Three-dimensional Slope Stability Analysis of Slopes in Clayey soils for a Heap Leach Pad

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ABSTRACT: Generally, stability analysis in heap leach pad determines that the most critical failure surface develops along the liner system. However, specific conditions in the foundation, such as the presence of clayey soils, justify an analysis aimed at evaluating potential failure surfaces through it. This paper presents a slope stability analysis on foundation failure applied to both two- and three-dimensional models of a heap leach pad located in Peru; just under its toe, the local presence of clayey soils -resulting from the weathering of andesitic tuffs- was identified, and combined with saturation, these would cause regions of weakness. These conditions motivate a comparison between two- and three-dimensional stability analysis, the latter considers geometry of the stacked mineral, spatial distribution of the foundation materials and relief of the foundation. The analyses employed the limit equilibrium method, using the Mohr-Coulomb and generalized Hoek-Brown failure criteria. The results and paid special attention to the concave and convex zones of the pad and were compared in terms of safety factors and extent of the failure surface in these areas, these results show that the FoS in a 3D analysis are higher than in a 2D analysis and show the ratio between these two FoS varies between 2% and 46%.

KEYWORDS: Leaching pad, three-dimensional stability analysis, limit equilibrium method, foundation failures and clayey soils.

1. INTRODUCTION

The limit equilibrium method (LEM) is commonly used for two-dimensional and three-dimensional slope stability analyses in various mining facilities, such as leach pads. With this method a factor of safety (FoS) is calculated for a failure surface using the concept of limit equilibrium which in the two-dimensional analysis approximates the problem to one of plane deformation and in the three-dimensional analysis considers the forces and moments in the three orthogonal directions. One of the known methods is the one proposed by Spencer 1967, which satisfies the equilibrium of forces and moments and uses slices for the two-dimensional case and columns for the three-dimensional case; the latter has more restrictions such as slip direction, plane of symmetry, among others.

The importance of a three-dimensional analysis grows significantly when the nature of the slope is more complex and therefore it is difficult to execute a two-dimensional analysis (Chakraborty & Goswami 2018). One aspect contributing to this complexity involves the variation of the radius of curvature as observed in the plan view geometry, classifying slopes as concave and convex. A concave slope is more stable than a convex slope and both are more stable than a straight slope (Kang et al. 2022), this could be explained because the lateral pressure of a concave slope offers a higher level of confinement or additional lateral support that a convex slope does not have (Wines 2016).

Slope stability is fundamental in the design of leach pads, it evaluates the possibility of failures through the stack, the liner system, and the foundation, with the result that failures originating at the interface of the liner system are the most critical; however, in particular situations, failures through the foundation materials are the most detrimental. For example, below the foundation level of the pad in this study (located in Peru), residual soil with regions of low mechanical strength is encountered, which would generate the most critical failure surfaces. Two-dimensional stability analyses are also typically performed on leach pads and are advisable if the geometry of the pad stack is moderately simple; these analyses would be difficult for the pad stack of this study, since it has concave and convex slopes seen in plan.

This study focuses on the stability analysis of the failures that cross the foundation of a leach pad due to the existence of low strength materials in the foundation, performing both two-dimensional and three-dimensional analysis. The three-dimensional analysis is justified due to a geological model with a strong variability both in types of materials and their spatial distribution (residual soil is located only at the foot of the west zone and andesitic tuff rock in the rest of the foundation) and a complex stacking geometry convex and concave slope seen in plain view. In addition, special emphasis was placed on discretizing the types of residual soil materials, highlighting regions of saturated soft clayey soils, to analyze the influence on the stability of their short term undrained and long-term drained behavior.

The objective is to understand the differences between two-dimensional (2D) and three-dimensional (3D) analyses of concave and convex slopes of a leach pad located in the Peruvian Andes, considering the difference in the 2D and 3D factor of safety (FoS), calculated by the limit equilibrium method. Additionally, due to the presence of saturated clayey soils, 2 stability models were compared, one considering a mechanical resistance in drained condition and the other in undrained condition.

Finally, the present paper proposes to advance the understanding of slope stability in a leach pad by critically analyzing the effectiveness of two-dimensional models compared to three-dimensional models in static condition, through the limit equilibrium method (LEM).

2. OVERVIEW

2.1 Geology

The heap leach pad of the present study is in the Peruvian Andes. The local geology of the site is defined by residual soils from the weathering of andesitic tuffs.

