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Análise de estabilidade tridimensional de um talude urbano localizado em João Monlevade, Brasil

Three-dimensional stability analysis of an urban slope located in João Monlevade, Brazil

Análisis de estabilidad tridimensional de un talud urbano ubicado en João Monlevade, Brasil

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Resumo

Análise de estabilidade geotécnica é uma importante ferramenta de decisão em projetos de engenharia civil. O uso de análises tridimensionais de estabilidade cresceu nos últimos anos. Rocscience Inc. criou Slide3 em 2017. Slide3 é um programa computacional que permite que engenheiros geotécnicos calculem o fator de segurança em complexas geometrias tridimensionais que modelos bidimensionais não são capazes de simular de forma efetiva. Neste contexto, esse artigo apresenta uma análise de estabilidade tridimensional de um talude urbano localizado em João Monlevade no estado de Minas Gerais, Brasil. O talude foi selecionado devido ao histórico de instabilidade durante períodos chuvosos. A topografia do talude foi fornecida pela prefeitura da cidade. Solo residual jovem e solo residual maduro foram identificados no talude estudado. O solo residual jovem foi classificado como argila sem pedregulhos e apresentou in natura, valores de coesão e ângulo de atrito igual a 32 KPa e 23,97°, respectivamente. Solo residual maduro foi classificado silte argiloso sem pedregulhos e apresentou in natura, valores de coesão e ângulo de atrito igual a 19 KPa e 23,30°, respectivamente. O solo foi classificado como silte argiloso e apresentou valores de coesão e ângulo de atrito iguais a 0,19 KPa e 23,3°, respectivamente. O fator de segurança do talude saturado foi igual a 0,977 e do talude drenado foi igual a 1,415. O método de equilíbrio limite utilizado foi o método do Equilíbrio Generalizado (GLE). O resultado da análise de estabilidade do talude é coerente, uma vez que instabilidades previas ocorreram em período em que foi identificada precipitação acima da média.

Palavras-chave: Estabilidade de taludes; Análise tridimensional; Método do equilíbrio limite generalizado; Taludes urbanos.

Abstract

Geotechnical stability analysis of slopes is an important tool for decision making in civil projects. Use of three-dimensional software for analysis of soil slope stability has increased in recent years. Rocscience Inc. created Slide3 software in 2017. Slide3 is a software that allows geotechnical engineers to calculate the factor of safety of complex 3D slope stability geometries that 2D models cannot fully simulate. In this context, this paper presents a three-dimensional stability analysis of a slope located in an urban area at city of João Monlevade, Minas Gerais, Brazil. The slope was selected due to the instability history in rainfall periods. Topography of the area was provided by the city council. Young and mature residual soils were identified in the studied slope. Young residual soil was physically classified as clay without gravels and presents in natura values of cohesion and friction angle, equal to 32 KPa and 23.97º, respectively. Mature residual soil was physically classified as clayey silt without gravels and presents in natura values of cohesion and friction angle, equal to 19 KPa and 23.30º, respectively. The factor of safety of the soil slope was equal 0.977, considering the slope saturated. The factor of safety of the drained slope was equal to 1.415. Generalized limit equilibrium (GLE) method was used in this equilibrium-limit analysis. The results stability analysis of the slope was coherent, once previous instability occurs in a period that was identified above average rainfall.

Keywords: Slope stability; Three-dimensional analysis; Generalized limit equilibrium method; Urban slopes.

