

# Interface shear strength non-linearity and its effects on heap leach pad block failure stability

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## Abstract

In designing heap leach pads it is very common to use liners composed of a geomembrane over a low-permeability soil or soil liner. A granular overliner is used on top of the geomembrane in order to prevent damage from the impact of the oversize ore. In general, the upper interface, geomembrane versus overliner or ore, will usually provide higher shear strength than the clayey soil used as a soil liner due to its granular nature. Therefore, in order to increase the shear strength of the lower interface, a single-sided textured geomembrane is used in contact with the soil liner.

The research performed by Ayala et al. (2014)—related to the relationship between the interface shear strength and its dependency on normal stress, asperity height, and soil liner classification—is used and extended in this study, as a way to determine and empirically support the effects of non-linearity of the post peak shear strength behavior of this kind of interface, which is commonly used in heap leach pad projects. The following research will explain empirically the nonlinear behavior of the interface shear stress based on the normal stress applied to it.

A sensitivity analysis based on 2-D limit equilibrium slope stability analysis of block failures in heap leach pad projects is performed based on the following criteria: heap geometry, nonlinear model for interface shear strength based on Ayala et al. (2014) curves, asperity height variation, and soil classification. The asperity height variation is a key issue added because of evidence indicating a difference of the asperity measured by manufacturer quality assurance (MQA) and the one measured by control quality assurance (CQA), corresponding to an asperity reduction in the field, which, as noted by other authors, corresponds to a decrease in the shear strength. This research also adds recommendations for 2-D limit equilibrium software for slope stability analysis on heap leach pads when a linear interface shear strength is used.

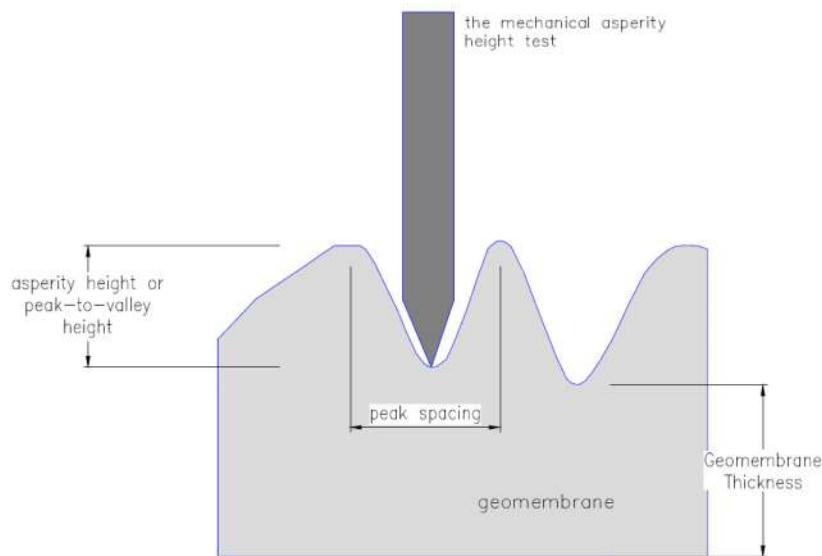
## Introduction

In designing heap leach pads it is very common to use liners composed of a geomembrane over a low-permeability soil or soil liner, as a way to prevent or decrease leakage of the pregnant solution into the heap foundation, which may cause environmental damage and financial losses.

It is usual in practice for heap leach pad projects to use mainly textured linear low-density polyethylene (LLDPE) geomembrane over a clayey soil as a liner system. In Peruvian mining projects the construction of such systems has followed the GRI recommendations provided on the GM 12 (2002), GM 13 (2012), and GM 17 (2012) specifications.

In the geotechnical design and the slope stability analysis of a leach pad, the main restriction is related to the liner system, which usually provides an interface with low shear strength due to the relatively high fines content of the soil liner; thus the interface controls the slope stability conditions by a block failure. Some efforts have been made to model or predict the shear strength of this kind of liner (Reddy and Butul, 1999; Ivy, 2003; Yesiller, 2005; Blond and Elie, 2006).

Based on these studies and the expertise of the authors in projects related to the slope stability of heap leach pads, it should be noted that the interface shear strength increases with the increment of the geomembrane asperity height (for details of the asperity in a geomembrane, see Figure 1), normal stress increment ( $\sigma'_N$ ), and the increment of granular material in the soil liner.



**Figure 1: Geomembrane asperity height**

This research is focused on the normalization of the interface shear strength behavior of textured geomembrane and soil liner based on the asperity height of the geomembrane, soil liner classification, normal stress and, soil liner fines content. The interface shear strength was determined through large-scale

direct shear (LSDS) tests according to the ASTM D 5321 standard, the geomembrane samples for testing were obtained from manufacturers or sheets currently placed in actual projects, while the soil liner samples came from borrow areas used on many heap leach pad projects under construction or already constructed in several mines in Peru. A sensitivity analysis is performed to determine the effects of the non-linearity of the normal-shear stress relationship of a liner interface in a slope stability analysis of a heap leach pad block failure. For the latter, different geometries were provided to simulate the most typical heap heights and slope inclinations used on these kind of projects.

