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Soil physical properties and slope stability in Serra do Mar, southeastern Brazil

Propriedades físicas do solo e a estabilidade das encostas na Serra do Mar, Sudeste do Brasil

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Resumo: As propriedades físicas do solo desempenham um papel importante nos mecanismos de ruptura de deslizamentos, uma vez que mudanças na textura, estrutura e porosidade do solo podem afetar a permeabilidade da encosta. Este estudo caracterizou um perfil de intemperismo granítico e avaliou as mudanças nas propriedades de seus materiais, relacionando aos principais mecanismos que desencadeiam deslizamentos. O estudo identificou três camadas com características distintas em relação a macromorfologia e micromorfologia: solo residual maduro (bem desenvolvido), solo residual jovem (saprolítico) e saprolito. Foram realizadas a caracterização morfológica, além da análise textural, e testes de porosidade do solo e condutividade hidráulica saturada (K_{sat}). O perfil de intemperismo apresentou claras diferenças na morfologia, porosidade e textura, o que pode indicar graus distintos de intemperismo. Os resultados sugerem que tais características associadas a chuvas intensas e contínuas podem contribuir para o aumento da poro-pressão entre o solo residual maduro e o solo residual jovem, favorecendo a ocorrência de rupturas na encosta.

Palavras-chave: *Escorregamento; Solo Residual; Propriedades Físicas do Solo; Granito; Intemperismo.*

Abstract: *Soil physical properties play an important role in landslide rupture mechanisms, since changes in soil texture, structure, and porosity can affect slope permeability. This study characterized a granitic weathering profile and assessed the changes in the properties of the materials related to the main mechanisms that trigger landslides. The study identified three layers with distinctive particularities in macromorphological and micromorphological terms: mature residual soil (well-developed), young residual soil (saprolitic soil), and saprolite. Morphological characterization was carried out in addition to textural analysis, and soil porosity and saturated hydraulic conductivity (K_{sat}) tests. The weathering profile presented clear differences in morphology, pore size and soil texture, which could indicate distinct weathering grades. The results suggested that continuous heavy rainfall could contribute to the increase in pore-water pressure between mature residual soil and young residual soil, favoring the occurrence of slope failure.*

Keywords: *Landslide; Residual Soil; Soil Physical Properties; Granite; Weathering.*

1. Introduction

The occurrence of shallow landslides in tropical environments is usually associated with material heterogeneity in weathering profiles (IRFAN; WOODS, 1988; LACERDA, 2007; CHE *et al.*, 2012). Vertical and horizontal variations in soil physical properties directly affect slope stability (FURIAN *et al.*, 2002; WIEGAND *et al.*, 2013). Therefore, weathering profile characterization can be an essential tool for understanding landslide-triggering mechanisms (BARATA, 1969; DEERE; PATTON, 1971; VARGAS JR *et al.*, 1986; WOLLE; HACHICH, 1989).

Soil properties play an important role in slope stability and some physical features, such as texture, morphology, and porosity can directly influence water dynamics on slopes (ZUNG *et al*., 2009; BIDYASHWARI *et al*., 2017). In addition, soil heterogeneity and anisotropy make understanding and analyzing soil permeability and hydraulic conductivity difficult (SIDLE; OCHIAI, 2006; SIDLE; BOGAARD, 2016).

The textural differences between soil layers can be determinant in landslides occurrences. Kitutu *et al* (2009) indicate that the grain size differences between the layers conditioned significant permeability changes favoring the slope failure. Pore size distribution and soil structure can influence hydraulic conductivity (K_{sat}). Vieira and Fernandes (2004) linked K_{sat} variations to changes between macro and microporosity in weathering profile, as well as highlighted that the behavior of Ksat is strongly influenced by clay content.

