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Influence of the degree of saturation and the wetting front on the stability of cliffs: a case study on a cliff located on the beach of Tabatinga-RN-Brazil

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Article

Keywords
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Limit-equilibrium methods
Stress analysis methods
Barreiras formation

Abstract

Coastal zones are of great interest in civil engineering due to their economic relevance and active geological dynamics. In Brazil, the development of these regions is related to the use of their geomorphological features in the landscape, among which the cliffs stand out. Although there are studies that consider the influence of the wetting front in stability analysis with cliffs, in general, the studies only consider extreme saturation situations (dry and saturated). In this sense, the present study aims to understand the influence of the wetting front and the degree of saturation reached by the materials in the stability of cliffs composed of Barreiras Formation soil. The stability analyses were carried out using the limit equilibrium method and stress analysis, varying the degrees of saturation of the materials and wetting fronts of a model of a cliff located at Praia de Tabatinga, State of Rio Grande do Norte, Brazil. Failures were identified, in different wetting fronts, by the limit equilibrium method from degrees of saturation around 20%, and by the stress analysis method around 40%. Thus, it was concluded that the variation in the degree of saturation has a preponderant effect on the destabilization of a cliff, since partial saturations are already enough to trigger significant mass movements. It was also noticeable that the wetting front is a relevant effect on instability, although conditioned to the degree of saturation reached, which may enhance the order of magnitude of the identified failures.

1. Introduction

Due to the active dynamics of coastal regions, the study of slope stability conditions in these regions, as well as the monitoring of mass movements that occur on these slopes, is a relevant topic for society (Collins & Sitar, 2008; Epifanio et al., 2013; Marques et al., 2013; Martino & Mazzanti, 2014; Barbosa et al., 2020; Prémaillon et al., 2021). In Rio Grande do Norte, the economy of the coastal regions is usually linked to the development of tourism, which is related to the scenic beauty associated with the presence of cliffs. The term coastal cliff refers to a vertical, or nearly vertical surface angle, formed from the meeting of the continent with the ocean. Cliffs are geomorphological features that occur at all latitudes along about 80% of the world's coastlines (Emery & Kuhn, 1982). In general, the stability of a cliff cannot be guaranteed, since retreat movements and increases in the continental line are continuous in the long term, being a cyclical process of failure and temporary stabilization (Richards & Lorriman, 1987; Silva et al., 2020). Within this cyclical process, the cliffs become unstable when the mobilizing stresses in the massif reach the limit of the mechanical strength of the material. This condition can be reached by the intervention of internal or external agents. In this context, one can highlight the increase in the degree of saturation of the materials.

It is common in engineering, especially in project development, that the soil is considered only under saturated

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condition. However, the suction present in situations of lower saturation causes increases in the mechanical strength of the soil, in the form of apparent cohesion. This increment may be sufficient, for example, to stabilize a natural slope (Fredlund et al., 2012).

Due to their coastal location, coastal cliffs, especially those in tropical regions, tend to show intermediate degrees of saturation over time. The intermediate saturations are justified due to the natural seasonality of the contact between the waves and the cliffs, and the rainfall patterns in these regions. The increase in the degree of saturation in the profile of soils that make up a cliff can trigger mass movements (Duperret et al., 2002; Hampton, 2002; Collins & Sitar, 2008; Barbosa et al., 2020). Thus, aiming at a better understanding of cliff stability conditions, it is rational to realize the importance of considering saturation gradually. Associated to this thougth, it is important to identify under which material range saturation will occur, since it is in this area that there will be a decrease in strength.

Therefore, although the importance of this gradual variation in the saturation of coastal cliffs is perceived, in general, the dry and/or saturated horizons are considered in the development of stability analysis (Pacheco et al., 2006; Barbosa et al., 2020). In view of the above, this study aims to evaluate how the variation in the degree of saturation and the increase in the wetting front can influence the stability of a cliff, based on the case study of a cliff located in northeastern Brazil.

2. Materials

In several stretches of the Brazilian coast, the presence of cliffs is the result of the meeting of the sea with the Barreiras Formation. The edge of the coastal tablelands in contact with the sea through continental and marine erosion processes originate the cliffs that appear as abrupt changes in terrain. The cliff evaluated in the present study is the same one studied by Silva (2019) and Morais et al. (2020). This cliff can be found along the coastline of Barra de Tabatinga Beach, located on the southern coast of the state of Rio Grande do Norte, Brazil, as shown in Figure 1. It is composed of layered sediments from the Barreiras Formation. The Barreiras Formation has an origin dated between the Miocene and the Pliocene, and extends from Rio de Janeiro to Amapá. This geological unit consists of a sedimentary cover, with intercalated layers of claystones, siltstones and sandstones, presenting in its composition different contents of silt, clay, and conglomeratic sandstones. (Santos Júnior et al., 2015).

To determine the geotechnical characteristics of the sediments that make up the cliff, it was divided into three distinct layers, called Top, Middle and Bottom layers. The geotechnical characteristics were necessary for the implementation of numerical models applied to the cliff. The Top and Middle layers are approximately 15 meters thick, while the Bottom layer is approximately 10 meters thick, as shown in Figure 2. The materials that make up this cliff are stratified sediments of the Barreiras Formation,

