Alto do Padre Cícero Hillside 3D Stability Analysis in Camaragibe - PE / Brasil

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Abstract

Alto do Padre Cícero is an occupied hillside, classified as a high degree of risk. Its location is in Camaragibe, a municipality that belongs to the Recife Metropolitan Region (RMR), Pernambuco State, Brazil. Studies conducted in the area reported that the slope belongs to Barreiras Formation, which is a geological unit that concentrates the highest number of landslides and erosions in the RMR. In June 2010, the heavy rains that occurred resulted in an accumulated monthly volume of around 500 mm. In this scenario, after a storm, a slump block and significant cracks appeared in the top of the slope, which indicates the activation of a gravitational mass movement. Besides, disorderly and informal occupation on the hillside levels has been advancing over the years, bringing it closer to a scenario of instability due to anthropic actions, such as solid waste disposal, performing cut and landfills without technical criteria, deforestation, among others. Given these characteristics, Alto do Padre Cícero became the objective of several studies developed by the Geotechnical Engineering Group for Hillsides, Plains and Disasters, as seen in Magalhães and Coutinho (2015) and Souza (2014) who carried out intense geotechnical investigations to analyze the stability of the slope using two-dimensional sections. This paper's objective is to realize an expansion of these studies considering the effect of the 3D stability analysis on the security factors and failure mechanisms found. For this, the limit equilibrium method is applied and implemented in Rocscience's Slide3 2019 software. It is considered the suction variation throughout the driest and most humid period of the year. In the critical section, the results followed the prediction of literature that is the safety factor in 3D analyses presented results superior to those obtained through the 2D stability analyses. Additionally, the 3D analyses were able to predict with sufficient precision the mass movement signs above mentioned, indicating that the slope can reach the imminent failure for intense rain periods presenting average safety factors of 1.065. The safety factors values obtained in the natural condition, corresponding to a drier period, were higher than those determined in the submerged condition due to the increase in shear strength resulting from the consideration of suction. It corroborates with the occurrence of mass movements in the RMR, which is concentrated between the months of intense rainfall.

1 INTRODUCTION

Overall, slope failures are three-dimensional (3D) in nature, but two-dimensional (2D) modeling is usually adopted as this greatly simplifies the analysis (Cheng & Lau, 2014).

These simplifications in two-dimensional models can lead, in some cases, to safety factors not consistent with reality. According to Cheng and Lau (2014), this phenomenon occurs for the following reasons:

- The application of additional safety factors on the soil parameters is quite common.
- There is heavy rainfall with long recurrent periods in the analysis.
- Three-dimensional effects are not considered in the analysis.
- Additional stabilization due to the presence of vegetation or soil suction is not considered.

It is expected in fact that the safety factors resulting from 3D analyses be greater than those obtained through 2D analyses. The main reason for this difference is the ability of three-dimensional analyses to be more realistic including the slope geometry, the distribution of soil and rock mass domains, the orientation of geological structures with respect to the excavation face, the orientation of the in situ stresses, and the distribution of pore pressure (Wines, 2016).

Besides, as stated by Fredlund et al. (2018), the geotechnical engineer selects a slice to analyze in 2D assuming that this is the critical slice. However, it does not always correspond to reality.

According to Bahsan and Fakhriyyanti (2018), for natural hills that have the complexities of slope surfaces, 3D modeling may also be considered since it can represent the more realistic geometry of the slope.

However, 3D analysis can be used if more detailed data are available such as the more accurate topographic maps, more accurate groundwater conditions, complete information on the soil layers with the detailed soil parameters.

Alto do Padre Cícero became the objective of several studies developed by the Geotechnical Engineering Group for Hillsides, Plains and Disasters (GEGEP / UFPE), as seen in Magalhães and Coutinho (2015) and Souza (2014), due to factors such as complexities of slope surfaces, signs of instability, disorderly and informal occupation on the slopes, and identification of anthropic actions that favor the mass movements occurrence. The authors mentioned above performed intense geotechnical investigations to analyze the slope stability using two-dimensional sections.

In this sense, this work's objective is to realize an expansion of these studies, considering the effect of 3D stability analysis on the security factors and failure mechanisms understanding. It presents a comparison between the safety factors obtained from 3D and 2D stability analyses considering the suction variation throughout the driest and the most humid period of the year.

