GEOTECHNICAL CHARACTERIZATION AND RISK ANALYSIS OF URBAN SLOPE INSTABILITY IN THE CITY OF ARACAJU - BRAZIL

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ABSTRACT

Areas naturally characterized by the presence of hilly relief often marked by the irregular occupation of slopes and their surroundings. This fact, which increases the risk associated to mass gravitational movements. This paper presents a risk analysis of mass movements in 16 slopes in the city of Aracaju, capital of the state of Sergipe, Brazil, using a qualitative method. Geotechnical characterization of soils from of slopes selected for analysis of stability was carried using the OptumG2® software developed by Optum Computational Engineering using the Strength Reduction Method (SRM) to obtain the safety factor. The aim of this study is to conduct a systematic analysis, associating subjective landslide risk studies with rational studies on slope stability analysis. It was found that 50% of the slopes analyzed exhibited a high or very high degree of risk, justifying the landslide risk management policies in the city. Moreover, stability analyses produced coherent results in terms of slope stability, whereby slopes with high and very high risk were classified as unstable, while the slope deemed to be stable presents medium risk of mass movements.

KEYWORDS: risk analysis, soil characterization, stability analysis.

CARACTERIZAÇÃO GEOTÉCNICA E ANÁLISE DE RISCO DE INSTABILIDADE DE ENCOSTAS URBANAS DA CIDADE DE ARACAJU - BRASIL

RESUMO

Áreas naturalmente caracterizadas pela presença de relevo acidentado são muitas vezes marcadas pela ocupação irregular de encostas e do seu entorno. Fato esse, que eleva o risco associado a movimentos gravitacionais de massa. Este artigo apresenta uma análise de risco de movimentos gravitacionais de massa em 16 encostas existentes na cidade de Aracaju, capital do Estado de Sergipe – Brasil, empregando-se uma metodologia qualitativa. Também foi realizada a caracterização geotécnica dos solos dos taludes selecionados para a execução de análises de estabilidade utilizando-se o método de redução de resistência (MRR) para obtenção do fator de segurança. O objetivo desta pesquisa é realizar uma análise mais sistêmica, associando os estudos de risco de deslizamentos, de caráter subjetivo, aos estudos racionais de análise de estabilidade de encostas. Foi possível constatar que 50% dos taludes analisados apresentaram grau de risco alto e muito alto, justificando-se a aplicação de políticas de gestão de risco de deslizamentos na cidade. Além disso, as análises de estabilidade forneceram resultados coerentes quanto à condição de estabilidade das encostas, em que as encostas com risco alto e muito alto foram classificadas como instáveis, enquanto a encosta julgada como estável apresenta risco médio a movimentos de massa.

KEYWORDS: análise de risco, caracterização dos solos, análise de estabilidade.

1 INTRODUCTION

The illegal occupation of areas subject to mass movements in large urban centers accelerates these events, which often assume catastrophic proportions, given that cutting, backfills, the irregular reject of waste, deforestation, drainage conditions, and other aggressions strengthen the conditioning factors associated with the geomorphology of slopes (Benedet, 2015). As such, it is important to conduct more systematic diagnoses and analyses, associating landslide risk studies with analyses of slope stability. These actions related to mass movement risk management in urban areas provides both in interventions by departments responsible for risk monitoring and to prevent the occupation of unstable urban areas, resulting in mapping to quantify and hierarchize geotechnical risk.

The first step in risk mapping is to select an analysis methodology to determine the nature and extent of risk, using analysis of potential risk and assessment of existing vulnerable conditions that might threaten life and damage property (UNI/ISDR, 2004). Risk analysis can be qualitative or quantitative. Qualitative analysis uses the degree of risk (low, medium, high, etc) or numerical scales (1, 2, 3, 4, etc) to quantify risk. Quantitative analysis includes the numerical variables of vulnerability, probability and consequences. As such, risk is expressed in numerical values (Corteletti, 2014). Qualitative analysis can also function as a preliminary assessment, indicating the areas most prone to natural events and would therefore justify the use of quantitative analysis.

To complement risk analysis, slope risk is quantified based on stability analysis. The Finite Elements Method has been employed in analysis methods of this nature, characterized by determining simplified hypotheses considered in Limit Equilibrium Methods, primarily with respect to the stress-strain relation. Furthermore, the use of this method makes it possible not only to determine the safety factor but also to obtain the characteristics of the rupture mechanism.

The city of Aracaju, represented in Figure 1, is located in Northeastern Brazil. Despite being predominantly flat, displays different areas of rough terrain characterized by disorderly occupation and unsafe dwellings, in which clear cutting, landfills, deforestation and the absence of basic sanitation are some of the factors that contribute to the occurrence of landslides in these areas. This was, therefore, the main reason for conducting this research.

Accordingly, the aim of this study was to assess the landslide risk on 16 slopes of Aracaju, as well as conduct geotechnical characterization and slope stability analyses in order to relate the degree of risk with slope stability. As such, it is possible to assist the public entities responsible for risk management identify areas susceptible to events involving mass movements by studying the physical and environmental characteristics of the city.