## **Data preparation**

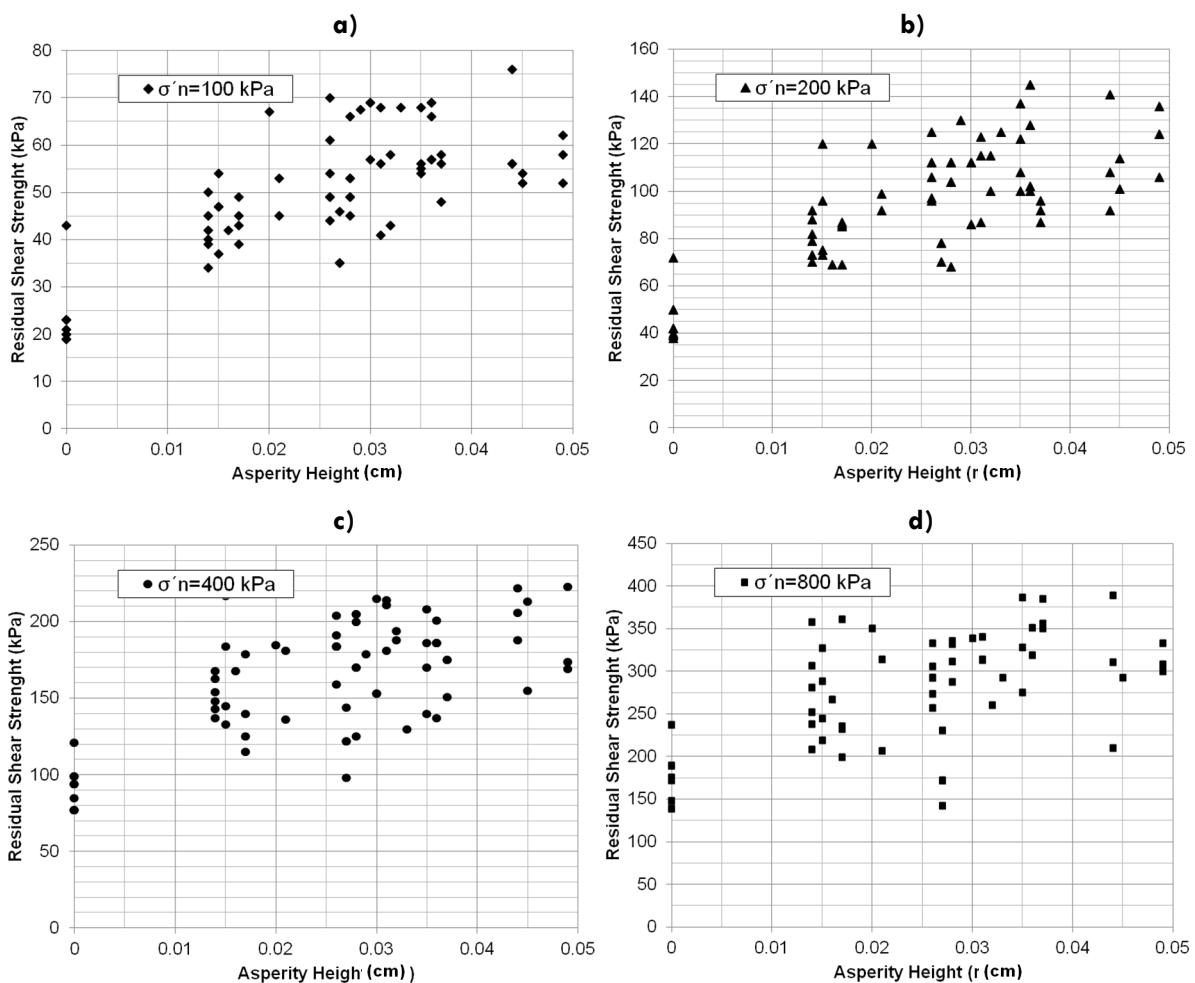
The interface shear strength has a clear nonlinear behavior as discussed by Stark et al. (1996), Stark and Choi (2004), Parra et al. (2011), and Ayala et al. (2014); therefore, this research went deeper into the experimental data to observe the behavior of the interface shear strength by evaluating a normalization of the shear stress by the normal stress values obtained by LSDS test results, instead of using the Mohr-Coulomb approach (angle of friction and cohesion).

Ayala et al. (2014) reviewed a total of 191 LSDS tests, which included the following information: type of geomembrane—LLDPE or high-density polyethylene (HDPE), most of the data corresponds to LLDPE geomembrane—nominal geomembrane thickness (1.5 mm or 2 mm), asperity height measured in the laboratory, soil liner classification, Atterberg limits, peak shear stress (taken as 2.5 cm of deformation), post peak shear stress (taken at 7 cm of deformation) and their corresponding normal stress, and final soil moisture content at the end of the test. The values of strengths at 2.5 cm and 7 cm are common standards for LSDS results, however, the following remarks are made regarding the use of the data for this study:

- Regarding the peak value of shear strength at 2.5 cm, it should be considered that 2.5 cm of displacement on the test does not always match the peak shear strength; this value may vary from 1 cm to 2.5 cm depending on the sample, so there was a possibility of bias if the peak behavior was chosen for the shear strength analysis.
- Not all interfaces have a peak and post peak behavior—some samples reach a maximum shear strength and remain constant for the rest of the test (similar to Mohr-Coulomb model).
- The tendency of shear strength behavior to depend on geomembrane asperity height and soil liner is not as clear as that for post peak shear strength noted by Ayala et al. (2014); this could be due to the bias noted in the first point.
- Regarding the 7 cm, it is common that even with 4 cm displacements, the post peak value is reached and the shear strength remains constant until the end of the test; thus 7 cm is a more reliable value to deduce the post peak shear strength of an interface.

- By constructing a leach pad by stages with a numerical model, it has been observed by the authors that the static strains developed at the interface reach the post peak strains obtained by the LSDS tests, primarily in heap leach pads of 60 m height and above.
- When analyzing pseudo static conditions, it is likely that strains larger than the strain sustained by a peak shear strength will be reached, which adds to the value obtained by static accumulative strains on a heap leach numerical stage construction.
- In practice, it usually adds to the conservatism of a heap leach pad slope stability analysis to use the post peak values of the LSDS tests.