In the present study, the Limit Equilibrium Method (LEM) for 3D stability analysis, implemented in Rocscience's Slide3 2019 software, is applied.

2 DESCRIPTION OF THE STUDY AREA

Alto do Padre Cícero is a densely populated hillside that is classified by Bandeira et al. (2004) as a high risk to landslides and erosion. Its location is in the Recife Metropolitan Region (RMR), specifically, in the municipality of Camaragibe (Figure 1). It has the following geographical coordinates: 8°1'30.32"S e 34°58'47.74"W.

In the municipality of Camaragibe, two morphological groups are identified: the hills and the plains. The high areas with immature (active) terrains dominate 80% of the municipality relief and reach altitudes of 150 meters above sea level (Bandeira et al., 2004).

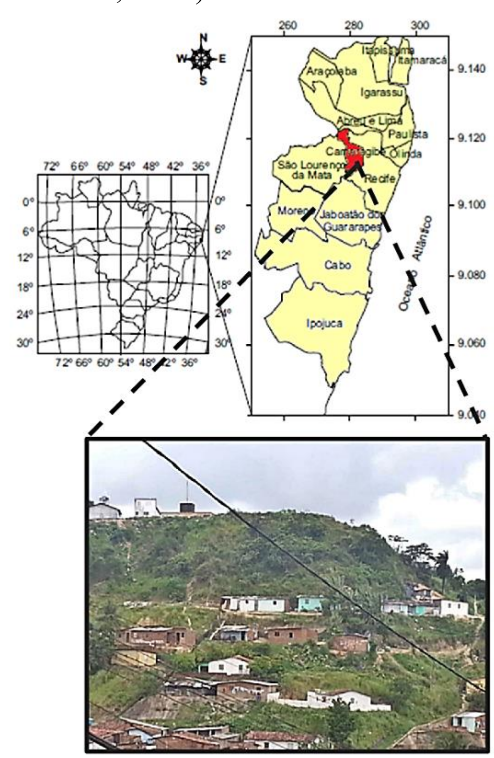


Figure 1. Location of Alto do Padre Cícero hillside, Camaragibe/PE - Adapted from Souza (2014).

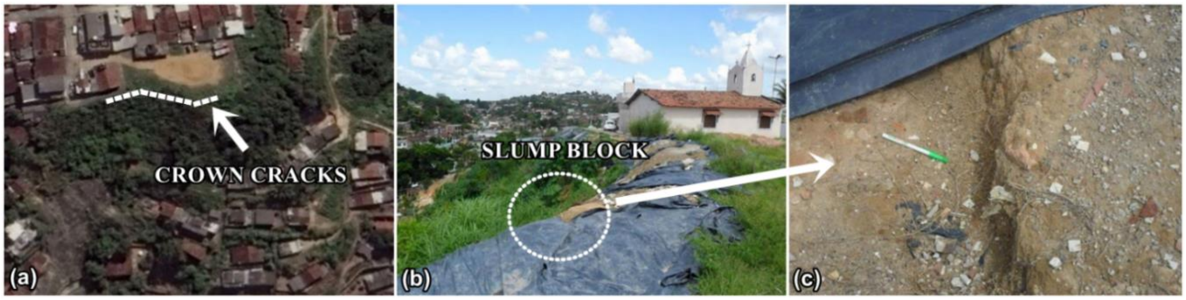


Figure 2. Location of the (a) cracks and (b, c) slump block - Adapted from Souza (2014).

The slope studied is the highest difference in elevation in the municipality and has been showing signs of instability since 2002.

In June 2010, the heavy rains that occurred resulted in an accumulated monthly value of around 500 mm. In this scenario, after a storm, a slump block and significant cracks appeared at the top of the slope, as shown in Figure 2, which indicates the activation of a gravitational mass movement.

By the time of this paper, there are no stabilization measures, and the process continues to threaten the lives and possessions of many people. Besides, disorderly and informal occupations have been advancing on the hillside level over the years.

As a result, it is observed in the natural slope the increase in the realization of several anthropic actions that favor the occurrence of mass movements, such as solid waste disposal, performing cut and landfills without technical criteria, wastewater disposal on the surface and increased overload on the slope due to the construction of houses on its levels.

