Proceedings of Heap Leach Solutions, 2014
November 10–13, 2014, Lima, Peru
Published by InfoMine, © 2014 InfoMine, ISBN: 978-0-9917905-6-2

3-D slope stability analysis of heap leach pads using the limit equilibrium method

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Abstract

The physical stability of a heap leach pad is a key issue in its design since critical failure surfaces tend to run along the liner system and tear the geomembrane, causing leakage of pregnant solution, economic losses, and severe environmental damage. Current geotechnical design of heap leach pads involves a two-dimensional (2-D) slope stability analysis using the limit equilibrium (LE) method; usually, critical failure surfaces are translational, running through the liner system. Previous three-dimensional (3-D) analysis for translational failures were reviewed and showed that the "3-D effect" is more important for rotational failures.

In order to quantify the 3-D effects not accounted for by the 2-D analysis and evaluate the overconservative 2-D analysis for heap leach pad (and high associated costs), a 3-D model of a case study located in a common Peruvian aggressive terrain, where 3-D effects are higher, was created and evaluated. The results showed that the factors of safety (FoS) increased by 20 to 49% for the static analyses and 74 to 86% for the pseudo-static compared with the minimum 2-D factors of safety for translational failures. Complex layout heap leach pads and topography are usual in the Andes region, so greater differences between the results of 2-D and 3-D analysis are expected for more complex cases.

Introduction

Modern mining operations manage many facilities specifically designed for storing material with high engineering and environmental standards. These materials are removed, produced, or used by the mining operation itself. Some examples of these materials are: tailings, ore, mine waste or low grade ore, water, and topsoil. Heap leaching technology has become more usual due to increasing mineral demand and diminishing high grade ore reserves. The physical stability of a heap leach pad is important not only because of the economic and environmental threats related to its operation, but also because after the leaching is over, a heap leach pad becomes a spent ore facility containing material that can leach with the liner system as a weak layer for potential failure surfaces.

In Peru and in the countries among the Andes region, mining operations are undertaken at altitudes higher than 2,500 meters above sea level and in rugged, mountainous, and often aggressive terrain. For this reason, when designing a heap leach pad, problems such as slope stability and locating a suitable site for disposing the ore are encountered. Valleys are usually the only place available for heap leach pads, so civil and geotechnical design require additional effort and specific design criteria that differ from those used on flatter terrain at lower altitudes (César et. al., 2013).

The geotechnical design of heap leach pads involves site investigations that include geotechnical-geological mapping, boreholes, test pits, geophysical and in situ tests on the foundation soils, and an extensive laboratory program to properly characterize the geotechnical properties of the ore, liner system, and foundation soils. Current state of practice of slope stability analysis involves the use of the limit equilibrium (LE) method in 2-D sections selected to represent the most critical heap leach pad conditions. Critical rotational failures are usually not used when the foundation is composed of dense soils or competent rock after removing all unsuitable soil, therefore, translational failures are most of the time the most critical. However, the selection of both representative and critical sections is often difficult due to the aggressive terrain and complicated heap layouts, so the tendency is to be conservative.

This paper focuses on the slope stability analysis of a heap leach pad located in southern Peru in a very narrow valley with a complex heap leach pad layout. Previous case studies of translational failures were reviewed in order to understand the 3-D translational failure mechanism of heap leach pads. A 3-D analysis was performed for this facility, and because conventional 2-D stability analysis was performed as part of the design, differences between 2-D and 3-D factors of safety (FoS) are addressed. This 3-D analysis represents another step for Peruvian geotechnical practitioners and the mining industries in performing 3-D slope stability analysis in mining facilities.

The limit equilibrium method for heap leach pads

In current practice slope stability analyses are usually done with the LE method using a 2-D procedure, due to their simplicity and because they are general understood. Calculations usually consist of computing a FoS using one of several LE procedures, each one of them using the same definition of the FoS and equations of static equilibrium (Duncan and Wright, 2005). In the LE method the FoS is defined as the minimum factor by which the soil strength must be reduced to bring the slide to the verge of failure. The soil mass is assumed to be at the verge of slide failure and the equilibrium equations are solved for the unknown FoS (Akhtar, 2011). The FoS equations of static equilibrium for all LE procedures can be written in the same form if it is recognized whether momentum and/or force equilibrium is explicitly satisfied (Fredlund and Krahn, 1977). 2-D procedures assume that the slope is infinitely wide (plane strain) in the direction perpendicular to the plane of interest, and therefore 3-D effects are negligible. Clearly, all slopes and failure surfaces are not wide and generally are not symmetric, so 3-D effects influence the stability of the slope. Gitirana et al. (2008) found that analyzing 3-D models can lead to differences in the lowest FoS between 15% and 50%; these differences are greater when dealing with translational failures (Stark and Eid, 1998; Arellano and Stark, 2000).