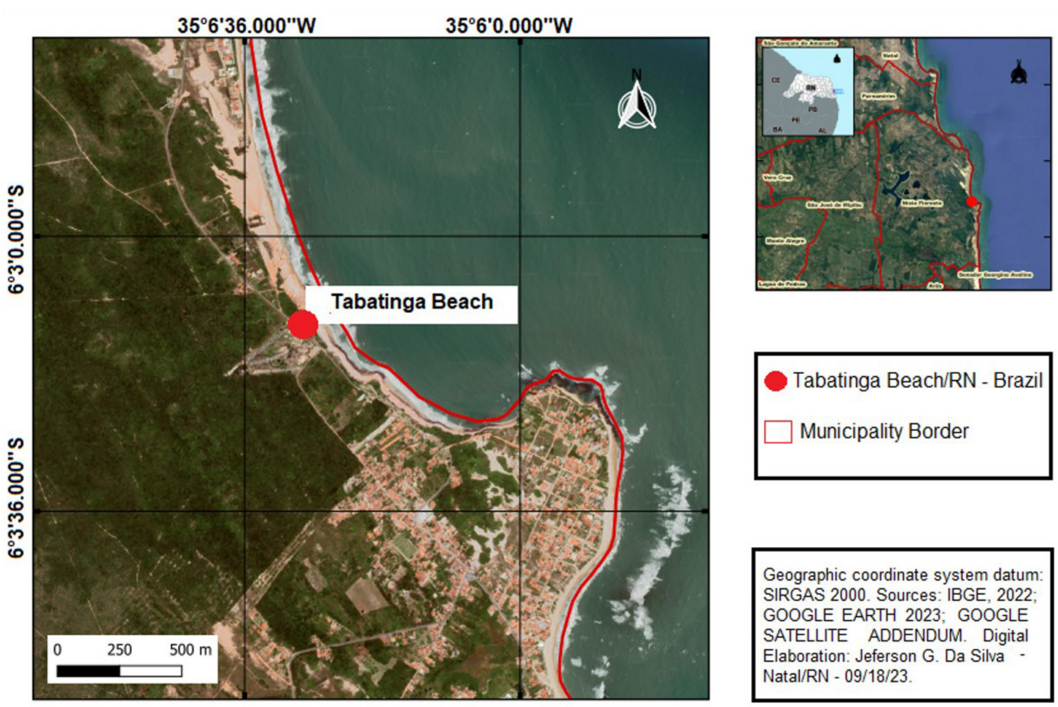


Figure 1. Location of the study area.

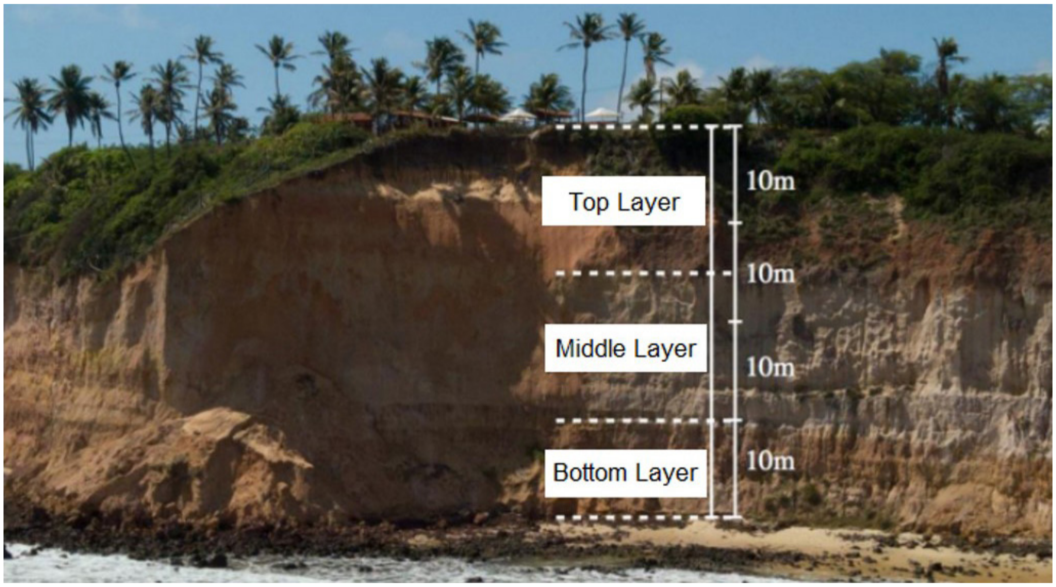
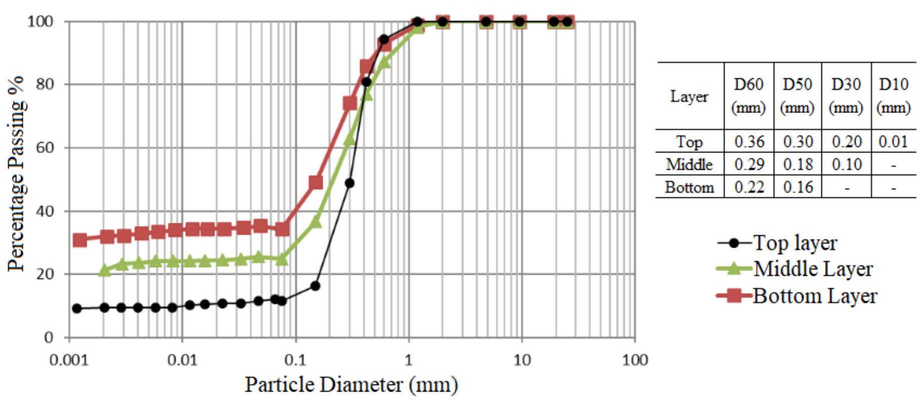


Figure 2. Typical profile and height of the sediment layers that make up the cliff (Adapted from Silva, 2019).



Layer	D60 (mm)	D50 (mm)	D30 (mm)	D10 (mm)
Top	0.36	0.30	0.20	0.01
Middle	0.29	0.18	0.10	-
Bottom	0.22	0.16	-	-

Figure 3. Granulometric Curve of materials (Adapted from Morais et al., 2020).

predominantly sandy, and present different levels of natural cementation. The occurrence of tension cracks on the top of the cliff resulting from the concentration of tensile stresses in this region, and incisions at its base resulting from maritime action were observed (Silva, 2019).

Morais et al. (2020) carried out geotechnical characterization and mechanical strength tests from undisturbed samples collected from each of the three cliff layers. These results were used as input parameters for the stability analysis performed in this study.