3 GEOLOGICAL CHARACTERIZATION

Three large geological units compose Camaragibe geology. The geological units are the Crystalline basement, constituted by rocks from the Granite Gneiss Complex, covered by its residual soil; sediments from the Barreiras Formation; and alluvial deposits (Bandeira et al., 2004). Figure 3 presents the spatial distribution of these geological units and the location of the studied slope. As observed at the studied hillside, the strata of the Barreiras Formation is detected.

The Barreiras Formation is commonly found in the hillside areas of RMR; its sediments' location coincides with the areas where landslides frequently occur (Bandeira and Coutinho, 2015). This geological unit extends along the Brazilian coast from Rio de Janeiro (Southeast) to the State of Amapá (North), covering Mesozoic sedimentary deposits in several coastal basins (Bandeira and Coutinho, 2015). The soils of this formation can be predominantly clayey or sandy, and are susceptible to gravitational mass movements and erosive processes in slope areas (Coutinho et al., 2019).

According to Bandeira et al. (2004), the Barreiras Formation is associated to the fluvial processes and shows three different facies: proximal alluvial fan, distal fan / alluvial plain and fluvial channel. The facies identified on the studied hillslope is the fluvial channel facies characterized by sandy texture, highly susceptible to erosive processes.

4 CLIMATE

The coast climate of RMR, according to the classification of Köppen (1948), is of the type As', that is a tropical rainy with total annual precipitation above 750 mm and average temperature always above 18 ° C.

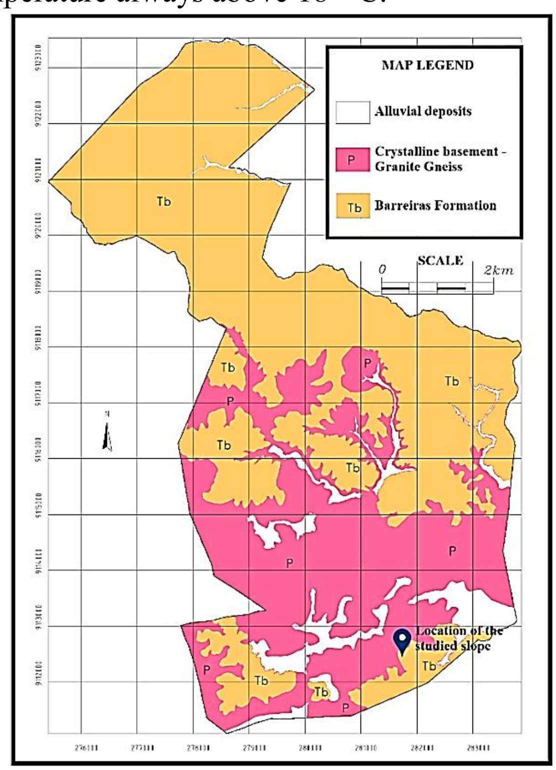


Figure 3. Distribution of the geological unities - Camaragibe

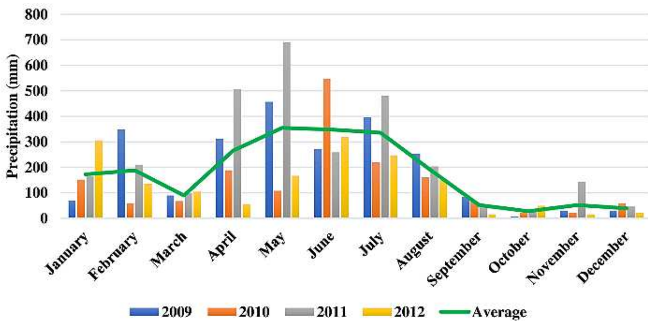


Figure 4. Accumulated rainfall in Camaragibe - PE.

Data from a pluviometer installed in the city hall of Camaragibe reveal that the months between January and September concentrate the rain, as presented in Figure 4.

In this period, it is common that the accumulated average monthly rainfall surpasses 200 mm, reaching in May, June, and July values higher than 300 mm.

In these months, the higher intensity of the rains leads to an increase of the total unit weight and moisture content, as well as a suction reduction in the soil that results, consequently, in a decrease of strength; thus, it alters the soil mechanical properties resulting in landslides.