Resumen

Análisis de estabilidad geotécnica es una herramienta de decisión importante en proyectos de ingeniería civil. El uso del análisis de estabilidad tridimensional ha crecido en los últimos años. Rocscience Inc. creó Slide3 en 2017. Slide3 es un software que permite a los ingenieros geotécnicos calcular el factor de seguridad en geometrías tridimensionales complejas que los modelos bidimensionales no pueden simular de manera efectiva. En este contexto, este artículo presenta un análisis de estabilidad tridimensional de un talud urbano ubicado en João Monlevade, Minas Gerais, Brasil. El talud fue seleccionado debido a la historia de inestabilidad durante los períodos de lluvia. La topografía del talud fue cedida por el ayuntamiento de la ciudad. Se identificaron suelo residual joven y suelo residual maduro en el talud estudiado. El suelo residual joven se clasificó físicamente como arcilla sin gravas y presentó valores in natura de cohesión y ángulo de fricción, igual a 32 KPa y 23.97°, respectivamente. El suelo residual maduro se clasificó físicamente como limo arcilloso sin gravas y presentó valores in natura de cohesión y ángulo de fricción, igual a 19 KPa y 23.30°, respectivamente. El factor de seguridad del talud saturado fue 0,977 y del talud drenado fue 1.415. El método de equilibrio límite utilizado fue el Método de Equilibrio Generalizado (GLE). El resultado del análisis de estabilidad del talud es consistente, ya que inestabilidades previas han ocurrido durante un período en el que se identificaron precipitaciones superiores al promedio.
Palabras clave: Estabilidad de taludes; Análisis tridimensional; Método de Equilibrio Generalizado; Taludes urbanos.

1. Introduction

Landslides lead to changes in the relief formation and natural landscape. The absence or inefficiency of Brazilian territorial planning, inappropriate occupation of urban areas and incorrectly design of cut and fill contribute effectively to urban slope instability. Concerns about human, socioeconomic and environmental consequences are related to these urban slope instabilities.

According to Massad (2003), landslides are mass movements directly influenced by the gravity action, which present a tendency of naturally stabilize after failure occurrence. High levels of rainfall and undue anthropogenic actions are the main causes of urban landslides. Slope stability condition is conditioned by resisting and driving agents. Resisting agents are related to soil characteristics, like its shear strength. Driving agents are the external agents that can lead to slope instability, like climatic conditions, groundwater condition, tectonic movements and anthropic action (Caputo & Caputo, 2015).

Geotechnical stability analysis of slopes is an important tool for decision making in civil projects. Use of three-dimensional software for soil slope stability analysis have been

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increased in recent years. Rocscience Inc. created Slide3 software in 2017. Slide3 is a tool that allows geotechnical engineers to calculate the factor of safety of complex 3D slope stability geometries that 2D models cannot fully simulate (Rocsience, 2019).

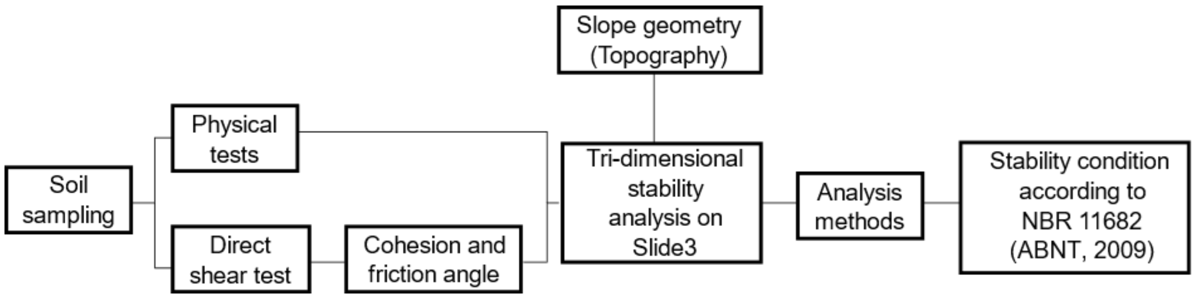
A governmental Brazilian geological company, named Companhia de Pesquisa de Recursos Minerais (CPRM), published a landslide susceptibility map of João Monlevade city (Companhia de Pesquisa de Recursos Minerais, 2012). Several geotechnical risk sectors were identified as results of this survey and the trigger factors of landslides in the city are related to rugged relief, urban slopes with high inclinations and disorderly occupation.

