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Development of graphical design charts for the stability of veneer cover system

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ABSTRACT: Two types of design charts based on deterministic and reliability-based analyses are produced for determining the interface shear strength required for the stability of cover system to achieve the target safety factor of 1.5 and failure probability of 1×10^{-2}. The deterministic design chart enables the selection of different types of geosynthetics for lining materials based on the required interface shear strength for stability, while the reliability-based design chart enhances decision-making by including the uncertainties in the design parameters, such as variability associated with different types of interface materials. The design chart can also be used to determine the optimum slope angle for a containment facility that will satisfy both the targets factor of safety and probability of failure.

1 INTRODUCTION

Veneer cover soil in containment facilities such as landfills, dams and liquid impoundments involves geosynthetic-soil layered system, which consists of either single or multiple layers of geosynthetics and soils. One of the design criteria for veneer cover soil is to ensure that no slippage occurs between the layers during and after construction. Instability can be caused by the weight of the cover soil, equipment loadings, seepage forces within the cover soil, and/or seismic forces in seismic active areas. Numerous researchers have introduced and adopted different methods to counter instability such as tapered cover soil, toe berms, reinforcement and modifying the geometry of the facility. They have analysed the stability using simple limit equilibrium wedge method for preliminary design to relatively cumbersome finite element methods for forensic studies.

In this paper, the limit equilibrium wedge method with modified formulations from Giroud et al. (1995) are used to produce the design charts. A design chart provides an explicit graphical solution, which can be useful for preliminary design. It depicts the behavior of a system if a significant design parameter changes and thus, assists in determining the optimum design. A deterministic design chart is created initially as a first step to producing a reliability-based design chart that incorporate the uncertainties in the significant parameters to the veneer cover soil stability.

2 MODIFIED LIMIT EQUILIBRIUM WEDGE METHOD

Unlike most researchers who defined the factor of safety in the limit equilibrium two-wedge method as the ratio between the assumed and mobilized values of the strength parameters, Giroud et al. (1995) defined the factor of safety in the two wedge method as the ratio of the resistance over the driving forces. Their proposed formulations are adopted for the development in this paper because they are computationally simpler and involve less geometric manipulation. However, the formulations are modified so that the terms are expressed as shear strengths rather than individual shear parameters of friction angle and cohesion or adhesion. This modification allows more flexibility in choosing lining materials of different strength characteristics.

The modified formulations inherit similar limitations and assumptions as those asserted in Giroud et al. (1995), which include uniform thickness of the cover soil, dry conditions, no other slippage occurs except at the weakest interface and the contribution of geosynthetics tensile strengths to stability are ignored.

2.1 *Definitions and formulations*

Some of the definitions used in the formulations are self-explanatory in the schematic diagram shown in Figure 1. Other definitions which are used throughout the paper are as follows:

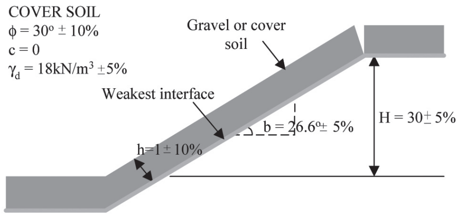

Figure 1. Schematic diagram of the veneer cover soil showing parameter values used as base case in the examples.

- γ_d : Dry unit weight of cover soil (kN/m^3);
- δ : Interface friction angle (°);
- α : Apparent adhesion of interface (kPa);
- τ_{IN} : Interface shear strength defined in Equation (3) (kPa);
- ϕ : Friction angle of the cover soil (°);
- c : Cohesion of the cover soil (kPa);
- τ_{soil} : Shear strength of the cover soil defined in Equation (4) (kPa);
- FS : Factor of safety against sliding (–);
- V[…] : Coefficient of variation defined as the ratio of standard deviation over the mean value of the parameter stated in the bracket (–);
- β : reliability index (–);
- $\Phi(...)$: standard normal distribution function;
- μ_{FS} : mean value of FS (–);
- σ_{FS} : standard deviation of FS (–).