5 GEOTHECNICAL CHARACTERIZATION

Magalhães and Coutinho (2015) and Souza (2014) performed field and laboratory tests, and 2D stability analyses in two sections of the slope studied, nominated respectively, Section 1 (S1) and Section 2 (S2). To define the geotechnical characteristics of the ground, the studies mentioned were consulted.

In this study, data were obtained through field and laboratory tests. It was performed 06 Standard Penetration Tests (SPT), particle size analyses, Atterberg limits, soil-water characteristic curves, and shear strength determined through direct shear tests in natural and submerged conditions.

A synthesis of the test results of the particle size analyses and Atterberg limits (physical characterization tests) is illustrated in Table 1. The soil-water retention curves (SWRC), adapted from Magalhães and Coutinho (2015), are shown in Figure 5. These curves were obtained from the samples collected at the top and toe of S1, then classified as CL and SC, respectively.

Both curves present a bimodal configuration due to the presence of macropores and micropores within the soil mass, characteristic of heavily altered soils. The shape of the curves is typical of sandy soils. The initial curve extent presents a high moisture content variation with a tiny suction change. The following curve extent presents a small moisture content variation that leads to a significative increment in suction.

Figure 6 presents the shear strength envelopes and their corresponding strength parameters. According to the soil behavior model adopted, the results are linear. The direct shear test was not realized with suction control. Consequently, to determine the suction value under natural conditions, the SWRC - Figure 5 - curves were employed in both sections, and the suction was estimated based on water content verified in the field during the samples collection. As expected, the cohesion intercept (c) presents an increase with the decrease of the moisture content (increasing with suction).

The results of the direct shear test presented a good agreement with the direct shear test with controlled suction performed by Coutinho et al. (2019) in soils classified as SC on a slope inserted in the Barreiras Formation also located in Camaragibe, being similar in the submerged condition and equivalent to those found by the authors in the controlled suction interval between 25-90 kPa in the natural condition.

The geotechnical profiles, based on the SPT and soil characterization tests, are presented in Figure 7. The top of the elevation presents a superficial layer of silty-sandy clay with consistencies that vary from soft to stiff and thicknesses of 6 - 13m.Then, there is a layer of clayey-silty sand whose resistance to penetration increases with depth. SPTs performed by Coutinho et al. (2006) in soils also classified as SC belonging to the Barreiras Formation were similar.

Table 1. Results of physical characterization tests – Adapted from Souza (2014) and Magalhães & Coutinho (2015).

SECTION	BOREHOLE	DEPTH OF THE COLLECTED SAMPLES (m)	LABORATORY IDENTIFICATION TESTS			DESCRIPTION	SUCS
			WL (%)	WP (%)	IP (%)		
	SP 01	(2.00-2.30)	38	52	14	Silty-sandy clay	CL
S1	SP 02	(2.00-2.30)	32	44	12	Clayey silty sand	SC
	SP 03	(2.00-2.30)	31	44	13	Clayey silty sand	SC
	SP 04	(1.00-1.50)	43	76	33	Silty-sandy clay	CL
S2	SP 05	(1.00-1.50)	40	62	22	Silty-sandy clay	CL
	SP 06	(1.00-1.50)	39	69	30	Clayey silty sand	SC

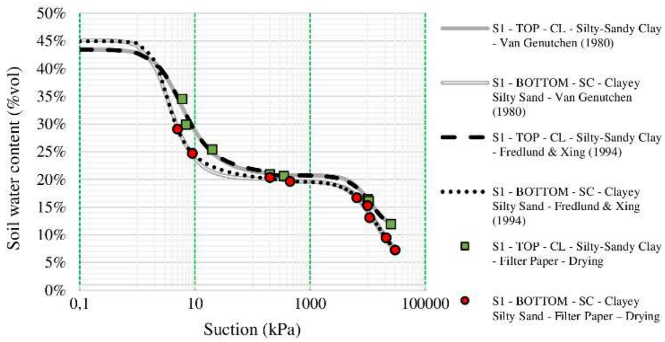


Figure 5. SWRC of the Section 1 (S1) soils - Adapted from Magalhães and Coutinho (2015).

The water table on the date of the execution of the tests was only found in the boreholes SPT 03 and SPT 06, with depth varying between 4,00 and 5,00 m from the surface.