Site inspection revealed the presence of fat clay and elastic silt (CH, MH), silt and lean clay (ML, CL), clayey sand/silty sand (SC/SM) and clayey gravel/silty gravel (GC/GM) with fines content greater than 30% and saturated at the base of the leach pad (see Figure 2.1 and Figure 2.2). The consistency of the lean clay and fat clay (CL and CH) ranges from soft to firm and in the silt and elastic silt (ML and MH) ranges from soft to stiff; the compactness of the clayey sand, silty sand and silty gravel (SC, SM, GC and GM) varies from medium dense to dense.

These layers are likely the result of weathering of andesitic tuffs, in turn generating rock with hardness less than R2, which is below residual soil levels. These soil areas were indicated as saturated, which encouraged a detailed evaluation in drained and undrained conditions.

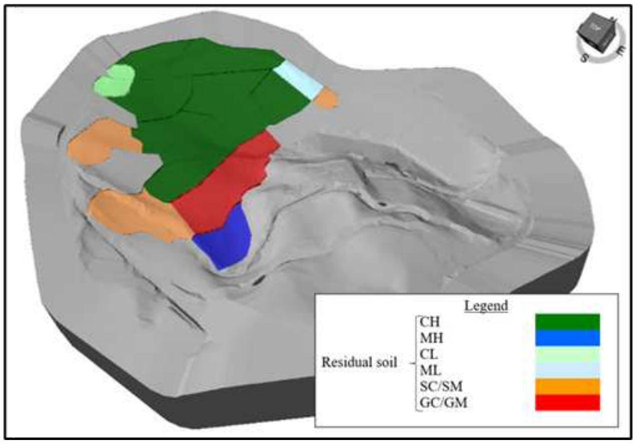


Figure 2.1 Three-dimensional model generated in Slide 3, where the local geology in drained conditions is represented.

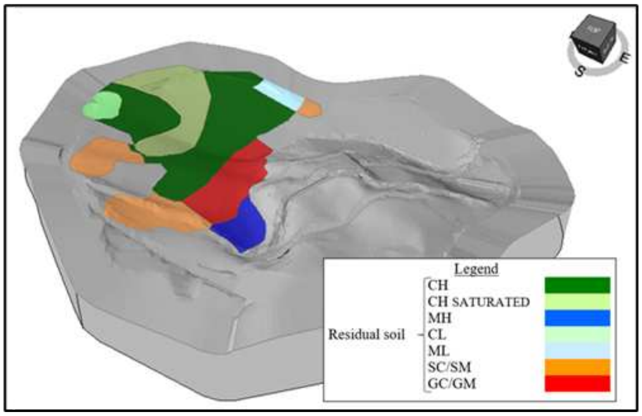


Figure 2.2 Three-dimensional model generated in Slide 3, representing the local geology in undrained conditions.

2.2 Parameters

The mechanical strength parameters for foundation soil and leached mineral were calculated from consolidated undrained (ASTM D4767) and consolidated drained (ASTM D7181) triaxial compression tests and specialized literature, considering post-peak values. Table 2.1 summarizes the parameters of the materials that compose the leach pad and its foundation according to the Mohr-Coulomb failure criterion.

The mechanical strength parameters of the foundation rock were obtained from unconfined compressive strength tests (ASTM D7012) and geomechanical stations. Table 2.2 presents the parameters of the bedrock according to the generalized Hoek-Brown failure criterion.

Table 2.1 Parameters of the materials that constitute the leach pad and foundation materials.

Type of soil/ deposit	*UW*	*C' (kPa)*	*PHI' (°)*	*C (kPa)*	*PHI (°)*
Mineral	18	0	38	-	-
GC/GM Residual soil	19	0	33	-	-
SC/SM Residual soil	18	0	30	-	-
ML Residual soil	17	0	26	-	-
CL Residual soil	17	0	23	-	-
MH Residual soil	17	0	17	-	-
CH Residual soil	17	0	15	-	-
CH (saturated) Residual soil	17	-	-	20	12

UW: unit weight, C': cohesion in drained condition; PHI': angle of friction in drained condition; C: cohesion in undrained condition; PHI: angle of friction in undrained condition.

Table 2.2 Parameters of the bedrock that composes the leaching pad foundation.

Type	*UW*	*UCS*	*GSI*	*mi*	*D*
Tuff	24	50	45	13	0

UW: unit weight, UCS: unconfined compressive strength; GSI: geological strength index; mi: constant for intact rock, D: disturbance factor.