In this context, this article presents a three-dimensional stability analysis of a slope located in an urban area in João Monlevade city, Minas Gerais State, Brazil. This slope presents instability history in rainfall periods. Topography of the area was provided by the city council, laboratory tests for soil characterization and tri-dimensional stability analysis using Slide3 software of the slope were carried out.

2. Methodology

Figure 1 presents a flowchart of required methodology to perform the tri-dimensional stability analysis of the slope.

Figure 1: Research methodology.



Source: The authors, 2017.

Young residual soil and mature residual soil were identified in the slope. Soil sampling, physical tests and direct shear test were carried out in both types of soil. The soils were classified according to this particle size and plasticity index and the unit weights were also determined by the physical tests. Cohesion and friction angle, parameters of Mohr-Coulomb criterion were defined by direct shear tests. The required parameters provided by the tests and

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the slope geometry are used to define the stability condition of the slope through the tri-dimensional analysis using Slide3.

2.1 Case study

The studied slope (Figure 2) is located at Alberto Lima Street, in city of João Monlevade. The city is located in the central part of Minas Gerais State in Médio Piracicaba region. It has a territorial extension of 99.65 km², 73610 inhabitants and 21665 residences (Instituto Brasileiro de Geografia e Estatística, 2010).

Figure 2. Studied slope.

Source: Secretaria Municipal de Obras, João Monlevade, 2017.

Slope is upstream of a busy city street and above of it, two buildings and some residences were built. The mature residual soil is exposed and there is vegetation cover only in some parts of the slope.

The city has a high-altitude tropical climate, hot summers and two clearly defined seasons. The average altitude is 900 meters above sea level and the periods of rainfall are normally between November and March. In these months, instability of slopes occurs more frequently.

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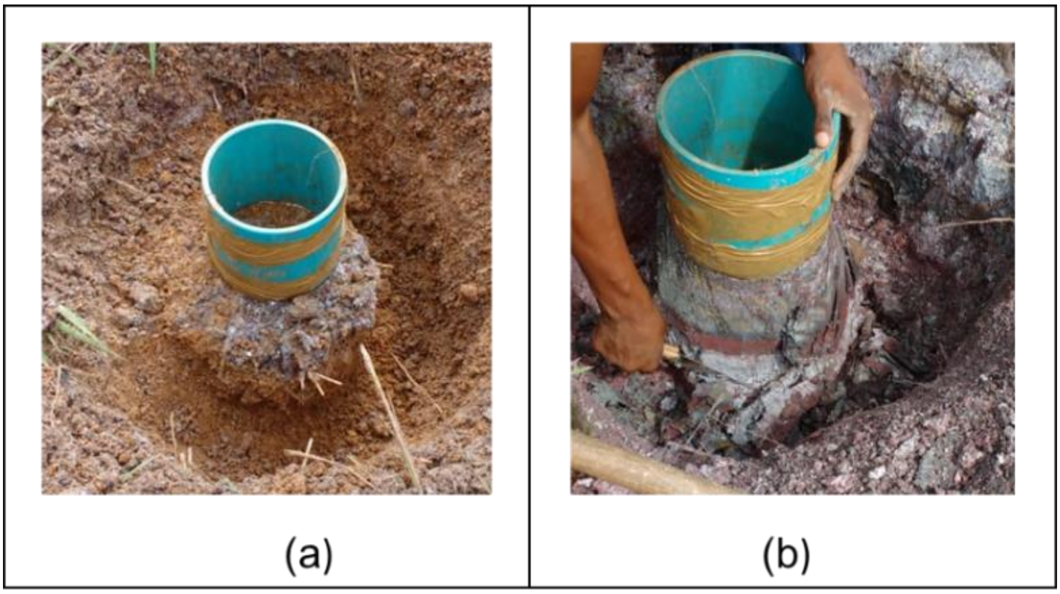
2.2 Soil sampling

Undisturbed sample of young residual soil (Figure 3-a) and undisturbed sample of mature residual soil (Figure 3-b) were collected for characterization of the slope material. The sampling was carried out according to standard NBR 9604 (Associação Brasileira de Normas Técnicas, 1986).