6 STUDY OF THE STABILITY OF THE SITE

To determine the slope Safety Factor (SF), 2D and 3D stability analyses were performed applying the LEM and implemented in Slide2 and Slide3 software (2019 version), both developed by Rocscience Inc.

In the 2D analysis, the sliding mass is discretized into vertical slices. The 3D version, on the other hand, discretizes the sliding mass in vertical columns with a square cross-section with soil weight and vertical load acting in the center of each column.

Thus, traditional 2D stability methods can turn into 3D since this technique allows the unknowns of the problem, forces, and moments to be solved in two orthogonal directions. By the Mohr-Coulomb criterion, the Safety Factor (SF) is defined according to Equation 1:

$$SF = {S_{fi}}/{S_i} = {C_i + N_{i'}.\tan(\varphi_i)}/{S_i} \qquad (1)$$

Where: SF is the safety factor; Sfi is the ultimate resultant shear strength available at the base of column i; Si is the shear strength mobilized along the failure surface; Ni' is the effective base normal force and; Ci is c' Ai (c' effective cohesion and Ai is the base area of the column).

6.1 Geometry

For the creation of the 3D model, data from the Digital Terrain Model (DTM) of RMR, derived from a remotely detected elevation data set collected using LiDAR, were applied with the scale 1: 5000.

Initially, the slope area was cut from the DTM using the ArcMap software, version 10.3. Then, the cut data was exported into a file in ASCII format.

After this step, the geometry as a point cloud was imported to Slide3. In this modality, the software interprets the data and generates a surface; it allows the user to choose a method for interpolating the points. The Linear/Triangulation method was adopted for this analysis.

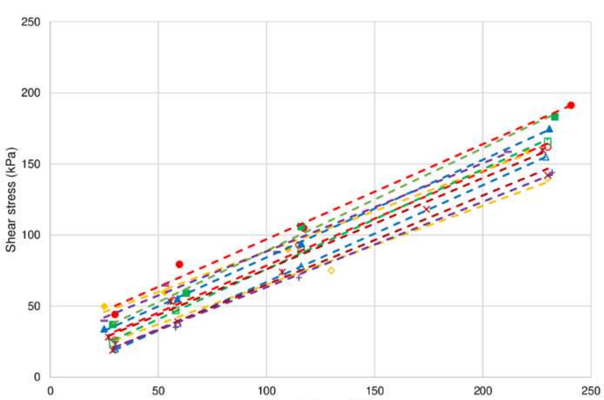
Since it is a natural slope, the geometry is complex, with declivities up to 70º, and alternation between concave and convex sectors, as shown in Figure 8.

6.2 Soil behavior model

The average of the parameters, shown in Figure 6 of soils with the same classification and compactness, were used for the development of the modeling considering the natural and submerged conditions.

Besides, in the analyses performed in the submerged condition, the following simplifications were adopted: i) the infiltration of water did not create an internal water table; ii) the soil is partially saturated; iii) there was no increase in positive pore pressure.

The material behavior model adopted for stability analysis was the Mohr-Coulomb criterion, characterized by being a linear rupture criterion, as presented in Equation 2:



SECTION 1 (S1)						
Hillside location	Top		Half		Toe	
Classification	CL - Silty-sandy clay		SC - Clayey silty sand		SC - Clayey silty sand	
Condition	Submerged	Natural	Submerged	Natural	Submerged	Natural
Simbol	○	●	◇	◆	□	■
Vol. Water Content (%)	43.50*	21.00	40.00*	22.00	45.00*	20.00
Estimated Suction** (kPa)	0 - 1	200	2	15	0 - 1	70
Coesion (kPa)	12.26	30.04	9.48	31.62	5.69	16.78
Phi (°)	33.5	33.8	29.1	29.6	35.1	35.8
Unit Weight (kN/m³)	19.27	16.93	19.90	18.13	19.04	16.29
SECTION 2 (S2)						
Classification	CL - Silty-sandy clay		CL - Silty-sandy clay		SC - Clayey silty sand	
Condition	Submerged	Natural	Submerged	Natural	Submerged	Natural
Simbol	△	▲	×	×	+	−
Vol. Water Content (%)	48.18*	22.00	42.20*	21.00	36.00*	20.00
Estimated Suction** (kPa)	0 - 1	55	1.5	200	3	70
Coesion (kPa)	1.30	15.48	2.40	11.75	3.08	26.53
Phi (°)	34.3	34.5	32.1	32.7	31.0	31.8
Unit Weight (kN/m³)	18.14	14.63	19.14	15.98	19.91	17.86

*Considering almost saturated
**Estimated by SWRC

Figure 6. Shear strength determined through direct shear tests in natural and submerged conditions.

