Proceedings of the 10th International Conference on Civil Structural and Transportation Engineering (ICCSTE 2025)
July, 2025 | Imperial College London Conference Center, London, United Kingdom
Paper No. 154
DOI: 10.11159/iccste25.154

Comparative Analysis Of Slope Stability Between FEM And LEM In An Area Of Limited Accessibility. Case: Section Of The Rímac River - San Martín De Porres

Castro Quispe, Brando[1], Clemente Huaman, Nataly[2], Soto Dueñas, Milagros[3]
[1,2,3]Universidad Peruana de Ciencias Aplicadas
Santiago de Surco 15023, Lima, Perú
[1]u20201b582@upc.edu.pe ; [2]u20201b741@upc.edu.pe
[3]milagros.soto@upc.edu.pe

***Abstract* -** This study analyzes the slope stability in a section of the Rímac River with the aim of comparing the safety factors obtained using two methodologies: Limit Equilibrium Method (LEM) with the Slide software and the Finite Element Method (FEM) using Plaxis 2D. Using these methodologies, safety factors were obtained that revealed a general condition of instability in the 14 sections analyzed, with LEM values ranging from 0.203 to 0.812 and FEM values from 0.01 to 0.51. The results showed low similarity between both methods, suggesting that combining approaches is crucial for obtaining a more accurate and reliable evaluation of slope stability, as the analysis of local deformations with FEM complements the global safety evaluations obtained with LEM. Additionally, it is concluded that additional factors, such as the presence of erosion and vegetation, should be considered for a more comprehensive analysis. Photogrammetry is presented as an efficient alternative for obtaining precise topographic profiles, given its accessibility and speed.
Furthermore, it is highlighted that the current national standards do not include specific guidelines for the analysis of deformations in complex slope conditions, focusing only on the evaluation of safety factors through conventional limit equilibrium methods. This limits the precision of stability diagnoses, especially in terrains with heterogeneous behavior, where deformations play an essential role in determining safety.

***Keywords*:** FEM, LEM, stability, slope, accessibility

1. Introduction

Slope stability is a fundamental aspect in geotechnical engineering, as it involves the evaluation of the conditions under which a natural or artificial slope can remain in equilibrium without experiencing failure or landslides. This analysis is crucial in mining projects, riverbank defences, roads and civil works, where slopes must be stabilized to ensure the safety of the projects and the people who use them. In this context, several calculation approaches have been developed to obtain safety factors. One of the most conventional is the evaluation using numerical methods such as the Limit Equilibrium Method (LEM) based on the static equilibrium of forces. However, another evaluation approach has been implemented using Finite Element Methods (FEM) where the stress-strain relationship and progressive failure mechanisms are considered. In response to this, this approach has been implemented with a first application in the analysis of slope failures for a better understanding of the failure mechanism, identifying triggering factors, and selecting an optimized stabilization technique [1]. With this first approach, comparative models began to be developed for the implementation of the FEM as a tool for obtaining safety factors using the Strength Reduction Method (MRR) and supported by analysis with the LEM [2]. This analysis was refined with the development of computational models with basic concepts such as the bisection method that facilitated the development of the MRR and reduced computational time for an evaluation with finite elements [3]. Due to the potential of this approach, it was possible to evaluate models that allow obtaining stability parameters in a three-dimensional space based on the calculation of stress with the FEM. [4] These three-dimensional models were compared with values obtained in a two-dimensional analysis using FEM, obtaining significant similarities in most of the results [5].

Although this approach has been developed for slope stability analysis, the conditions proposed in these studies present an unrealistic representation of the slope because it considers an ideal geometry with a well-defined slope, where it is inferred that there is complete accessibility for obtaining data in the field. Faced with this, the need arises to evaluate and compare the precision of the FEM and LEM geotechnical approaches in the analysis of slopes with uneven geometries, particularly in areas with limited accessibility. The irregular configurations of the slopes, with counterslopes and non-ideal shapes, complicate the application of traditional methods, so new tools must be explored that allow obtaining more precise results in complex conditions.