The material present in the bottom layer of the cliff is quite heterogeneous, predominantly yellow in color, with rusty reddish-purple veins. It presents a higher degree of consolidation among the studied samples. The material present in the middle layer of the cliff is white or gray in color. Like the bottom layer, it has reddish veins, although to a lesser extent. This material presents an intermediate level of consolidation among the studied materials. The component material of the top layer of the cliff presents greater homogeneity among those studied, having a reddish color and the absence of ferruginous veins. It presents easy disintegration and a lower degree of consolidation among the studied materials. The results of the characterization tests obtained by Morais et al. (2020) are shown in both Figure 3 and Table 1.

The authors experimentally determined soil-water characteristic curves using both the filter paper and tensile table methods. These curves were adjusted by the equations proposed by Van Genuchten (1980), when unimodal, and Durner (1994), when bimodal. Furthermore, the authors conducted CU (Consolidated Undrained) and CD (Consolidated Drained) triaxial tests to assess the saturated condition, and CW (Constant Water Content) triaxial tests to assess the unsaturated condition, resulting in the determination of friction angles and cohesive intercepts.

Table 1. Results of characterization tests of the sediments that make up the cliff (Adapted from Morais et al., 2020).

Layer	γ_s (kN/m³)	γ_d (kN/m³)	γ_{sat} (kN/m³)	Void Ratio	*LL* (%)	*PL* (%)	SUCS
Top	26.3	16.5	20.3	0.60	N.L.	N.P.	SP
Middle	26.3	17.6	20.9	0.50	18	15	SM
Bottom	26.6	18.8	21.7	0.41	25	19	SM-SC

Table 2. Sediment strength parameter (Adapted from Morais et al., 2020).

Layer	Saturated Condition		Unsaturated Condition	
	φ'(º)	c' (kPa)	φ'(º)	c'_{ap} (kPa)
Top	30.7	4.65	35.67	65.48
Middle	29.7	12.01	37.92	120.93
Bottom	30.2	17.8	42.74	276.38

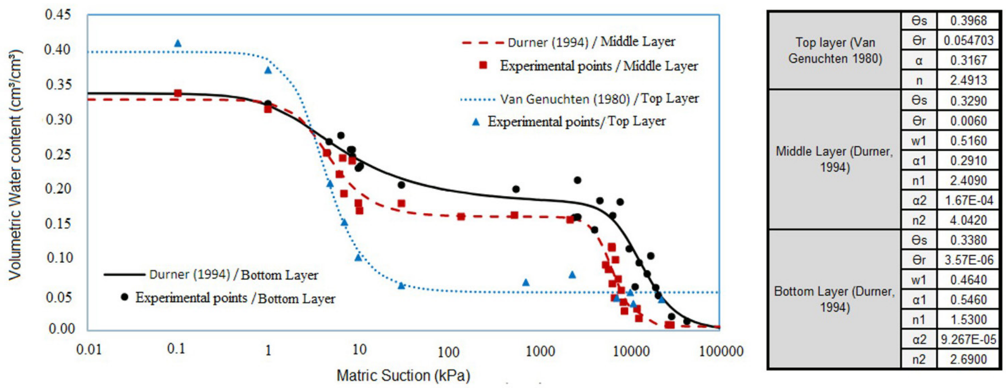


Figure 4. Soil-water characteristic curves and adjustments used (Adapted from Morais et al., 2020).

The average moisture content obtained in the test specimens for the apparent cohesion are 2.47% for the Bottom Layer, 0.47% for the Middle Layer and 2.01% for the Top Layer (Morais, 2019). The experimental retention curves and their respective adjustments are shown in Figure 4, and the strength parameters are shown in Table 2.

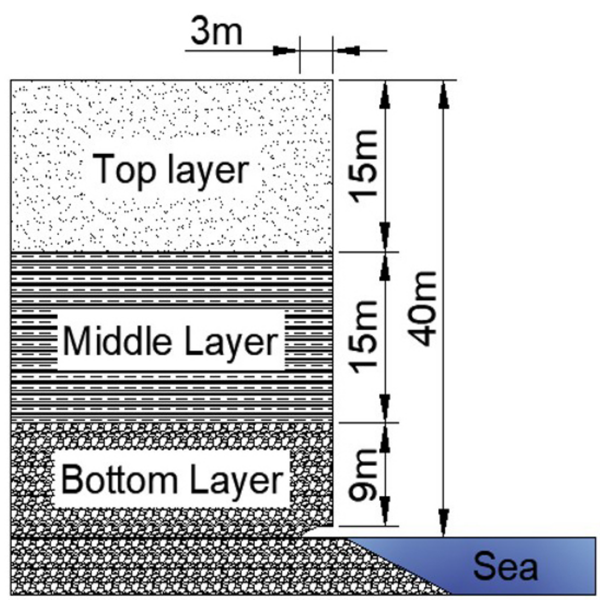


Figure 5. Geometry of the cliff used for stability analysis.

3. Methods

Stability analysis were performed using the Morgenstern-Price method (Morgenstern & Price, 1965), based on the concept of limit equilibrium, using the Mohr-Coulomb failure criteria. Furthermore, was used the stress analysis method proposed by Collins & Sitar (2011). According to Barbosa et al. (2020), in order to study an unfavorable condition of stability, a geometry was adopted for the cliff that has a basal incision one meter high and three meters deep. The geometry model is shown in Figure 5. The GeoStudio software library was used employing Slope/W for the limit equilibrium analysis and Sigma/W for the stress analysis.

3.1 Limit equilibrium analysis methodology

Seven hypotheses were considered to simulate the variation of the wetting front, as shown in Figure 6. The regions of the massif not specified as wet/humid were considered completely dry, while those considered wet/humid had their degree of saturation varied.