3. METHODOLOGY

The first step was to create a three-dimensional model including the geology below the foundation level and its respective discretization (differentiation of soil materials according to fine content and saturated zones) and the complexity of the pad stack geometry (concave and convex slope zones, see Table 4.1). The analyzes were carried out for the static case, the seismic effect is not considered. Due to the fat clay saturated soil (CH saturated), 2 models were created to consider its drained (long term analysis, see Figure 2.1) and undrained (short term analysis, see Figure 2.2) behavior, the rest of the materials have drained behavior in both models.

Then, a three-dimensional LEM analysis in static condition (see Figure 2.1 and Figure 2.2) was performed to obtain a failure surface for the concave zone and another one for the convex zone of the pad with its respective three-dimensional factor of safety (3D FoS). Along each failure surface, sections are plotted to generate two-dimensional models and run the two-dimensional LEM analysis to obtain two-dimensional failure surfaces with their respective two-dimensional factor of safety (2D FoS) in static condition. The total number of cases is summarized as follows:

- Drained model: one failure surface from the three-dimensional analysis and 4 sections from the two-dimensional analysis for the west convex zone (see Figure 4.1); one failure surface from the three-dimensional analysis and 2 sections from the two-dimensional analysis for the concave zone (see Figure 4.2).
- Undrained model: one failure surface from the three-dimensional analysis and 4 sections from the two-dimensional analysis for the western convex zone (see Figure 4.3).

The limit equilibrium method considers the slope behavior as a rigid-plastic model that reaches its strength at imminent failure and at the same time throughout the failure, it does not analyze the stress-strain relationship or the corresponding deformation within the soil body (Fredlund 1984). Based on the above conditions, the factor of safety (FoS) is defined as a numerical ratio that compares the shear strength of the soil with the shear stress at the failure surface (Bishop 1955). The LEM used is the Spencer method, which satisfies all the static stability equations and assumes that the interslice forces are parallel (Spencer, 1967). In two-dimensional analyses, voussoirs are used and, in three-dimensional analyses, spatial columns (Cala, 2007). To find the most critical failure, an iterative process is carried out to find the failure with the minimum FoS.

3.1 Anecdotal evidence

The differences in the results of 2D and 3D analyses are due to the ability of the last one to consider the three-dimensional nature of the model variables (Wines 2016), in addition to the above, the literature points out that, although two-dimensional analyses are common due to their simplicity, they omit the three-dimensional effects, assuming a plane deformation where the analysis section does not change in direction of movement of the sliding mass (Chakraborty & Goswami 2018).

An important effect is the three-dimensional geometry of the slope, which significantly influences stability. Differences in FoS between the two analyses (2D and 3D) can be notable, with 3D FoS generally higher (Kang et al. 2022). Regarding the difference between 2D and 3D FoS, the reviewed literature highlights variability. Some authors, such as Cavounidis (1987), suggest that 3D FoS are typically slightly higher than their corresponding 2D FoS; others, like Gens et al. (1988) and Mowen et al. (2011), report that this difference could reach up to 30% in certain cases.

Another aspect to consider is the mechanical behavior of the soil, the relationship between the 3D FoS and the 2D FoS is quite sensitive to the magnitude of the cohesion and the friction angle; In the case of a weak layer, the 3D FoS can be higher than the 2D FoS by up to 10%; furthermore, the difference between 3D FoS and 2D FoS decreases as the soil cohesion parameter decreases (Kalatehjari & Ali 2013).

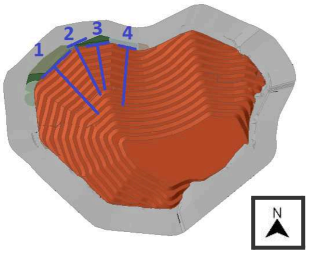
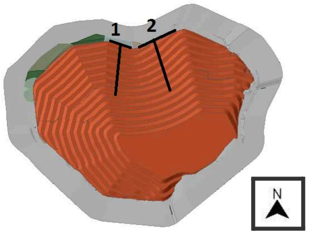
On the other hand, some authors have focused their studies on the comparison of the three-dimensional analysis of convex, concave and flat slopes (Wines 2016). This complexity is not reflected in two-dimensional analyses, which is why engineering practice in stability problems requires considerable attention to the three-dimensional effect of the slope plan curvature (Sun et al. 2017). For example, Gomez et al. (2002) report that a convex slope is stable than a straight slope due to the reduction in the volume of material available to be mobilized as the radius of curvature decreases and Wines (2016) that a concave slope will be more stable than a straight slope. due to the additional support associated with the lateral confinement provided by the concave geometry. Furthermore, anecdotal evidence suggests that convex slopes may be less stable than concave slopes, Hoek et al. (2000) maintain that convex slopes in plan are less stable than concave slopes due to the lack of confinement on convex slopes and the beneficial effect of confinement on concave slopes.