Figure 3. Physical tests.



Source: The authors, 2017.

The sampling consisted of the soil core excavation with 10.2 centimeters. The core was sampled, detachable and hermetically capped for maintaining the natural properties of the soil. This procedure was carried out for both soils.

2.3 Soil geotechnical characterization

Physical tests of soil were carried out according Brazilian standards. NBR 6457 (Associação Brasileira de Normas Técnicas, 1986), NBR 7181 (Associação Brasileira de Normas Técnicas, 1984), NBR 6459 (Associação Brasileira de Normas Técnicas, 1984), NBR 7180 (Associação Brasileira de Normas Técnicas, 1984) and NBR 6508 (Associação Brasileira de Normas Técnicas, 1984) were used. Granulometry, moisture content, liquidity and plastic limit, unit weight of young and mature residual soil were defined. Figure 4 shows the soil physical tests of studied slope.

Figure 4. Physical tests.

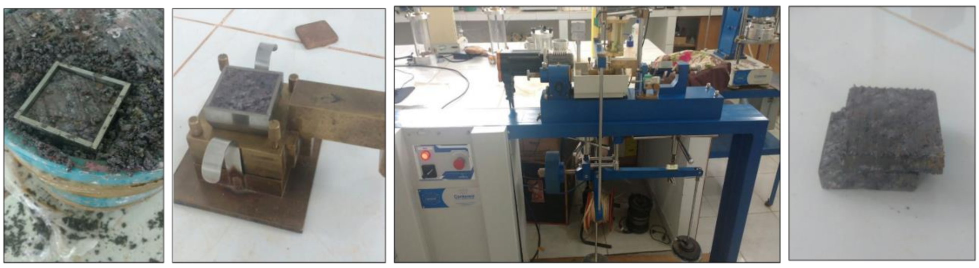
Source: The authors, 2017.

Procedures for determining the unit weight and particle size of soils can be seen in Figure 4. The unit weight was determining using wetting and drying cycles and laboratory precision scale. The particle size analysis of soils was determining by sedimentation. The test consists of a suspension composed by soil, water and dispersant to separate the particles used to separate in ranges of size the soils.

2.4 Direct shear tests

Direct shear tests were carried out on saturated and in natura samples according to D3080 recommendations of ASTM for determining cohesion and friction angle of young and mature soil (American Society for Testing and Materials, 2004). The tests performed in saturated samples were carried out with the goal of analyze the soil cohesion variation in presence of water. The test is presented in Figure 5.

Figure 5. Direct shear test



Source: The authors, 2017.

Three specimens of young mature soil and three specimens from mature residual soil were extracted from the undisturbed samples. The specimens were place to the shear box

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which has two stacked rings to hold the sample. A normal stress equal to 50 KPa, 100 KPa and 200 KPa ware applied vertically to the specimens and the upper ring was pulled laterally until the samples fail.

2.5 Tri-dimensional stability analysis of the slope

Tri-dimensional slope stability was carried out in software Slide3. Slide3 is a 3D limit equilibrium slope stability program for evaluating the safety factor of 3D failure surfaces in soil or rock slopes. Groundwater, support, and loading can be included in the analysis. Slide3 analyzes the stability of 3-dimensional slip surfaces using vertical column limit equilibrium methods (Rocscience, 2019).