The post peak shear strength is shown in Figure 2, which has been separated by the normal stress applied during the LSDS test. No differentiation of soil classification is presented in this figure.



**Figure 2: Post peak shear strength behavior of all the testing data for different normal stresses (Ayala et al., 2014)**

As shown in Figure 2, the interface post peak shear strength features a clearer tendency to increase with the increment of the asperity height. However, some scattering is observed, which may be caused by

the soil properties or fines content. Therefore, the samples were identified based on their classification according to the Unified System of Soil Classification (USSC); the main features of the soil liner samples are summarized in Tables 1, 2, 3, and 4.

**Table 1: Clayey gravel with sand (GC)**

	<b>Gravel content (%)</b>	<b>Sand content (%)</b>	<b>Fines content (%)</b>	<b>Liquid limit (%)</b>	<b>Plastic index (%)</b>
<b>Average</b>	41.9	27.8	30.3	31.5	12.6
<b>Maximum value</b>	59.8	34.3	44.7	45.5	20.0
<b>Minimum value</b>	32.5	21.6	15.7	22.0	9.0

**Table 2: Clayey sand with gravel (SC)**

	<b>Gravel content (%)</b>	<b>Sand content (%)</b>	<b>Fines content (%)</b>	<b>Liquid limit (%)</b>	<b>Plastic index (%)</b>
<b>Average</b>	24.3	36.7	38.6	34.4	15.0
<b>Maximum value</b>	33.0	60.1	50.0	50.9	26.5
<b>Minimum value</b>	11.3	28.3	19.2	27.0	8.0

**Table 3: Clay with sand (CL) and high plasticity clay with sand (CH), fines content below 65%**

	<b>Gravel content (%)</b>	<b>Sand content (%)</b>	<b>Fines content (%)</b>	<b>Liquid limit (%)</b>	<b>Plastic index (%)</b>
<b>Average</b>	10.4	36.3	53.3	40.3	20.4
<b>Maximum value</b>	25.6	50.5	65.0	57.0	36.0
<b>Minimum value</b>	0.0	25.2	50.0	17.0	6.0

**Table 4: Silt with sand (ML) and high plasticity silt with sand (MH), fines content below 75%**

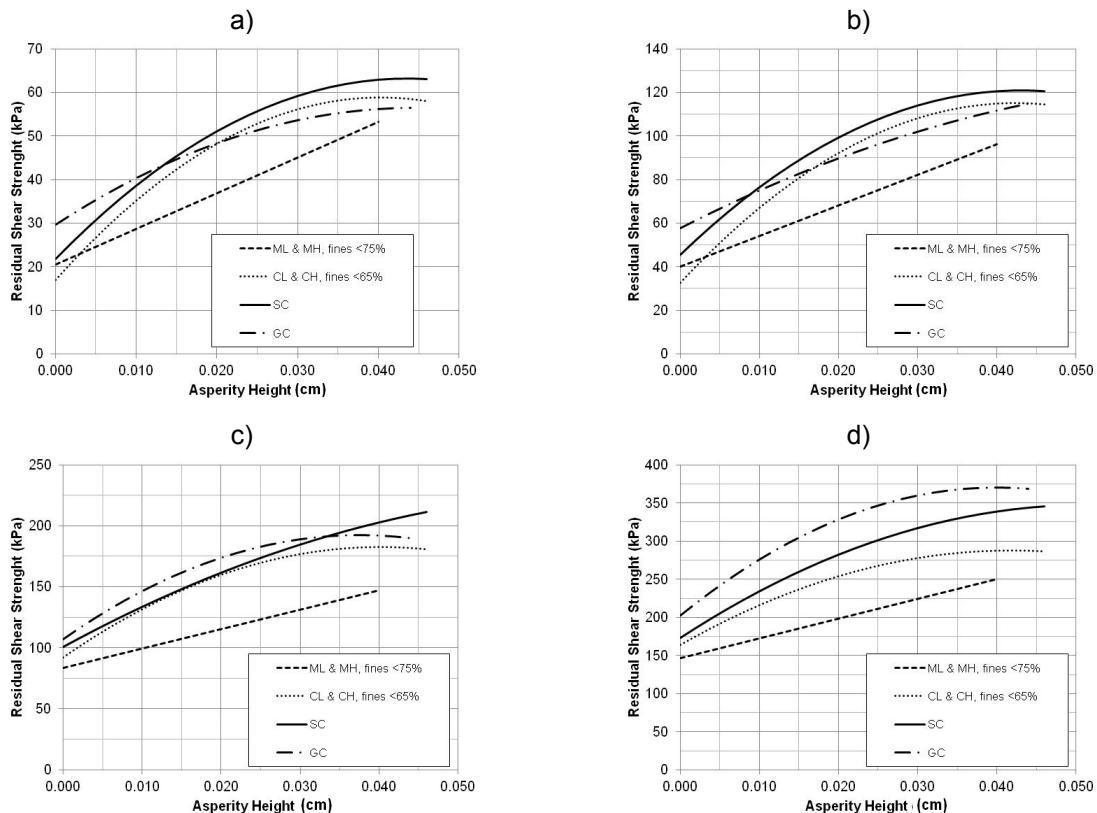
	<b>Gravel content (%)</b>	<b>Sand content (%)</b>	<b>Fines content (%)</b>	<b>Liquid limit (%)</b>	<b>Plastic index (%)</b>
<b>Average</b>	9.9	28.4	61.7	59.8	23.5
<b>Maximum value</b>	27.9	39.7	75.0	83.0	30.0
<b>Minimum value</b>	3.5	13.4	54.0	50.0	15.0

There were other features that may be involved with the interface shear strength behavior, such as the type of geomembrane (LLDPE or HDPE) and geomembrane thickness; however, no clear tendency was observed when the data was classified by those parameters as well, and there was not enough data to make a clear correlation.