Risk analyses were conducted based on qualitative methodology (Gusmão Filho et al., 1992). The method is completely subjective and effective in terms of the need to conduct

preliminary hierarchization of risk of slopes, without requiring significant precision when determining the extent of risk. The geotechnical characterization of soils that make up the slopes selected for stability assessments involved grain size analysis tests, as well as Atterberg limits and direct shear tests. Slope stability was evaluated using the SRM (Strength Reduction Method), applying the Finite Element Method (FEM). The SRM is based on the principle that the safety factor is calculated from the relation between the shear strength of soil and shear stress that acts on the surface of the rupture. Therefore, it consists of the gradual decline in the shear strength of the soil, using FEM, until the first indications of rupture emerge (Krabbenhoft et al., 2015).
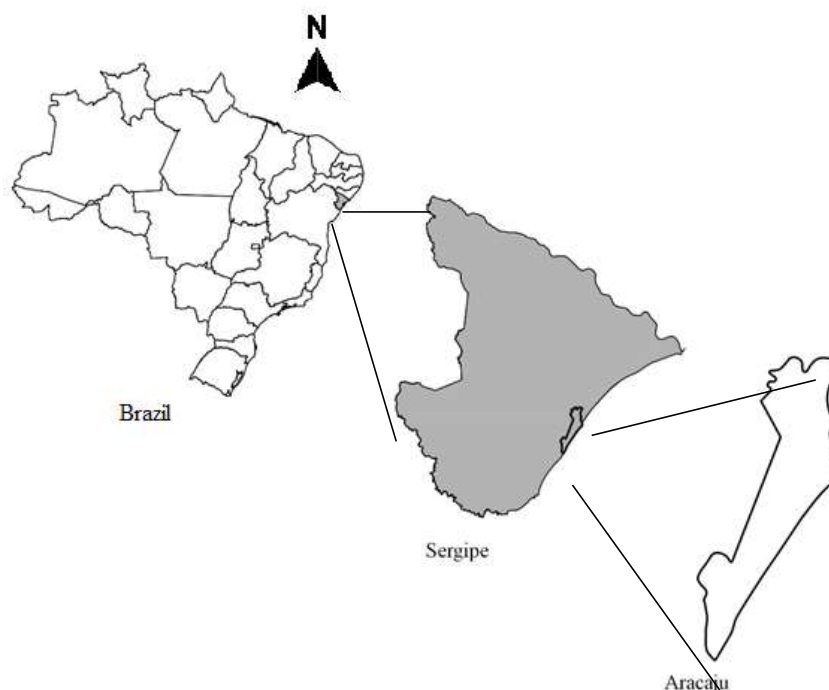

Figure 1: Geographic location of Aracaju city.

1.1   Main aspects of Aracaju city

Aracaju encompasses an area of 182.163 km². In the 2019 census conducted by IBGE (Brazilian Institute of Geography and Statistics), the population of the city was 657,013 inhabitants.

Sergipe has three main climate zones: semiarid, arid and wet weather. Aracaju, located on the coast, is a tropical region, with high temperatures and humidity along the eastern coast. The state of Sergipe has irregular rainfall, which declines from the coast to the semiarid area. The highest annual rainfalls are recorded on the coastal strip of Aracaju, which exhibits three dry months, from December to February (Santos, 2012). Excessive rain is one of the primary causes of slope instability in the city, such as the 101.5 mm recorded in May 24, 2015, which caused serious problems for the population that inhabits areas susceptible to flooding and landslides in the city. In fact, May had the highest rainfall in 2015, 3-fold higher than the total recorded for the 3 dry months (BDMEP/INMET, 2015).

The profiles of slopes in Aracaju are classified as concave, convex or both for natural slopes, and rectilinear in the case of artificial slopes. The geometric features of slopes are influenced by lithology and climate. In Aracaju, they are sculpted on the lithologies of the Barreiras Group, which consists mainly of clay (Araújo, 2006a). The city of Aracaju is located in a region covered by surface formations, represented by two relief units, namely, the Coastal Plain and Coastal Tablelands, characterized by the development of hills on the lithologies of the Barreiras Group (Araújo, 2006b). The Coastal Plain of Aracaju is composed of Quaternary marine (marsh and mangrove deposits) and Quaternary continental deposits (Fluvial-lagoon and coastal deposits). This unit is limited to the continental portion of the Barreiras Group. Hills were formed on the Coastal Tablelands, with predominance in the northern part of Aracaju, resulting in the highest rounded formations in the city, up to 100m high. Coastal tablelands also extend into the western and southern parts of the city, where Barreiras Group outcrops occur. In other parts of the city, altimetric values are as low as 2m (Araújo, 2006b).

