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On the 3-D effect of valley-fill heap leach pad slope stability

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Abstract

Two-dimensional (2D) limit equilibrium slope stability analyses are widely used today in the design of geotechnical structures. However, the 2D assumption of plane strain behavior on mining earth structures can be over-conservative, particularly when dealing with complex topography, geometry and geology (Reyes and Parra, 2014; Reyes et al., 2014, 2015).

Among those structures, valley-fill heap leach pads have shown a high "three-dimensional (3D) effect", primarily due to the geometry of their translational failure mechanism, the topography of the valley and the shear strength of their liner system (Reyes et al., 2015). Moreover, Reyes et al. (2015) showed the significant design and economic advantages of considering 3D over 2D analysis. In order to evaluate and quantify the 3D effect for this type of structure, over 2000 idealized 3D models of valley-fill heaps were analyzed, considering standard design parameters, such as the leach pad and heap slopes, valley geometry, heap height and width, interface shear strength, among others.

The results allowed to authors to elaborate several charts and trends, defining which geometrical or strength characteristics may yield the higher ratio for 3D/2D factor of safety, which for the ideal vary between 1.03 and 1.67. These findings can be useful for practitioners to decide when it is useful to use 3D analysis and under which circumstances 2D evaluations may be overconservative.

Introduction

In areas where valleys are usually the only place available for heap leach pads (HLP), such as the Andean region in South America, the civil and geotechnical design require additional effort and specific design criteria that differ for those used in flatter terrain at lower altitudes (César et. al., 2013, 2014; Garay et al., 2014). Currently, stability analysis of these facilities is performed through the use of the limit equilibrium (LE) method in two-dimensional (2D) sections that should be chosen to be representative and critical. The 2D approach is based on plane strain conditions, assuming a non-variable cross-section perpendicular to the sliding direction (SD), therefore three-dimensional (3D) effects, such as the end effects, are negligible and conservative. Usually, the 2D sections chosen for valley-fill HLP are critical but not necessarily representative due to the aggressive terrain and complicated heap layouts, so the tendency is to be conservative.

3D LE slope stability analysis are a practical option take into account the 3D effects of valley-fill heap leach pads. Reyes and Parra (2014) and Reyes et al. (2015) showed the viability of 3D slope stability analysis by the LE method on mining structures and presented two case studies of 3D analyses of a mine waste dump and HLP, respectively. Based upon their findings, Reyes et al. (2015) studied four case studies of practical application of 3D analysis of a valley-fill HLP, whose results showed a 25% to 31% increase of the factor of safety (FS) when compared with the minimum 2D FS for translational failures. Reyes et al. (2015) identified several components of the HLP, such as its geometry, valley configuration and interface shear strength that influence the 3D effect of its FS.

This paper extends the findings of Reyes et al. (2015) by evaluating a large number of idealized valley-fill HLP in order to properly identify which geometrical or geotechnical indexes influence the increase of the 3D FS over the 2D FS. The findings are important in the sense that can guide practitioners to identify when it is useful to use 3D analysis and under which circumstances 2D evaluations may be overconservative.

Parametric analysis

The evaluate which geometrical or geotechnical parameters influence the 3D effect of valley-fill HLP, a parametric analysis was carried out using the ratio of 3D FS and 2D FS (3D/2D FS) as principal index. Several 2D and 3D slope stability analyses by the LE method were performed using Spencer (1967) procedure for both 2D and 3D conditions. SVSLOPE 3D (SoilVision Systems Ltd., 2016), a part of the SVOffice 5 geotechnical software suite, was the computer program used for all the 3D slope stability analyses. Additionally and following Akthar's (2011) recommendations, over 90 000 columns (natural 3D extensions of 2D slices) were used in the 3D analysis. The following sections describe the models analyzed and the parameters evaluated.

Model description

Figure 1 shows an example of one of the symmetric HLP evaluated. Since only translation failures are of concern, the foundation was not modeled and interpreted by in the analysis as a bedrock with infinite strength. Two planes were defined in the model to represent a symmetric valley configuration, as highlighted in Figure 1. This kind of configuration allowed to authors to easily perform several analysis in SVSLOPE 3D (SoilVision Systems Ltd., 2016), since for a single heap configuration, several valley geometries could be analyze in a relatively short amount of time.