In Brazil, the Serra do Mar mountain range is one of the areas most affected by shallow landslides (**Figure 1**), especially during the rainy season, due to complex interactions between conditioning factors (CRUZ, 1975; VIEIRA; FERNANDES, 2004; CERRI *et al*., 2017). Serra do Mar is a geomorphological compartment located on the Brazilian coast constituted by a set of escarpments with extensive steep slope segments, cut by valleys with rugged relief of hills and mountains (ALMEIDA; CARNEIRO, 1998; VIEIRA; GRAMANI, 2015). The region is scenario of several catastrophic events linked with rainfall-induced landslides. Some examples of high magnitude events in region are: Caraguatatuba in 1967 (DE PLOEY; CRUZ, 1979), mountainous region of Rio de Janeiro state in 2011 (AVELAR *et al*., 2013; NETTO *et al*., 2013) and Itaóca in 2014 (BROLLO *et al*., 2015; BATISTA; JULIEN, 2019).

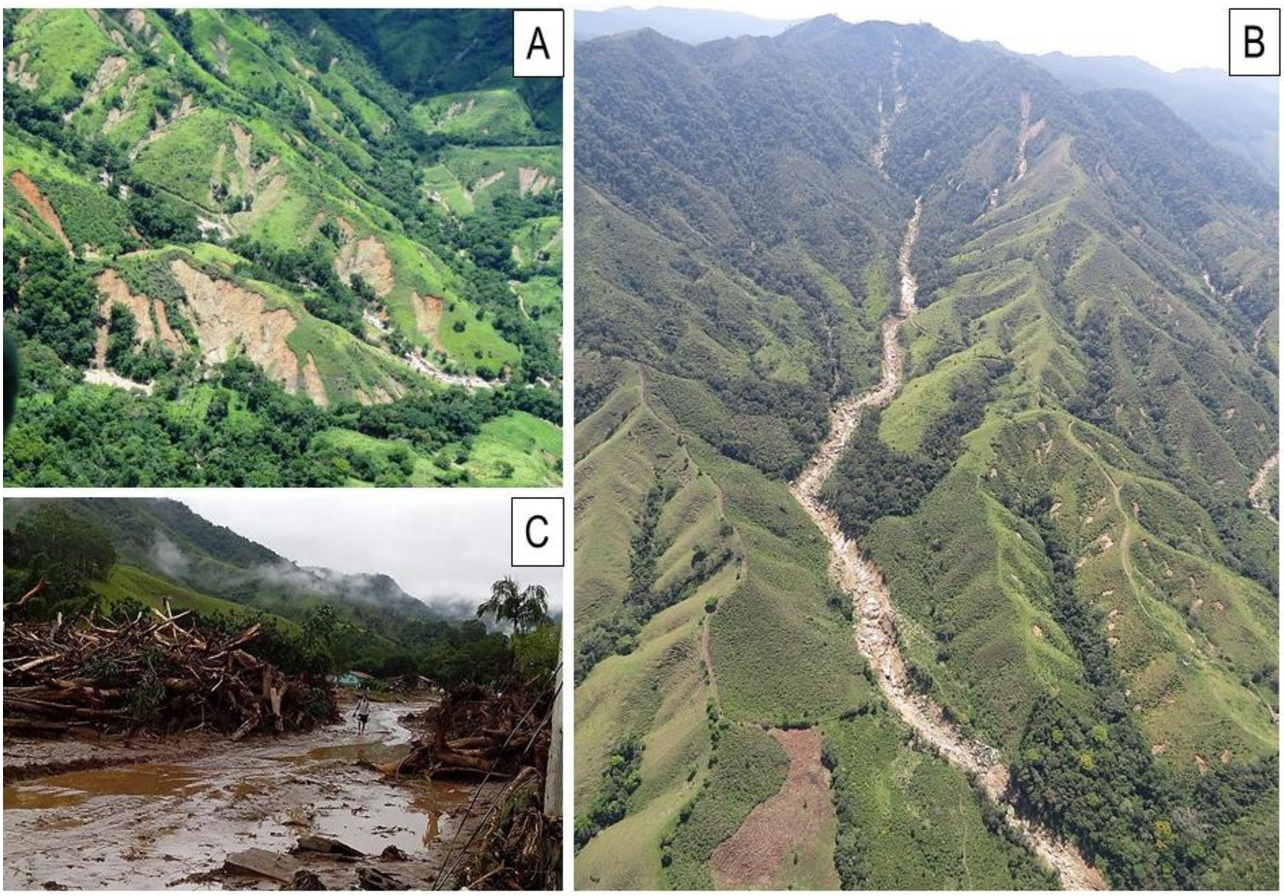

Figure 1: Several mass movements triggered by intense rainfall in January 2014 in the Ribeira Valley region, Serra do Mar. (A) Shallow landslides in the Gurutuba watershed. (B) Debris flow and shallow landslides in the Guarda-Mão watershed. (C) City of Itaóca affected by debris and floods. Source: (A) and (B) Courtesy of Marcelo F. Gramani. (C) Public archive of Itaóca municipality.