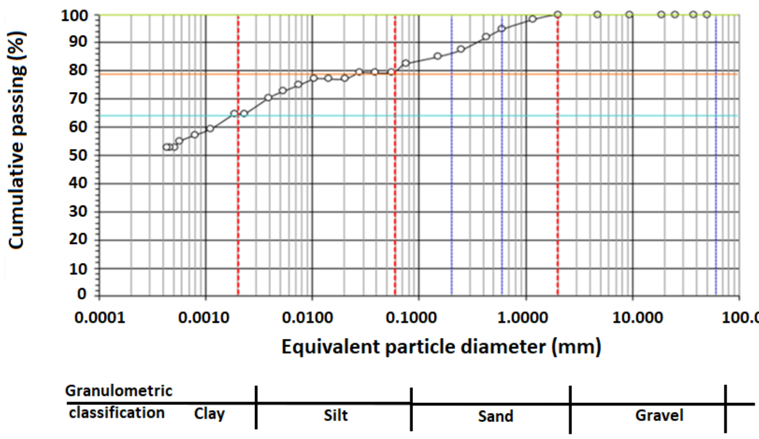
João Monlevade city council provided the slope geometry and the soil strength was estimated through directs shear test. Slip surface search method and GLE/Morgenstern-Price method was used in the equilibrium limit analysis.

3. Results and discussion

3.1 Physical tests

The granulometric curves of young and mature residual soils are presented in Figure 6 and 7, respectively. The granulometric curves of young and mature residual soils consists of a cumulative soil percentage according to the particle diameter in millimeters. The percentage of each particle size fraction of soils was determined.

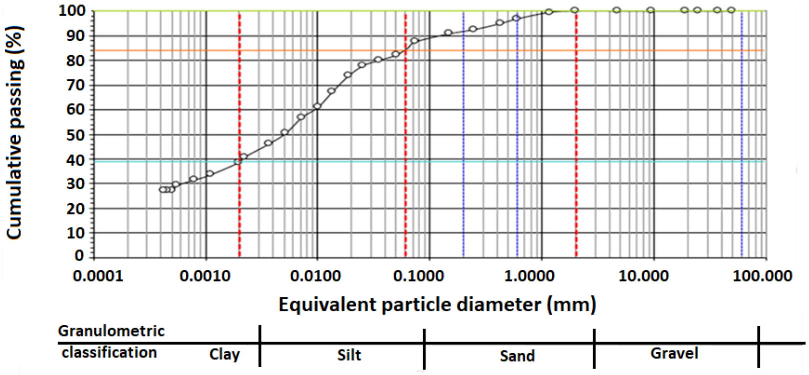
Figure 6. Granulometric curve of young residual soil.



Source: The authors, 2017.

The young residual soil presented 64% of particles with size until 0.002 mm (clay), 15% of particle with size until 0.06 mm (silt), 21% of particles with size until 2 mm (sand) and 0% of particles above 2 mm (gravel). Then, the young residual soil was classified as clay without gravels. The mature residual soil presented 39% of particles with size until 0.002 mm (clay), 45% of particle with size until 0.06 mm (silt), 16% of particles with size until 2 mm (sand) and 0% of particles above 2 mm (gravel). Then, the mature residual soil was classified as clayey silt without gravels.

Figure 7. Granulometric curve of mature residual soil.



Source: The authors, 2017.

The young residual soil of studied slope presents liquidity index, plastic limit and plasticity index equal to 67%, 32% and 35%, respectively. Then, it can be classified as a highly plastic soil. The unit weight of in natura soil is 16.13 KN/m3, respectively. The mature residual soil of studied slope presents liquidity index, plastic limit and plasticity index equal to 71%, 35% and 36%, respectively. Then, it can be also classified as a highly plastic soil. The unit weight of in natura soil is 16.17 KN/m3, respectively. The soils do not present significant differences in their physical characteristics.

Table 1 presents the percentage of each particle size fraction and the granulometric classification of young residual soil and mature residual soil.

Table 1. Granulometric classification of soils.