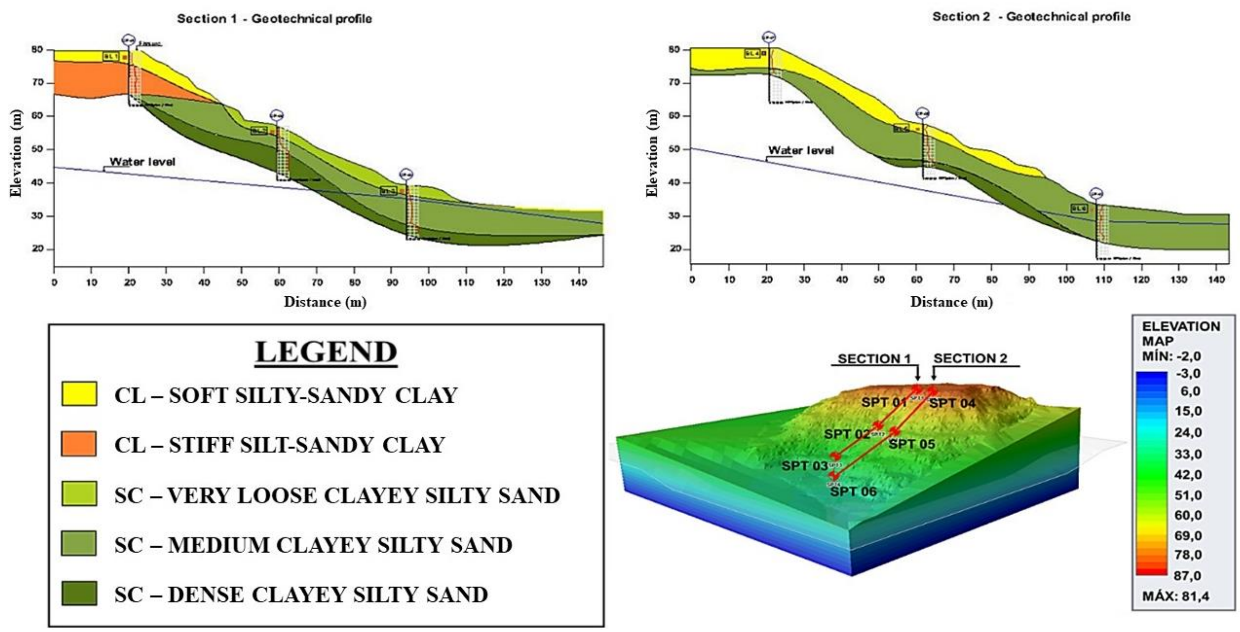


Figure 7. Geotechnical profiles obtained by interpreting SPTs and particle size analyze.

$$s = c' + (\sigma_n - u)\tan\varphi' \quad (2)$$

Where: s = shear strength; c' = effective cohesion; σ_n = total normal stress; u = pore pressure; φ' = effective angle of internal friction (phi).

6.3 Definition of soil layers

After defining the materials, they were arranged in layers according to the geotechnical profiles presented in Figure 7. The method adopted for the interpolation of materials between the boreholes was the Linear/Triangulation.

6.4 2D Stability analysis results

Stability analyses in 2D, using shear strength parameters in natural and submerged conditions, were so conducted considering the following methods: Bishop, Spencer, and Morgenstern-Price (GLE).

For this, two sections were chosen, both passing through the sections where SPT tests were performed – Section 1 and Section 2. The results are exhibited in Table 2.

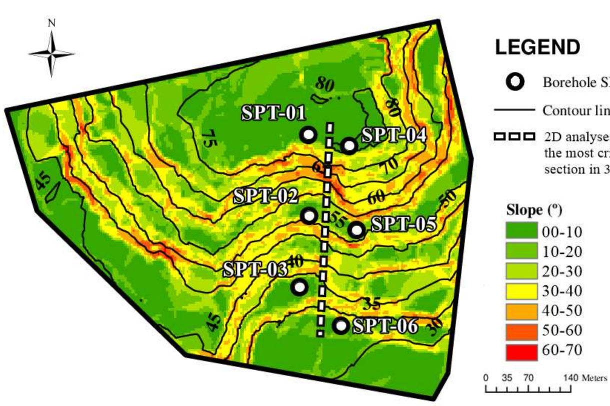


Figure 8. Contour lines and other slope information.