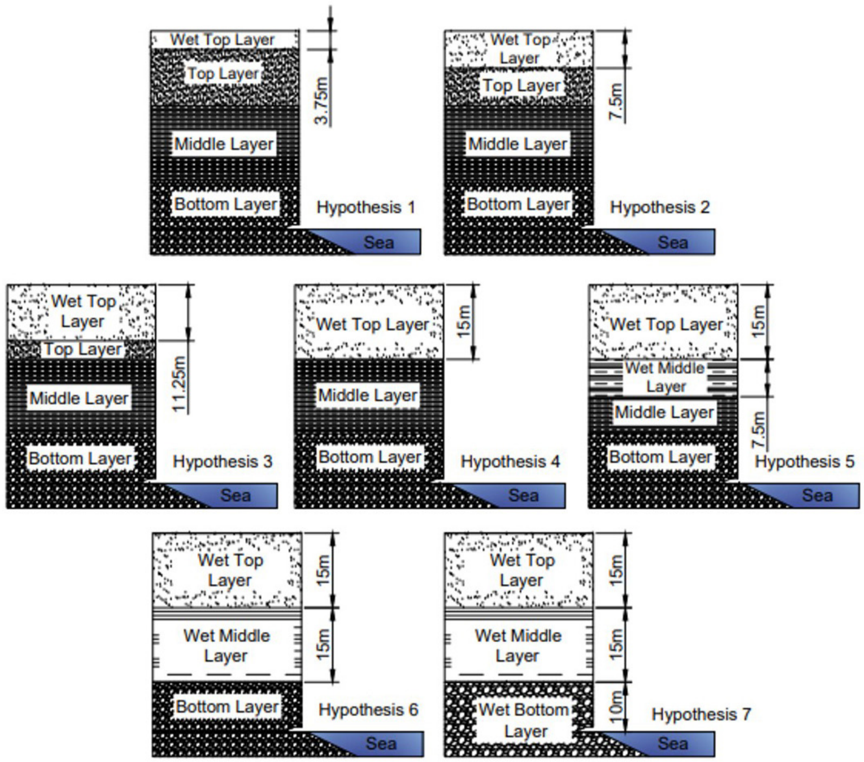


Figure 6. Wetting front depth assumptions used in limit equilibrium analysis.

Table 3. Variation of cohesion and specific weight according to the degree of saturation (Adapted from Morais et al., 2020).

Layer	S (%)	0%	10%	17.5%	20%	40%	47.5%	48.5%	60%	80%	100%
Top	c' (kPa)	65.2	65.1	22.3	15.3	8.04	7.35	7.27	6.58	5.65	4.65
	γ (kN/m³)	16.5	16.9	17.2	17.3	18	18.3	18.3	18.8	19.5	20.3
Middle	c' (kPa)	120.2	118.7	118	117.9	116	97.6	38	16.7	14.2	12
	γ (kN/m³)	17.6	17.9	18.2	18.3	18.9	19.2	19.2	19.6	20.3	20.9
Bottom	c' (kPa)	276.1	275.8	268.7	268	261.8	260.9	260.5	243	24. 1	17.8
	γ (kN/m³)	18.8	19.1	19.3	19.4	20	20.2	20.2	20.5	21.1	21.7

For each wetting front condition, 10 different degrees of saturation were applied to the wetted fractions. The friction angles of the saturated condition obtained by Morais et al. (2020) were used in the analysis, as shown in Table 2. The degrees of saturation applied in the limit equilibrium analysis were 0%, 10%, 17.5%, 20%, 40%, 47.5%, 48.5%, 60%, 80% and 100%. The determination of the degrees of saturation used for the development of the stability analysis was made from an evaluation of the sensitivity of the apparent cohesion. Cohesion variation was performed according to the prediction of active cohesion using Vilar (2007) hyperbolic model. The hyperbolic adjustments were calibrated according to the soil-water characteristic curves and strength parameters obtained by Morais et al. (2020). Due to the bimodal format of the soil-water characteristic curves, as shown in Figure 4, it was noticed that the ranges with saturation between 10% and 20% and between 40% and 60%, present a more sensitive variation in the c parameter, therefore intermediate values were adopted in these cases. Variations in cohesion and specific weights depending on the degrees of saturation are shown in Table 3. The Bottom, Middle and Top Villar's hyperbolic envelopes as showed in the Figure 7.

3.2 Stress analysis methodology

The methodology adopted for stress analyses, as presented by Collins & Sitar (2011), consists of determining the state of stress in the massif using a numerical model based on the finite element method and comparing the acting stresses with the values of mechanical strength of the soil components of the cliff. Two situations related to wetting fronts were considered for this analysis. The first occurred from the wetting of the Bottom layer only, this situation being related to the increase in the degree of saturation caused by the effect of the tides and/or the water table. The second situation aimed to represent the effects of rainfall, from the cliff in all layers.

Aiming to facilitate the understanding with regard to the influence of the variation in the degree of saturation,

