3D-Stability Validation of a Heap Leach Pad in the Peruvian Andes Using LEM and SSR Technique
(Operaciones Mineras y Gestión Activos - Geotecnia / Geomecánica)

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RESUMEN
Three-dimensional slope stability analyses using the Limit Equilibrium Method (3D-LEM) often raise questions about the realism of assumed failure surface shapes. While spherical, ellipsoidal, and spline geometries are commonly used, spline surfaces offer greater flexibility and often yield lower factors of safety. To validate these surfaces, a comparison with the Shear Strength Reduction Method (SSRM) is appropriate, as SSRM does not rely on predefined assumptions about failure surface shape or location. This study presents a 3D-LEM stability analysis of a heap leach pad located in the Peruvian Andes, characterized by complex stacking geometry (including concave and convex plan-view zones) and a heterogeneous foundation composed of sectorized soft clayey soils. The analysis considers drained conditions and adopts the Mohr-Coulomb failure criterion. Failure surfaces—spherical, ellipsoidal, and spline—were generated using the Particle Swarm Search algorithm. Validation was performed using SSRM, demonstrating that spline-shaped surfaces provide the closest match and most representative factor of safety compared to SSRM results.

1. Introduction

In slope stability analyses, the limit equilibrium method (LEM) is one of the most widely used, which, through the use of a priori defined surfaces, seeks the one with the lowest safety factor to define the critical failure surface (Duncan, 1996; Rocscience, 2004); however, there is always the question of whether these studied failure surfaces can occur in reality. In the case of three-dimensional analyses, 3D-LEMs have been developed that test spherical, ellipsoidal and spline surfaces, the latter standing out because it is more flexible and adopts almost any shape providing lower factors of safety than spherical or ellipsoidal ones (Ma & Javankhoshdel, 2023).

A common practice is to compare LEM results with failure surfaces obtained with the shear strength reduction method (SSRM), since this method has the advantage of not requiring preliminary hypotheses to define failure surface mechanisms, such as shape or location (Griffiths & Lane, 1999; Rocscience, 2004). Several authors have studied theoretically the SSRM and how close to reality the obtained surfaces could be (Duncan, 1996; Griffiths & Lane, 1999); which would allow affirming that the SSRM is an adequate validation methodology for the fault surfaces obtained by the LEM.

This study analyzes the three-dimensional slope stability of a heap leach pad located in the Peruvian Andes, which has a complexity inherent to its stacking geometry (concave and convex zones seen in plan) and to the stratigraphic distribution of its foundation (sectored clayey soils in the northwest foot); and focuses on the comparison and validation of the critical failure surfaces obtained with the 3D-LEM, using the Slide3 program, with those obtained by the 3D-SSRM in conjunction with the finite element numerical method, using the RS3 program.

2. Geology and parameters

The heap leach pad in the Peruvian Andes is underlain by residual soils from the weathering of andesitic tuffs, consisting of saturated fat clay (CH) with a soft to firm consistency and up to 5 m thick (see Fig. 1).

Table 1 presents the stacking and foundation soil parameters (Mohr-Coulomb), while Table 2 summarizes the bedrock parameters (Generalized Hoek-Brown).

Table 1. Parameters of the soil that composes the leaching pad foundation.

Material	Mineral	Residual soil (CH)
Color		
UW (kN/m^3)	18	17
c' (kPa)	5	0
ϕ' (°)	38	15
Young Modulus (MPa)	40	10
Poisson's ratio	0.3	0.2

Table 2. Parameters of the bedrock that composes the leaching pad foundation.