This article proposes to carry out a comparative analysis between the FEM and the LEM, using data obtained by photogrammetry in an area of difficult access, such as the bank of the Rímac River. The contributions of this study include obtaining safety factor (SF) data using geotechnical software that handles different calculation approaches (FEM and LEM) on slopes where physical access is limited, analyzing the current stability of the slopes in the study area, and comparing the results in rugged geometries, where irregular topographic conditions and counterslopes present significant challenges for both analysis approaches.

2. Methodology

In this study, the stability of slopes is analyzed using physical and mechanical parameters corresponding to poorly graded gravel (PG), extracted from the soil mechanics study of the "Bella Unión" project. The elevations of the 14 cross sections of the slopes were obtained by photogrammetric topographic surveys, mainly due to the limited access available to the river banks and the interrupted pedestrian access due to its proximity to a major road. The elevations obtained will be analyzed using two approaches: the Limit Equilibrium Method (LEM) with the Slide software and the Finite Element Method (FEM) with the PLAXIS software, both in two dimensions (2D). Although it is noted that the FEM is more advantageous for slopes with complex geometry, this study will validate and compare the results obtained by both methods [2]. The comparison will focus on the safety factor and the failure surface identified in each analysis. This is reflected below in Fig. 1.

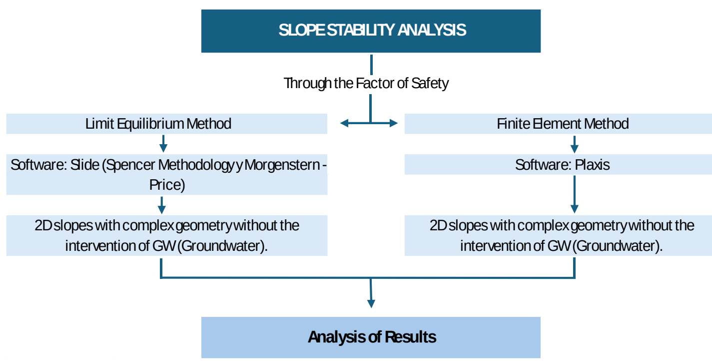

Fig. 1: Flowchart of the methodology used

In Fig. 1, the LEM and FEM methods will be considered within the stability assessment process. Each of them presents a different calculation process where the geomechanical parameters of the soil are used in a different way. This is how software is used that handles each of these calculation systems with a greater number of values for different slope geometries. For a better understanding of the terms mentioned and the tools used, these are defined below.

3. Geotechnical information

For the development of the study, a study section belonging to the Rimac River located in the district of San Martín de Porres in the department of Lima was delimited. This section is located between two infrastructures: the Belaunde Terry Bridge and Bella Unión. Thanks to previous projects, information was obtained from geotechnical studies based on test pits, trenches and geophysical methods to obtain an approximate stratigraphy of the study sector, as shown in Fig. 2, which allowed the soil type to be classified and its geomechanical parameters to be obtained.

Table 1: Mechanical and dynamic parameters of the stratum

Stratum	γ (kN/m3)	C (kPa)	Φ (°)	E (Pa)	Featric level
Anthropic filling	17	0	30	10000	-
Poorly graded gravel (GP)	20	3	34.5	30000	-

In addition, to obtain the sections, cuts were made every 100 meters along the entire length of the section using the contour lines obtained from the topographic survey carried out by photogrammetry, from which their geometric characteristics such as height and slope were identified. This information can be seen in Table 2.

Table 2: Geometric characteristics of the sections

Section	1-1	2-2	3-3	4-4	5-5	6-6	7-7	8-8	9-9	10-10	11-11	12-12	13-13	14-14
Height (m)	7.9	10.7	9.65	11.6	11.55	10.7	12.9	11.6	8.51	11.74	10	10.8	10.7	10.85
Slope gradient (°)	48	78	36	41	52	63	61	56	46	46	85	85	86	88
Overload (kN/m2)	-	-	-	-	-	-	-	-	-	-	-	-	-	-

With the parameters of the stratigraphic profile shown above, the modeling on the calculation platforms begins. For this, profiles created from a point cloud obtained by topographic survey using photogrammetry will be used. The geometry generated by these points was appropriately imported into each software with the assignment of strata and corresponding geomechanical and dynamic properties according to the information required by each software.