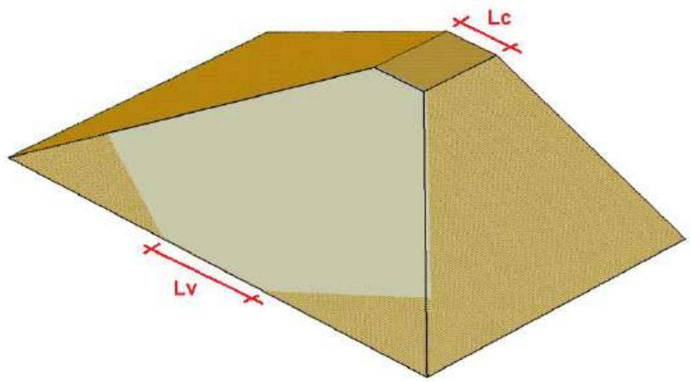

Figure 1. Isometric view of the idealized 3D model of a valley-fill HLP

Geometrical and strength indexes

Figure 1 shows an example of one of the symmetric HLP evaluated. Since only translation failures are of concern, the foundation was not modeled and interpreted by in the analysis as bedrock with infinite strength. Two planes were defined in the model to represent a symmetric valley configuration, as highlighted in Figure 1. This kind of configuration allowed to authors to easily perform several analysis in SVSLOPE 3D, since for a single heap configuration, several valley geometries could be analyze in a relatively short amount of time. An overall heap slope of 2.5H:1V was kept constant for all the models, since its typical for most HLP. Also, the heap pyramidal configuration of heap was maintained, varying only its height and width. The following sections describe the other geometrical and geotechnical index included in the parametric analysis that the author considered of importance for the 3D effect of FS.

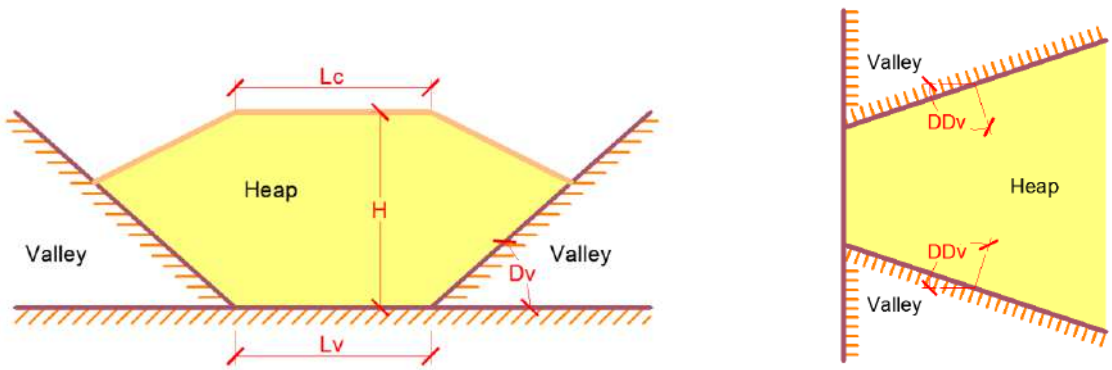

Figure 2. Frontal (left) and plan (right) view of the idealized 3D model of a valley-fill HLP

Heap geometry

The analysis considered the values of 50 and 100 m of crest width (Lc) of the heap (its top lift) which influenced the magnitude of the failure surface. Figures 1 and 2 show Lc within the analyzed HLP configuration. Similarly, the overall heap height (H) was influential on the size of the 3D failure surface. H defines the level of normal stresses the interface would be subjected to. Since nonlinear envelopes of resistances were considered on this study, H values were crucial. Heights of 75, 150 and 250 m were considered. Figure 2 show H in a frontal view of the analyzed HLP.

Valley geometry

This study only considered narrow, symmetrical and "closed" valleys for simplicity. The side slopes of the valley were modeled as planes and primarily characterized by their dip (Dv), dip direction (DDv) and minimum distance between side valley slopes (Lv). Dv values of 15, 30, 45 and 60° were considered in the analysis and were consistent with real side valley slopes of the Andean region which are used for HLP design. Angles of 90, 105, 120, 135 and 150° were considered as DDv for the side valley geometry, which represent the orientation of sides of the slope and determine, along with the Lv, how narrow the valley is. Finally, Lv values of 25, 50 and 100 m were considered in the analysis. Figures 1 and 2 show Dv, DDv and Lv within the idealized HLP model.

Underliner-geomembrane shear strength

The shear strength of the interface generated by the contact of the geomembrane and underliner of the containment system of typical HLP was modeled as a nonlinear envelope, following the findings and recommendations of Parra et al. (2012), Ayala et al. (2014) and Ayala and Huallanca (2014) for low permeability soils as underliner. The nonlinear nature of HLP interface shear strength has an important influence on its stability (Parra et al. 2012) that was validated in this study. To account for different magnitudes of shear strength, three different envelopes were defined based primarily on the research and database of Ayala et al. (2014) and the authors' database low permeability soils-geomembrane interfaces at high confining pressures. The three envelopes were labeled as I1, I2 and I3 and are shown in Figure 3.