Two and three-dimensional limit equilibrium procedures

Reyes and Parra (2014) did an extensive review of the research of Fredlund and Krahn (1977), Duncan (1996), Akhtar (2011) and Kalatehjari and Ali (2013) and compared the most used LE 2-D procedures and most of the available 3-D procedures to date.

Bishop's simplified (Bishop, 1955) and Janbu's simplified (Janbu et al., 1956; Janbu, 1973) are two of the non-rigorous procedures often used by geotechnical practitioners. Spencer's (1967), Morgenstern and Price's (1965), and the General Limit Equilibrium (Fredlund et al., 1981) are rigorous procedures that have been successfully implemented in most of the commercially available software and are among the most used procedures for routine design of heap leach pads (Reyes and Parra, 2014).

Since 1969, several 3-D LE procedures have been proposed; however, after more than four decades, geotechnical practitioners have not yet accepted 3-D procedures over the various 2-D procedures used nowadays. Extending 2-D LE procedures to 3-D necessitates more assumptions for rendering the problem statically determinate (Akhtar, 2011) and building the 3-D geometry of a real slope and determining its critical failure surface are issues still not well understood for practitioners, particularly for translational failures. Reyes and Parra (2014) reviewed most of the 3-D LE procedures available and noted that most of them were direct extensions of 2-D procedures of slices by adding the third dimension and changing them into columns.

Akhtar (2011) concluded that 3-D FoS is greater than 2-D FoS and showed that there were serious inaccuracies involved in the studies that indicated the opposite. Additionally, past researchers used assumptions and geometries that did not represent field behavior. Furthermore, less than half of the 3-D procedures reviewed utilized field case histories to validate their formulations—and even then, only field case histories that were applicable to their formulations were studied instead of a wide range of case histories with different conditions. Despite the disagreement between researchers and the general confusion between practitioners, commercially available software usually performs 3-D analysis using columns and published 3-D extensions of 2-D LE procedures. 3-D software must properly model slope geometry, material properties, and general failure surfaces (Reyes and Parra, 2014).

Side strength in translational failures

As previously stated, 2-D LE analysis is based on plane strain conditions, assuming a nonvariable cross section in the direction perpendicular to the direction of sliding (DOS), therefore 3-D "effects", such as the end effects, are negligible. 2-D analyses are conservative because the resistance along the out-of-plane faces of the slide mass is neglected in the analysis (Akhtar, 2011).

Neglecting the end effects can severely affect the FoS, particularly in narrow slopes with slope angles higher than 20 degrees (Lefebvre and Duncan, 1973). Stark and Eid (1998) and Arellano and Stark (2000) showed that translational slides, which are the most critical in heap leach pads, exhibit a significant difference up to 40% between 2-D and 3-D FoS. Differences are less pronounced in slopes that fail in rotational failure mode (Akhtar, 2011). Stark and Eid (1998) and Arellano and Stark (2000) cite the following reasons for the more pronounced end effects in translational failures:

- Slopes failing in translational mode usually involve either a significantly higher or lower mobilized shear strength along the back scarp and sides of the slope mass than along the base. This specifically applies to heap leach pads, where the ore always has higher shear strength than the liner system interface, usually consisting of a low permeability soil or geosynthetic clay liner (GCL) and a textured geomembrane.
- A translational failure can occur in relatively flat slopes because of the weak underlying material (e.g., liner system).
- A translational failure often involves a nearly horizontal failure surface through a weak underlying layer or a geosynthetic interface, such as the ones found in landfills and heap leach pads.
- A translational failure often involves a drained shearing condition. This facilitates the estimation of the mobilized shear strength of the materials involved because the shear-induced pore-water pressures do not have to be estimated, only the hydrostatic pressures.

As the inclination of the sides parallel to the direction of motion of the slide mass increases, the shear surface area decreases. Therefore, in translational slides, vertical sides provide the minimum amount of 3-D shear strength, because the effective normal stress acting on these sides is only due to lateral earth pressure (Akhtar, 2011). However, in heap leach pads located in narrow valleys, sides that match the liner system along of the valley may provide the minimum 3-D FoS.