There were a total of 21 samples classified as GC (clayey gravel), 27 samples as SC (clayey sand), 15 samples as CL (low compressibility clay) and CH (high compressibility clay) with fines content (FC) below 65%, and 10 samples as ML (low compressibility silt) and MH (high compressibility silt) with FC below 75%.

### Shear strength data processing based on soil classification

Based on the results of Ayala et al. (2014), the data of shear strength based on different kinds of soil classification, geomembrane asperity height, and normal stresses was correlated as shown in Figure 3. The data on shear strength corresponds to the interfaces of geomembrane and soils classified as: GC, SC, CL, and CH with FC below 65%, and ML and MH with FC below 75% soils.



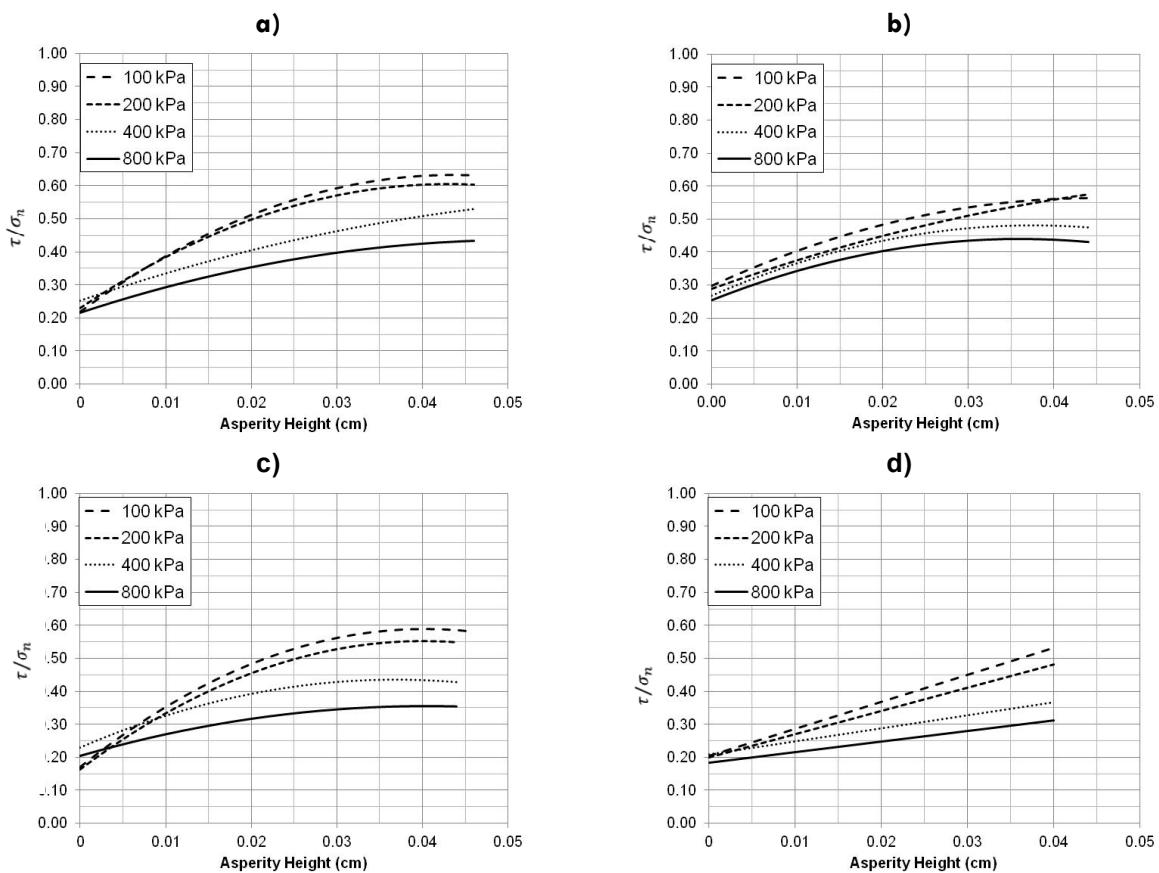
**Figure 3: Comparison of interface shear strength behavior for different kind of soils for normal stresses of (a) 100 kPa, (b) 200 kPa, (c) 400 kPa and (d) 800 kPa**

Ayala et al. (2014) concluded that there is a reliable nonlinear tendency of shear strength increment for GC, SC, and CL and CH soils with FC content below 65%, where the behavior tends to be asymptotic at asperity heights of 0.04 cm. This conclusion agrees with that of Blond and Elie (2006) and also adds an asperity of 0.04 cm as a trigger value for larger normal stresses (400 kPa and 800 kPa). It is also observed that for GC, SC, and CL and CH soils with FC content below 65%, the rate of increment of shear strength

is reduced around an asperity height of 0.03 cm. In general, the shear strength of CL and CH soil with FC below 65% is around 5% to 15% less than SC soil. Finally, the tendency curves for ML and MH with FC below 75% are used to prove that these kinds of interfaces provide very low shear strength compared to other soil liners, and also their shear strength behavior needs more testing to provide a better correlation. However for future reference, its rate of increment of shear strength may increase linearly with the asperity height.

### Normalized shear strength data processing based on soil classification

By using the information shown by the curves in Figure 3, the shear strength was normalized by its corresponding normal stress for each kind of soil listed above. The results of this normalization are shown in Figure 4.

