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A Study on Interface Shear Strength Variability and Probability of failure of Land Filled Stability Analysis

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Abstract

Now a day's failure of modern landfills by slippage of lining materials is common. The majority of failures are controlled by slippage at interfaces between lining components. Information and variability of interface shear strength is required to carry out both limit equilibrium stability analysis using characteristic shear strengths and probability of failure analysis. Current practice is to carry out a limited number of site specific tests and this provides insufficient information on the variability of interface strength for design. The implications of variable shear strength are examined though probability of failure analysis of two common design cases: veneer and waste body slippage. The reliability analyses show that relatively high probabilities of failure are obtained when using variability values from the literature and an internal database even when factors of safety ≥ 1.5. The use of repeatability data produces lower probabilities for typically used factors of safety, although they are still higher than recommended target of probability failure (P_f) values.

Keywords- Land filled Stability, Shear strength variability, Geosynthetic layers, Veneer stability.

1. Introduction

Landfill lining systems are comprised of multiple geosynthetic and mineral layers. The interface between these materials can form preferential slip surfaces. The majority of failures reported in the literature are controlled by slippage at interfaces between lining components. Koerner & Soong (2000) back analyses landfill failures and demonstrated that assessment of stability was most sensitive to shear strength parameters defined for the critical surface. There is growing evidence that measured values of interface shear strength show considerable variability (Criley & Saint john 1997, Koerner & Koerner 2001, Stoewahse et al. 2002, McCartney et al. 2004).This makes selection of appropriate shear strength values for use in design problematic. The relatively high rate of landfill failures has led some researchers to propose that risk assessment using probability of failure analysis can be used to quantify uncertainty in selection of appropriate interface shear strengths (Koerner & Koerner 2001, Sabatini et al.2002, McCartney et al. 2004).

However, before design engineers can use the reliability based stability analysis, guidance is required to quantifying variability of interface shear strength and on use of outputs from such analyses, in conjunction with traditional factors of safety, in the decision making process leading to design of stable slopes. This paper presents information on the variability of measured strengths obtained from data set for interfaces commonly encountered in landfill lining systems. The use of reliability assessment in landfill stability is demonstrated through consideration of two common landfill design cases: Veneer and waste slope stability. Veneer stability has previously been used by Koerner & Koerner (2001) and McCartney et al. (2004) and waste slope stability by Sabatini et al. (2002), to demonstrate the sensitivity of landfill design to interface variability. These two design cases were selected for use in this

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study in order to add to the existing published information on relationships between probability of failure and traditional factors of safety. The aim is to produce a body of information that can be used by engineers to carry out and interpret reliability based landfill designs.

2. Statistical analysis of interface strength variability

Although this paper focuses on the use of probabilistic stability assessment methods it is worth noting that information on variability of parameters required for such analyses are also needed to carry out traditional limit equilibrium stability calculations. In Euro code 7 (1997), the characteristic value of a soil property is defined as 'A *cautious estimate of the value affecting the occurrence of limit state.* The characteristic value should be a cautious estimate of the mean value over the governing zone of soil (Orr & Farrell, 199), or in this case over the area of the interface. Schneider (1997) has a proposed a statistical approach for determining the characteristic value (X_k) using the mean value of the test results (X_m) and the standard deviation of the test results (σ_m):

$$X_k = X_m - 0.5\sigma_m \qquad (1)$$

The approach aims to ensure in the order of 95% confidence that the real statistical mean of the parameter is superior to the selected characteristic value (X_k). In this application, it is the mean and standard deviation of interface shear strengths that are required. This is the same information that is required to undertake probability of failure analyses as discussed below.

2.1. Derived interface shear strength parameters

Interface shear strength parameters are obtained by plotting peak and large displacement, assumed to be close to residual values in most cases (Dixon & Jones 2003b); shear strengths measured in direct shear apparatus on a shear stress vs. normal stress graph. Coulomb failure criteria are defined by linear best-fit lines through sets of peak and residual data measured at normal stresses relevant to the design problem. Although linear regression provided the best fit for the interface reported, some geosynthetic interfaces display non-linear or bilinear strength envelope. Shear strength envelopes are defined by pairs of apparent adhesion (α) and interface friction angle (δ) parameters. While it is common practice in many applications involving soil to ignore apparent cohesion values in design, this approach is not recommended for geosynthetic interfaces. Apparent adhesion values can be considered in design of structures that incorporate interfaces with a true strength at zero normal stress (e.g. *Velcro* TM type effect between non woven needles punched geotextile and textured geomembranes). Apparent adhesion can also be used to define a failure envelope over a range of normal stresses (i.e. assuming a linear failure envelope) or to define a best fit straight line through limited variable test data. In these specific cases it would be over conservative to assume $\alpha = 0$, especially for design cases with low normal stresses (e.g. design of cap systems). Negative α can also be produced by best fit lines through limited test data. If negative α is ignored this will result in an over estimate of shear strength and hence potentially unsafe designs. Negative values are produced by best fit lines through a number of test data sets included in this paper, and these demonstrate limitation of data sets in terms of number of points and their distribution.