Material	Tuff
Color	
UW (kN/m^3)	24
UCS (MPa)	50
GSI	45
m_i	13
D	0
Young Modulus (MPa)	2000
Poisson's ratio	0.25

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

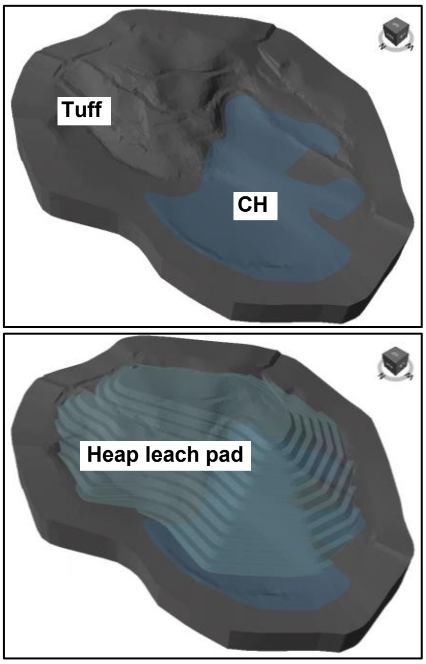


Fig. 1. Three-dimensional model generated in Slide3, representing the local geology in drained conditions.

3. Methodology

Three-dimensional stability analyses were run to determine the global potential failure surface across the soft clay stratum of the heap leach pad foundation for long-term static conditions (i.e., drained conditions), using the LEM and SSRM methodologies with Slide3 and RS3 programs, respectively.

The 3D-SSRM employed the finite element numerical method, with 4-node tetrahedral elements; the Mohr-Coulomb constitutive model was used for the pile and the clay foundation; in addition, 2 refinement regions (see Fig. 2) were created for a sector of the northwest side of the pile (RR1) and for the whole clay layer (RR2) to study the sensitivity of the failure according to the number of elements.

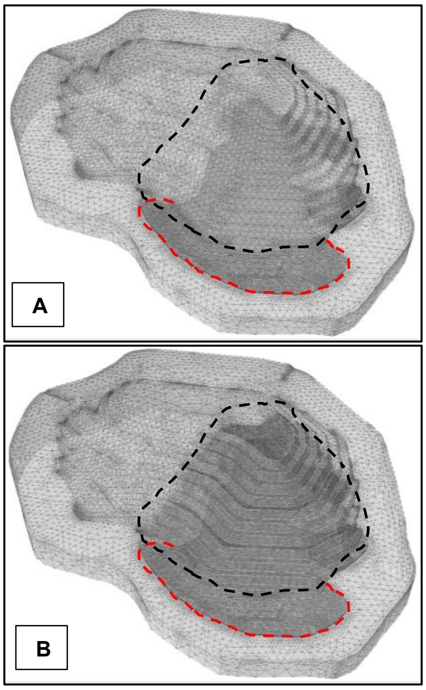


Fig. 2. Three-dimensional tetrahedral mesh generated in RS3. Case A is for 1 662 785 elements with SRF=1.11 and Case B is for 5 130 490 elements with SRF=1.09. The dashed black line is the boundary of the refinement region of a sector of the northwest side of stacking (RR1) and the dashed red line is the boundary of the refinement region of the residual soil (RR2).

The Spencer 3D-LEM searched for failure surfaces with spherical, ellipsoidal and spline shapes (both optimized and non-optimized) with Particle swam search method; the Mohr-Coulomb failure criterion was used for stacking and clay foundation; additionally, in order to improve the results, the above shapes were combined with the weak layer type surface (tool developed by Slide3) embedded in the clay foundation at different depths with respect to the foundation level (0.5, 1.5, 2.5, 3.5 and 4.5 m).

Finally, the critical failure surface obtained with the 3D-SSRM is selected to proceed to validate the failure surfaces obtained with the 3D-LEM (with and without weak layer) and to identify the 3D-LEM failure shape that would better represent the real behavior of the heap leach pad.

This study will focus on evaluating the convex region because its foundation consists of soft clays, making it the most unstable area according to previous 3D LEM analyses (Tapia et al., 2024). The concave region was not evaluated, as it is the most stable due to its rocky foundation and stacking curvature. These results align with the findings of

Sun et al.,2017 who determined that the concave region is more stable than the convex one.