In total, 28 sections were imported, of which 14 were inserted in the Slide interface; while the rest were graphed in PLAXIS respecting the limits in all models.

4. Result of modeling and analysis

4.1. SLIDE results

Initially, the limit equilibrium method was used to determine the safety factor of the 14 sections under evaluation. It should be noted that for this analysis, the delimitation at the foot of the slope was not carried out, but the software outputs show the possible general failures of the slope, which are predominant in local sectors. Therefore, to carry out a first analysis, the local failures were evaluated, which will be compared with the results obtained from the Plaxis software, while for a second analysis it is planned to redirect the failure planes taking into account the results of the analysis with FEM in order to delimit the failure planes where greater deformations are evident.

When carrying out the runs of the 14 sections under evaluation, the following results of the analysis of local failures and global failures were obtained as shown in the following table.

Table 3: Results of slide stability analysis in SLIDE.

Section	1 – 1	2 – 2	3 – 3	4 – 4	5 – 5	6 – 6	7 – 7	8 – 8	9 – 9	10 – 10	11 – 11	12 – 12	13 – 13	14 – 14
Local Failure	0.454	0.501	0.331	0.211	0.767	0.624	0.812	0.375	0.212	0.405	0.687	0.203	0.487	0.383
Global Failure	1.41	1.55	1.3	1.19	1.03	1.07	1.05	1.18	1.29	1.09	1.42	1.3	1.05	1.18

4.2. PLAXIS results

The PLAXIS run is carried out in a similar way using the FEM. The result provided by the program after the calculation using MRR is a colorimetric representation related to the displacements presented in the slope in the most unfavorable condition after reducing its resistance parameters. The safety factor is calculated continuously in each calculation step where the reduction is carried out until reaching an interval that the program uses to provide a general FS value.

After running the 14 selected sections of the study section, colorimetries were obtained. For an analysis with FEM, local safety factors were obtained, as well as its maximum total displacement recorded in the unstable condition of the slope with its reduced parameters.

Table 4: Results of slide stability analysis in PLAXIS.

Section	**1 – 1**	**2 – 2**	**3 – 3**	**4 – 4**	**5 – 5**	**6 – 6**	**7 – 7**	**8 – 8**	**9 – 9**	**10 – 10**	**11 – 11**	**12 – 12**	**13 – 13**	**14 – 14**
SF	0.16	0.44	0.023	0.14	0.001	0.44	0.019	0.02	0.001	0.009	0.54	0.38	0.17	0.15
Maximum total displacement (m)	0.0217	1.213	0.158	0.135	0.2294	0.1464	0.1418	0.0786	0.939	0.2018	0.0065	0.0791	0.1591	0.1046
Maximum displacement in X (m)	0.0192	0.985	0.134	0.079	0.1953	0.1263	0.126	0.0672	0.703	0.1556	0.0053	0.0699	0.0683	0.0882
Maximum displacement in Y (m)	0.0006	0.308	0.001	0.003	0.0012	0.0009	0.0002	7E-05	0.002	0.00047	0.000099	0.00126	0.1591	0.00164

As shown in Table IV, the maximum displacements in different axes were recorded in relation to the maximum values per section. With these results obtained, the data of total displacements and safety factor were inserted in a bar graph as shown in Fig. 11.