The following factor of safety used to produce the design charts is derived using a similar force diagram to the one given in Giroud et al. (1995).

$$FS = \frac{\alpha + \gamma_d h \cos b \tan \delta}{\gamma_d h \sin b} + \frac{c + \dfrac{\gamma_d h}{2 \cos b} \tan \phi}{\gamma H \sin b (\cos b - \sin b \tan \phi)} \quad (1)$$

Equivalently,

$$FS = \frac{\tau_{IN}}{\gamma_d h \sin b} + \frac{\tau_{soil}}{\gamma H \sin b (\cos b - \sin b \tan \phi)} \quad (2)$$

where,

$$\tau_{IN} = \alpha + \gamma_d h \cos b \tan \delta \quad (3)$$

$$\tau_{soil} = c + \frac{\gamma_d h}{2 \cos b} \tan \phi \quad (4)$$

In order to avoid infinite values of calculated FS (e.g., ϕ = 60° and b = 30°), the denominator of the second term in Equation (2) is maximized with slope angle, which would result in a conservative FS. In a sensitivity analysis which is not included in this paper, this assumption yields insignificant differences of less than 0.01 compared to FS values calculated using the stated Equation (2). However, this is only true for friction angles of cover soil, ϕ, not greater than 40°, cohesion of cover soil, c, not greater than 5 kPa, and slope angles, b, between 15° and 32°, γ_d between 17 to 20 kN/m^3, but for any height, H, and thickness of cover soil, h. Any design parameters that fall outside these ranges will result in higher FS values than using the stated Equation (2), and therefore, overly conservative. A chart of maximum values for the denominator of the second term in Equation (2) is illustrated in Figure 2.

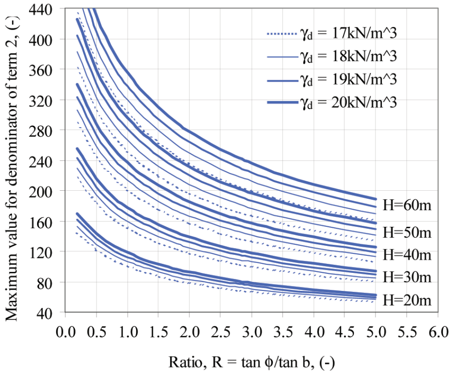

Figure 2. Maximum value for the denominator of term 2 in Equation (2).

3 DETERMINISTIC DESIGN CHART

To produce a deterministic design chart, a parametric study was conducted to evaluate the significant parameters for the veneer stability model. A design parameter was varied in its normal range stated in Table 1, with other parameters kept at the base case values. The parameters that change FS less than 5% of the target FS of 1.5 within their ranges (i.e., 1.425 < FS < 1.575), are considered to be insignificant. These parameters include friction angle, ϕ, and cohesion, c, of cover soil, height of the facility, H, and dry unit weight of cover soil, γ_d. For a reliability-based design chart, insignificant parameters are kept at constant mean values.

Figure 3 shows a deterministic design chart for veneer cover stability for cover height, H, and thickness, h, of 30 m and 1 m, respectively. The applications of the deterministic design chart are illustrated in Section 3.1. The deterministic design chart enables the selection of different types of geosynthetics for lining materials based on the required interface shear strength for stability. Therefore, one can choose easily the suitable and economical geosynthetic materials for use as liner, that will satisfy the minimum requirement of safety against sliding. Additionally, one can also optimize landfill capacity by adopting the highest possible slope angle that satisfies safety against sliding, given that the site and lining materials have been selected. However, one major limitation of the deterministic design chart is

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Table 1. Normal ranges for deterministic parametric study (the bold values are the varied normal range).