In 3-D slope stability software, the side resisting forces due to cohesion and/or friction generated by earth pressure applied to the vertical sides of the end column of the slide mass are not computed (Akhtar, 2011). Stark and Eid (1998), Arellano and Stark (2000), Eid et al. (2006) and Eid (2010) proposed techniques to account for side resistance using the concept of including forces calculated from lateral earth pressure coefficients. Akhtar (2011) performed a parametric study to improve previous techniques and calculate an accurate earth pressure coefficient, using 3-D finite difference and finite element analyses. Akhtar (2011) found that an earth pressure coefficient (K_T) that is between the classical at rest (K_O) and active (K_A) earth pressure coefficients provides a better estimate of shear strength acting along two vertical sides. It is important to mention that the earth pressure concept is only being used as a reasonable approximation of the side shear strength and does not explain the lateral pressure applied to the slide mass. The applied earth pressure is really not applicable to the side shear strength because the strength is developed along the sides of the slide mass as it moves perpendicular to the applied earth pressure (Akhtar, 2011).

Limit equilibrium accuracy for heap leach pads analysis

Duncan (1996) concludes that even though it is difficult to know the correct FoS, it is possible to determine sufficiently accurate values of FoS. This conclusion is based on findings that all methods that are considered to be accurate provide a similar FoS. The continuum mechanics method has the ability to model complex problems without simplifying assumptions, which is an advantage over the LE method. Within the continuum mechanics method, finite element (FE) and finite difference (FD) are different procedures. Researchers such as Griffiths and Lane (1999), Chugh (2003) and Griffiths and Marquez (2007) have performed slope stability analyses using FE and FD procedures and shown that these procedures provide comparable results to LE methods.

Akhtar (2011) compared LE, FE, and FD methods of analyzing 2-D and 3-D slope problems. For 2-D LE analyses, the procedures of Morgenstern and Price, and Spencer, yielded reasonable estimates of the 2-D FoS for any shape of failure surface; however, Spencer's procedure is preferred because Morgenstern and Price's procedure needs to select an appropriate interslice force function. Bishop's and Janbu's simplified procedures are also suitable for routine analyses. In their experience, the authors have found that the difference of the 2-D FoS yielded by Spencer's, and Morgenstern and Price's, procedures are greater when analyzing translational failures of heap leach pads over 100 meters high.

For 3-D LE analyses, accepted 3-D extensions of Bishop's simplified, Morgenstern and Price's, and Spencer's, 2-D procedures provided comparable results with continuum methods and are within 3% of each other. As Morgenstern and Price's, and Spencer's, procedures satisfy all conditions of equilibrium, they are preferred over Bishop's simplified procedure. However, as in 2-D, Morgenstern and Price's procedure requires the selection of an appropriate function for interslice forces, so the 3-D extension of Spencer's procedure is preferred. Akhtar (2011) also suggests correction factors for the 3-D extension of Janbu's simplified procedure. For translational slides, the 3-D extension of Spencer's procedure frequently has convergence problems so Janbu's simplified procedure (with the 3-D correction factor) is preferred. Using Akhtar's (2011) correction factor, Bishop's and Janbu's simplified procedures are viable alternatives to the 3-D extension of Spencer's procedure.