4. DISCUSSION

4.1 3D Analysis

The three-dimensional model constructed for the leach pad of the present study considers the complexities of the geometry (concave and convex zones) and the spatial distribution of the foundation materials.

Table 4.1 Geometric characteristics of the leach pad

	Convex zone - 4 regions - Region 1: r_0 = 1355 m, h = 108 m. - Region 2: r_0 = 46 m, h = 101 m. - Region 3: r_0 = 137 m, h = 100 m. - Region 4: r_0 = 564 m, h = 88 m.
	Concave zone - 2 regions: - Region 1: r_0 = 643 m, h = 102 m. - Region 2: r_0 = 707 m, h = 94 m.

Soft clay soils are distributed only in the foundation of the western foot of the pad, in the rest of the western side, gravelly and sandy soils are found; The foundation on the east side is made up mainly of tuff rock, as seen in Figure 2.1 and Figure 2.2. As previously described, the pad stability analysis of this study must be framed in the three-dimensional case to consider the effects of the complexities of both the geology and the geometric characteristics of the stacked mineral, since a two-dimensional analysis cannot contemplate them. Chakraborty & Goswami (2018) maintain that when the nature of the slope is highly complex, the importance of three-dimensional analysis increases significantly, since this makes it difficult to select a suitable plane for two-dimensional analysis that supports the plane deformation hypothesis. Furthermore, ignoring the impact of the lateral pressure of the mineral in the stability analysis can generate substantial error in the analyses, which is why a two-dimensional model would not be appropriate (Chakraborty & Goswami 2018).

The three-dimensional stability analyzes of the pad, shown in Figure 4.1, Figure 4.2 and Figure 4.3, were executed to find the most critical failures due to foundation in the western convex zone for the drained and undrained case and in the concave zone for the drained, respectively.

Analyzes were carried out in both drained and undrained conditions only in the western convex zone of the pad, since the fine soils are located at the foot of this zone, thus constituting the most unstable zone.

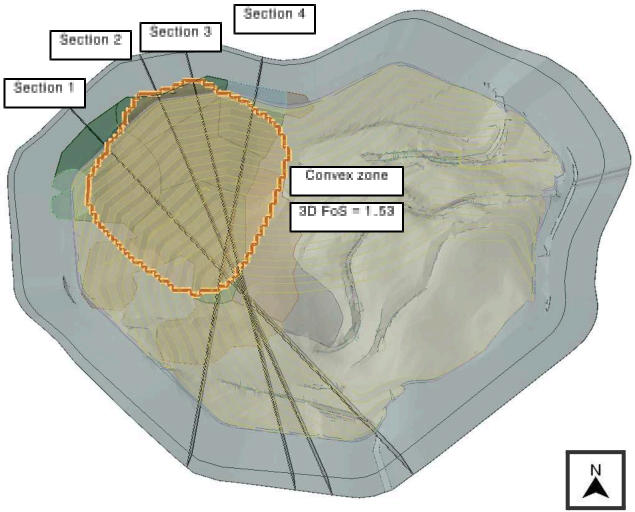


Figure 4.1 Plan view of failure surface in Slide3 in the convex zone and sections generated for the analysis in Slide2 (drained conditions).

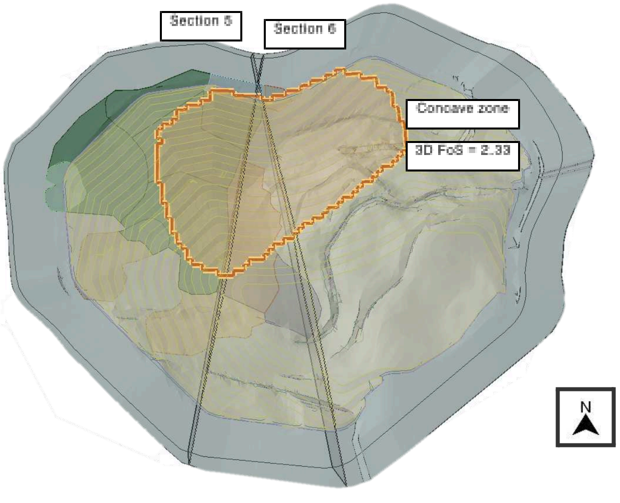


Figure 4.2 Plan view of failure surface in Slide3 in the concave zone and sections generated for the analysis in Slide2 (drained conditions).

