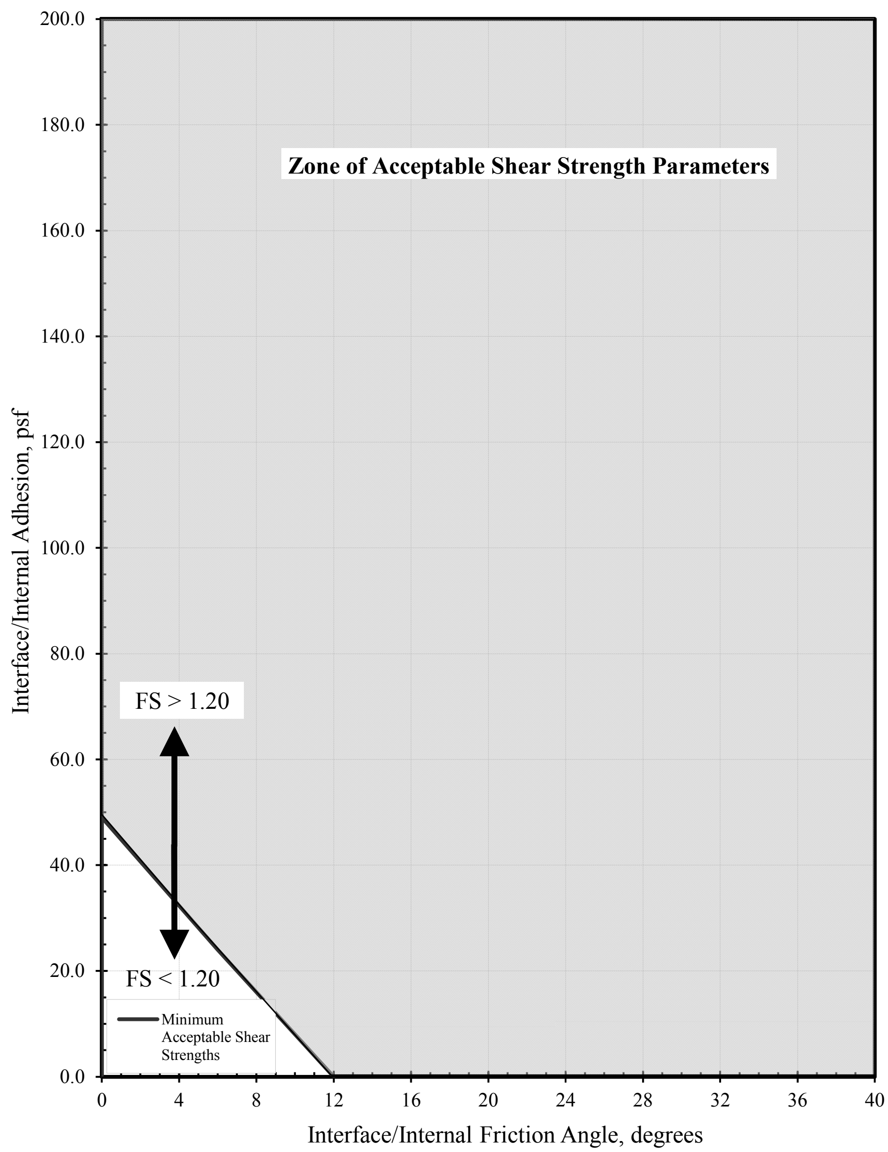

Figure 7. Acceptable Zone of Residual Interface/Internal Shear Strength Parameters for Final Cover System Components on Top Deck Side Slopes
(Effective friction angle of 30° was assumed for the final cover soil)