As the quantification of interface shear strength requires two parameters (α and δ) variability of measured shear strengths requires consideration of linked pairs of these parameters. Dixon et al. (2002) proposed an approach based on calculating the variability of measured shear strength for each normal stress and using this data to derive the appropriate shear strength parameters for using in design. For example, Figure.1 shows how characteristics values can be obtained for use in a limit equilibrium analysis.

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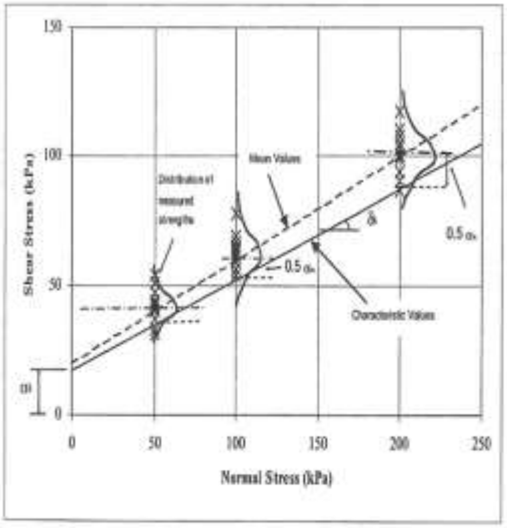

Fig.1 Derivation of interface shear strength parameters from measured shear strength.

2.2. Statistical data for measured interface shear strengths

Two approaches are available for obtaining information on the variability of interface shear strength for use in assessment of stability. The preferred approach is to undertake a sufficient number of site specific tests at each moment normal stress to enable statistics analysis of the measured strengths .This will allow the mean (X_m) and the standard deviation (σ_m) of measured strength to be calculated for each stress level. As discussed above, this approach is based on assessing the variability of measured shear strength and not the derived strength parameters. It is believed that at present this approach is considered too costly (both in time and money) by the majority of designers.

A second approach is to carry out a limited number of tests to obtained site specific strength values and to obtained information from the literature on possible variability for that specific type of interface. However, a limitation of this approach is that there is no information available to indicate whether the measured site specific strengths are representative of mean values. If in comparison to the estimated mean values (i.e. using data from previous similar materials)the measured strength are considered to be high, or there is limited experience of testing the interface, then further tests should be conducted and the first approach described above must be used.

Where there is limited data available, an alternative approach is to calculate standard deviation using three sigma rule, which used the fact that 99.73% of all values of a normally distributed parameter fall within three standard deviation of the average (Duncan 2000).The three-sigma rule has been used by Sabatini et.al (2002) to quantify the variability of Geosynthetics/soil interface strength. In this paper, Variability of interface strengths have been expressed as a function of the mean using coefficient of variation (V) defined as:

$$V = \sigma_m / X_m \qquad (2)$$

3. Probability of failure stability analysis

3.1. Analysis method for probability of failure

Risk assessment of landfill stability using probability of failure (P_f) has been discussed by Koerner & Koerner (2001), Sabatini et al. (2002) and McCartney et al. (2004). All employed the first-order, second moment reliability – based methodology (Duncan 2000).In all three cases, use of reliability method was made possible by access to databases providing information on variability of measured interface strengths. A brief description of the methodology purposed by Duncan (2000) and this is essential if a sufficient body of experience is to be gained to guide designers on both selection of interface strength variability inputs and interpretation of probability of failure outputs from such studies.

3.2 Veneer stability

A common designs case in landfill engineering is stability assessment for thin veneers of soil above one or more geosynthetics layers. These conditions are encountered during construction of side slope lining systems (i.e. stability assessment of drainage layers prior to waste placement) and capping systems. In both cases slopes are long in relation to the soil veneer and the average normal stresses are low on the interfaces. Figure.2 shows the problem analyzed, with the key variables defined. Soong & Koerner (1995) purposed a limit equilibrium assessment based

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on a two part wedge failure more and including shear strength of the cover soil and seepage forces.

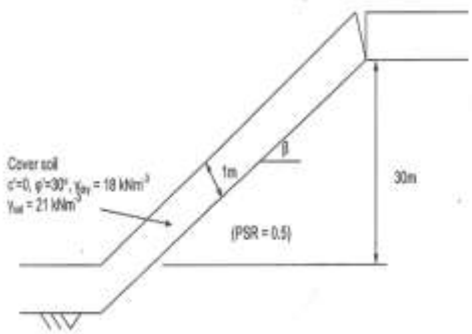

Fig.2 Diagram of the model used in Veneer stability analysis.