6.5 3D Stability analysis results

Stability analyses, using shear strength parameters in natural and submerged conditions, were performed considering the Bishop, Spencer and Morgenstern-Price (GLE) methods.

The study of the 3D stability model by the different methods (Table 3) revealed that the critical ellipsoidal surfaces were located at the top of the slope, specifically between the SPTs realized.

In Figures 9 and 10, these surfaces, highlighted in black and obtained by the GLE method, are presented. The position of the cracks, highlighted in white, are also illustrated.

In the natural condition, the calculated values represent the behavior of the slope in a period of less intense precipitation (relative to December), and the effects of suction are now considered, being reflected in the increase in apparent cohesion, as illustrated in the shear strength envelopes present in Figure 6, consequently, in the increase of safety factors (SF 3D).

In both cases, the rupture surface proceeded around 6 m in deep, as shown in Table 3, which

Table 2. Results of SF obtained by 2D analyses.

Method	Natural		Submerged	
	Section 1	Section 2	Section 1	Section 2
Bishop	1.538	1.488	1.117	1.194
Spencer	1.513	1.487	1.122	1.204
GLE	1.516	1.474	1.114	1.190
Average	1.522	1.483	1.118	1.196

Table 3. Results of SF obtained by 3D analyses.

Method	Natural			Submerged		
	SF	Volume (m³)	Max Depth (m)	SF	Volume (m³)	Max Depth (m)
Bishop	1.471	1124.66	6.438	1.042	537.308	5.926
Spencer	1.483	1124.66	6.438	1.065	854.635	6.455
GLE	1.495	1565.65	6.316	1.088	537.308	5.926
Average	1.483	1271.66	6.397	1.065	643.084	6.102

indicates that its occurrence covered, predominantly, the soil classified as CL and part in the interface between this material and that classified as SC (very loose clayey-silty sand).

With the 3D analysis results, a new 2D analysis was conducted, located in the middle of the 3D critical section, specifically between Sections 1 and 2, as indicated in Figure 8. The results for this analysis are presented in Table 4. Figure 11 illustrates this analysis for the GLE method in a submerged condition.

7 DISCUSSION

The results from the geotechnical characterization are matching the literature. It was noticed that the soils on the slope profile present SWCR with bimodal configuration, characteristic of altered tropical soils. It was observed a significant suction effect in the cohesion intercept,

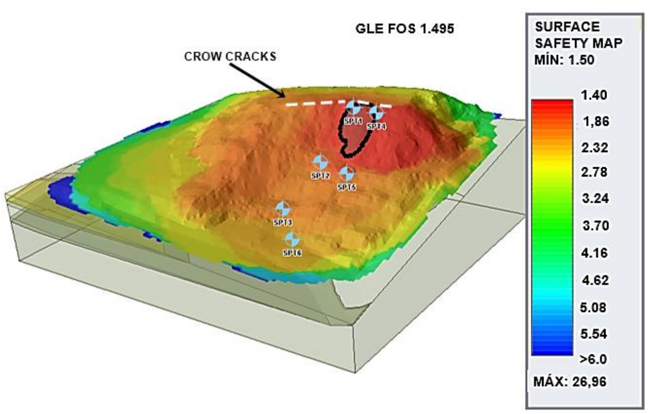


Figure 9. Surface safety map obtained by GLE's method - 3D modelling under natural condition.

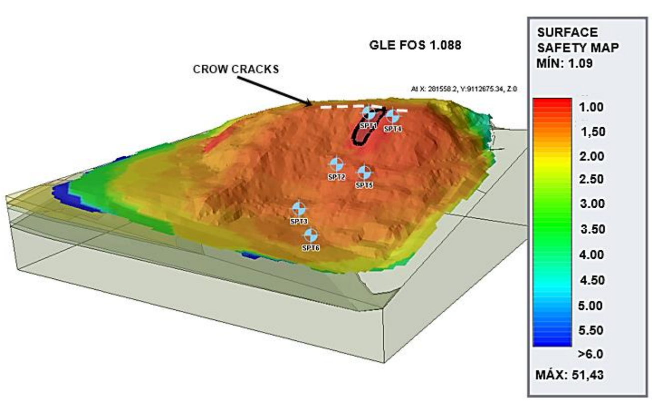


Figura 10. Surface safety map obtained by GLE's method - 3D modelling under submerged condition.

and the obtained parameters are agreeing with other studies about Barreiras Formation slopes.