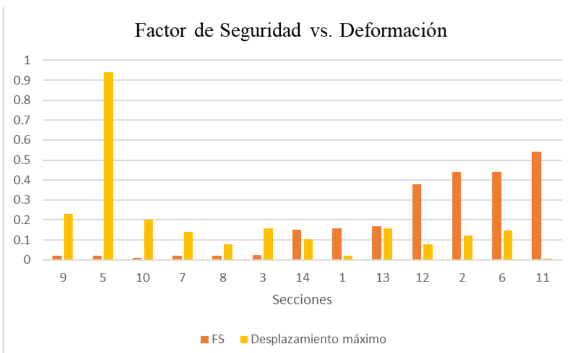

Fig. 2: Graph of safety factors and maximum deformations

As can be seen in Fig. 2, there is a tendency for total displacements to decrease as the slope has higher local safety factor values. The displacement trend is not linear, mainly due to the variable geometry analyzed in this case study, which includes counterslopes, variation in the natural slope inclination angle and the stratification of the slope analyzed, since a greater length of the fill stratum is reflected in a greater length of total displacement. This increase in length can occur due to the accumulation of masses on the slope surface, generating convex, uneven geometries susceptible to failure. Another factor that influences the variation is the precision in obtaining and importing points that were obtained in areas of limited access.

4.3. Slide result based on Plaxis

After evaluating the safety factors obtained in the Slide and Plaxis software, a discrepancy in the results is observed for most of the sections. This variation can be attributed to the fact that Slide presents failure surfaces that do not coincide precisely with the areas of greatest deformation identified in Plaxis.

To reduce this difference and perform a more precise analysis, a second analysis was carried out, which involves delimiting specific sections, so that the failure surfaces determined by Slide crossed the areas of maximum deformation reported in Plaxis. In this way, the safety factors of both programs are compared, ensuring that these values correspond to the most critical areas, according to the deformation colorimetry obtained, which, as it becomes more critical, represents a lower safety factor value.Below are the results obtained from this second analysis, in contrast with the local faults obtained in the first analysis, in both cases developed with Slide.

Table 5: Results of slide stability analysis based on plaxis deformations

Section	1 – 1	2 – 2	3 – 3	4 – 4	5 – 5	6 – 6	7 – 7	8 – 8	9 – 9	10 – 10	11 – 11	12 – 12	13 – 13	14 – 14
Local Failure	0.454	0.501	0.331	0.211	0.767	0.624	0.812	0.375	0.212	0.405	0.687	0.203	0.487	0.383
Slide Delimited Faults	0.454	0.542	0.22	0.198	0.3	0.6	0.88	0.376	0.212	0.405	0.758	0.897	0.519	0.383

4.4. Analysis of results

With the results obtained from the first analysis without any fault redirection in Slide and Plaxis, the following results were obtained, shown in Table 6, where the percentage of similarity between both programs is established based on the highest F.S value obtained.

Table 6: Table 7: Summary of results of the first analysis SF.

Section	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Slope gradient (°)	48	78	36	41	52	63	61	56	46	46	85	85	86	88
SF (SLIDE)	0.454	0.501	0.331	0.211	0.767	0.624	0.812	0.375	0.212	0.405	0.687	0.203	0.487	0.383
SF (PLAXIS)	0.16	0.44	0.023	0.15	0.02	0.44	0.019	0.02	0.02	0.009	0.54	0.38	0.17	0.15
% similarity	35.24%	81.18%	10.45%	71.42%	6.67%	73.33%	2.16%	5.32%	9.34%	2.22%	71.24%	187.19%	32.76%	39.16%

As shown in Table VI, the values obtained directly are found to have a higher value in the results obtained with the Slide. Although in both results the values represent an unstable condition, those using the LEM represent a higher value. On the other hand, the similarity percentages in both results reflect that there is no strong relationship between obtaining these factors with each method. Although there are very close values that exceed 50% similarity in values, approximately 65% of the sections evaluated present a similarity percentage lower than 50%, which reflects an acceptable range where there may be significant error ranges that interfere with a significant SF. Likewise, the variation of these values in a high difference range could classify the slope in an unstable condition.