Effective stress analyses have been carried out for a 1.0 meter thick soil veneer with pore water pressures on the interface calculated using a parallel submergence ratio (PSR) of 0.5. Slope angles (β) between 14° (1 in 4) and 33.7° (1 in 1.5) have been analyzed. Only the variability of interface shear strength has been considered in these analyses; however the method outlined by Duncan (2000) can be used to assess the influence of other parameters if required. Sliding has been analyzed for three interfaces: textured HDPE geomembrane / coarse soil, textured HDPE geomembrane / non-woven geotextile and non-woven coarse soil.

Figure.3 shows plots of P_f vs. FS_{MLV} for each interface. The interfaces with greatest variability of measured shear strengths (i.e. those involving coarse soil) show the largest P_f values for a given FS_{MLV} as expected. If a minimum FS_{MLV}=1.5 is required in design ,as a common practice ,even the analyses based on the repeatability test data do not give a probability of failure low enough to be considered acceptable for design. It could be argued that it is more appropriate to compare P_f values with factors of safety calculated using characteristics shear strengths, FS_K, as these take in to consideration variability, and hence uncertainty in measured strength.Figure.4 shows plots of P_f vs.FS_k and FS_{MLV} for the textured HDPE geometric/coarse soil interface based on the combined and Criley & Saint John (1997) data sets. Using characteristics shear strength result in lower calculated factors of safety as expected, however the analyses do not indicate the full implication of the variability when compared to probability of failure values.

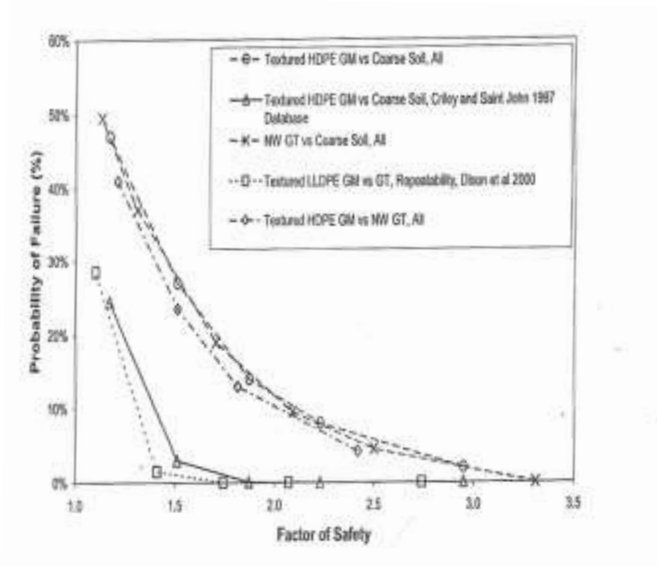

Fig.3 Probability of failure vs. factor of safety from Veneer stability analysis Criley and Saint John (1997) and Dixon et. al. (2000)

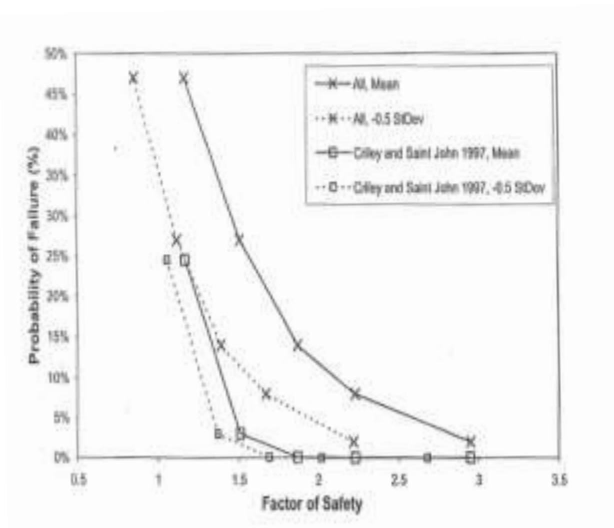

Fig. 4 Probability of failure vs. factor of safety from Veneer stability analysis, showing relationship between the mean characteristic values for factor of safety based on combined data and Criley and Saint John (1997) for textured HDPE geomembrane vs. coarse soil.

3.3. Waste body stability

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A second common design case in landfill engineering is stability assessment for a waste body placed against a side slope. This is a temporary condition in many quarry landfills and a permanent condition in valley landfills. There have been failures, as discussed in the introduction, with sliding taking place along one or more interfaces within the lining system. Slope and waste geometries similar to those used to Sabatini et al. (2002) were selected for the reasons discussed above Figure.5 shows the problem analyzed with the key variables defined .Effective stress limit equilibrium analysis has been carried out using a standard slope stability computer package (Slope W).