3.1. 3D-LEM vs. 3D-SSRM

The 3D-LEM is simple and requires less data, but it has limitations as it does not consider stress-strains or the real interaction between slides or columns (Rocscience, 2004). The critical failure surface is determined by searching for the one with the lowest safety factor (SF) by testing surfaces with a priori established shapes that meet kinematic criteria (Boutrop and Lovell, 1980; Siegel et al., 1981; Duncan, 1996), becoming a global optimization problem based on spatial parameters and the sliding direction (Lu et al., 2013; Ahmad et al., 2020). The Spencer method is the one that offers the greatest reliability (Griffiths et al., 1999).

On the other hand, the 3D-SSRM evaluates stability considering stresses and strains without assuming a predefined failure surface (Zienkiewicz et al., 1975; Ahmad et al., 2020). Although computationally expensive, it allows modelling complex soil geometries and behavior (Matthews et al., 2014). Failure is identified when the model does not numerically converge by increasing the strength reduction factor (SRF; Rocscience, 2004), without assuming a sliding direction (Lu et al., 2014) unlike the 3D-LEM (Hongjun et al., 2011). It is sensitive to the mesh size and type, constitutive model and convergence criteria (Hongjun et al., 2011, Sun et al., 2017); this constitutes a limitation of the present study, since the sensitivity is not evaluated based on the type of element and the influence of more suitable constitutive models to the Mohr-Coulomb for the clayey foundation or the stacking is not considered.

4. Discussion and results

Table 3 presents the safety factors obtained using the 3D-LEM method for spherical, ellipsoidal and spline surfaces, considering scenarios with and without weak layer.

For the weak layers located at a depth of 4.5 m with respect to the pad foundation, the composite surfaces (spherical+weak layer, ellipsoidal+weak layer, spline+weak layer) found the lowest safety factor. It is observed that the spline surface provides a lower safety factor of about 20 % with respect to the spherical and ellipsoidal without considering the weak layer; this difference is reduced when the weak layer is considered, where the composite spline is 4 % lower with respect to the composite spherical.

Table 3. Failure surfaces and safety factors (SF) obtained from 3D-LEM.

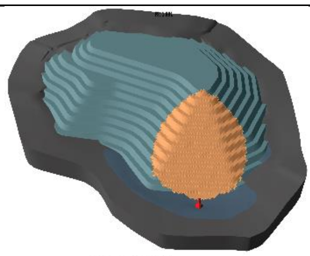
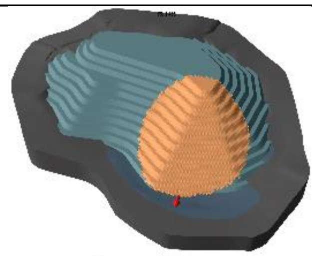
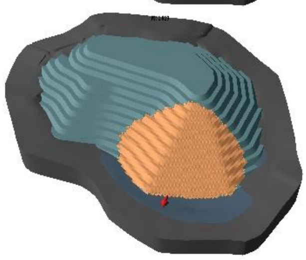
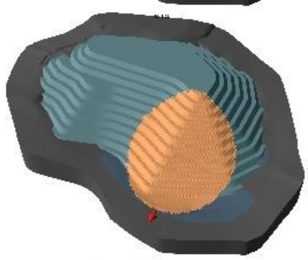
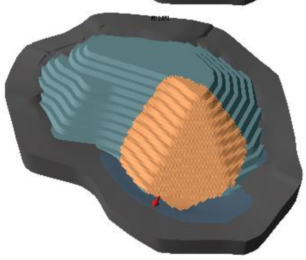
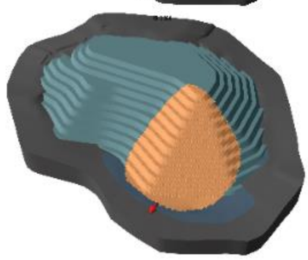
Type	Without weak layer		With weak layer	
	SF	Scheme	SF	Scheme
Spherical	1.631		1.495	
Ellipsoidal	1.619		1.210	
Spline	1.272		1.160	

Table 4 presents the results of the 3D-SSRM analysis considering the mesh density in the residual soil area and part of the lech pad, where the size of the element in each refinement region has been varied, resulting in an increase in the number of elements.