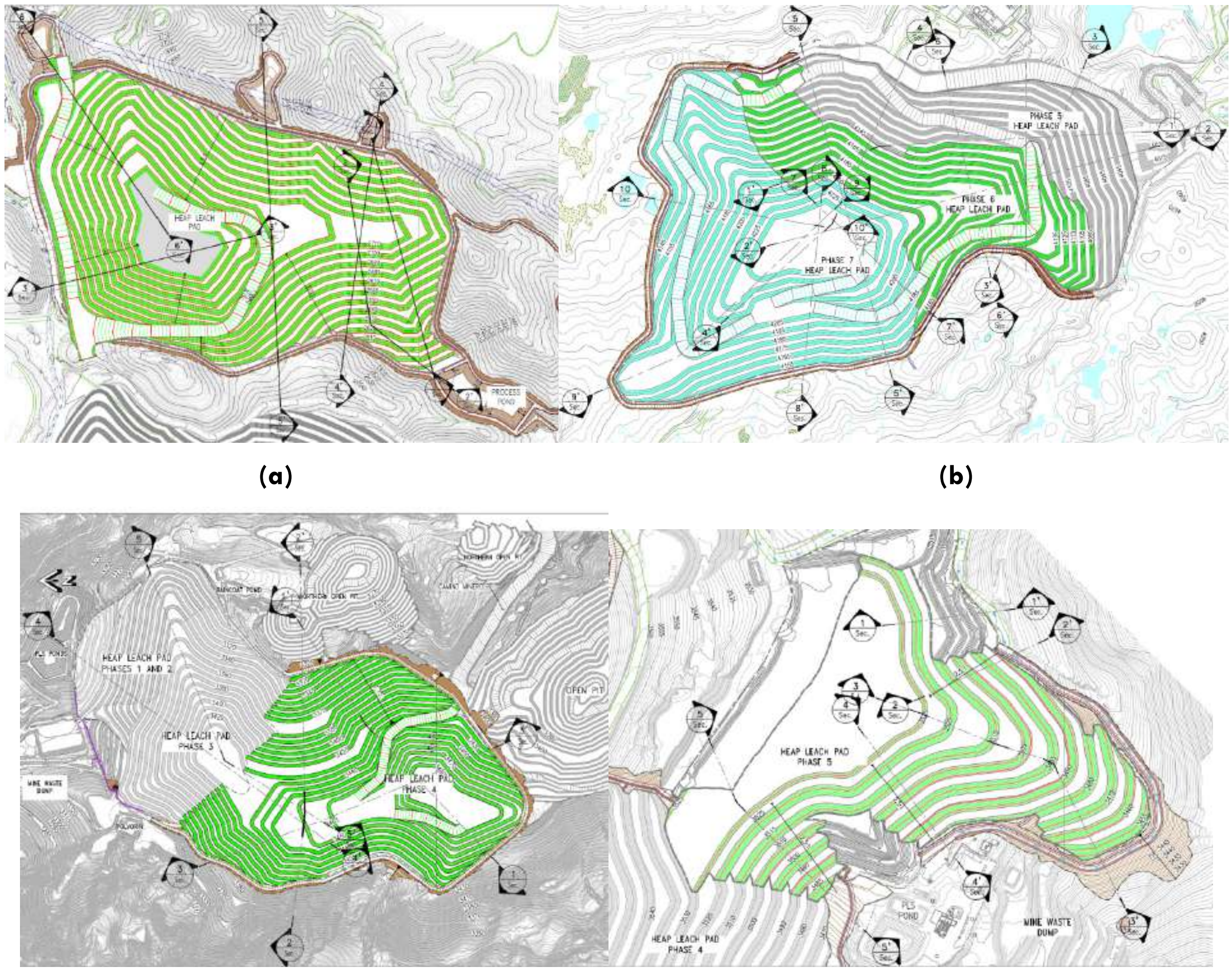
Slope stability analysis of heap leach pads in current practice

In 2-D analyses, a number of cross sections are selected in such a manner that they represent the inherent 3-D problem, simplifying 3-D geometry, 3-D failure surface shape and length, soil variability and, in the case of translational failures, side shear strength. Hence, the accuracy of the analysis depends on the ability to select both representative and critical cross sections, determine the DOS, and even assume overconservative simplifications (Reyes and Parra, 2014).

In relatively flat slopes or in side-fill leach pads, cross sections used to determine the 2-D FoS are considered sufficient because the material's properties and configuration involved in the analysis do not vary significantly in the perpendicular direction of the cross section and the assumed DOS (Reyes and Parra, 2014). Figure 1 shows examples where 2-D analyses may yield overconservative FoS. Cross sections used to analyze each example are also shown in plan view. It can be noted that a large number of sections are used; some of them specifically modeled for analyzing particular soil layers and geometry configurations, especially to evaluate translational failures. It is also really difficult to determine the main DOS. It is important to mention that in all of these examples of real projects, an extensive program of geotechnical investigations were carried out to characterize all materials involved in each section, with special effort made to determine the non-linear shear strength envelope for the liner system. Heap leach pads configurations such as those shown in Figure 1 are very common in the Andes region.

The focus of this paper is to present a 3-D analysis of a heap leach pad, such as the ones shown in Figure 1. During the authors' consulting experience, they have designed and analyzed several heap leach pad facilities, most of them located in the rugged, mountainous, and aggressive South American Andes' terrain. Heap leach pads in the Andes region are located in heterogeneous terrains and in consequence they have complicated layouts. In order to get proper FoS on 2-D analysis for cases such as the ones showed in Figure 1, the design must incorporate the use of stability platforms, interior berms or trenches, gentle slopes, buttressing, massive inadequate material removal, use of higher cost but stronger interfaces for the liner system, and also limiting the height of the facility. In order to quantify the 3-D effects not accounted for by the 2-D analysis and evaluate the overconservative 2-D analysis for heap leach pad (and high associated costs), a 3-D model was built.