For the analysis in the concave zone, only the drained case was evaluated, since its foundation is mainly made up of tuff rock and granular soils and, therefore, it is not an unstable zone for foundation failures.

The three-dimensional LEM used uses the column method that seeks to satisfy the equations of forces and moments in orthogonal directions, with some assumptions of the intercolumn forces to achieve a static definition of the problem (Chakraborty & Goswami 2018). The program chosen was Slide3 from

Rocscience, which has the Particle swam method for searching for critical failures with and generating Spline-type failure surfaces (Ma & Javankhoshdel).

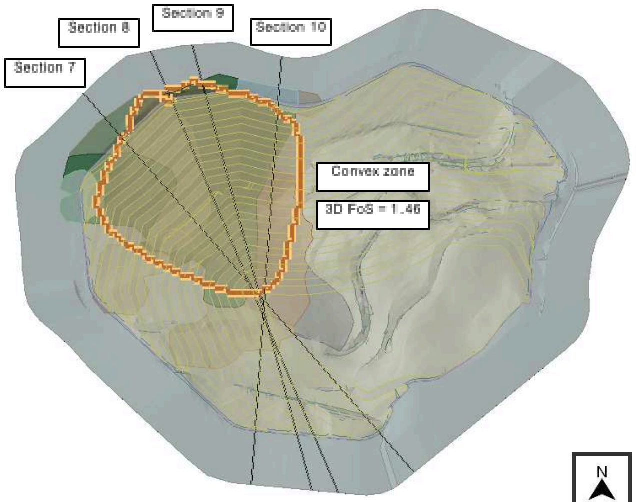


Figure 4.3 Plan view of failure surface in Slide3 in the convex zone and sections generated for the analysis in Slide2 (undrained conditions).

4.2 2D Analysis

It is well known that a slope stability analysis is typically a three-dimensional problem, and many studies show that two-dimensional slope stability analyzes lead to conservative estimates, that is, low 2D FoS (Michalowski & Drescher, 2009); since when the problem is reduced to two dimensions the lateral pressures and structural effects are ignored, therefore, the precision of the analysis can be low and imprecise (Kang et al. 2022).

Consequently, to study the variability of the two-dimensional analyzes for the same slope, different two-dimensional sections were chosen with directions perpendicular to the slopes in the convex (see Figure 4.1 and Figure 4.3) and concave (see Figure 4.2) and that cut the failure surfaces obtained in the three-dimensional analyses. The two-dimensional analyzes were executed through the LEM limit equilibrium method, with the help of the Rocscience Slide2 program, which uses the Particle Swarm search method for critical failures (Rocscience n.d.).

Figure 4.4 to Figure 4.7 show the foundation failure surfaces obtained for the two-dimensional analysis in drained conditions in the convex zone. The failure surface of the two-dimensional analysis of Section 4 has a greater extension, crossing more soft clay soil, compared to the section of the failure surface of the three-dimensional analysis (see Figure 4.6). The other sections are similar in length.

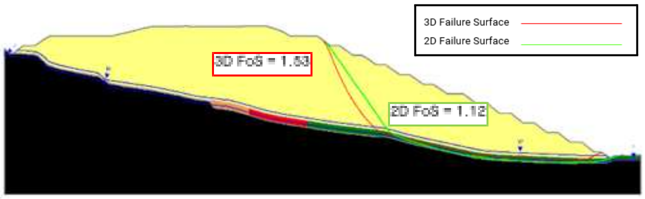


Figure 4.4 Section 1: Failure surfaces obtained from the analysis in Slide 2 for drained conditions in the convex zone.

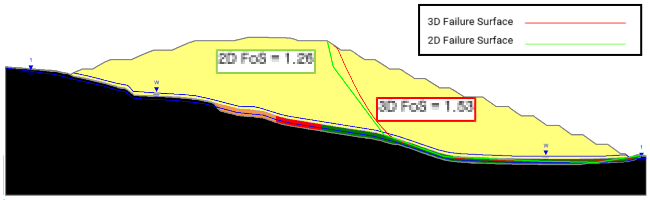


Figure 4.5 Section 2: Failure surfaces obtained from the analysis in Slide 2 for drained conditions in the convex zone.

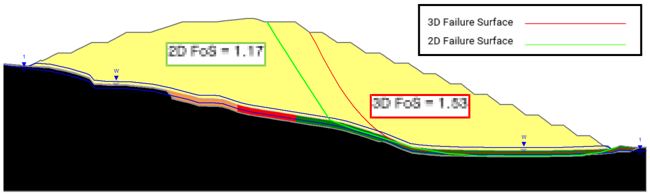


Figure 4.6 Section 3: Failure surfaces obtained from the analysis in Slide 2 for drained conditions in the convex zone.