In the three-dimensional analysis, there is an agreement between the different methods, being the average SF obtained of 1.483 in the natural condition and 1.065 in the submerged condition – Table 2.

The surface safety map presented in Figure 10 shows that the all slope top has SF 3D close to 1 in submerged condition; this includes the region where the cracks and the slump block appeared.

Meanwhile, the SF obtained show that the slope is stable considering the shear strength parameters for a drier period due to the effect of the suction, simplified in the increase of the apparent cohesion (Figure 9).

These results show that the modeling is representative and indicates that the slope was in the imminence of failure near to the submerged condition.

The 2D analyses conducted under the submerged condition, simulating a critical rain, in Sections 1 and 2 indicate a stable slope although the low safety factors vary between 1.12-1.20. These values demonstrate that the verified sections are not capable of explaining the signs of instability noticed in the field.

The 3D analysis in the same conditions, however, presented a medium 3D SF of 1.065. Thus, it can explain the cracks and justify the slightly mass movement that originated the slump block, and then reaching a new condition of stability since the slope did not in fact.

As presented in Figures 9 and 10, the critical surface of the 3D analyses was located between Sections 1 and 2. It confirms the hypothesis of Fredlund et al. (2018), because the 2D sections analyzed were assumed to be critical, and this supposition was not confirmed in 3D analyses even

Table 4. SFs obtained by 2D analyses in the most critical section in 3D.

Method	Condition	
	Natural	Submerged
Bishop	1.290	0.901
Spencer	1.304	0.917
GLE	1.291	0.905
Average	1.295	0.908

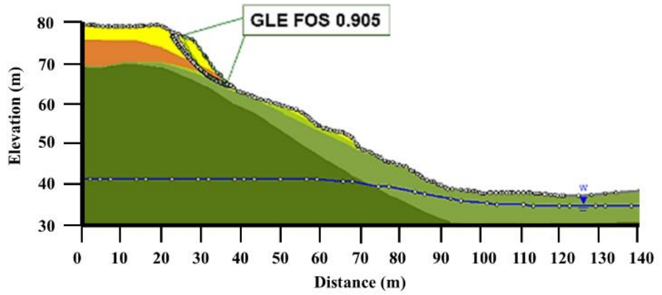


Figura 11. SF obtained by GLE's method 2D analyses under the submerged condition of the most critical SF in 3D

SF presenting lower values in a different section from those that were initially selected.

The 2D analysis proceeded in the 3D critical section presented safety factors lower than the ones obtained from the 3D analysis, with medium values of 1.295 in the natural condition, and 0.908 in the submerged condition that means a difference of 15% and 17%, respectively, concerning the values obtained from the three-dimensional analysis to this same section under natural and submerged conditions.

These differences verified between two and three-dimensional analyses are the result of simplifications assumed in the two-dimensional model. These simplifications, consequently, lead to more conservative results due to the non-consideration of the topography variation, of the lateral resistance provided by soil wedge to the failure surface, and of the distribution of soil domains.

8 CONCLUSION

The geotechnical investigation effectuated was adequate for the problem analyzed and the obtained shear strength parameters are agreeing with the literature. It was observed that the increase in moisture content and the decrease in suction during intense precipitation periods reflect the decrease in apparent cohesion and, consequently, in the safety factors in 2D and 3D analyses that were conducted.

The results obtained considering the three-dimensional effect of factors, such as the complex geometry of the slope studied and the three-dimensional arrangement of the soil layers, were consistent with the current stability condition of the Alto do Padre Cícero hillside, revealing more consistent with the reality than the bi-dimensional analyses that were conducted.

The modeling proved to be representative and can explain the instability phenomena identified in the field, indicating that in the condition near to saturation, coherent with the heavy rains at the time, the slope was in the imminence of failure.

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