2 METHODOLOGY

Figure 2 shows the location of the 16 slopes selected with the most representative characteristics for risk analyses, based on the survey of risk areas in terms of flooding and mass movements in Aracaju (CPRM, 2013). Stability analyses were conducted in slopes with the highest degree of risk in the four districts of the city.
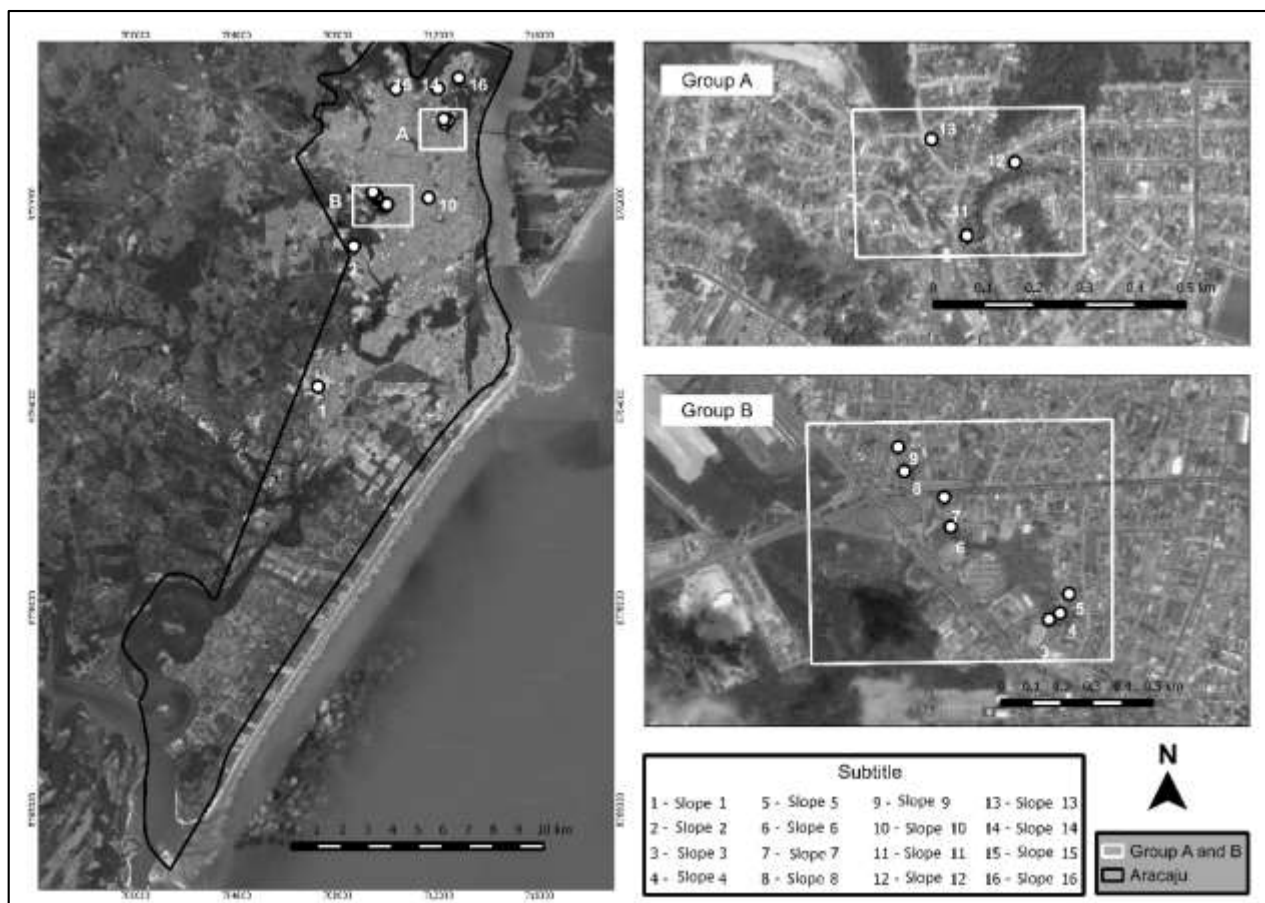
Figure 2: Representation of slope areas of Aracaju.

2.1 Landslide risk analysis in Aracaju

Degrees of risk were attributed by applying the qualitative methodology developed by Gusmão Filho et al. (1992), which considers the factors that influence the stability of the slopes. These factors are subdivided into groups of attributes. Calculating the degree of final risk for each slope followed the method proposed by Alheiros (1998).

The methodology involves compiling a risk assessment chart where the following factors are considered: topographic, geological and environmental, each with its respective attributes. Sanitation was added to the environmental factor, which corresponds to the existence or not of sewage treatment, according to Moura et al. (Moura et al., 2006). Four degrees of final risk were considered for the city of Aracaju: R1 (Low Risk), R2 (Medium Risk), R3 (High Risk) and R4 (Very High Risk).

Thus, it was possible to define the ranges corresponding to each risk level, as well as the linguistic terms for Aracaju, in Table 1.

Table 1: Range of Degrees of Risk of Attributes Corresponding to the Risk Factors.

Factors	Degree of risk			
Topographic	Low - 1	Medium - 2	High - 3	Very High - 4
Height (m)	<10	10-14	14-18	>18

Extent (m)	<159	159-302	303-445	>445
Declivity (%)	<91	91-135	136-180	>180
Morphology (profile)	Concave	Rectilinear	Concave-convex	Convex
Morphology (plant)	Convex	Rectilinear	Meandering	Concave
Geological	**Low - 1**	**Medium - 2**	**High - 3**	**Very High - 4**
Lithology	Mature residual soil	Barreiras Group	Quaternary Unit (Continental)	Quaternary Unit (Marine)
Texture	Clayey-sand	Silty-sand	Sandy-clay	Sandy/Clayey
Structure	Homogeneous	Opposite dip	Sub-horizontal	Sub-vertical
Mass movement and transport	Absent Surface gullying	Scars	Erosion at the foot of the slope	Deep gullying Fissures
Environmental	**Low - 1**	**Medium- 2**	**High - 3**	**Very high - 4**
Vegetation (%)	>70	70-30	<30	Absent
Drainage	Extensive Partial	Insufficient	Topical	Nonexistent
Clear Cutting	Isolated	In plateaus	Disordered (-)	Disordered (+)
Population density (inh/ha)	<44	44-70	71-98	>98
Sanitation	Sewage totally treated	Treatment plant	Septic tank	Improper wastewater disposal
Treatment	Extensive Partial	Insufficient	Topical	Nonexistent