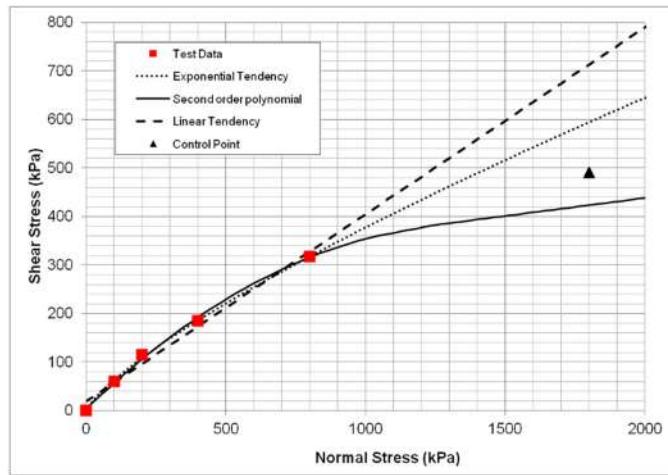


**Figure 4: Summary of the normalized shear strength tendency for (a) GC, (b) SC, (c) CL & CH with FC ≤ 65% and (d) ML & MH with FC ≤ 75%**

Figure 4 shows that the rate of increment of the shear strength is reduced as the normal stress increases; this is related to a nonlinear behavior of the interface shear strength that is quite similar to a typical granular soil behavior. Also it should be noted that the rate of increment of shear strength tends to be asymptotic

from 0.03 cm of asperity height. Additionally, it can be inferred that at higher normal stresses a lower rate of increment for the interface shear strength is to be expected. Furthermore, information about the interface shear strength can be extrapolated from the normal stresses of the curves obtained by Ayala et al. (2014) shown in Figure 3. The criteria for such extrapolation is taken from Parra et al. (2011), where a control point is chosen in the function of an expected normal stress to be experienced in a heap leach pad block failure.

For this research, a methodology was developed for characterizing the interface shear strength for normal stresses higher than 800 kPa. By using the trends shown in Figures 3 and 4, 3 tendency lines from the data of Ayala et al. (2014) were drawn (see Figure 5). The tendency lines correspond to linear, exponential, and square models. As is shown in Figure 5, the linear tendency (typical behavior for low normal stresses) overestimates the shear strength at higher normal stresses, while the exponential and second order polynomial trend line models show a decreasing rate of shear strength at high normal stresses. Thus by using information obtained from previous projects, a control point was chosen between the exponential and second order polynomial trend lines in order to avoid over-conservatism by the exponential approach and underestimation by the polynomial approach. It should be noted that more information should be collected for LSDS tests at higher normal stresses to verify these estimates; however, from the trends obtained in this study for tests from 0 to 800 kPa range, these estimates could be used for a rational and practical approach.

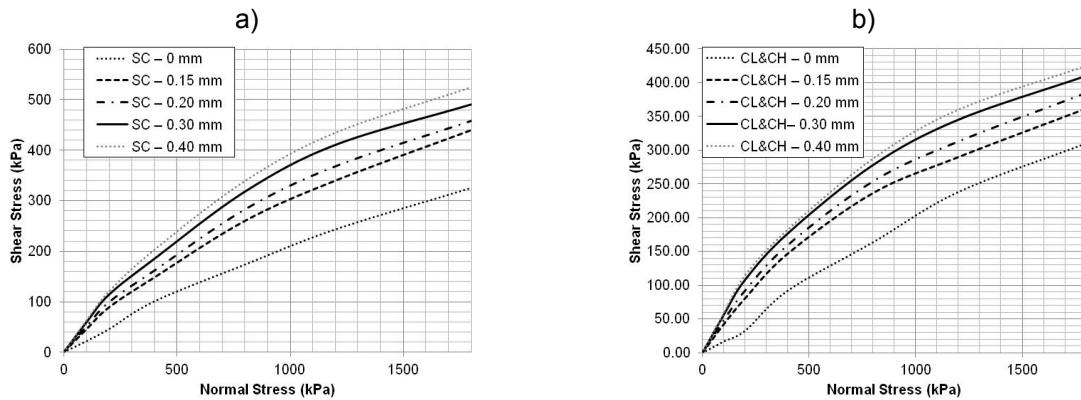


**Figure 5: Normal and shear stress extrapolation of the interfaces shear strength for SC with 0,03 cm asperity height**

### Interface and heap leach pad geometry sensitivity analysis of slope stability

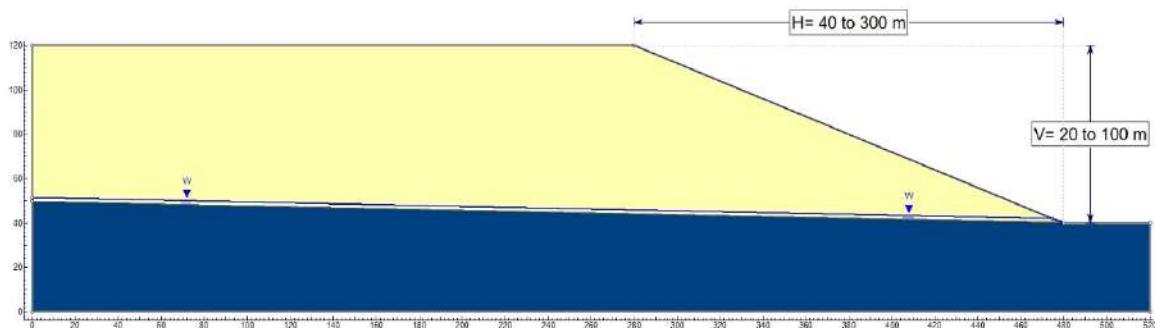
The main objective of this study was the determination of the sensitivity of heap leach pad slope stability by block failure in relation to the heap height, global slope, and type of interface employed as a liner.