Landslide conditioning factors in Serra do Mar have been related to soil properties (COlÂNGELO, 2012; CERRI *et al*., 2020; COELHO *et al*., 2021). However, soil collection and analysis are often challenging due to regional environmental features such as extensive geographical area, dense rainforest, and considerable topographic amplitude, among others (CERRI *et al*., 2020).

Although landslides constitute the most prominent hazard in the Serra do Mar (**Figure 1**) data on soils affected by landslides are still incipient in Brazil. Therefore, the objective of this work is to characterize the soil cover, describe the physical properties in a landslide-prone area, and identify the main predisposing factors. Multidisciplinary methodologies were used to study and characterize soil behavior (morphological descriptions, porosity, texture, etc.). Furthermore, we aim to add tropical residual soil data and contribute to the international literature on landslides.

2. Materials and methods

2.1 Study site

In January 2014, the municipality of Itaóca was affected by extreme rainfall of approximately 210 mm in 2 h, which triggered widespread movement of soil masses. Several urban areas were damaged by landslides, which destroyed houses, farms, roads, and bridges. Intense mobilization of vegetation in river networks occurred and many points in the rivers of the region silted up (BROLLO *et al*., 2015; GRAMANI; MARTINS, 2016). The representative cut slope was located in Itaóca Municipality in the south of São Paulo state (**Figure 2**). The cut slope was close to several shallow landslide scars, which indicated high landslide susceptibility.