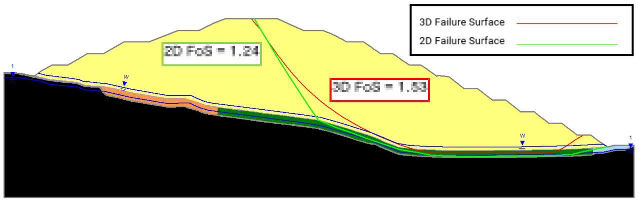


Figure 4.7 Section 4: Failure surfaces obtained from the analysis in Slide 2 for drained conditions in the convex zone.

Figure 4.8 and Figure 4.9 show the foundation failure surfaces obtained by the two-dimensional analysis in undrained conditions for the concave zone. It is observed that the failure surfaces of the two-dimensional analyzes cut the foundation; However, the failure surface of the three-dimensional analysis cuts only the stacked mineral. This may be because the soil is only located in a small sector of the convex zone and the rest is tuff rock with greater resistance than the stacked mineral, which requires to the three-dimensional failure surface to pass through the stack.

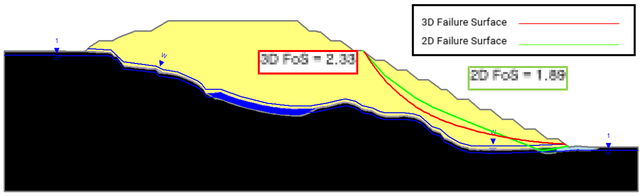


Figure 4.8 Section 5: Failure surfaces obtained from the analysis in Slide 2 for drained conditions in the concave zone.

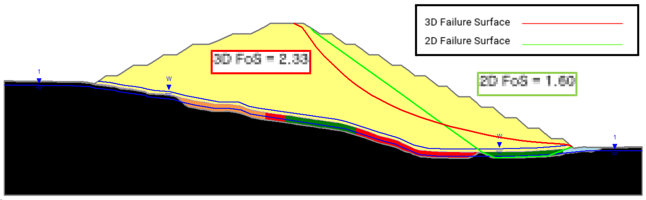


Figure 4.9 Section 6: Failure surfaces obtained from the analysis in Slide 2 for drained conditions in the concave zone.

Figure 4.10 to Figure 4.13 show the foundation failure surfaces obtained for the two-dimensional analysis in undrained conditions for the convex zone. The failure surface of the two-dimensional analysis of Section 10 has a smaller extension, crossing a smaller amount of foundation soil, compared to the cut of the failure surface of the three-dimensional analysis, which cuts a greater amount of mineral (see Figure 4.13). The other sections are similar in length.

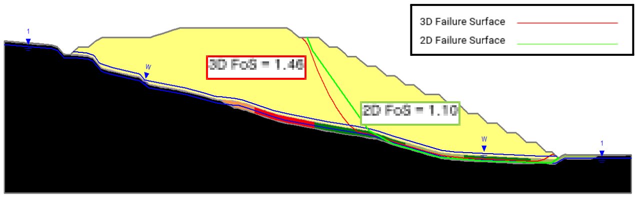


Figure 4.10 Section 7: Failure surface obtained from the analysis in Slide2 for undrained conditions in the convex zone.

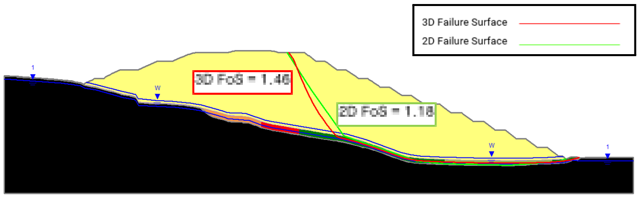


Figure 4.11 Section 8: Failure surface obtained from the analysis in Slide2 for undrained conditions in the convex zone.

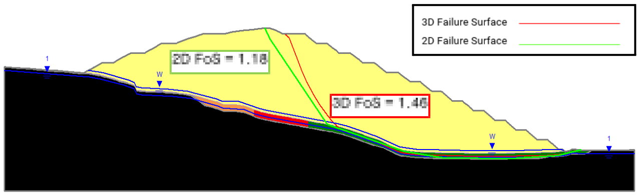


Figure 4.12 Section 9: Failure surface obtained from the analysis in Slide2 for undrained conditions in the convex zone.