Topographic, geological and environmental risks were calculated using the arithmetic mean of risk values assigned to their respective attributes. Equations (1) to (3) present the calculations topographic, geological and environmental risks.

$$TR = \frac{\sum Attributes}{5} \tag{1}$$

$$GR = \frac{\sum Attributes}{4} \tag{2}$$

$$ER = \frac{\sum Attributes}{5} \tag{3}$$

Where TR, GR and ER correspond to topographic, geological and environmental risks, respectively.

This study considered the reducing factor of environmental risk due to treatment (Alheiros, 1998), considering the four degree of risk ranges, expressed in Equation (4).

$$RA_t = RA_i - \left[\left(\frac{RA_i - 1}{3}\right).(4 - T)\right] \tag{4}$$

Where RA_t is the risk of an environmental attribute including treatment, RA_i corresponds to the risk of an environmental attribute without treatment and T is the treat-ment score (between 1 and 4).

The final risk was calculated based on the proposal of Alheiros (Alheiros, 1998), attributing a weight of 2 for the topographic factor, 1 for the geological factor and 3 for the environmental factor, in Equation (5).

$$FR = \left[\frac{(2TR) + (1GR) + (3ER_t)}{6} \right] \qquad (5)$$

In Equation (5), FR is the final risk of the slope, TR the topographic risk, GR the geological risk and ER_t the environmental risk including the treatment score.

2.2   Geotechnical Characterization

The slopes 1, 3, 11 and 14 were selected for stability analysis using strength reduction methodology. These slopes represent the greatest risk to the areas in which they are located, according to qualitative risk analysis.

The remaining tests were carried out with chips of undisturbed blocks separated during the molding of test specimens used in direct shear testing, except characterization   of slope 14 soil, conducted on a disturbed sample. The samples used in soil characterization tests were prepared according to ME standard 041 (DNER, 1994a). Grain size analysis tests and Atterberg limits were in accordance with NBR standards 6459, 7180 and 7181 (ABNT, 1984a, 1984b, 1984c), respectively. Grain density tests were based on ME standard 093 (DNER, 1994b).

Direct shear tests were conducted with test specimens of undisturbed samples collected on the slopes selected for stability analyses according to standard D3080 (ASTM, 2011), under consolidated and drained conditions. Three test specimens were analyzed in the flooded conditions for each soil. The test specimens from slopes 3, 11 and 14 were analyzed under normal stresses of 50, 150 and 300 kPa. Those from slope 1 were tested under normal stresses of 100, 200 and 300 kPa. The shear speed of the samples from slopes 1, 11 and 14 was 0.1 mm/min, while those from slope 3 were sheared at 0.08 mm/min.

2.3   Slope stability analyses

Stability analysis of the slopes was conducted using the OptumG2® program developed by Optum Computational Engineering, which uses the direct finite elements method to define the safety factor of the slopes.

The program provides the safety factor in the stability analysis of slopes using Gravity Increase Method (GIM) and Strength Reduction Method (SRM). In this study SRM was selected to obtain the safety factors of the slopes under study. Strength reduction analysis is based on the calculation of the factor by which the strength parameters of the material needs to be reduced to reach the initial state

of collapse. The same factor must be used to reduce cohesion and the friction angle (c, tanϕ) of the material that makes up the slope. Thus, it is possible to determine the strength reduction factor that is equivalent to the safety factor calculated using the Strength Reduction Method, applying Equation (6).

$$FS_s = \frac{c}{c_{cr}} = \frac{\tan\phi}{\tan\phi_{red}}$$

(6)

In Equation (6), FS_s is the safety factor of the slope, c and $\tan\phi$ are cohesion and the friction angle, respectively and c_{cr} and $\tan\phi_{red}$ are their values critics.

The analyses developed by the program enable the use of an adaptive finite elements grid and select a certain number of adaptability interactions to refine the grid, as well as define the number of elements in the initial grid and the control variable to which the grid must be adapted (Krabbenhoft et al., 2015). OptumG2® 2016.08.19 provides safety factors in terms of lower and upper limits, whereby the value of the safety factor that defines the stability condition belongs to the range between the values of the two limits.

Analyses were conducted disregarding the generation of neutral pressures, that is, prolonged analyses, since effective strength parameters are involved. One thousand elements were used for the initial finite elements grid. An adaptive grid was used with 3 adaptations according to plastic shear strain. On slopes with any type of building at the foot or top of the slope, a value of 25 kPa was used for the overload in all buildings, due to the lack of knowledge of the overload produced in each situation. This value was obtained from Menezes et al. (2016), who studied the size of low-income housing, which is the case of the dwellings found in the risk areas of Aracaju.