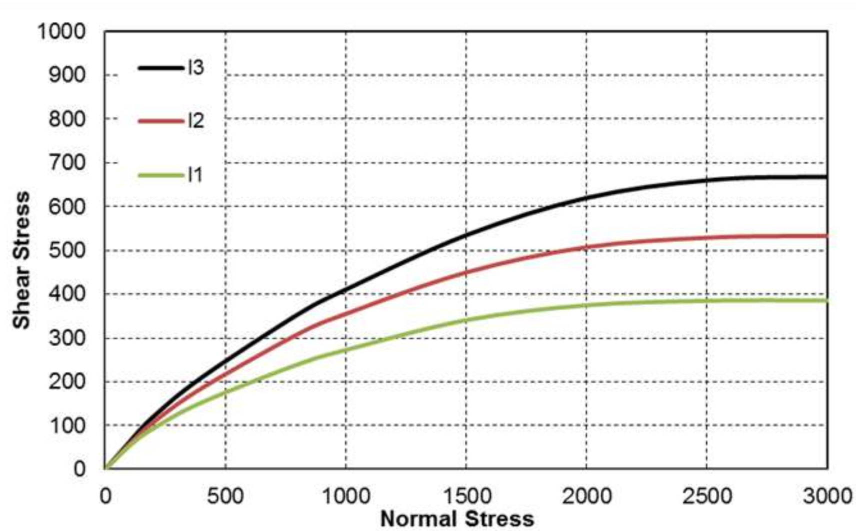

Figure 3: Interfaces nonlinear shear strength envelopes defined for the parametric analysis

Results and interpretation

Over 1000 analysis were performed varying in each one the geometrical and geotechnical indexes described in previous sections. By reviewing the results, several graphs were built to evaluate the influence of the valley and HLP geometry on its 3D/2D FS. It is important to note that past research, including Reyes et al. (2015), used the ratio of slope width and height as a geometrical index to assess the variation of 3D/2D FS; however, defining and/or using this ratio for valley-fill HLP may lead to incorrect conclusions since particularly the width of valley-fill HLP depends of the side valley geometry (e.g. Dv, DDv, Lv). As consequence, all the figures presented in the next paragraphs relate the 3D/2D FS and side valley slope dip (Dv) with another of defined indexes.

In all the analyses, it was very clear that the greater the value Dv, the greater is 3D/2D FS ratio was obtained, regarding of the value of all the other variables. 3D/2D FS ranged from 1.03 to 1.67: the lowest values correspond to the widest, flattest and lowest valley, while the highest value corresponds to the narrowest, steepest and highest valley.

Figure 4 shows trends of 3D/2D FS and Dv for different values of DDv. It can clearly be seen that, in general, the higher the values of DDv, the higher the 3D FS and 3D effect is obtained. Particularly, Figure 4 shows the results for Lc=50m, H=75m, Lv=25m and interface I1. Similar trends are obtained for all the other cases analyzed.

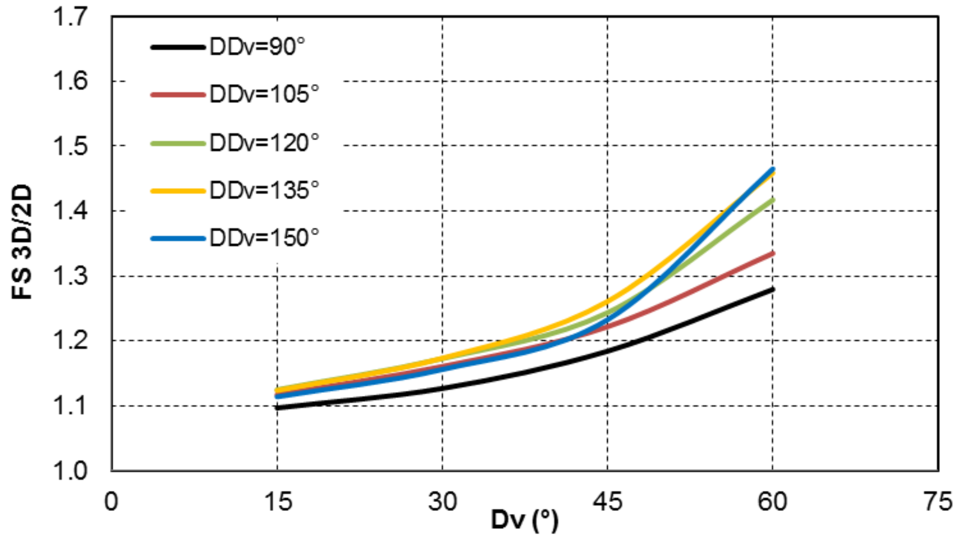

Figure 4: 3D/2D FS trends for different DDv and for Lc=50m, H=75m, Lv=25m and interface I1