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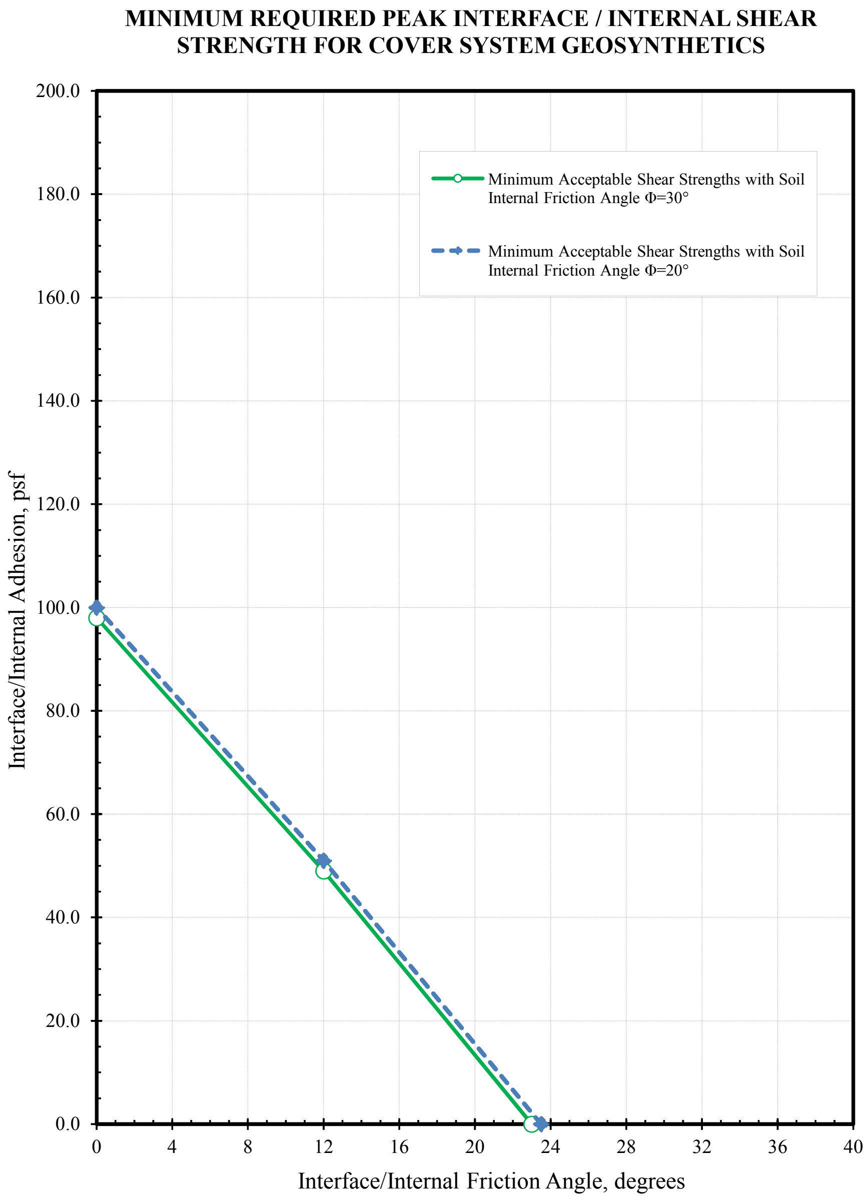

Figure 8. Sensitivity of Required Peak Interface/Internal Shear Strength Parameters with Respect to Soil Internal Friction Angle for Main Deck Side Slopes

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Attachment 1: Verification of Excel Spreadsheet

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FS Above GEOMEMBRANE

Input Parameters:		
γ_t (Moist soil unit weight):	120	pcf
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t_w (water depth above critical interface):	0.012	ft
t* (water depth at slope toe):	0.012	ft
δ (interface friction angle):	*23.0*	deg
ϕ (soil internal friction angle):	30	deg
a (interface adhesion intercept):	*0.0*	psf
c (soil cohesion intercept):	0	psf
h (vertical height of slope):	30	ft
t (depth of cover soil above critical interface):	2.00	ft
β (slope inclination):	16.7	deg
FS:	1.50	

$$FS = \left[\frac{\gamma_t(t-t_w)+\gamma_b t_w}{\gamma_t(t-t_w)+\gamma_{sat}t_w}\right]\frac{\tan\delta}{\tan\beta} + \frac{a/\sin\beta}{\gamma_t(t-t_w)+\gamma_{sat}t_w}$$
$$+\left[\frac{\gamma_t(t-t^*)+\gamma_b t^*}{\gamma_t(t-t_w)+\gamma_{sat}t_w}\right]\left[\frac{\tan\phi/(2\sin\beta\cos^2\beta)}{1-\tan\beta\tan\phi}\right]\frac{t}{h}$$
$$+\left[\frac{1}{\gamma_t(t-t_w)+\gamma_{sat}t_w}\right]\left[\frac{1/(\sin\beta\cos\beta)}{1-\tan\beta\tan\phi}\right]\frac{ct}{h}$$