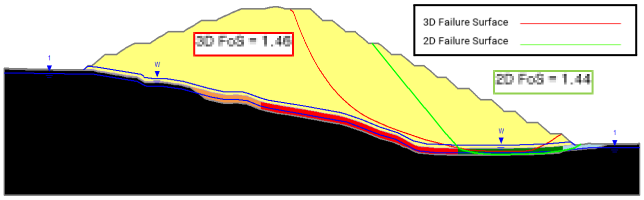


Figure 4.13 Section 10: Failure surface obtained from the analysis in Slide2 for undrained conditions in the convex zone.

4.3 Results

3D FoS of concave zone is greater than convex zone by 52% (see Table 4.2), result is expected since a concave slope is more stable than a convex one (Sun et al. 2017); however, large difference is due to different spatial distribution of foundation materials, soft clay soils are located only in the western convex area of the pad.

Table 4.2 Results of the three-dimensional analysis in drained conditions

Zone	*FoS*	*Volume (m³)*	*Slip direction*
Convex	1.53	1 430 970	N 336.52°
Concave	2.33	869 923	N 348.38°

The undrained behavior of the saturated clay soil in the convex zone produced a 5% decrease in the 3D FoS compared to the drained case (see Table 4.2 and Table 4.3), the impact is not significant because the saturated zone does not extend throughout the clay soil, but in a small sector.

Table 4.3 Results of the three-dimensional analysis in undrained conditions

Zone	*FoS*	*Volume (m³)*	*Slip direction*
Convex	1.46	1 617 480	N 337°

The two-dimensional stability analyzes support what was already obtained in the three-dimensional analyses, because the soft clay soil is only found in the foundation in the convex zone, 2D FoS have been greater for the concave zone (see Table 4.4).

Table 4.4 Results of two-dimensional analysis in drained conditions

Zone	*Type of failure*	*Description*	*2D FoS*
Convex	Foundation	Failure 1	1.12
		Failure 2	1.26
		Failure 3	1.17
		Failure 4	1.24
Concave	Foundation	Failure 5	1.89
		Failure 6	1.60

The undrained behavior of the clay soil has only generated lower 2D FoS in Failure 7 and Failure 8 compared to Failure 1 and Failure 2 (see Table 4.4 and Table 4.5), since the clay soil is saturated only in the surroundings of this fails.

Table 4.5 Results of two-dimensional analysis in undrained conditions

Zone	*Type of failure*	*Description*	*2D FoS*
Convex	Foundation	Failure 7	1.10
		Failure 8	1.18
		Failure 9	1.18
		Failure 10	1.44

It is observed that the ratio of 3D and 2D FoS in the convex zone ranges between 1.23 and 1.36 in the drained condition, and between 1.02 and 1.33 in the undrained condition (see Table 4.6 and Table 4.7).

Table 4.6. 2D vs 3D Analysis results in drained conditions

Zone	*2D FoS*	*3D FoS*	*Ratio 3D/2D FoS*
Convex	1.12	1.53	1.36
	1.26		1.21
	1.17		1.30
	1.24		1.23
Concave	1.89	2.33	1.23
	1.60		1.46

In the case of the concave zone, the ratio between the 3D and 2D FoS varies from 1.23 and 1.46 in the drained condition (see

Table 4.6); however, this relationship is not representative since the three-dimensional failure is in the stack, while the two-dimensional failures manage to traverse part of the foundation (see Figure 4.8 y Figure 4.9).

Table 4.7 2D vs 3D Analysis results in undrained conditions

Zone	*2D FoS*	*3D FoS*	*Ratio 3D/2D FoS*
Convex	1.10	1.46	1.33
	1.18		1.24
	1.18		1.24
	1.44		1.02

5. CONCLUSIONS

Analysis of soft clay soils at the foundation of a leach pad located in the Peruvian Andes under drained and undrained conditions confirms the contribution of these soil types to slope instability.

The presence of soft clay soils at the foot of the pad produces critical foundation failures, highlighting the importance of developing stabilities in undrained conditions for saturated regions. For the present pad, no significant difference was found between the 3D and 2D FoS for the drained and undrained cases, since the saturated sector is very small.

Due to the differentiated distribution of the types of foundation materials, three-dimensional failure surfaces were obtained that mainly crossed the mineral stacked in the concave zone, while in the convex zone the surfaces did cross the foundation. However, this did not occur in the two-dimensional analyses, which determined failures surfaces that travel along the foundation for both the concave and convex zones.