By using the extrapolation methodology proposed in Figure 5, shear-normal stress envelopes were developed for 2 typical soils used as soil liner on heap leach pads (SC and CL and ML with FC below 65%) for 5 asperity heights (0, 0.015, 0.020, 0.030 and 0.040 cm), these were introduced as the interface parameter for the sensitivity slope stability analysis. Figure 6 shows these envelopes from 0 to 1,800 kpa.



**Figure 6: Normal and shear stresses of the interfaces for (a) SC and (b) CL & CH with FC < 65% soils**

The geometrical models were based on typical global slopes (2H:1V, 2.5H:1V and 3H:1V), a minimum slope inclination provided for the collection system as the liner surface (2%), and different heap heights, which corresponded to small-, medium-, and large-sized leach pads. In Figure 7, the typical geometry employed for different heap heights (20, 40, 60, 80, and 100 m) is shown. The soil properties to be used in the 2-D limit equilibrium slope stability analysis were based on typical values for leached ore and bedrock. For the interface, 10 different shear strengths envelopes were employed, as shown in Figure 6. A summary of this data is shown in Table 5.

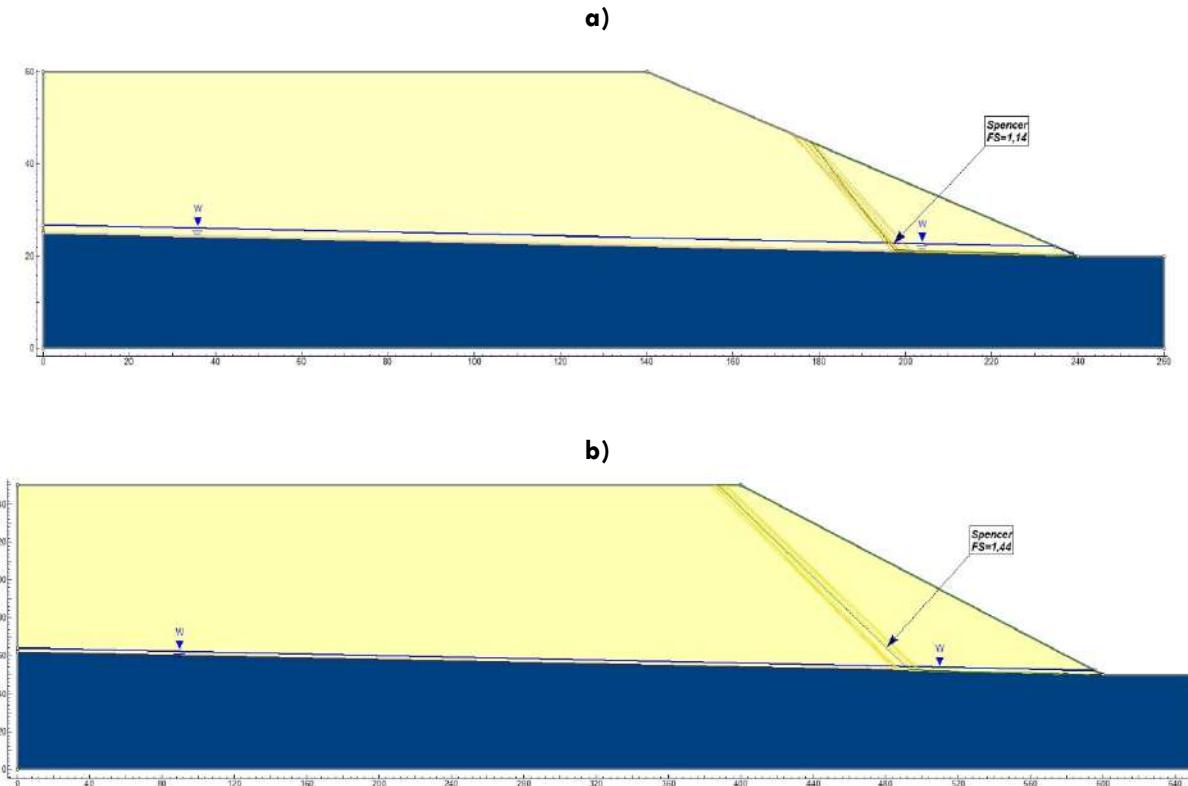


**Figure 7: Typical heap leach pad geometrical model employed for the sensitivity analysis by the 2-D limit equilibrium method in a heap leach pad slope block failure**