Now, the second analysis of the results of the safety factors obtained in Slide is presented, with the fault redirection based on the maximum deformations evidenced by the software colorimetry. This is evidenced in Table 7, where the percentage of similarity is established, as in the first analysis, between both programs based on the highest F.S. value obtained.

Table 7: Summary of results of the second analysis SF

Section	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Slope gradient (°)	48	78	36	41	52	63	61	56	46	46	85	85	86	88
SF (SLIDE)	0.454	0.542	0.22	0.198	0.3	0.6	0.88	0.33	0.212	0.405	0.758	0.897	0.519	0.383
SF (PLAXIS)	0.16	0.44	0.023	0.15	0.02	0.44	0.019	0.02	0.02	0.009	0.54	0.38	0.17	0.15
% similarity	35.24%	81.18%	10.45%	75,76%	6.67%	73.33%	2.16%	6.06%	9.43%	2.22%	71.24%	42.36%	32.76%	39.16%

In this second analysis, it is observed that the similarity percentages are consistent in most sections, with the exception of section 12, where the safety factor increased from 0.203 to 0.897. This change represents a decrease in the percentage variation, going from 187.19% to 42.36%, as shown below in Figure 3.

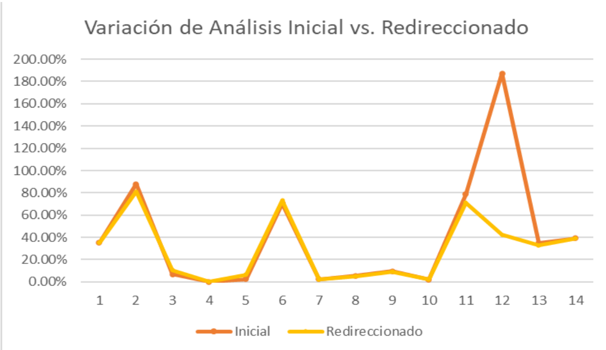

Fig. 3: Initial Analysis Variation Chart in Slide vs. Redirected

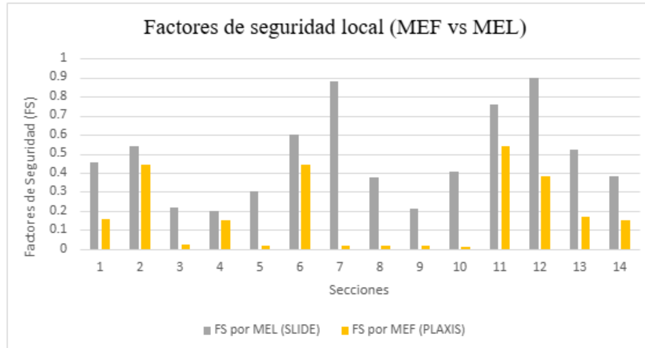

Fig. 4: Initial SF Variation Graph in Slide vs. Redirected

Therefore, the analysis carried out allows us to validate the results obtained from the Slide software, either without delimitation or including it, since Figure 4 shows the minimum variation that exists. However, it should be noted that the direct comparison between methodologies shows constant variations with respect to the LEM and MEF methodology, as shown below.

4. Validation

To ensure the reliability of the results obtained, the data are validated by comparing them with previous studies that use methodological approaches other than the Limit Element Method (LEM) to obtain safety factors, considering the ductile behaviour of the soil and its deformation capacity. In particular, representative studies were selected in which finite element methods (FEM) were applied, and stability data, strength parameters and safety factors were documented. The comparison focuses on verifying the degree of agreement between the safety factors obtained in this analysis and those recorded in previous studies for similar geotechnical and geomorphological conditions.

For this analysis, the study carried out in 2022 [8] is available, in which an alternative method to the LEM was used to calculate local safety factors. This method considers the detection of displacements in areas of potential failure using the strength reduction method. In their study, reduction factors (Rf) were applied for geomechanical parameters in ranges from 0.5 to 1.38, obtaining percentages of difference that vary from 5% to 140% in a conventional slope and in a real application case.