An evaluation of the results for different values of Lv shows something expected: the wider the width of valley, the lowest values of 3D/2D FS are obtained. However, while Lv influence the 3D/2D FS is clear in all the analysis, relatively high values of 3D/2D FS can be obtained for wide valleys if, for example, the side slope angles (Dv) are higher than 30°. Figure 5 shows this comparison for Lc=100m, H=250m and interface I2.

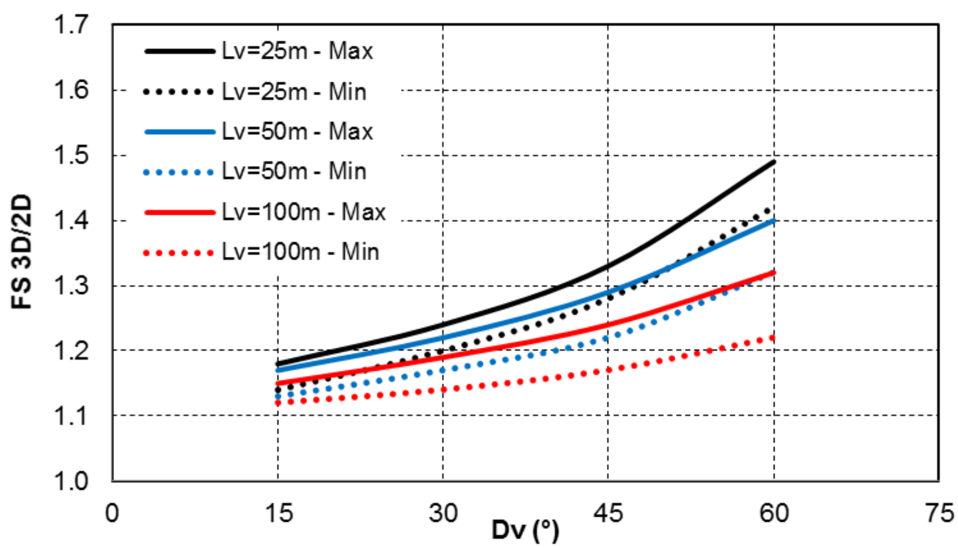

Figure 5: 3D/2D FS trends for different Lv and for Lc=100m, H=150m and interface I1

Figure 6 shows a comparison of 3D/2D FS and Dv versus different heights of heap (H). It can be seen that greater values of 3D FS are obtained for higher heaps. However, for the lowest height considered, there is an important variability, obtaining low to high values of 3D/2D FS. This is an indicative that for smaller heaps, the valley geometry has a greater influence on the 3D FS than the HLP configuration.

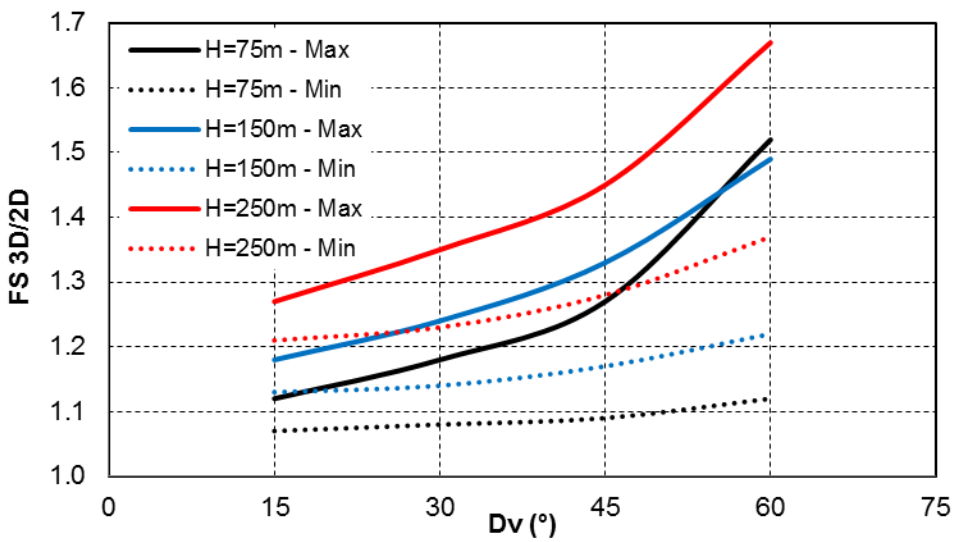

Figure 6: 3D/2D FS trends for different H and for interface I2

The analysis results showed that Lc of the heap had no direct impact or influence in the 3D/2D FS by his own. Finally, Figure 7 shows the influence of the interface shear strength on the 3D/2D FS. It can be deduced that the higher strength of interface, the lower that 3D/2D FS is obtained. However, the difference between the results for each interface may not be significant.