**Table 5: Material Properties**

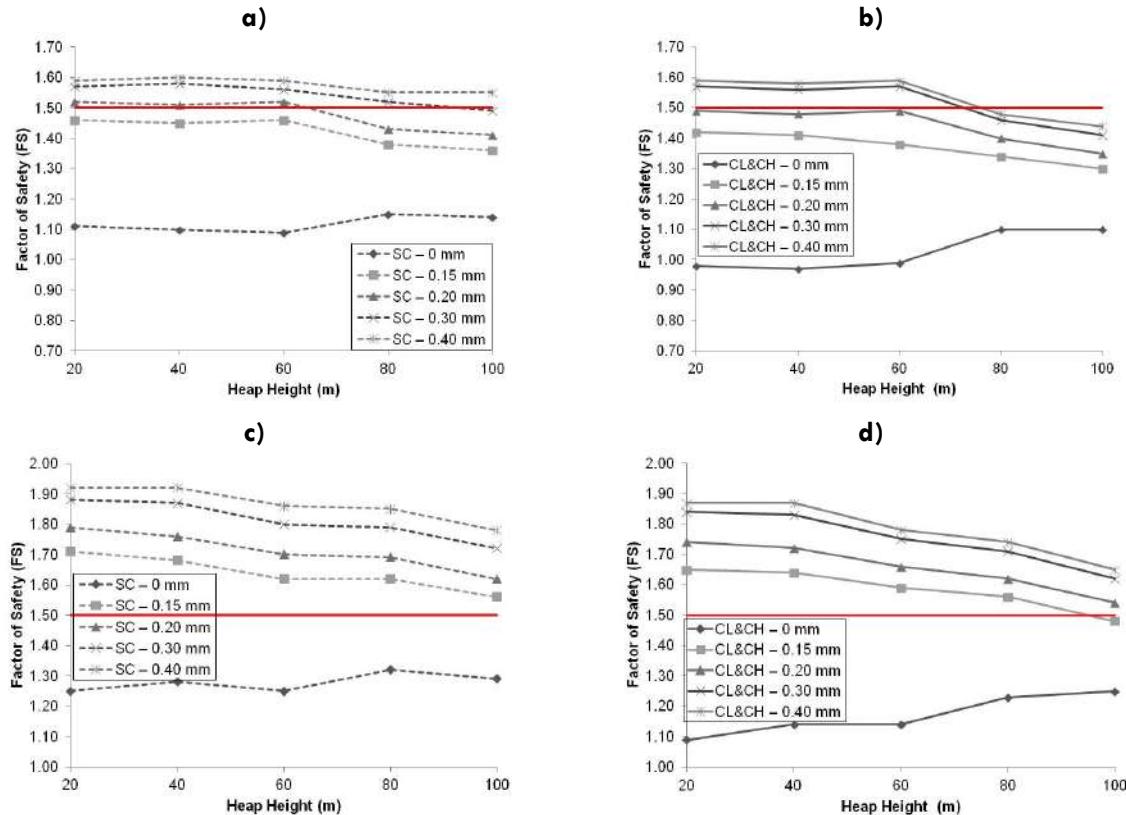
Material	Total unit weight (kN/m <sup>3</sup> )	Saturated unit weight (kN/m <sup>3</sup> )	Friction angle (°)	Cohesion (kPa)
Leached ore for heap height 20 to 40 m	18	19	37	0
Leached ore for heap height 60 to 100 m	19	20	37	0
Interfaces	17	18	See Figures 6a and 6b	
Bedrock	24	25	Slide 6.0 Infinite strength model	

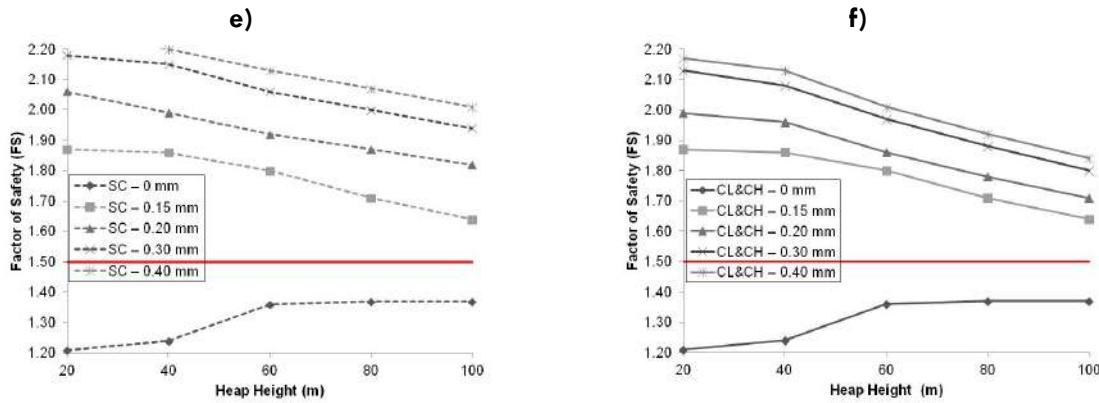
Fifteen different geometries were introduced, and for each of them, 10 different kinds of interface shear strength envelopes were used, for a total of 150 models. For the 2-D limit equilibrium slope stability analysis of a block failure, the software Slide 6.0 was employed; an example of typical block failures obtained are shown in Figures 8a and 8b. After running the models, the tendency for each global slope and liner used is shown in Figure 9, where 0 mm means smooth geomembrane.



**Figure 8: Typical block failure obtained by slope stability analysis for (a) smooth geomembrane and (b) asperity height 0,04 cm**

From the results shown in Figure 9, it can be noted that the less steep the global slope is, the greater is the variation of the 2-D limit equilibrium factor of safety and the larger are the factors of safety (see Figures 9e and 9f). The steeper the global slope is, the less sharp are the variations, and the lower are the factors of safety (see Figure 9a and 9b). As for the 2.5H:1V global slope, it is shown that for almost all typical shear strength envelopes the factors of safety are larger than the typical minimum factor of safety for static conditions (1.5) (see Figures 9c and 9d). This explains why this global slope is the most commonly used for heap leach design. For all cases, the factors of safety for smooth geomembrane and soil interface are less than 1.5, however more test results for supporting the smooth geomembrane interface shear strength may be required, even though an eventual increment based on more results is not likely to increase the factor of safety to more than 1.5. Thus, as a general recommendation, smooth geomembrane should not be used for seismic regions by itself—unless berms, trenches, or buttresses are used to improve stability. There is a slight increment of factor safety for smooth geomembrane as the heap height increases, due to an effect at the heap toe—which in slope stability analysis tends to be quite a small failure with a very low factor of safety, so the failure was constrained until half of the heap height and onwards (see Figure 8a). These results should be taken for static conditions, and should not be extrapolated for other liner surface inclination and seismic (pseudo static) conditions.