In the present study, the safety factors for local failures were obtained using the PLAXIS software, which, by default, handles reduction factors less than unity in its stability analysis. Therefore, the comparison range with the aforementioned study is limited to the percentages of difference corresponding to an Rf equal to 1. In this context, the results of the first analysis show an acceptable agreement with the percentages of the reference study, reaching difference values close to 50% in most cases, which is significant. This finding suggests that, although the methodologies and analysis geometries are different, both approaches generate comparable results, demonstrating the variability of safety factors in real slopes. This shows that these methodologies could complement each other for a more complete and detailed analysis of slope stability, maximizing the precision in the evaluation of failure conditions.It is evident that these methodologies could complement each other for a more complete and detailed analysis of slope stability, maximizing the precision in the evaluation of failure conditions.

Additionally, critical deformations were evaluated with PLAXIS. According to the Mexican standard N PRY CAR 8 01 001 [9], the maximum permissible displacement in areas adjacent to important infrastructures is 2.5 cm. However, the displacements obtained ranged between 6.5 cm and 93.9 cm, with safety factors less than 1.5, indicating unstable conditions. This confirms that the displacements exceed the normative limits and reflect significant instability in the slopes.

4. Conclusions

In the slope stability analysis carried out in 14 sections of a stretch of the Rímac River using the Slide software and the Modified Limit Equilibrium (MLE) methodology, safety factors were obtained in a range of 0.203 to 0.812, indicating a general condition of instability. Although a correlation was expected to be observed between the slope inclination angle and the safety factor, that is, that lower safety factors would be associated with greater slopes, the results showed a significant dispersion. This dispersion is attributed to the particular geometric complexity of each section, where variations in the geometric configurations, such as the presence of counterslopes, prevent a direct and consistent relationship between the slope and the safety factor. Consequently, no clear trend was observed that would allow linking the slope inclination with the obtained safety factors.

In the same stability analysis for the slopes studied using the Plaxis 2D program based on the finite element methodology (FEM) and resistance reduction (Rf=1), safety factors were obtained between ranges of 0.01 to 0.51, all in unstable conditions, in relation to the maximum deformations presented during the calculation, since the deformations present a decreasing tendency as higher safety values were recorded.

The comparison of both results results in varied similarity percentages for different sections, reaching values much lower than 50% similarity, which gives a considerable margin of error where contradictory SF values can be found when evaluating them by different methods (FEM or LEM). This only reflects the need for a stability evaluation with both approaches to obtain more accurate results, which favors the solution proposals in cases of instability with high risk. In this sense, the deformation factor becomes relevant to determine the stability condition, even in the design phases of containment proposals.

Obtaining safety factors (SF) using the FEM, due to its calculation process, is especially useful for the detailed analysis of deformations in a local environment, as it allows a more precise focus on specific areas of the slope geometry where greater deformations are evident. However, this method can be limited for global stability assessments in rugged geometries, as it focuses on local deformations and does not capture the complete behavior of a slope as a whole. In contrast, the limit equilibrium method (LEM) is more versatile and suitable for global assessments, although its results are not always representative of real conditions due to simplifications in its calculation hypotheses.

Current national regulations do not contain specific guidelines for the evaluation of deformations in this type of conditions and only consider safety factors based on conventional limit equilibrium methods. This limits the accuracy of the diagnosis of slope stability, especially in complex contexts where deformations are essential to understand the real behavior of structures.

Although local failures were analyzed in this study, the approach used could be extended to global assessments, provided that additional software is used that uses FEM and can generate more accurate safety factors in accordance with real ground conditions. Currently, there are few software programs that fully integrate both calculation approaches (FEM and LEM), which complicates the performance of comparative studies. Most specialized tools tend to focus on one of these methods, which underlines the importance of complementing both approaches for a better understanding of slope stability.