Grain size	Young residual soil	Mature residual soil
Clay	64%	39%
Silt	15%	45%
Sand	21%	16%
Gravel	0%	0%

Source: The authors, 2017.

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3.2 Direct shear tests

The direct shear test results of young residual soil and mature residual soil are presented in Table 2. The test was carried out for the soils in natura and saturated conditions.

Table 2. Results of direct shear tests.

Soil	Friction angle (°)		Cohesion (KPa)	
	In natura	Saturated	*In natura*	Saturated
Young residual soil	23.97	35.20	32	0
Mature residual soil	23.30	24.01	19	16

Source: The authors, 2017.

The direct shear test provides the strength parameters of Mohr-Coulomb criterion. The parameters are friction angle and cohesion. The young residual soil presented friction angle and cohesion in saturated and in natura condition equal to 35.2°, 0 KPa, 23.97°, 32 KPa, respectively. The mature residual soil presented friction angle and cohesion in saturated and in natura condition equal to 24.01°, 16 KPa, 23.3°, 19 KPa, respectively.

The shear strength tests presented low values of cohesion and friction angle for booth in natura and statured soils. These low values were expected as the slope has visual characteristics of low quality and cohesion.

3.3 Tri-dimensional analysis

Stability analysis were carried out using generalized limit equilibrium method and slip surface search method for the slopes *in natura* and saturated conditions. Figure 8 and 9 presents the results of analysis using the strength parameters obtained through direct shear test. According to city council, the slope presents previous instability that occurs in rainfall period.

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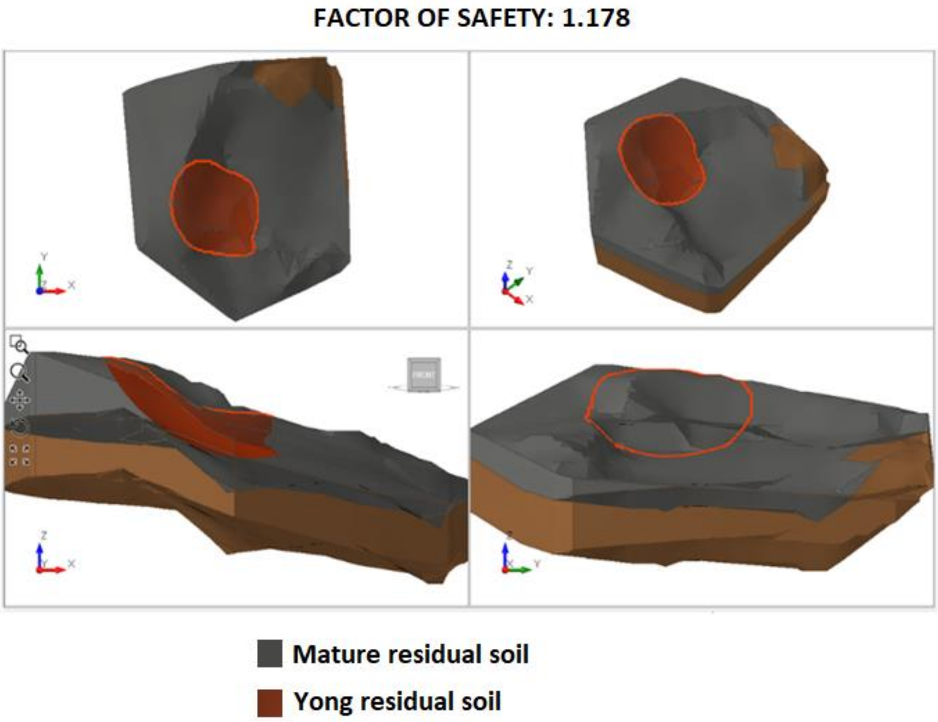
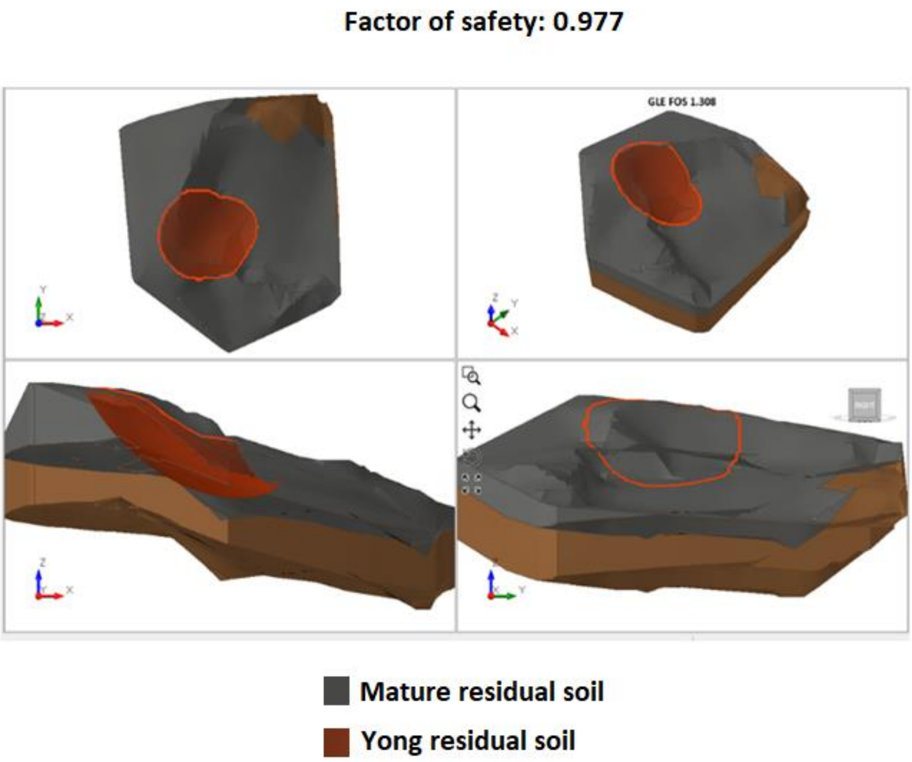
Figure 8. Stability analysis of slope in natural conditions.