**Figure 9: Factor of safety variability for global slope, heap height and interface envelopes.**

- (a) 2H:1V and SC envelopes, (b) 2H:1V and CL&CH with  $FC \leq 65\%$  envelopes,
- (c) 2.5H:1V and SC envelopes, (d) 2.5H:1V and CL&CH with  $FC \leq 65\%$ ,
- (e) 3H:1V and SC envelopes, and (f) 3H:1V and CL&CH with  $FC \leq 65\%$

## Conclusions

- The shear strength of the soil liner versus the geomembrane increases based on the granular content of the soil liner—the more granular the soil liner, the greater the shear strength.
- The results obtained by the normalization of the shear strength by normal stress supports the value of a trigger geomembrane asperity height that makes no meaningful increment on the interface shear strength, which is about 0.03 cm with an asymptotic behavior at 0.04 cm. This agrees with Blond and Elie (2006).
- The shear strength behavior for soils used in practice as a soil liner in heap leach pad projects is quite nonlinear, depending on the asperity height and the normal stress.
- The asperity height and soil liner classification are very important parameters in the determination of the interface shear strength for the slope stability analysis of a block failure in heap leach pads; any unexpected change to these parameters during the design or construction stages will imply a change in the stability, therefore another stability assessment is needed to ensure that the slope stability of the facility has not been affected.
- As the normal stress increases, the rate of the shear strength increment is reduced. This is related to the nonlinear behavior of the interface shear strength, which is similar to typical granular soil behavior.
- A methodology was developed to extrapolate the shear strength data for higher normal stresses that includes the criteria introduced by Parra et al. (2011). This is supported by the normalized shear strength analysis and the limited LSDS tests for normal stresses higher than 800 kPa that the authors were able to gather.

- A sensitivity analysis of a 2-D limit equilibrium slope stability analysis was performed for 150 models, which included different slope geometries and shear strength interfaces, the latter based on Ayala et al. (2014) and the present study. This analysis confirmed that the typical 2.5H:1V global heap slope with the most typical shear strength interface envelopes shows factors of safety larger than 1.5 (typical minimum factor of safety). Thus this geometry allows for good geotechnical stability performance and is economical (more volume capacity).
- The sensitivity analysis also resulted in factors of safety below 1.5 for all geometries with smooth geomembrane. Thus as a general recommendation, this kind of geomembrane should not be used by itself for projects in seismic regions (where the factor of safety for pseudo static conditions may be less than 1, which is the typical minimum allowable value)—unless berms, trenches, or buttresses are deployed for improving stability.
- These results should be complemented with interface surface inclination sensitivity analysis, plus higher heaps, as well as pseudo static conditions—provided that more test results are gathered for a smooth geomembrane and soil liner interface, and more tests are conducted for higher normal stresses.
- The interfaces that include a soil liner of SC soil provide higher factors of safety than CL and CH soils with FC  $\leq$  65%, regardless of the geometry of the heap leach pad.

## References

ASTM D5321. 2002. Standard test method for determining the coefficient of soil and geosynthetic or geosynthetic and geosynthetic friction by the direct shear method, *ASTM Standards*, 04(13), Philadelphia, Pennsylvania, USA.

Ayala, R., Huallanca, W., Soto, C. and Olaya, T. 2014. Trends on leach pad liner shear strength: Textured geomembrane and soil liner classification, *Proceedings of the Geosynthetics Mining Solutions 2014 Conference*, Vancouver, Canada: InfoMine, Inc.

Blond, E. and Elie, G. 2006. Interface shear-strength properties of textured polyethylene geomembranes, viewed 15 December 2013, [http://www.solmax.com/wp-content/uploads/2012/08/1\\_ShearStrengthproperties-PEmembrane.pdf](http://www.solmax.com/wp-content/uploads/2012/08/1_ShearStrengthproperties-PEmembrane.pdf)

Geosynthetic Institutes Editor. 2002. GRI Test Method GM12 Asperity measurement of textured geomembranes using a depth gage, Philadelphia, Pennsylvania, USA.

Geosynthetic Institutes Editor. 2012. GRI Test Method GM13 Test methods, test properties and testing frequency for high density polyethylene (HDPE) smooth and textured geomembranes, Philadelphia, Pennsylvania, USA.

Geosynthetic Institutes Editor. 2012. GRI Test Method GM17 Test Methods, test properties and testing frequency for linear low density polyethylene (LLDPE) smooth and textured geomembranes, Philadelphia, Pennsylvania, USA.

Ivy, N. 2003. Asperity height variability and effects, GFR Engineering Solutions, viewed 15 December 2013, <http://www.geosynthetica.net/Uploads/GFRAsperity.pdf>

Reddy, D.V. and Butul, B. 1999. *A comprehensive literature review of liner failures and longevity*, Florida Center for Solid and Hazardous Waste Management, University of Florida.

Parra, D., Valdivia, R., and Soto, C. 2012. Analysis of shear strength non-linear envelopes of soil-geomembrane interface and its influence in the heap leach pad stability, Second Pan American Geosynthetics Conference & Exhibition, Geo Americas 2012.

Stark, T. and Choi, H. 2004, Peak versus post peak interface strengths for landfill liner and cover design, *Geosynthetics International Journal*, 11 (6): 491-498.

Stark, T., Williamson, T. and Eid, H. 1996. HDPE geomembrane/geotextile interface shear strength, *Journal of Geotechnical Engineering, ASCE*, 122 (3): 197-203.

Yesiller, N. 2005. Core thickness and asperity height of texture geomembranes: A critical review, *GFR Engineering Solutions*, 23(4), viewed 15 December 2013 <http://www.geosynthetica.net/resources/core-thickness-and-asperity-height-of-textured-geomembranes-a-critical-review/>