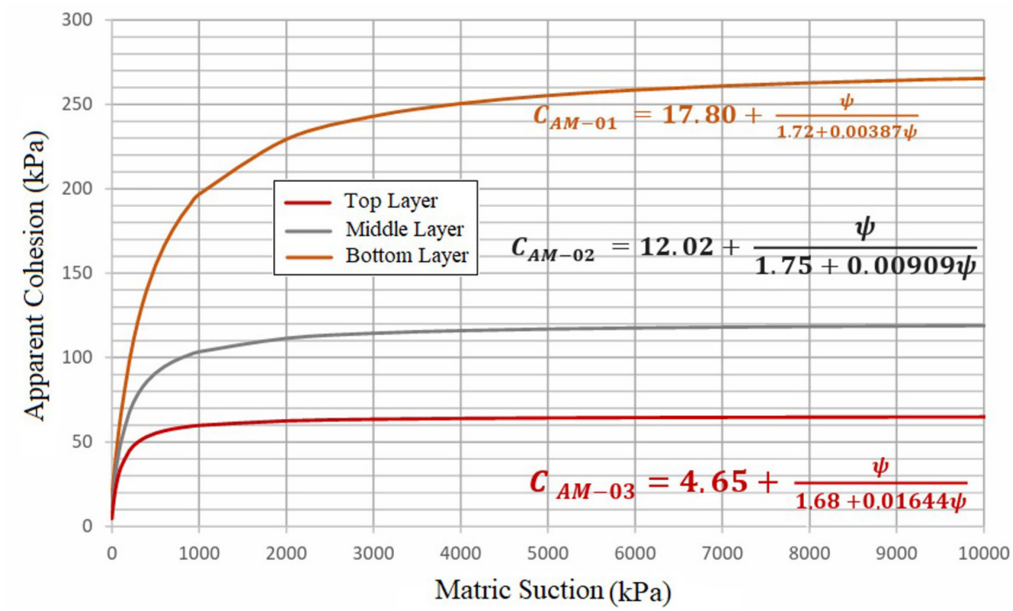


Figure 7. Villar's hyperbolic envelopes (Adapted from Morais, 2019).

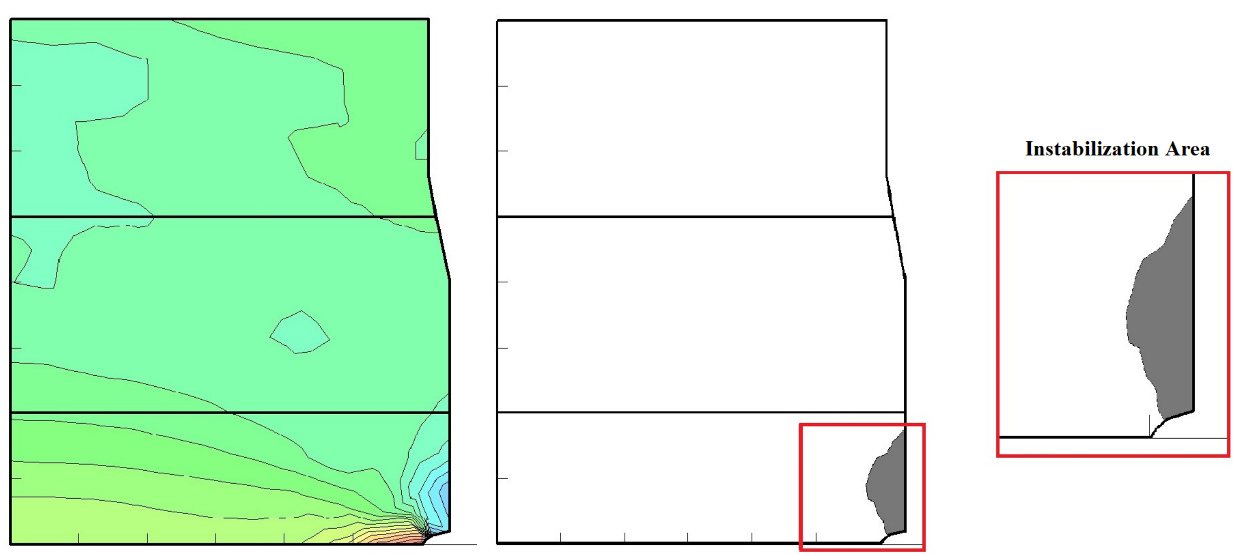


Figure 8. Representation of the definition of a mobilization area by tensile stresses.

areas of instability were defined. The areas of instability refer to regions where, upon evaluating the stress distribution map, resulted in stress analyzes using the finite elements net. The tensile stresses greater than or equal to the soil's tensile strength in the analyzed situation were identified. The process for determining an area of instability is illustrated in Figure 8. In hypothetical scenarios involving deep areas of instability, such as extreme saturation situations, regions with a maximum depth of 3 meters (constrained by the length of the basal incisions) and with simplified geometries, nearly parallel to the slope faces, were defined.

The acting stresses and areas of instability were evaluated for each of the following degrees of saturation in the wetting fronts: 0%, 10%, 20%, 40%, 60%, 80% and 100%. The variation of the degree of saturation in these regions provokes the variation of the acting stresses and of the tensile strength of the soils. A Poisson's coefficient of 0.3 and a deformability modulus of 30 MPa were adopted, which are the same values used by Barbosa (2017), in accordance with the findings of Severo (2011). The parameters used to model the Top, Middle, and Bottom sediments, as obtained from diametral compressive tests conducted by Morais et al. (2020), are summarized in Table 4.

4. Analysis and results

4.1 Results of stability analysis by the Morgenstern-Price method

Table 5 displays safety factors obtained using the Morgenstern-Price method (Morgenstern & Price, 1965). In cases of identified failures characterized by a safety factor less than 1, the critical slip surfaces only developed through the Top layer, as illustrated in Figure 9. No critical slip surfaces were identified passing through the Middle or Bottom layers.

The material that composes the Top layer shows greater variations in apparent cohesion in relation to small increments in the degree of saturation. Thus, before higher degrees of saturation are reached and/or the wetting front reaches lower layers, superficial mass movements occur, which alter the geometry of the cliff and create a new situation to be evaluated, as highlighted by Silva et al. (2020). Aligning with this, Río et al. (2009) observed behaviors similar to those indicated in Table 5 in failures that occurred on the coast of Spain. The authors justify that the rotational landslides studied by them are related to the contrast between the local stratigraphic layers, occurring because of the saturation of the upper layer after intense rainfall.

For this type of analysis, the degree of saturation is the factor with the greatest influence on the stability of the cliff. Degrees of saturation in the order of magnitude of 20% in the Top layer can destabilize the studied cliff, leading to the occurrence of localized failures in this layer. For this type of analysis, the increase in the wetting front was perceived

Table 4. Parameters used in stress analysis (Morais et al., 2020).

Layer	Degree of Saturation (%)	0%	10%	20%	40%	60%	80%	100%
Top	Tensile Strength (kPa)	38	28	19	0	0	0	0
Middle	Tensile Strength (kPa)	90	74	59	28	0	0	0
Bottom	Tensile Strength (kPa)	116	102	87	59	30	1	0

Table 5. Slip safety factors determined by the Morgenstern-Price method.