	H (m)	b (°)	γ_d (kN/m^3)	ϕ (°)	c (kPa)	h (m)	δ (°)	α (kPa)
Base	30	26.6	18	30	0	1	22.8	5
H	**20-50**	26.6	18	30	0	1	22.8	5
b	30	**15-50**	18	30	0	1	22.8	5
γ_d	30	26.6	**16-20**	30	0	1	22.8	5
ϕ	30	26.6	18	**25-45**	0	1	22.8	5
c	30	26.6	18		**0-10**	1	22.8	5
h	30	26.6	18	30	0	**0.2-2**	22.8	5
δ	30	26.6	18	30	0	1	**15-35**	5
α	30	26.6	18	30	0	1	22.8	**0-10**

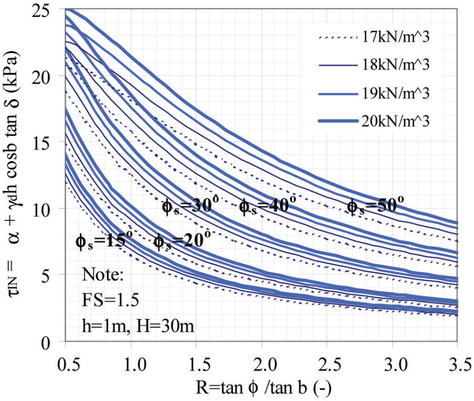

Figure 3. Deterministic design chart for stability of veneer cover soil.

that it does not consider the uncertainty associated with each design parameter, and therefore, the resulting FS of 1.5 is ambiguous.

3.1 *Application and Examples*

Example 1(a) – Selection of liner materials:
Given the veneer cover configuration in Figure 1, R is calculated as 1.15, which results in the required interface shear strength, τ_{IN}, of 11.8 kPa using Figure 3. Some examples of interface shear strength parameters satisfying τ_{IN} of 11.8 kPa to achieve factor of safety of 1.5 are stated in Table 2. Therefore, any geosynthetics materials that have the combination of interface shear parameters stated in Table 2 are suitable as lining materials.

Table 2. Interface shear strength parameters to achieve τ_{IN} = 11.5 kPa.

Interface adhesion, α (kPa)	Interface friction angle, δ (°)
0	36.2
2	31.2
5	22.8
10	6.3

Example 1(b) – Optimizing landfill capacity:
A few iterations are required in order to obtain the maximum allowable slope angle for the landfill that satisfies FS of 1.5 against sliding. The iteration steps are as follows:

Step 1 : Assume an initial value for τ_{IN};
Step 2 : Acquire R from Figure 3 and calculate b;
Step 3 : Calculate τ_{IN} using Equation (3);
Step 4 : Compare τ_{IN} calculated in Step 3 with the assumed τ_{IN} in Step 1 and repeat the process until the two values converge.

Given similar cover soil as Example 1(a), and that the weakest interface in the lining system has α and δ of 5 kPa and 20° respectively, assume the initial value for τ_{IN} is 10 kPa. R is obtained using Figure 3 as 1.4 and subsequently, b is calculated as 22.41°. τ_{IN} is then calculated using Equation (3) and the new value is 11.06. This value is not equal to the initial assumed τ_{IN}, which is 10 kPa. The process is repeated until τ_{IN} from consecutive iteration converges. Three iterations are needed for this example as demonstrated in Table 3.

Table 3. Iteration process to obtain maximum slope angle given that a = 5 kPa.

Iteration	Initial τ_{IN} (kPA)	R (-)	b (°)	τ_{IN} (kPA)
1	10 (assume)	1.40	22.4	11.06
2	11.06	1.25	24.8	**10.95**
3	10.95	1.27	24.5	**10.96**

Therefore, the maximum allowable slope angle for the landfill to ensure safety against sliding is 24.5°.

4 UNCERTAINTY IN THE DESIGN PARAMETERS

Most uncertainty and variability are dealt statistically, which involves the estimation of expected values and standard deviations of the design parameters taken as random variables. In probabilistic or reliability methods, uncertainties reflected in the input parameters are evaluated statistically to produce corresponding uncertainties in the performance function such as factor of safety. The value of an input parameter or random variable is represented using a probability distribution. A probability distribution function states all the possible values that a random variable can take and their corresponding probability of occurrence. Statistical moments of a variable, namely, mean and standard deviation, are usually required to define a distribution or a probability density function.