The three-dimensional and two-dimensional stability analyzes for the pad consistently reveal higher safety factors in concave areas compared to convex ones, but both cases higher on straight slopes, which are represented by the 2D FoS, because of confining stresses on slopes with curvature in plan.

The obtained FoS ratios for the three-dimensional and two-dimensional analysis of the pad in this study vary between 1.02 and 1.46 (2% to 46%). This great variability is due not only to the curvature of the slopes in plan, but also to the marked distribution of different materials in the foundation.

One of the limitations of this research is that the Mohr-Coulomb failure criterion was used for all soil types; However, other more suitable criteria can be used to describe the behavior of clay soils (for example, the SHANSEP method proposed by Ladd and Foote 1974). Another important limitation is that the orientation of in situ stresses and the distribution of pore pressures have not been considered, effects that are part of the true three-dimensional nature of the slope stability problem (Wines, 2016).

In a next stage, it is recommended to evaluate the stability of the pad through three-dimensional and two-dimensional analyzes that use the Shear Strength Reduction method (SSR), which has the great advantage that it automatically determines the critical failure surface, eliminating the need to make a priori assumptions about failure mechanisms (Rocnews 2004).

6. ACKNOWLEDGEMENTS

We would like to wish thank to reviewers Pedro Mendoza, Ivan Benites and Jose Ordinola for insightful comments that helped improved the quality of the investigation.

7. REFERENCES

ASTM D4767 (2020). Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils, ASTM International, West Conshohocken.

ASTM D7012 (2023). Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures, ASTM International, West Conshohocken.

ASTM D7181 (2020). Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils, ASTM International, West Conshohocken.

Bishop, A. (1955). The Use of The Slip Circle in the Stability Analysis of Earth Slope.

Cala, M. (2007). Convex and concave slope stability analyses with numerical methods.

Cavounidis, S. (1987). On the ratio of factors of safety in slope stability analyses. Geotechnique 37 (2), 207–210.

Chakraborty, A., & Goswami, D. (2018). Three-dimensional (3D) slope stability analysis using stability charts.

Fredlund, D. (1984). Analytical Methods for Slope Stability Analysis,.

Gens, A., Hutchinson, J., & Cavounidis, S. (n.d.). Three dimensional analysis od slides in cohesive soils. Geotechnique 38, 1-23.

Gomez, P., Diaz, M., & Lorig, L. (2002). Stability analysis of waste dumps at Chuquicamata Mine.

Hoek, E., Rippere, K., & Stacey, P. (n.d.). Large-scale slope designs – A review of the state of the art. Slope Stability in Surface Mining. Society for Mining Metallurgy and Exploration., 115-124.

Kalatehjari , R., & Ali, N. (2013). A Review of Three-Dimensional Slope Stability Analyses based on Limit Equilibrium Method .

Kang, X.-P., Wang, Y.-F., Zhang, Z.-R., Xie, H., & Yang, Y. (2022). 3D Limit Equilibrium Stability Analysis of Concave and Convex Slopes Considering Kinematic Constraints.

Ladd, C.C. and Foote, R. (1974). A new design procedure for stability of soft clays. Journal of the Geotechnical Engineering Division. ASCE, Vol. 100, No. GT7. pp. 763-786.

Ma, T., & Javankhoshdel, S. (Jan 24, 2023). Slide3's New Search Surface Type & Fast Weak Layer Algorithm. Rocscience. https://www.rocscience.com/learning/slide3-new-search-surface-type-fast-weak-layer-algorithm

Michalowski, R., & Drescher, A. (2009). Three-dimensional stability of slopes and excavations.

Mowen, X., Zengfu, W., Xiangyu, L., & Bo, X. (2011). Three-Dimensional Critical Slip Surface Locating and Slope Stability Assessment for Lava Lobe of Unzen Volcano. ournal of Rock Mechanics and Geotechnical Engineering, 82-89.

Rocscience (s.f.). Particle Swarm Search. https://www.rocscience.com/help/slide2/documentation/slide-model/slip-surfaces/non-circular-surfaces/particle-swarm-search

Rocnews (2004), “A New Era in Slope Stability Analysis: Shear Strength Reduction Finite Element Technique”, Rocnews Summer, 2004.

Spencer, E. (1967). A method of analysis of the stability of embankments assuming parallel inter-slice forces.

Sun, C., Chai, J., Xu, Z., & Qin, Y. (2017). 3D Stability Charts for Convex and Concave Slopes in Plan View with Homogeneous Soil Based on the Strength-Reduction Method.

Wines, D. (2016). A comparison of slope stability analyses in two and three dimensions.

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