Hypothesis	Degree of Saturation									
	0%	10%	17,5%	20%	40%	47.5%	48.5%	60%	80%	100%
1	1.255	1.250	1.202	1.194	1.178	1.176	1.176	1.170	1.162	1.161
2	1.255	1.246	1.152	1.118	<1	<1	<1	<1	<1	<1
3	1.255	1.243	1.024	<1	<1	<1	<1	<1	<1	<1
4	1.255	1.240	<1	<1	<1	<1	<1	<1	<1	<1
5	1.255	1.234	<1	<1	<1	<1	<1	<1	<1	<1
6	1.255	1.230	<1	<1	<1	<1	<1	<1	<1	<1
7	1.255	1.230	<1	<1	<1	<1	<1	<1	<1	<1

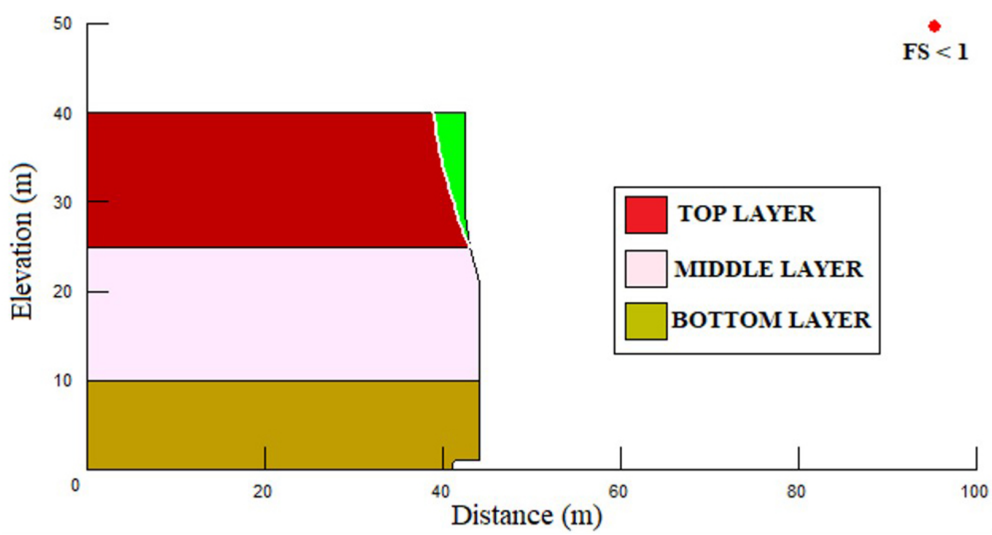


Figure 9. Representive rupture surface on the Top Layer using the Morgenstern-Price method.

as having less relevance for stability. For lower degrees of saturation, the increase in wetting range can trigger, or even potentialize, failures.

This methodology was not able to predict deep failures and, therefore, was not able to assess the effects of the presence of the basal incision on the stability of the cliff. Studies such as Hampton (2002), Collins & Sitar (2011) and Barbosa et al. (2020) point to the existence of limitations in the ability of methods based on the concept of limit equilibrium to predict all the real equilibrium conditions of cliffs with incisions at the base. This observation justifies the adoption of other methods of analysis, in a complementary way.

4.2 Results of stability analysis by the stress analysis method

In the first wetting front hypothesis, the variation in the degree of saturation was considered only in the base material of the cliff. For all degrees of saturation adopted, only variations in tensile stresses were noticed. As for these stresses, increments of up to 12 kPa were identified at some points. This variation in the magnitude of stresses results from the direct relationship between the specific weight of the soil and the degree of saturation.

Thus, only the stress maps are presented, in the "X" and "Y" directions (Figures 10a and 10b, respectively), for the situation of the completely saturated base material of the cliff. This situation was chosen because it is the most unfavorable in terms of cliff stability.

In this study the tensile stresses were considered as negative and the compressive stresses were considered positive. Analyzing Figure 10, it can be seen that the highest tensile stresses observed tend to act on the cliff face of the Middle and Base layers, considering the stresses in the X direction (Figure 10a). In the Y direction (Figure 10b), the tensile stresses have smaller magnitudes, and are concentrated primarily in the top layer. As described in the methodology, comparisons were made between the applied tensile stresses and the tensile strength of the layers, to determine the mobilization areas.

The stresses that were identified on the face of the Middle layer, the higher being applied on the cliff face of the layer, are always smaller than the tensile stresses of the completely dry material, so that there is no generation of mobilization areas in this layer for this saturation condition. Therefore, these efforts were not considered. The tensile stresses acting in the Y direction also did not generate mobilization areas due to their distribution on the top of the cliff. Therefore, they too were not considered. Table 6 shows the results of the applied maximum tensile stresses, tensile strengths of the bottom layer and the calculated mobilized areas, varying according to the degree of saturation adopted.

Tensile stresses mobilized in the X direction (Figure 10a), as they are distributed along the cliff face, are responsible for causing failures. As shown in Table 6, it was noticed that increases in the degree of saturation, although causing little increase in applied tensile stresses (maximum 12 kPa), considerably reduced the tensile strength of the base material. In this context, failure situations were identified only in the base layer. This decrease in strength justifies the variations in the areas of mobilization. The application of degrees of saturation from 40% trigger the appearance of areas of instability. Therefore, before the situation of total saturation is reached, significant mass movements occur on this cliff.