The location and shape of the failure surface is independent of the number of finite elements; however, the strength reduction factor may decrease as the number of elements increases, this reduction is due to the fact that local failures start to appear. It has been selected as SSR for global failure equal to 1.16 for the model with 657585 and SSR for local failure of 1.09 for the model 5130490 elements (see Table 5).

Table 4. Failure surfaces and strength reduction factors (SRF) obtained from 3D-SSRM

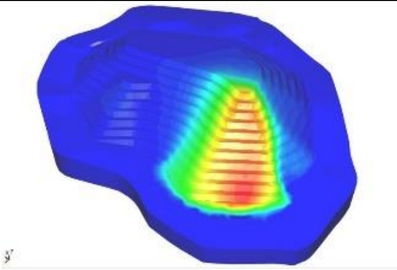
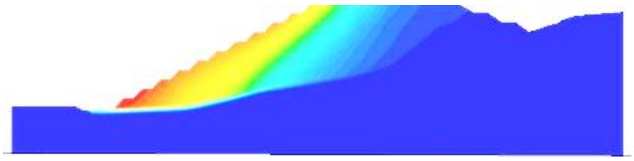
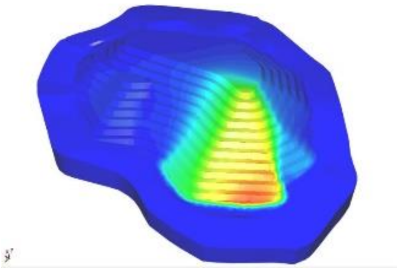
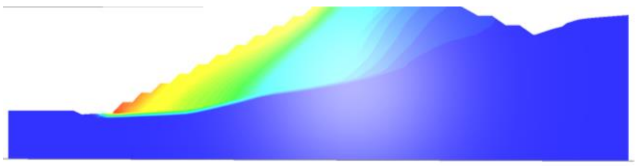
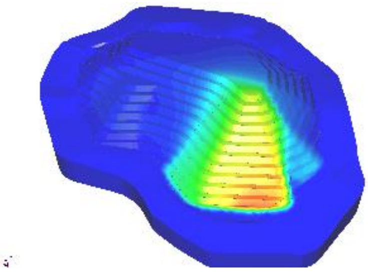
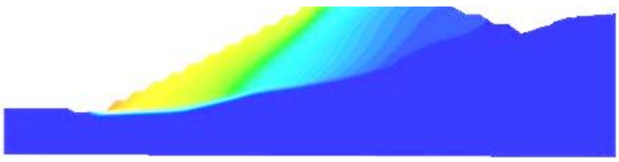
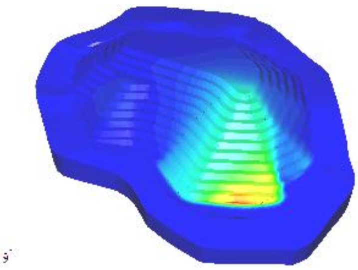
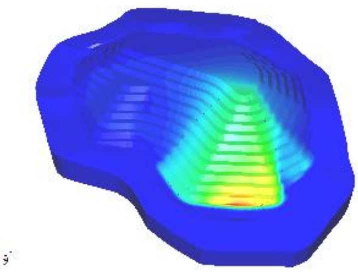
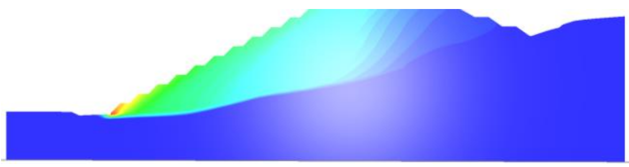
N° elements	SRF	Scheme	Section
61 309	1.26		 Failure: Global/ /RR1:30-40m/RR2:20m
305 533	1.17		 Failure: Global/ RR1:10-30m/RR2:4-10m
657 585	1.16		 Failure: Global/ RR1:4-30m/RR2:4-10m
1 662 785	1.11		 Failure: Global/RR1:10-30m/RR2:2-10m
5 130 490	1.09		 Failure: Global/ RR1:2-30m/RR2:2-10m