Source: The authors, 2017.

Figure 9. Stability analysis of slope in saturated condition.



Source: The authors, 2017.

The figures 8 and 9 present the slope topography, the young and mature residual soil, the possible volume of material moved in case of slope failure and the slope factor of safety. These volumes are presented in figures in color red. According to NBR 11682 (Associação Brasileira de Normas Técnicas, 2009), stable slopes for civil projects presents factor of safety equal or greater than 1.5. The studied slope presented values of factor of safety equal to 1.178 and 0.977 for *in natura* and saturated conditions, respectively. Then, the slope presents an unstable condition. The obtained values are coeherent, since tension cracks and movement signs are visually verified on the slope crest.

4. Conclusion

Mature residual soil and young residual soil were identified in the studied slope. Laboratory tests and geotechnical survey were successful carried out. The mature residual soil was classified as clayey silt without gravels and the young residual soil was classified as clay without gravels. Direct shear tests were carried out for the soils in natura and saturated conditions. The strength parameters obtained resented low values of cohesion.

Tri-dimensional analysis using generalized limit equilibrium method provided a coherent factor of safety. The obtained factor of safety values was lower than 1.5 and the studied slope was classified as unstable. Tension cracks and movement signs are visually verified on the slope crest. Therefore, it is possible to affirm that the soil physical characteristics, strength parameters and stability analysis were correctly carried out.

The stability analysis suggests that future instability will be occur in the slope. The slope failure can compromise the foundation of buildings that are located in the slope crest and the vehicles can be reached by the soil of the failure at the street located in the toe of the slope. The authors suggest some remediation actions like revegetation of the area and implementation drainage system in order to avoid new instabilities on the studied slope.

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