As seen in Figure 10, tensile stresses occur in the Y direction (Figure 10b). However, these tensile stresses, as seen in the stress distribution, do not occur significantly along the cliff face, since they remain concentrated in the top region. In this way, the stresses mobilized in the Y direction do not create situations in which regions of imminent failure are identified according to the stress analysis method, although these stresses can justify the appearance of tensile cracks,

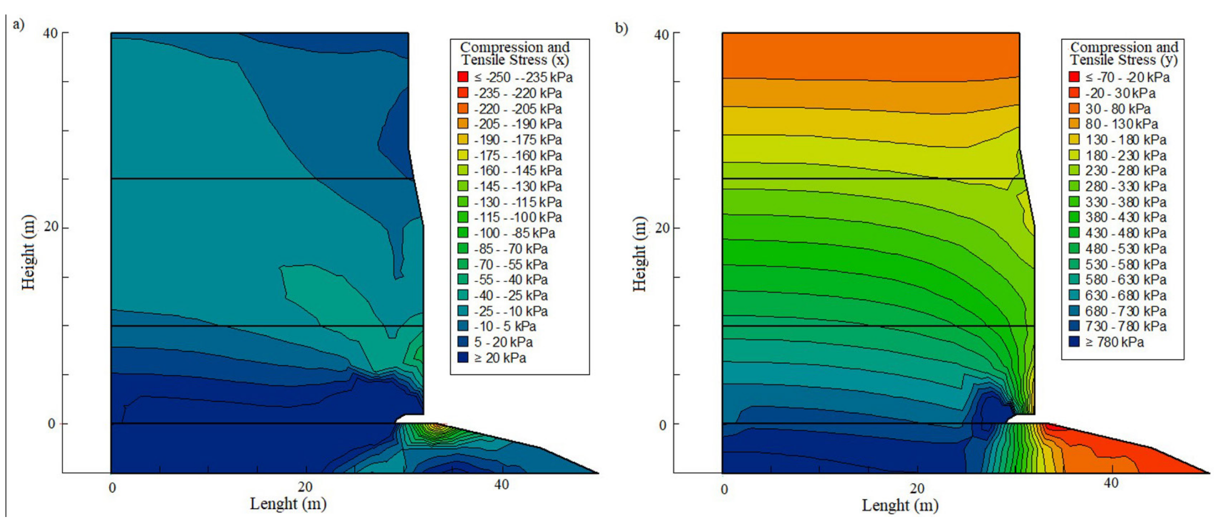


Figure 10. Maps of stresses acting on the cliff with only the base saturated in the X (a) and Y (b) directions.

Table 6. Results of stress analysis with the wetting front acting only from the bottom layer.

Degree of Saturation (%)	0%	10%	20%	40%	60%	80%	100%
Bottom Layer Tensile Strength (kPa)	116	102	87	59	30	1	0
Maximum Tensile Stress (x)	-210	-211	-212	214	-217	-219	-222
Mobilization Area X (m^2)	0	0	0	0.79	11.61	12.38	12.60

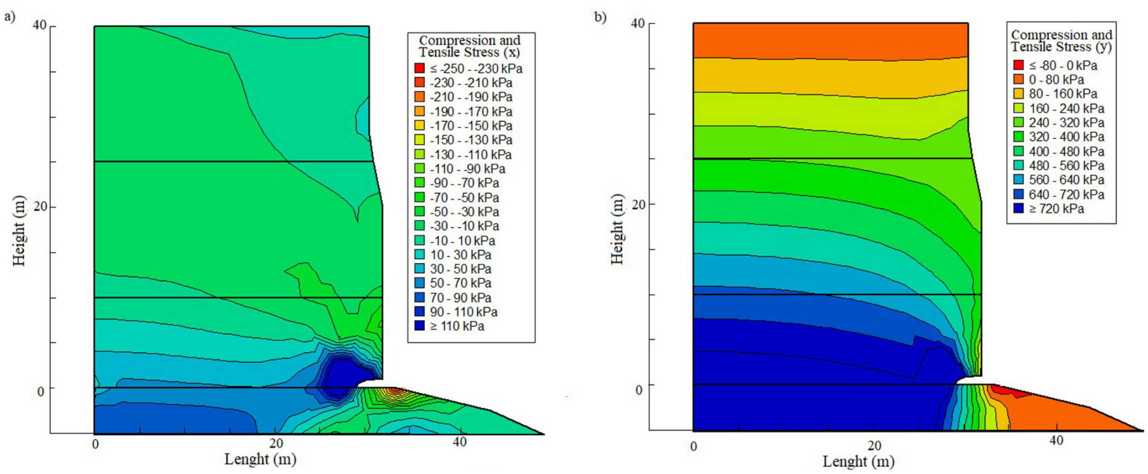


Figure 11. Map of stresses acting on the cliff with all layers saturated in the X (a) and Y (b) directions.

perceived in the studied cliff, as reported by Silva (2019). The appearance of tensile cracks in surface regions of cliffs, especially when filled with water, may be related to another type of failure, triggering block toppling.

In the second hypothesis of the wetting front studied, all layers of sediments are wet. As in the previous hypothesis, the shape of the stress distribution inside the cliff does not change significantly with the increase in the degree of saturation. For this case, increments of a maximum of 40 kPa were observed in tensile stresses, comparing extreme saturation situations. Figure 11 shows the distribution maps for the most critical situation (completely saturated sediments) in the X (a) and Y (b) directions.

The stress maps shown in Figure 11 indicate that, with the increase in the layers' own weight, there is the occurrence of more significant regions of tensile stress on the cliff face along the three layers. However, it was observed that for the top layer, the tensile stresses in the X direction (Figure 11a), as well as those identified in the Y direction (Figure 11b), did not generate significant mobilized areas on the cliff face. Thus, these results were disregarded in the analyses. It is important to point out that, as in the previous hypothesis, these stresses can generate the appearance of tensile cracks, which may consequently trigger another type of failure mechanism.

Comparisons were made between the applied tensile stresses and the tensile strength of the layers, to determine the mobilization areas, as defined in the methodology. Table 7 shows the results of the maximum tensile stress applied in the X direction, the tensile strength of the Base and Middle sediments and the mobilized areas, which varied according to the variation in the degree of saturation.