$$FS = \left[\frac{120*(2.00-0.012)+57.6*0.012}{120*(2.00-0.012)+120*0.012}\right]*\frac{\tan(23.0^o)}{\tan(16.7^o)}+\frac{0.00/\sin(16.7^o)}{120*(2.00-0.012)+120*0.012}$$
$$+\left[\frac{120*(2.00-0.012)+57.6*0.012}{120*(2.00-0.012)+120*0.012}\right]\left[\frac{\tan(30^o)/(2*\sin(16.7^o)*\cos(16.7^o)\wedge 2)}{1-(\tan(16.7^o)*\tan(30^o))}\right]*\frac{2.00}{30}$$
$$+\left[\frac{1}{120*(2.00-0.012)+120*0.012}\right]\left[\frac{1/(\sin(16.7^o)*\cos(16.7^o))}{1-(\tan(16.7^o)*\tan(30^o))}\right]*\frac{0*2.00}{30}$$

$$FS = \left[\frac{239.2512}{240}\right]*\frac{0.4245}{0.3000}+\frac{0}{240}$$
$$+\left[\frac{239.2512}{240}\right]\left[\frac{1.095}{0.827}\right]*\frac{2.00}{30.0}$$
$$+\left[\frac{1}{240}\right]\left[\frac{3.633}{0.827}\right]*\frac{0.00}{30.0}$$

FS = 1.41+0.00+0.09+0.00 = 1.50

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β (slope inclination):	16.7	deg
FS:	1.50	

$$FS = \left[\frac{\gamma_t(t-t_w)+\gamma_b t_w}{\gamma_t(t-t_w)+\gamma_{sat} t_w}\right]\frac{\tan\delta}{\tan\beta} + \frac{a/\sin\beta}{\gamma_t(t-t_w)+\gamma_{sat}t_w} + \left[\frac{\gamma_t(t-t^*)+\gamma_b t^*}{\gamma_t(t-t_w)+\gamma_{sat}t_w}\right]\left[\frac{\tan\phi/(2\sin\beta\cos^2\beta)}{1-\tan\beta\tan\phi}\right]\frac{t}{h} + \left[\frac{1}{\gamma_t(t-t_w)+\gamma_{sat}t_w}\right]\left[\frac{1/(\sin\beta\cos\beta)}{1-\tan\beta\tan\phi}\right]\frac{ct}{h}$$

Note: For FS below the geomembrane, set coefficient of tan(δ)/tan(β)=1.0, as discussed in the text.

$$FS = [\ 1.0\ ] * \frac{\tan(23.0^o)}{\tan(16.7^o)} + \frac{0.00/\sin(16.7^o)}{120*(2.00-0.012)+120*0.012}$$
$$+\left[\frac{120*(2.00-0.012)+57.6*0.012}{120*(2.00-0.012)+120*0.012}\right]\left[\frac{\tan(30^o)/(2*\sin(16.7^o)*\cos(16.7^o)^\wedge 2)}{1-(\tan(16.7^o)*\tan(30^o))}\right]*\frac{2.00}{30}$$
$$+\left[\frac{1}{120*(2.00-0.012)+120*0.012}\right]\left[\frac{1/(\sin(16.7^o)*\cos(16.7^o))}{1-(\tan(16.7^o)*\tan(30^o))}\right]*\frac{0*2.00}{30}$$

$$FS = [\ 1.0\ ] * \frac{0.424}{0.300} + \frac{0}{240}$$
$$+\left[\frac{239.2512}{240}\right]\left[\frac{1.095}{0.827}\right]*\frac{2.00}{30.0}$$
$$+\left[\frac{1}{240}\right]\left[\frac{3.633}{0.827}\right]*\frac{0.00}{30.0}$$

FS = 1.41+0.00+0.09+0.00 = 1.50