As the accuracy of the LE method has been clarified in previous sections, this method is recommended for 3-D slope stability analysis mainly because its mechanics and parameters are easier to understand. In consequence, the model geometry, the DOS, and in particular the translational failure shape, are the main issues when a 3-D model of a heap leach pad is analyzed. Model geometry is usually based on interpolating input cross sections or creating several 3-D surfaces, so realistic models depend on the amount of topographical, geological, and geotechnical information available. Failure surfaces should match field failure mechanisms; in the case of translational failure, failure surfaces should follow the interface in the base and have vertical sides or sides following lateral interfaces, if any.



(a) (b)

(c) (d)

Figure 1: Heap leach pads where 2-D LE analyses yield overconservative results: (a) narrow valley fill; (b) and (c) multiple narrow valley fills; (d) side fill with narrow ends

Akhtar (2011) reviewed field case histories and determined the nature of slides. Rotational failures are ellipsoidal, with aspect ratios varying from 0.8 to 2.67. Translational failures commonly occur when a stronger material underlies a weaker one, as is expected for a heap leach pad. 3-D analysis is strongly recommended for back-analysis of slope failures, because a 2-D analysis back-calculates in a conservative (higher) way the shear strength (Arellano and Stark, 2000). The unique DOS is hard to determine because common commercially available software analyzes models in one direction only. Also, most of them have not incorporated Akhtar's (2011) 3-D correction factor for Janbu's simplified procedure and the K_T

coefficient for side shear strength. Therefore, it is strongly recommended to consider choosing the most suitable software, depending on the characteristics of the slope stability analysis.

Three-dimensional slope stability analysis of a heap leach pad

General background

One of the biggest copper mining companies in Peru has its principal mining operation in the Andes region, where they deal, as is usual in Peru, with aggressive terrain, narrow valleys, and very limited space. Their rapid growth in production requires constant expansion plans and new designs for heap leach pads. Selecting the appropriate location for this kind of project is a mainly matter of civil design, so the geotechnical design must guarantee its stability. This scenario is similar all over Peru, where mining companies are forced to build not only heap leach pads, but mine waste dumps and tailing dams, in narrow valleys and with a complicated ore, mine waste, or tailings layout. Figure 1a shows a plan view of the heap leach pad analyzed in this study.

Geotechnical characterization

As is standard in Peru, design of heap leach pad projects includes extensive geotechnical investigation programs for ore, construction materials, and soil foundation characterization. Common investigations involve a large quantity of field work that includes geological-geotechnical mapping, boreholes (with depth as much as 1.5 times the maximum height of the heap leach pad), test pits, geophysical in situ tests, and in situ determination of global size particle distribution, along with an extensive laboratory test program to model accurately all material involved in the design.

Lately, large-scale direct shear (LSDS) tests with high confining pressures are being performed in order to properly define the non-linear shear strength envelope of the liner system interface, as it heavily influences the calculated 2-D FoS (Parra et al., 2012). Textured geomembrane asperity height measurements are performed before and after LSDS tests, as well as when geomembrane is being installed, due to its influence in the interface shear resistance. Peruvian regulatory agencies are also requesting mining companies for a constant reevaluation of the overall physical stability of most of their facilities. In order to do so, during operation it is common to compile engineering design and construction information (quality dossier) focusing on the data related to soil liner characteristics, take undisturbed and disturbed samples of soil liner and leached ore, respectively, and reevaluate the physical stability (Ayala et al., 2013).

For the case study evaluated in this paper, standard geotechnical investigations were performed around the area. Additionally, six LSDS tests were performed to evaluate shear strength of different kinds of interface: GCL and geomembrane, low permeability soil and geomembrane, overliner and geomembrane, among others. The design required that all unsuitable material had to be removed from the foundation and replaced with massive and structural fill; therefore, the heap leach pad was designed over competent rock and in small zones over structural fill or massive fill. As 2-D analysis showed that translational failures along the interface and rotational failures along the leached ore were the most critical, the 3-D model considered only the materials showed in Table 1.