The reliability-based design chart produced herein only considers uncertainty in values of the design parameters. Besides the errors that might occur during laboratory testing, uncertainty also stems in deciding the mobilised interface shear strength to adopt for design. Table 4 states the coefficient of variations of interface shear strength parameters between non-woven geotextile against a textured HDPE geomembrane (NWGT-TGM) and between the textured geomembrane against Mercia clay (TGM-Clay), obtained from an internal repeatability test program. The variations of the interface shear strength parameters are small compared to a compiled global database from a literature review, in which the variation could reach up to 60%. Additional information on the repeatability test program and the global database can be found in Sia and Dixon (2005).

Table 4. Coefficient of variation, V, for NWGT-TGM and TGM-clay interfaces for applied normal stresses not greater than 70 kPa (round-up to the nearest 5%).

	V[δ]	V[α]
Interface	NWGT-TGM	
Peak	5%	20%
Large displacement	10%	20%
Interface	TGM-Clay	
Peak	10%	25%
Large displacement	15%	30%

5 RELIABILITY-BASED DESIGN CHART

Similar to the deterministic analysis, an initial parametric study was conducted using Monte Carlo simulation from an Excel add-in, @RISK student version 4.5, to assess how uncertainty in design parameters affect the probability of failure for the veneer cover soil. The objective is to find out which uncertain inputs contribute most to output uncertainty and hence, are taken as random variables. The coefficient of variation, V, for base case values are stated in Table 5. The geometries of the veneer cover (i.e., H, h and b) were assigned uniform distributions, which express equal chances of error from lack of construction quality control and achievable construction tolerances. The cover soil properties were assigned normal distributions with variations in accordance to Duncan (2000), while the interface shear strength parameters were assumed to be lognormally distributed as both parameters are usually positive values for dry conditions.

Table 5. Base case values of coefficient of variation, V, for reliability-based veneer cover design parametric study.

	H (%)	b (%)	γ_d (%)	ϕ (%)	c (%)	h (%)	δ (%)	α (%)
Base	5	5	5	10	10	5	5	20

Due to the limitation of @RISK student version not being able to generate simulations greater than 10000 times, the probability of failure, P_f, is calculated using the following equations with the assumptions that FS is normally distributed:

$$\beta = \frac{\mu_{FS} - 1}{\sigma_{FS}} \tag{5}$$

$$P_f \cong \Phi(-\beta) \tag{6}$$

The mean, μ_{FS}, and standard deviation, σ_{FS}, of FS are obtained from the simulation after achieving convergence (i.e., changes in statistical moments of FS are less than 0.5% for subsequent simulations). By varying the coefficient of variation up to 20% for a random variable, while keeping the other parameters constant, it was found that the variations in H, γ_d, ϕ and c, are insignificant to the probability of failure, P_f (i.e., changes in P_f is less than one order of magnitude in the range of V considered). Therefore, the statistical moments of these parameters are kept constant for the development of the reliability-based design chart.

The reliability-based design chart is generated such that the target probability of failure, P_{ft}, for veneer cover soil is 1×10^{-2}, with the interface shear strength parameters corresponding to FS of 1.5. A discussion on selection of P_{ft} is given in Sia and Dixon (2005). The statistical moments of the design parameters are kept at base values except for the interface shear strength parameters (i.e., δ, V[δ], α, V[α]) and mean values of slope angles.

5.1 *Application of reliability-based design chart*

The reliability-based design chart shown in Figure 4 can be used either to find the minimum interface shear strength parameters to achieve FS of 1.5, as well as satisfying the failure probability of 1×10^{-2} for the associated uncertainty in the design parameters. Additionally, the chart can be used to find the maximum slope angle for veneer cover, given that the strength parameters and their uncertainties are known parameters (e.g., from laboratory testing).