Based on Table 7, it can be seen that the increase in the degree of saturation in all layers causes a more relevant increase in the maximum acting tensile stresses, when compared to the situation of saturation variation only in the base material. Failures passing through more than one layer (Base and Middle) are identified in Table 7, with magnitude depending on the applied stresses and the degree of saturation acting. When analyzing the development of the increase in the mobilization area, it is noticed that this increase occurs in an equivalent way to that observed in the previously analyzed situation.

Situations of imminent failure are identified in degrees of saturation of 40% and become more representative when the component materials of the layers reach a degree of saturation in the order of 60%, similarly to the wetting front in which variation was imposed in the degree of saturation only at the base. However, it is worth mentioning that the total magnitude of the failures found is higher, due to the development of ruptures in two layers. Even with the saturation of the top layer, the occurrence of tensile failures passing through it was not noticeable.

Therefore, it is possible to state that for both wetting front hypotheses, the degree of saturation of the layers plays a fundamental role in the destabilization of the massif, with considerable failures being developed from degrees of saturation in the order of 40%, regardless of the adopted wetting front. It is also possible to note that, in stress analyses, as well as for the limit equilibrium method, the wetting front has a

Table 7. Results of stress analysis with the wetting front acting on all cliff layers.

Degree of Saturation	0%	10%	20%	40%	60%	80%	100%
Maximum Tensile Stress (x)	210	214	218	226	234	246	250
Middle Layer Tensile Strength (kPa)	89.7	74.2	58.8	27.9	0	0	0
Mobilizated Area in the Middle Layer (m^2)	0	0	0	1.2	26.3	26.2	25.8
Base Layer Tensile Strength (kPa)	115.9	101.6	87.2	58.5	29.9	1.2	0
Mobilizated Area in the Bottom Layer (m^2)	0	0	0	0.7	10.1	12.2	12.2
Total Mobilizated Area (m^2)	0	0	0	1.9	36.4	38.4	38.4

secondary effect and is only responsible for enhancing the effects caused by the variation in the degree of saturation, increasing the failure area.

It is important to point out that the materials that make up the cliffs, due to natural coastal dynamics, infiltration and capillarity processes, spend a good part of their time subjected to situations of partial saturation. In this context for the studied cliff, developing analysis only under extreme saturation conditions (dry and saturated) would not be plausible. It was noticed, from the two analysis methodologies, the occurrence of relevant ruptures in conditions related to intermediate degrees of saturation. These failures related to partial saturation tend to create new geometries, which condition new stress distributions, which lead to a tendency for progressive failure processes to occur. Therefore, real situations in which the soil layers reach saturation are improbable.

5. Conclusion

In the present study, through slope stability analyses, the way the degree of saturation and the wetting front interfere in the stability of a cliff located on Tabatinga beach, in the Northeast Region of Brazil, were evaluated. Analyses were carried out using a method based on the concept of limit equilibrium and a method based on stress analysis. The wetting fronts and the geotechnical properties that make up the cliff were varied, according to the degree of saturation applied to each layer, which varied between 0% and 100%.

The stability analyses by the Morgenstern-Price method applied to the cliff studied, showed only superficial ruptures passing through the Top layer. Thus, it is concluded that, for this type of analysis, the degree of saturation of the layers is an extremely crucial factor for stability. Low degrees of saturation applied to the top layer, in the order of magnitude of 20%, are capable of triggering ruptures. Another conclusion is that the wetting front can be a crucial factor in the decrease in stability, however, only in the superficial layers and being conditioned by the degree of saturation applied.

Regarding the stress analyses, for both wetting fronts studied, values of saturation degrees around 40% in the middle and/or base layers are capable of triggering failures. Thus, it is possible to see that this is an extremely crucial factor in the analysis of stability. It was also noticed the appearance of surface tensile stresses, which can trigger the occurrence of tensile cracks, which can cause the blocks to tip over.

For the studied cliff, the use of different wetting fronts also becomes a relevant factor for the stability analysis, since, for this type of method, the wetting front will define the layers where the failures develop and may enhance the mobilized areas. Due to the natural dynamics of this region, it is common to see partial saturation conditions on coastal cliffs made up of soils from the Barreiras Formation. The results of this study point to the occurrence of ruptures in these conditions of partial saturation.

It is concluded that the consideration of the wetting front is important for the stability of cliffs with soils from the Barreiras Formation, enhancing failures, and should be implemented in stability analyses. And that, more strikingly, the consideration of the gradual variation in the degree of saturation, commonly adopted only at its extremes (saturated and completely dry soil), is not sufficient for the most credible simulation of the stability condition of a coastal cliff.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Allan Benício Silva de Medeiros: conceptualization, data curation, visualization, writing – original draft. Romário Stéffano Amaro da Silva: supervision, validation, writing – review & editing. Valteson da Silva Santos: supervision, validation, writing – review & editing. Olavo Francisco dos Santos Junior: conceptualization, data curation, methodology, supervision, validation, writing – original draft. Ricardo Nascimento Flores Severo: supervision, validation, writing – review & editing. Osvaldo de Freitas Neto: supervision, validation, writing – review & editing. Bruna Silveira Lira: supervision, validation, writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols

c'	Effective cohesion
c'_{ap}	Apparent cohesion
LL	Liquidity limit
LP	Plasticity limit
SP	Poorly graded sand
SM	Silty sand
SM-SC	Silt-clay sand
SUCS	Unified Soil Classification System
NL	The material has no liquidity limit
NP	The material has no plasticity limit
D_{10}	Diameter at which 10% of the soil mass passes the sieve
D_{30}	Diameter at which 30% of the soil mass passes the sieve
D_{50}	Diameter at which 50% of the soil mass passes the sieve
D_{60}	Diameter at which 60% of the soil mass passes the sieve
S	Degree of saturation
φ'	Effective friction angle
γ_s	Specific weight of solids
γ_d	Dry specific weight
γ_{sat}	Saturated specific weigh

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