Table 1: Shear strength parameters for soil layers involved in the two and three-dimensional analysis

Material	Specific total weight (kN/m³)	Specific saturated weight (kN/m³)	Cohesion (kPa)	Friction angle (°)
Leached ore	19	20	0	38
Interface	19	20	Nonlinear shear strength envelope	
Bedrock	21	23	100	30

Two-dimensional slope stability analysis

Due to the layout of the heap leach pad and the valley topography, six critical cross sections were selected to evaluate both rotational and translational failure surfaces. These cross sections, however, were by no means representative of the area correspondent to each section, as they were located within the valley, assuming only critical conditions. Thus, an unknown degree of overconservatism was incorporated. Furthermore, 2-D failure surface locations were selected not taking into account a possible 3-D failure surface that might limit the extension of the failure, which led to the assumption of even more critical conditions. Spencer's procedure was used in a long-term static and pseudo-static (0.19 seismic coefficient) 2-D LE slope stability analysis. FoS calculated for each cross section were higher than the minimum required by the design criteria. It is important to mention that these FoS were calculated for the final design of the heap leach pad; previous stabilization measures were used such as the decrease of the overall slope angle, design of intermediate benches (therefore, diminishing the heap leach pad storage capacity), and the selection of a borrow area of a stronger low permeability soil, but with higher associated costs.

Three-dimensional slope stability analysis

To quantify how overconservative 2-D analyses were, a 3-D model was built, that accounted for sufficient information to represent the geometry of the topography, slope, soil layer distribution, and geotechnical parameters (Reyes and Parra, 2014). For this case study, detailed topography and heap layout were available. The same geotechnical parameters as shown in Table 1 were used for the 3-D analysis. Only translational failures were analyzed in the 3-D, as they are the most critical for heap leach pads.

The SVSLOPE-3-D software package (Fredlund and Thode, 2011) from SoilVision Systems (2011) was used to create the 3-D model. SVSLOPE-3-D performs LE analyses using the columns method and 3-D accepted extensions of classical 2-D procedures (Fredlund and Thode, 2011), according to most of the recommendations presented on Akhtar's (2011) research. However, it does not include Akhtar's (2011) 3-D correction factor for Janbu's simplified procedure. In consequence, 3-D FoS based on this procedure are underestimated; additionally the K_T coefficient for side shear strength is not used, but it has implemented the K_O coefficient described by Stark and Eid (1998) and Arellano and Stark (2000).

Selection of direction of sliding

Prior to modeling, a 3-D DOS was selected for translational failures. The main valley that was analyzed previously by one cross section (referred to from now on as A-A') that had the lowest 2-D FoS for translational failure, was selected as the location for the critical 3-D DOS for the translational failure. Simplifications were only made to the sides of the valley in order to overcome limitations when locating the translational failure surface; no modifications were made to the critical cross sections so comparisons of the 2-D and 3-D FoS were possible. Section A-A' matched the 3-D DOS for the translational failure.

Model geometry and failure surface shape

SVSLOPE-3-D allows creating a 3-D model by, among other methods, interpolating cross sections and importing surfaces from, for example, a DXF file. Unlike Reyes and Parra (2014), who interpolated over 34 cross sections for a case with a complex foundation conditions, surfaces were imported mainly because only three materials were involved in the analysis. SVSLOPE-3-D represented accurately the heap leach pad complex site topography and layout. Figure 3 shows the model as presented in SVSLOPE-3-D, section A-A', and a typical section of the valley.