Based on a planialtimetric survey, it was possible to determine the most unfavorable profiles for stability analyses, that is, the profile with the steepest inclination of each slope. The profiles used in stability analyses of the slopes 1, 3, 11 and 14 are shown in Figures 3 to 6.
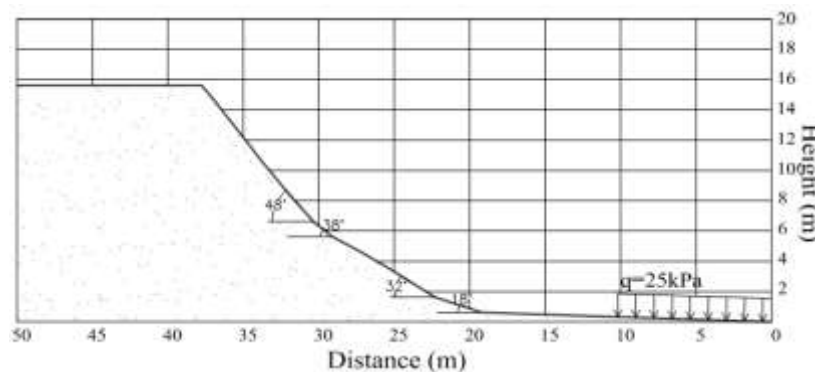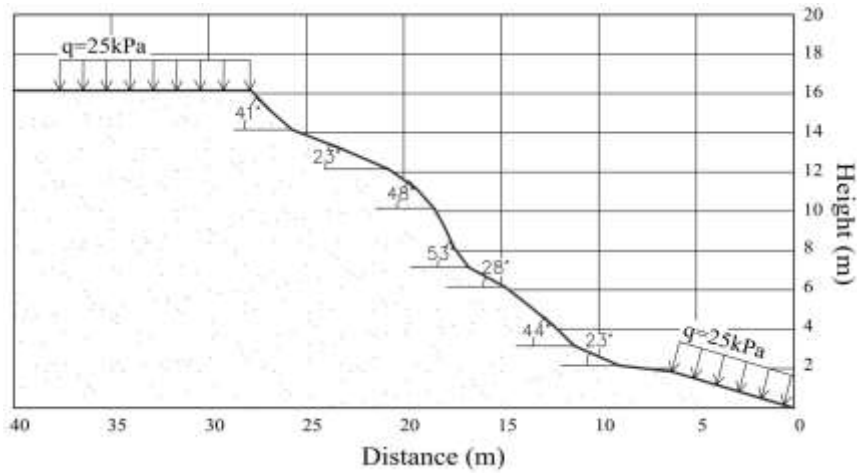

Figure 3: Profile of the slope 1.
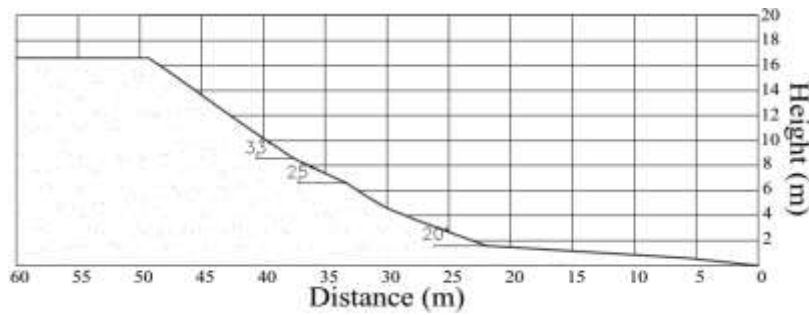
Figure 4: Profile of the slope 3.

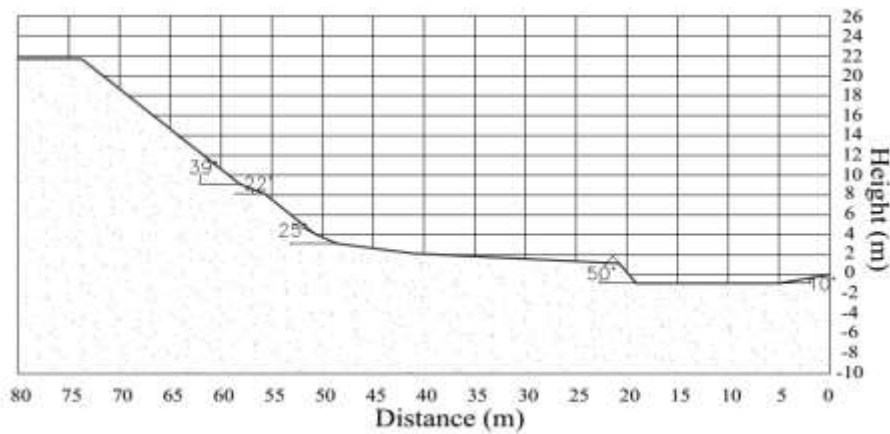**Figure 5: Profile of the slope 11.**

Figure 6: Profile of the slope 14.

3 RESULTS AND DISCUSSIONS

Risk analysis determined the ranges corresponding to each degree of risk, as shown in Table 2.

Table 2: Degree of risk ranges of Aracaju.

Degree of risk	Final risk
Low Risk	< 2.14
Medium Risk	2.14-2.40
High Risk	2.41-2.67

Very High Risk	> 2.67

The values of final risk, degree of risk attributed to the slopes and the region to which they belong are illustrated in Table 3. These data show that the results obtained were compatible with the risk characteristics exhibited in the field.

Table 3: Degrees of risk per slopes in Aracaju.