The four dotted lines extending almost diagonally from left to right in Figure 4 represent the interface adhesion of 0, 2 kPa, 5 kPa and 10 kPa. These lines are drawn such that the corresponding interface friction angle at a certain slope angle, will yield a factor of safety against sliding of 1.5. Other types of lines, namely, dark-colored continuous lines, dashed lines, and light-colored continuous lines, express the uncertainty in the interface adhesion in terms of coefficient of variation. The dark-colored continuous lines indicate coefficient of variation for interface adhesion of 10% with different magnitude of uncertainty in interface friction angle. Similarly, the dashed lines record uncertainty for interface adhesion of 20% while the light-colored continuous lines designate spread for interface adhesion of 40%. These lines connect the four dotted adhesion lines together, and any uncertainty that is beyond these lines in Figure

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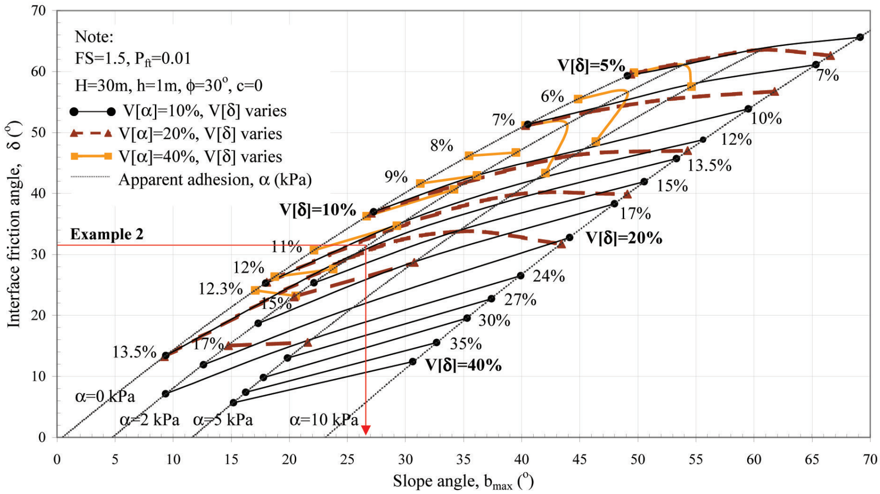

Figure 4. Reliability-based design chart for target FS of 1.5 and P_f of 1×10^{-2} (for units, refer to the notations in Section 2.1).

4, should not be interpolated. The percentages stated alongside with the different types of lines in Figure 4 indicate the uncertainty in the interface friction angle in terms of coefficient of variation.

For discussion, consider the coefficient of variation for interface adhesion of 10%, which is represented by the dark-colored continuous lines. If common practice such as ignoring the interface adhesion is adopted, the maximum allowable uncertainty in the interface friction angle based on Figure 4 is 13.5%. Any spread of interface friction angle greater than 13.5% will yield higher probability of failure (i.e., greater than 1×10^{-2}). Likewise, if the interface adhesions are 2 kPa, 5 kPa and 10 kPa with 10% associated uncertainty, the maximum allowable variations for interface friction angle are 24%, 40% and greater than 40%, respectively. Table 6 states the maximum allowable coefficient of variations for interface friction angle, given that the coefficient of variations for interface adhesion are 10%, 20% and 40%. Interface properties that have variation less than stated in Table 6 will satisfy probability of failure not greater than 1×10^{-2}. The term 'NS' denotes that interface friction angle should be determined with certainty. Therefore, if interface adhesion is equal or greater than 10 kPa but the estimation is subjected to high uncertainty up to 40% or greater, the interface friction value must be ascertained to achieve probability of failure not greater than 1×10^{-2}.

Given that the interface materials have been selected, steps in utilizing the reliability-based design charts are as follows:

Step 1 : Using Figure 4, determine the maximum slope angle for the landfill to achieve FS against sliding of 1.5 with the interface shear strength parameters obtained from testing programme.

Table 6. Maximum allowable V[δ] for interface adhesion of 0, 2 kPa, 5 kPa and 10 kPa and their V[α] of either 10%, 20% or 40% to achieve P_f not greater than 1×10^{-2}.