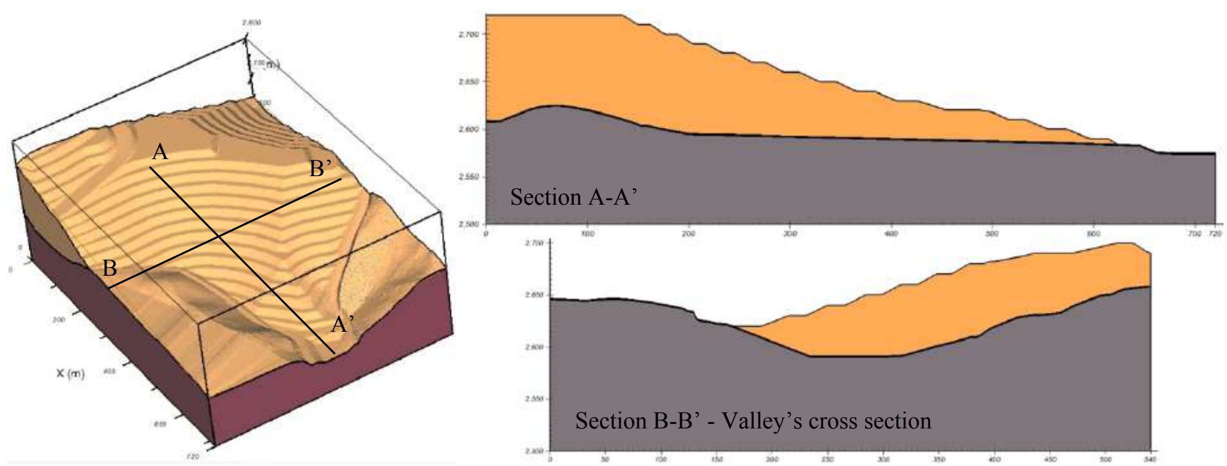


Figure 2: Three-dimensional model of the heap leach pad as presented in SVSLOPE-3-D

Translational failure surface shape was modeled using planes to form "wedges"—each plane is defined by dip and dip direction angles. As mentioned before, the lateral faces of the valley were smoothed, but no modifications were made that would affect the critical cross section. The moving wedges technique implemented in SVSLOPE-3-D, that varies the location of the planes that define a wedge, was used to determine the critical failure surface. Dip and dip direction angles of each plane were defined by the topography, with the exception of the angles of back-scarp plane that needed several iterations to find the critical values. As this is not a conventional translational failure, two shapes were defined. The first one, named "continuous" shape, had sides that matched the valley's lateral sides, so that it could run along the interface on the sides and the ore on the back with the same inclination. The second one, named "scalped" shape, had sides that first matched the valley sides and interface and then vertical sides when running through the ore, according to Akhtar's (2011) suggestions for translational failures. Figure 3 shows both shapes as modeled by SVSLOPE-3-D. The 3-D extensions of Spencer's, and Morgenstern and Price's, procedures were used in order to compare them with the 2-D results.

Results of the three-dimensional analysis

Table 2 present the results from the 3-D analyses for translational failures and Figure 3 shows the two translational failure surfaces shapes defined. The "continuous" shape yielded the lowest 3-D FoS, and the "scalped" shape was analyzed with and without the side shear forces. Ratios of 3-D/2-D FoS are presented, comparing the minimum 3-D FoS for both shapes and the minimum 2-D FoS for section A-A', as suggested by Cavounidis (1987). Results showed that 3-D FoS are greater than 2-D FoS for about 20 to 49% for the static analyses and 74 to 86% for the pseudo-static analyses. It is important to mention that all results presented were calculated with Spencer's procedure; FoS of Morgenstern and Price's procedure are sensitive to the interslice shear force function and were not used.

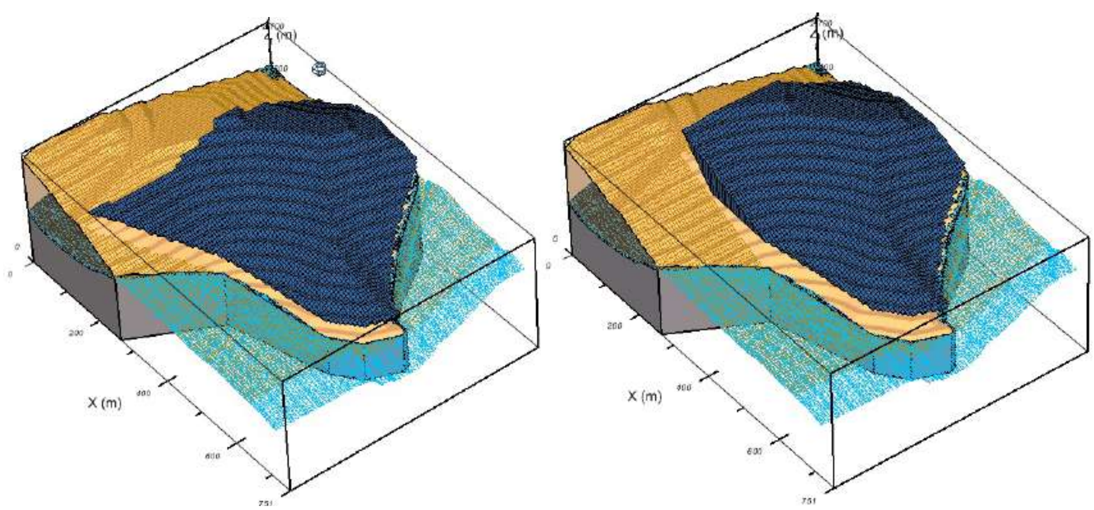


Figure 3: Continuous (left) and scalped (right) shapes for the translational failure

These results allowed the authors to understand the nature and failure mechanism of translational failures in heap leach pads, as well as measuring the overconservatism inherent in 2-D analysis for this type of facility. More research and 3-D analysis of real cases are needed to begin to optimize design of complex heap leach pads and reduce construction costs. This 3-D analysis represents another step for Peruvian geotechnical practitioners and the mining industry in performing 3-D slope stability analysis in mining facilities.