Slopes	Regions	Final Risk	Degree of Risk
01	South	2.23	Medium Risk
02	West	2.72	Very High Risk
03		2.93	Very High Risk
04		2.33	Medium Risk
05		2.52	High Risk
06		2.27	Medium Risk
07		2.37	Medium Risk
08		2.40	Medium Risk
09		2.80	Very High Risk
10		2.36	Medium Risk
11	North	2.54	High Risk
12		1.88	Low Risk
13		2.37	Medium Risk
14		2.63	High Risk
15		2.55	High Risk
16		2.41	High Risk

The Unified Soil Classification System (USCS) was adopted to classify hillside soils. The characteristics of the soils analyzed are depicted in Table 4. The soils selected for stability analyses exhibit coarse grain size, that is, composed of more than 50% gravel and sand. According Jenkins (Caputo, 2011), the soils of slopes 1 and 14 are highly plastic, with plasticity indexes higher than 15%, which corresponds to the highest clay percentages. The soil from slope 3 is non-plastic (NP), which may be attributed to the high percentage of silt, given that silts and coarse soils exhibit little or no plasticity. The soil from slope 11 was classified as slightly plastic, with 1% < PI < 7%. The low plasticity index may be attributed to the fact that the soil displays a low percentage of fine grains in its composition and a low clay activity index (Skempton, 1953) of 0.32.

The parameters of strength, cohesion and friction angle (c', ϕ') were obtained from direct shear tests, and defined based on the peak strength envelope of the tests. The soil properties and strength parameters obtained in shear tests are shown in Table 5.

The soil from slope 1 showed the highest cohesion intercept value, when compared to the other soils (20.5 kPa), which can be explained by the high percentage of clay in the soil and the high plasticity index (PI). In relation to the effective friction angle (ϕ'), the value obtained was 32.6°. The cohesive intercept obtained in the slope 3 sample was null, possibly due to the collapsible behavior that the soil exhibited when flooded in the direct shear consolidation phase in the first stress stage. In this case, a decrease in test specimen height of around 16% was observed after

only 15 minutes of first stage stress application (50 kPa). The friction angle obtained was 31.5°. The slope 11 soil exhibited a high percentage of sand and, as expected, low PI value, which resulted in the very low cohesion value obtained (1.4 kPa). The internal friction angle was 34.4°. The slope 14 sample also showed a low cohesion value of 7.9 kPa. As expected, due to the high sand percentage, despite the sand's highly plastic classification because of the presence of clay, the internal friction angle obtained was 32.9°.

Table 4: Characteristics of the soils analyzed.

Characteristics	Slope 1	Slope 3	Slope 11	Slope 14
w (%)	4.00	1.85	2.47	2.10
Gravel (%)	4.02	4.34	4.25	0.10
Sand (%)	50.38	61.99	69.48	64.53
Silt (%)	9.99	15.75	6.54	11.33
Clay (%)	35.62	17.92	19.74	24.05
w_L (%)	38		20	32
w_P (%)	21	NP	14	16
PI (%)	17		6	16
γ_g (g/cm³)	2.68	2.66	2.65	2.65
Soil Classification (USCS)	SC	SM	SC-SM	SC

w = hygroscopic moisture content; w_L= liquid limit; w_P= plastic limit; NP= non-plastic; PI= plasticity index; γ_g= grain density; SC= clayey sand; SM= silty sand; SC-SM= silty-clayey sand.

Table 5: Properties of the soils studied.

Properties	Slope 1	Slope 3	Slope 11	Slope 14
w_i (%)	6.6	2.8	3.3	5.1
w_f (%)	21.3	18.4	14.8	18.9
γ (kN/m³)	17.0	15.8	17.5	17.3
γ_d (kN/m³)	15.9	15.4	16.9	16.5
γ_{sat} (kN/m³)	20.0	19.6	20.6	20.3
e_i	0.68	0.73	0.56	0.61
n (%)	40.4	42.1	36.1	37.8
S_{ri} (%)	25.9	10.3	15.4	22.4
c' (kPa)	20.5	0.0	1.4	7.9
ϕ' (°)	32.6	31.5	34.4	32.9

w_i= initial moisture content; w_f= final moisture content; γ= weight density; γ_d = dry density; γ_{sat} = zero air voids density; e_i = initial void ratio; n = porosity; S_{ri} = initial degree of saturation; c' = effective cohesion; ϕ'= effective friction angle.

The geotechnical characterization of hillside soils in the selected slopes according to risk analysis, resulted in a sample of the soil properties from different regions of the city, where soils were obtained with varying classifications and strength. The properties and strength parameters were obtained from undisturbed samples to mold test specimens for testing under flood conditions. In addition to obtaining a sample of soils from different regions of the city, the aim of geotechnical characterization tests was also to conduct stability analyses of the slopes selected.

Knowledge of the strength characteristics and parameters of soils made it possible to model the slopes using the OptumG2® software and submit them to stability analyses. The analyses developed from the strength parameters obtained under the flood condition enabled determining the scenarios triggered by saturation of slope materials caused by high rainfall, for example.

The stability condition of slopes, in terms of the safety factor, was defined according to NBR 11682 (ABNT, 2009). The minimum safety factor for the slope to be considered stable is 1.4. After stability analyses, it was possible to define the safety condition of the slopes under study. The safety factors obtained from stability analyses and slope stability according to NBR 11682 (ABNT, 2009) are summarized in Table 6, whereby only one of the 4 slopes analyzed is considered stable.