V[α] α (kPa)	10%	20% V[δ], %	40%
0	13.5	13.5	13.5
2	24.0	18.8	12.3
5	40.0	17.0	7.0
10	> 40.0	13.5	NS

Note: NS: Not Satisfied

Step 2 : Pinpoint the intersection of the interface shear strength parameters and the maximum slope angle between two similar type of lines, which indicate similar variation for interface adhesion. For example, the intersection point may either be located between two dark-colored continuous lines (i.e., V[α] = 10%), or two dashed lines (i.e., V[α] = 20%), or two light-colored continuous lines (i.e., V[α] = 40%).

Step 3 : Observe the numbers specifying the variations for interface friction angles for those two lines, and interpolate the variation for the intersection point.

Step 4 : The variations of interface shear strength parameters obtained or expected from laboratory tests should not be greater than the one extracted in Steps 2 and 3 so that the probability of failure of less than 1×10^{-2} is satisfied.

However, one limitation of the reliability-based design chart is that it fails to answer the question of how much is the increase of FS to redress for higher uncertainty in the interface shear parameters.

Example 2:
Adopting similar configuration of cover soil in Example 1(a), the lining materials constituting the weakest interface should be selected based on the following combination of statistical moments asserted in Table 7 to achieve FS of 1.5 and P_{ft} of 1×10^{-2}. To obtain the values stated in Table 7, the steps described in Section 5.1 are employed as follows:

Step 1 : Assuming that the interface adhesion and friction angle obtained from laboratory testing are 2 kPa and 31.2°, the maximum slope angle for the cover soil to achieve FS against sliding of 1.5 using Figure 4 is 26.6°.

Step 2 : The intersection point of the interface shear strength parameters and the maximum slope angle is pinpoint between two similar type of lines. For example, if the variation in interface adhesion, V[α], is expected to be 10%, the maximum variation for interface friction angle, V[δ] to satisfy P_f of 1×10^{-2} is located between two dark-coloured continuous lines. Likewise, if V[α] is expected to be 40%, V[δ] is located between two light-colored continuous lines.

Step 3 : For interface adhesion of 2 kPa and V[α] of 10%, the intersection point is located along adhesion line (i.e., dotted line) of 2 kPa and between two dark-colored continuous lines with spreads in interface friction angle, V[δ] of 12% and 13.5% as shown in Figure 4. However, if V[α] is expected to be 40%, the intersection point is situated along adhesion line of 2 kPa and between two light-colored continuous lines with V[δ] of 11% and 12%.

Step 4 : Therefore, by interpolating along adhesion line of 2 kPa and between two dark-colored continuous lines for V[δ] of 12% and 13.5%, the maximum allowable V[δ] to satisfy P_f of 1×10^{-2} is 13.3%. Likewise, if V[α] is 40%, interpolating along adhesion line of 2 kPa and between two light-colored continuous lines yields maximum allowable V[δ] of 11.5%. Finally, the interface materials should be selected such that the interface shear strengths are greater, but the associated variations are lesser than stated in Table 7 to satisfy both FS and P_{ft} criteria.

Table 7. Combination of statistical moments for weakest interface given that the slope angle, b, is 26.6°.

α (kPa)	V[α] δ (°)	10%	20% V[δ], %	40%
0	36.2	10.0	10.0	10.0
2	31.2	13.3	13.0	11.5
5	22.8	19.5	15.8	NS
10	6.3	NS	NS	NS

NS: Not Satisfied

6 CONCLUSIONS

A design chart is a useful graphical tool for assessing the behavior of a stability model for preliminary design, and to obtain a safe as well as optimum design. Two types of design charts are produced based on the modified limit equilibrium two wedge method for evaluating the stability of veneer cover soil. The deterministic design chart provides information regarding minimum interface shear strength or maximum slope angle to achieve FS of 1.5, while the reliability-based design chart is capable of providing similar information, as well as the allowable uncertainties associated with the design parameters. However, the later chart imposes a more stringent criteria in selection of lining materials and requires practitioners to conduct more interface shear tests. Nevertheless, this instills higher confidence in the selection of lining material for design. Unfortunately, the current reliability-based design chart is not flexible to cater for different cover soil characteristics, types of loadings and their corresponding uncertainties, and is still under development.

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