Table 5. Comparison of the 3D-SSRM with failure surfaces from 3D-LEM

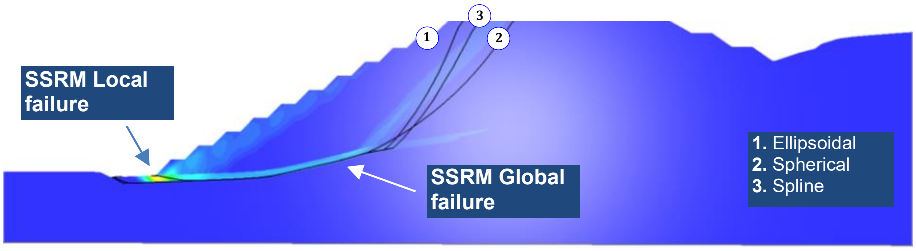
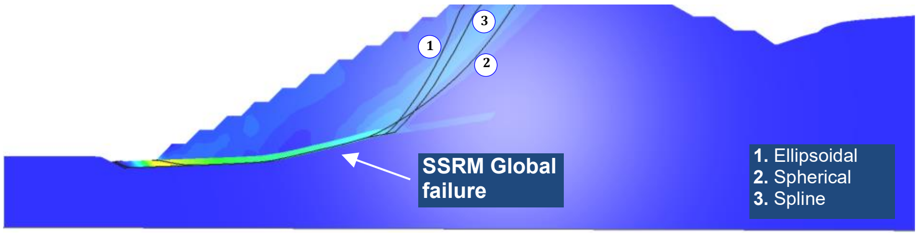
<table>
<tr><th>Type</th><th>Section</th><th>SRF</th></tr>
<tr><td rowspan="2">With weak layer (incremental shear strain)</td><td>
</td><td>1.09</td></tr>
<tr><td>
</td><td>1.16</td></tr>
<tr><td rowspan="2">Without weak layer (incremental shear strain)</td><td>
</td><td>1.09</td></tr>
<tr><td>
</td><td>1.16</td></tr>
</table>

Table 5 shows the failure surfaces obtained by the 3D-LEM and 3D-SSRM methods, where the spherical, ellipsoidal and spline fault surfaces (with and without week layer) are compared with the fault surfaces obtained from the SSRM model, using 5 130 490 and 657 585 elements, respectively.
For the surfaces obtained with the use of weak layer, it is observed that the spline and spherical surfaces are the closest to the SSRM failure surface, according to the maximum incremental shear deformation profile.

For the surfaces obtained without the use of weak layer, it is observed that the spline surface is the closest to the SSRM failure surface, according to the maximum incremental shear deformation profile.

Table 6 compares the volumes of the surfaces obtained with the 3D LEM versus those obtained with the 3D SSRM, the surfaces with weak layers have been chosen as they exhibit lower safety factors and shapes similar to the SSRM. It is observed that the volumes of the spherical and spline shapes are closer to those obtained with the 3D SSRM.

Table 6. Comparison of Volumes between 3D LEM and 3D SSRM

3D LEM Failure shape	Volume (m^3)	3D SSRM Number of elements	Volume (m^3)
Spherical (SF=1.495)	1 707 810	657 585 (SRF=1.16)	1 854 275
Ellipsoidal (SF=1.210)	1 578 760		
Spline (SF=1.160)	1 655 860		

5. Conclusions

Based on the above, it can be concluded that the spline failure surface best represents the actual stability behavior of the leach pad with soft clay foundation. In this regard, Terence Ma et al. (2023) point out that the spline surface is especially useful for identifying critical failures in three-dimensional slopes due to its geometric flexibility. As demonstrated, the spline is a versatile option that allows local optimization by various methods, such as the inclusion of weak layers, making it a more effective tool than ellipsoidal and spherical surfaces. In a next stage, it is recommended to evaluate the stability of the pad through three-dimensional that use the Shear Strength Reduction method (SSR) with an accurate constitutive soil model.

7. Referencias bibliográficas

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