Table 6: Safety condition of the slopes under study.

Slope	SF	Safety
1	1.76 ± 0.01	Stable
3	0.37 ± 0.05	Unstable
11	1.24 ± 0.01	Unstable
14	1.23 ± 0.01	Unstable

The finite elements grids indicating the potential for surface rupture of the slopes under study and distribution of strain (x, y) are presented in Figures 7 to 10.
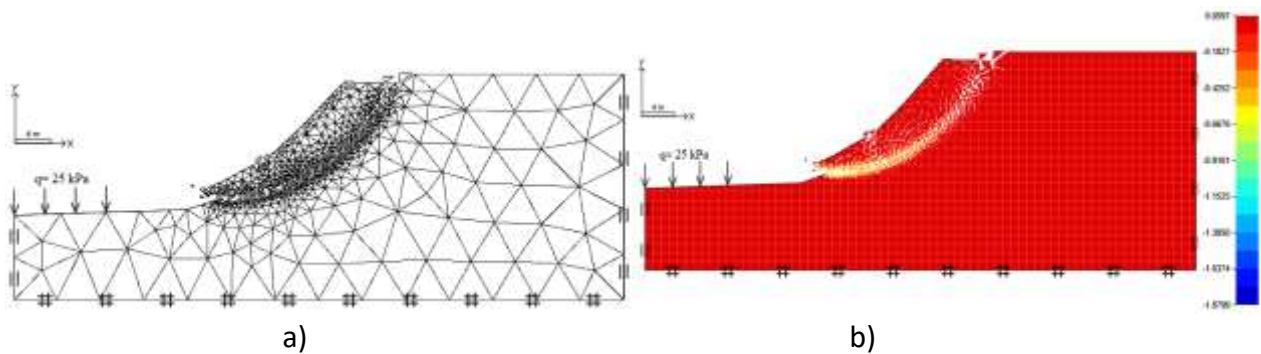

a)   b)

Figure 7: Stability analysis in slope 1 - a) Finite elements grid; b) Strains.

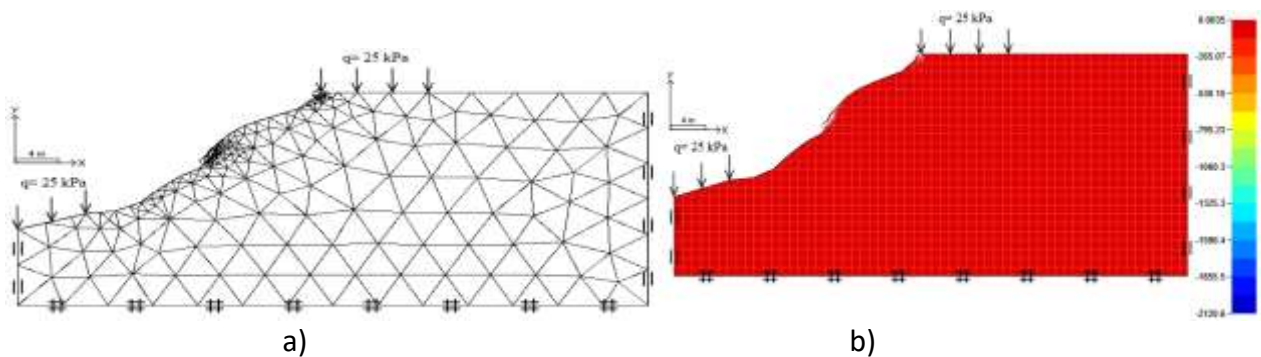a)   b)

Figure 8: Stability analysis in slope 3 - a) Finite elements grid; b) Strains.
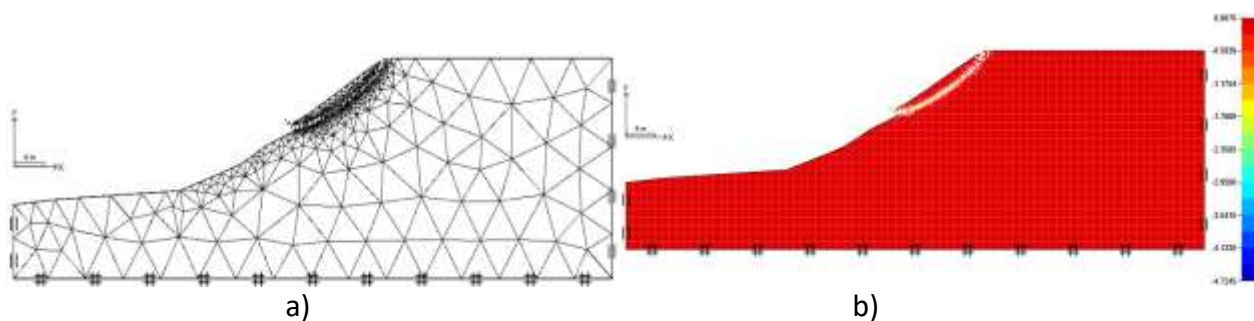
Figure 9: Stability analysis in slope 11 - a) Finite elements grid; b) Strains.
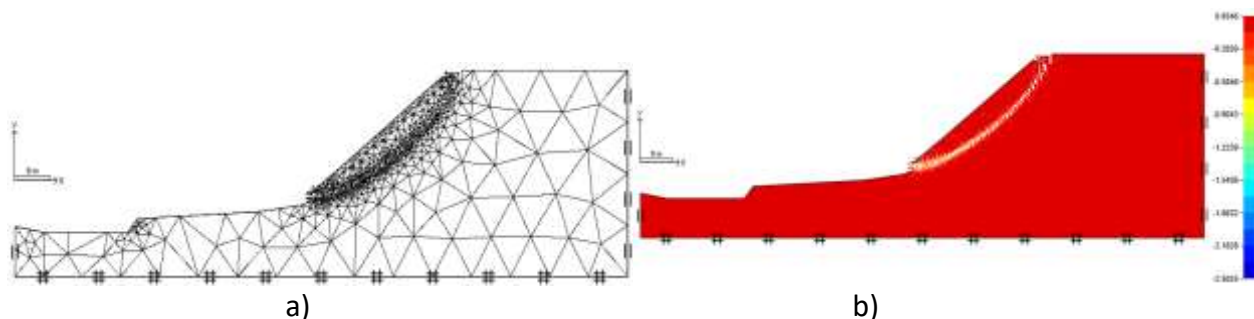