Table 2: Calculated factors of safety for the 2-D and 3-D analysis

Analysis type	Section/Shape	Failure Type	Static FoS	Pseudo-static FoS	Static 3-D/2-D ratio	Pseudo-static 3-D/2-D ratio
2-D	A-A'	Translational	1.983	1.041	–	–
3-D	Continuous	Translational	2.381	1.809	1.201	1.738
3-D	Scalped without side shear forces	Translational	2.306	1.753	1.163	1.684
3-D	Scalped with side shear forces	Translational	3.549	1.937	1.491	1.861

Conclusions

Current state of the art for evaluating slope stability involves 2-D LE analysis and the use of rigorous procedures, such as Spencer's, in cross sections that neglect 3-D effects. These effects are greater when analyzing translational failures, which is usually the main failure mechanism for heap leach pads. 2-D analyses in heap leach pads in the Andes are usually overconservative; however, conservatism is accepted because no real measure of 3-D/2-D FoS ratios applicable to its reality is known. 3-D LE method analysis can quantify this conservatism when geometry and soil strength parameters are known in detail and it is relatively simple to assume the DOS and the failure surface shape. More research and evaluation of complex models are needed to be able to use 3-D analysis for design since a heap leach pad failure represents important economic losses and environmental liabilities.

The potential for 3-D analysis in a given slope stability software should be evaluated before its use, as it needs to accurately model slope geometry and soil strength. Additionally, it must allow the user to evaluate the methods and techniques of 3-D LE procedures, and to understand failure surfaces search techniques and failure surface geometry. As 3-D analysis and procedures are constantly evolving, software developers should include important aspects, particularly for the calculation of side shear forces in translational failures.

A 3-D analysis of a heap leach pad was carried out using the software SVSLOPE-3-D, considering that 2-D analysis yielded overconservative 2-D FoS due to the complex topography with a narrow valley and complex facility layout, which is very common in the Peruvian Andes region. Only translational failures were analyzed since they represented the most critical scenario for the heap leach pad analyzed. Spencer's procedure was used in the calculations and comparison, since when using Morgenstern and Price's procedure, the selection of the interslice shear force function heavily influenced the results. Two failure surface shapes were considered. The continuous shape yielded the lowest 3-D FoS; however, it did not contain any vertical sides which, as suggested by previous researches, would yield the lowest FoS. The scalped shape, that had vertical sides outside of the valley, yielded higher 3-D FoS when considering side shear forces. 3-D FoS proved to be greater than 2-D FoS, showing an increase of 20 to 49% for the static analyses and 74 to 86% for the pseudo-static analyses. These results agree with charts provided by Akhtar (2011), who demonstrated that for a particular configuration of a slope similar to the heap leach pad analyzed, the "3-D effect" is high. However, Akhtar (2011) also proves that the usage of K_O (at rest earth pressure coefficient) to calculate side shear forces in SVSLOPE-3-D, may overestimate this effect. More research is needed to define a critical 3-D shape that matches real failures and a realistic interslice shear force function. As a lot of effort and budget is invested in determining a detailed topography, performing extensive field work and a laboratory program, additional effort could be made to perform 3-D analysis for a more realistic and precise slope stability evaluation in the near future.

These results will allow practitioners to know how conservative heap leach pad designs are when using 2-D analysis. More analyses of heap leach pads in aggressive terrain and complex layout, common scenarios in the Andes region, must be evaluated for a better understanding of 3-D effects. However, common design of slopes should be performed using 2-D analysis to maintain the current conservatism inherent in a 2-D analysis. Regulatory agencies and codes should specify a minimum 2-D FoS as a design criteria, and further research is needed to specify proper criteria for 3-D analyses.

Acknowledgements

This study was performed as a research project funded by Anddes Asociados SAC and the authors acknowledge their support. The continuous support of the SoilVision Systems team is gratefully acknowledged, especially that of Dr. Murray Fredlund, Hai Hua Lu, Rob Thode, and Todd Myhre. Professor Timothy D. Stark and Dr. Kamran Akhtar's research, commentaries, and advice are deeply appreciated and were a source of inspiration for this paper.

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