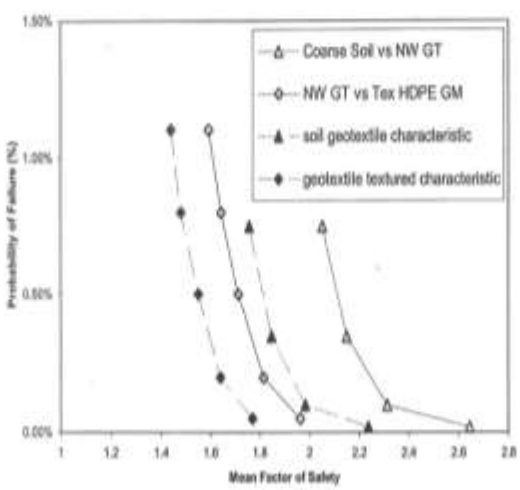

Fig. 5 Probability of failure vs. factor of safety for waste body stability, showing relationship between the mean characteristic values for factor of safety based on combined data.

Only the variability of interface shear strengths has been considered in this analysis. Sliding has been analyzed for two interfaces: non–woven geotextile/ coarse soil and textured HDPE geomembrane/non-woven geotextile. Each analysis has the same interface on the base and side slope. Analyses have been carried out using the mean standard deviations of the shear strengths from combined data sets. There are currently no repeatability data sets available for these interfaces. Both mean and standard deviation values have been taken over the appropriate normal stress range for the problem (i.e. 100 to 300 kPa). Shear strength parameters (α and δ) for mean, +1 σ_m and -1□σ_m measured shear strengths have been calculated for each interface. Fig.5 shows plots of P_f vs. FS_k and FS_{MLV} for non-woven geotextile/coarse soil and textured HDPE geomembrane/non-woven geotextile interfaces.

For limit equilibrium analyses using mean shear strengths, FS_{MLV} values greater than 2.6 and 2.0 are required for the two interfaces respectively to produce low P_f values (i.e. in the order of 0.1%. Even using characteristic shear strength, FS_k values greater than 2.2 and 1.8 are required respectively to produce low P_f values. As for Veneer stability, factors of safety typically used in design (i.e. in order of 1.5) do not reflect the full implication of interface strength variability when compared to probability of failure values. As only combined data sets have been used in this study the results are conservative (i.e. the degree of variability is likely to be an upper bound). Theses analyses extend those presented by Sabatini *et al.* (2002) by demonstrating the increased probability of failure.

4. Conclusion

The relationship between standard deviation and normal stress has been defined for combined data sets for each interface, except for interfaces involving fine soil. It is proposed that these summaries of test data can be used to supplement site specific test results in order to select appropriate mean and standard deviation for interface shear strength. These can be used to calculate shear strength parameters for use in stability assessment.

Current practice is to carry out a limited number of specific tests, but this provides insufficient information for the variability of interface strength to be considered in the design. It is recommended that a sufficient number of site specific direct shear interface tests to be carried to provide to statistical data for use in traditional limit equilibrium analyses using characteristic values, and probability of failure analyses using the simple procedure described by Duncan (2000).

In the combined data sets, large variability has been demonstrated which results in unacceptable P_f values for both Veneer and waste body slope stability. For Venner stability, the textured HDPE geomembrane

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vs. coarse soil combined data set gives a P_f of over 25% even when the FS_{MLV} = 1.5. using repeatability test data, the P_f for the same interface and slope angle (26.6°) reduces to 3% at FS_{MLV} = 1.5, However it is likely that this would still be considered unacceptable. These findings confirm the need for landfill designers to give greater consideration to the variability of interface shear strength and to the consequences of failure when collecting information for use in design.

Designing based on combined criteria for factor of safety and probability of failure would allow uncertainly in measurement of interface shear strength to be considered fully. However appropriate and attainable target factor of safety and probability of failure values need to be selected if this methodology is to be implemented into general practice. It is clearly unacceptable to rely on low values of FS_{MLV} using data with a large standard deviation conversely when repeatability tests have been carried out to derive interface shear strength, requiring a FS_{MLV} of in excess of 1.5 to achieve an acceptable P_f will in many case be considered over conservative, and this will inhabit use of the method. Repeatability data sets have been shown to produce lower variability and hence more realistic information. It is recommended that repeatability data be used for design in place of combined data sets.

Probability of failure analysis is an appropriate technique to apply to landfill design. The simple method used in previous studies (e.g. Koerner & Koener 2001 and Sabatine *et. al* 2002, Mc Cartney *et. al* 2004) and in this paper requires the same input information on shear strength variability as traditional stability analyses using characteristic values.

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