Figure 10: Stability analysis in slope 14 - a) Finite elements grid; b) Strains.

The finite elements grid is refined exactly where the rupture surface is placed, given that grid adaptability occurs according to plastic strains caused by shearing. The potential rupture surface assumes a circular shape, but wedge failure is not very deep. The slope 1 showed a safety factor of more than 1.4, the highest among the slopes analyzed, in line with the highest cohesive intercept value obtained.

The cohesive intercept of slope 3 soil was null, which is reflected in the low safety factor. The soil does not need to be totally saturated for the slope to collapse, since the safety factor of the flooded soil was less than 1 (one), the general condition for slope instability. This condition is compatible with the physical indicators of instability observed on the hillside.

Stability analysis with a null cohesion value resulted in a non-circular and superficial rupture surface. The results show the need to monitor this area, given the considerable number of dwellings in precarious positions.

Stability analysis of the slope 11 produced a safety factor of less than 1.4. As such, when high rainfall occurs, resulting in significant soil saturation, the slope may rupture. Due to the significant urbanization of slope 11, the damage caused by a possible slope rupture could be disastrous. The surface of the collapsed slope is circular with a low volume of mobilized material.

With respect to analysis conducted on the slope 14, the safety factor calculated was less than 1.4. Thus, the slope shows great potential of becoming unstable. This condition is compatible with the occurrences of mass movements in this area. The rupture surface was circular and superficial, with a low volume of mobilized material.

Another finding is that all rupture surfaces of the unstable slopes were shallow, that is, the slope does not need to be totally saturated for rupture to occur, rather, it is sufficient for the soil to be saturated beyond the potentially sliding surface.

Finally, it is important to underscore that slope stability is in line with the degree of risk attributed to the slopes, since the only slope 1 was considering stable, where a medium degree of risk was attributed. With respect to the remaining slopes, which exhibited safety factors below the minimum needed to be considered stable, slopes 11 and 14 were classified as high risk, whereas slope 3 showed a very high degree of risk.

4 CONCLUSIONS

In the present study, risk analysis was conducted in 16 slope in the city of Aracaju, 6% of which displayed a low degree of risk, 44% medium, 31% high and 19% very high.

The geotechnical characterization of soils from slopes selected according to risk analysis, resulted in a representative sampling of soil properties from different regions of the city. As such, soils were obtained with varying classifications and strength parameters.

The geotechnical characterization provided the properties and parameters of soil strength, necessary for conducting stability analyses. Soil from the Santa Maria district (slope 1) was classified as highly plastic clayey sand (SC). The material obtained a cohesive intercept value of 20.5 kPa and friction angle of 32.6°. These values coincide with the safety factor of the slope, considered the only stable.

The material collected in the America district was characterized as silty sand (SM) with no plasticity, a null cohesion intercept and friction angle of 31.5°. Material collected in the Industrial district displayed silty-clay sand (SC-SM) characteristics and weak plasticity, with a cohesive intercept value of 1.4 kPa and friction angle of 34.4°. Finally, in the Japãozinho district, the soil collected was strongly plastic clayey sand (SC), the cohesive intercept was 7.9 kPa and friction angle 32.9°. The low values of the strength parameters justify the instability of the slopes.

In addition to safety factors, stability analysis showed the location of rupture surfaces and the collapse mechanism of slopes. The results of stability analyses were in line with the risk classification of the slopes. The only slope that remained stable presented a medium degree of risk. The remaining slopeswith high and very high degrees of risk, were unstable. The wedge failures obtained from the analyses were superficial, involving a low volume of mobilized material. This explains why the mass movements that have occurred in these areas have yet to cause a major disaster.

It is important to underscore the need to foresee the damage that could be caused by heavy rainfall that saturates the soils of these slopes. Although intense rainfall is not frequent in Aracaju, there are exceptional cases that have disrupted the communities located in these areas.

The results obtained in the study of risk areas in Aracaju were considered satisfactory and promising for the desired purpose, since it contemplated different analytical methods in order to assist the entities responsible for risk management in the city and encourage more studies in the area.

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