While the analysis revealed the importance of applying multiple approaches to slope stability, there are other factors that should be included to obtain a more comprehensive analysis. The presence of the river was not specifically considered in this study in the stability calculations, but it is clear that such presence, together with the possibility of variations in the water table, would influence the results. The erosive action of the river on the slope, accumulated over time, can be a determining factor, progressively reducing the strength of the soil or rock and, therefore, decreasing the stability of the slope. This effect should be studied in future analyses, given its potential impact on safety conditions and its relationship with the possible modification of geomechanical parameters over time.

Another relevant aspect is the consideration of vegetation in the analysis. The presence of vegetation on the slope can improve stability, as the roots contribute to reinforcing the surface soil and reducing the risk of erosion. Including vegetation in the simulations not only increases the accuracy of the safety factors obtained, but also encourages more sustainable and ecological design solutions.

There are many alternatives on the market to obtain the topographic profiles required for a stability analysis. There is even the possibility of using a traditional topographic survey. However, the accessibility required for several of these methods represents a major limitation. Photogrammetry, on the other hand, offers an economic and optimal advantage in terms of time compared to other alternatives that are more complex and expensive. In addition, its accessibility in the national market makes it easy to choose, allowing you to obtain precise and detailed information about the terrain in less time and with fewer resources.

5. Acknowledgements / Agradecimientos

We sincerely thank Professor Milagros Soto for her valuable guidance and support throughout this research. We also thank the Research Department of the Universidad Peruana de Ciencias Aplicadas for their support through the UPC-EXPOST-2025-1 incentive.

Agradecemos sinceramente a la profesora Milagros Soto por su valiosa asesoría y apoyo durante este trabajo de investigación. Asimismo, agradecemos a la Dirección de Investigación de la Universidad Peruana de Ciencias Aplicadas por su respaldo a través del incentivo UPC-EXPOST-2025-1.

References

[1] M. Nobahar, R. Salunke, O.E. Alzeghoul, M. S. Khan, and F. Amini, "Mapping of Slope Failures on Highway Embankments using Electrical Resistivity Imaging (ERI), Unmanned Aerial Vehicle (UAV), and Finite Element Method (FEM) Numerical Modeling for Forensic Analysis," Transportation Geotechnics, vol. 40, pp. 100949–100949, Febrary 2023, doi: https://doi.org/10.1016/j.trgeo.2023.100949.

[2] M. Huaman, "Implementación del Método de Reducción de Resistencia para el análisis de Estabilidad de Taludes". Thesis Pontificia Universidad Católica del Perú, Lima, PUCP, Lima, 2023.

[3] A. P. Dyson and D. V. Griffiths, "An efficient strength reduction method for finite element slope stability analysis," Computers and Geotechnics, vol. 174, p. 106593, October 2024, doi: https://doi.org/10.1016/j.compgeo.2024.106593

[4] Z. Su and L. Shao, "A three-dimensional slope stability analysis method based on finite element method stress analysis," Engineering Geology, vol. 280, pp. 105910–105910, November 2020, doi: https://doi.org/10.1016/j.enggeo.2020.105910.

[5] C. Wu, Z. Z. Wang, S. H. Goh, and W. Zhang, "Comparing 2D and 3D slope stability in spatially variable soils using random finite-element method," Computers and Geotechnics, vol. 170, pp. 106324–106324, April 2024, doi: https://doi.org/10.1016/j.compgeo.2024.106324.

[6] Bra Das. Fundamentos de Ingeniería Geotécnica. México: Thomson Learning, 2002.

[7] L. I. González de Vallejo, M. Ferrer, L. Ortuño, and C. Oteo. Ingeniería geológica. Madrid: Prentice Hall, 2002.

[8] Cimentaciones Superficiales, N·PRY·CAR·8·01·004/19, México,dic. 2019.

[9] T. Yang, Y. Rao, N. Ma, J. Feng, H. Feng, and H. Wang, "A new method for defining the local factor of safety based on displacement isosurfaces to assess slope stability," Engineering Geology, vol. 300, p. 106587, Apr. 2022, doi: https://doi.org/10.1016/j.enggeo.2022.106587.