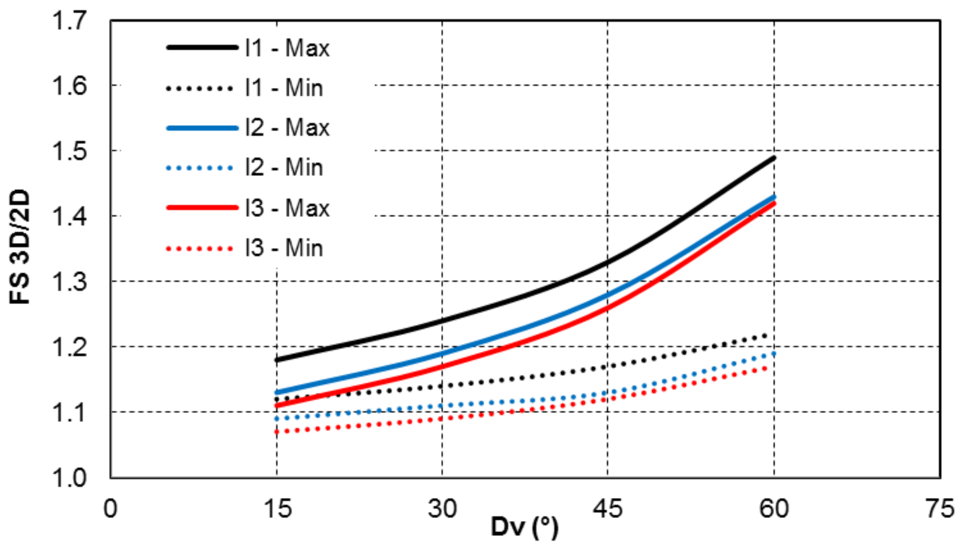

Figure 7: 3D/2D FS trends for different interface shear strength envelopes and for H=150m

The figures presented in this section summarize some of the results of all the analysis but the interpretations were completed by analyzing all the data obtained from the parametric evaluation. No additional figures are included in this paper due to space limitations.

Conclusions

The authors performed several 3D slope stability analyses using the limit equilibrium method on idealized models of valley-fill heap leach pads, which are typical in the Andean region. This parametric analysis was performed using the software SVSLOPE 3D (SoilVision Systems Ltd., 2016) and Spencer's (1967) procedure. The models evaluated several geometrical and strength indexes: heap height and crest width, side valley slope dip and dip direction, minimum distance between side valley slopes (see Figures 1 and 2) and soil-geomembrane interface shear strength envelope (see Figure 3).

The results indicate that the 3D/2D FS ratio can vary between 1.03 and 1.67: the lowest values correspond to the widest, flattest and lowest valley, while the highest value corresponds to the narrowest, steepest and highest valley. This variation is primarily influenced by the valley geometry (side valley slope dip and dip direction as well as the minimum distance between them), which indicates that for narrow and steep valleys, the 3D FS is much higher than the 2D FS. The heap height and shear strength envelope levels (see Figure 3) also influence the 3D/2D FS ratio but in a minor degree. It is important to note that the 3D/2D FS increase is significant and suggest that in several practical applications that the 2D analysis and its resulting heap design are over-conservative. Several figures are presented showcasing the parametric analysis results.

It can be concluded that 2D-based valley-fill heap leach pad geotechnical design is an overly-conservative design tool under many circumstances and may be leading to designs that can be optimized by a 3D evaluation, especially if apparent instabilities are obtained by the former that can be overcame by a 3D slope stability analysis.

The trends developed in this study can be used as a tool for a preliminary screening of any valley-fill heap leach pad. This screening can allow any practitioner to recognize whether a 2D slope stability analysis of the heap is representative or overly conservative. By doing this, the effort that represents performing a limit equilibrium 3D analysis may be worthwhile in order to achieve an optimal design and to avoid unnecessary stability countermeasures, as shown by Reyes et al. (2015). A complete summary of this research can be requested to the authors (ksmendozac@gmail.com, andresrp3@gmail.com). Finally, the results of this parametric analysis can be used as input for a future design code.

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