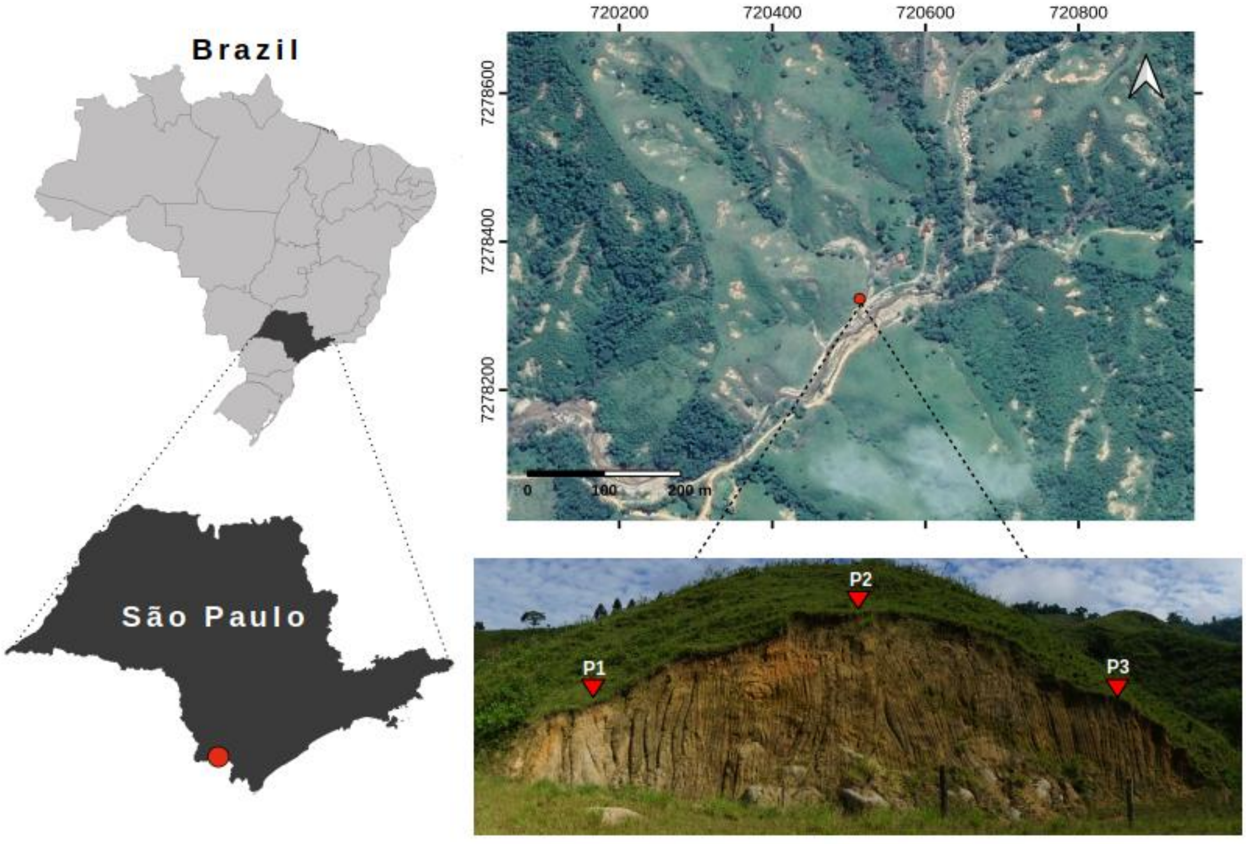

Figure 2: Location of the study site in the south of São Paulo State in Brazil, selected cut slope, and points of soil sample collection (P1, P2 and P3). The selected cut slope is near the shallow landslide scars (translational landslide) of the 2014 event and is approximately 47 meters in length and 12 meters in height. Satellite Imagery Sorcery: Google Earth Pro 2014.

The lithology is homogeneous because the bedrock is composed of Neoproterozoic granitic rocks of the Itaóca batholith, which covers an area of more than 200 km² (FALEIROS *et al*., 2012). The batholith is surrounded by metasedimentary and metacarbonate rocks of the Lajeado Sub-Group (CAMPANHA;

SADOWSKI, 1994). The rocks are predominantly composed of monzogranites, quartz-monzonites, and quartz-syenites rich in k-feldspar (MELLO; BETTENCOURT, 1998; FALEIROS *et al*., 2012).

The geomorphology is linked with the Serra do Mar context, consisting mainly of escarpments of angular tops and very steep slopes are to the north of the area (CARNEIRO *et al*., 1981; IPT, 1981; ROSS; MOROZ, 1996; ROSS, 2002;). Some sectors can reach 1000 - 1100 m, generally maintained by metamorphic rocks such as quartzite, presenting elongated and continuous crest morphology or intrusive granitic masses, which extend over large areas (ROSS, 2002).

The regolith shows variable degrees of weathering due to the intense alteration of the Itaóca granite. In general, the weathering mantle is approximately 6 m in depth with a mineral matrix dominated by quartz, biotite, muscovite, and feldspars; within this mantle, phenocrysts of feldspar are easily identified by the naked eye. Soil coverage on the steep areas is composed by Litholic Neosols, Haplic Cambisols and rock outcrops. On gentle slopes, Red-Yellow Argisols predominates and near main drainages Gleysols (ROSSI, 2017).

The native vegetation is Mata Atlântica (rainforest), mainly covering the escarpment area, while the remainder is covered by degraded pastures. The climate according to the Köppen classification is Cfa, which is characterized by humid summers and cold to mild winters (ALVARES *et al*., 2013). The rainy season is from October to March with January being the wettest month with an average rainfall of 219.8 mm, followed by February with averages of 161 mm (ANA, 2020).

2.2 Soil sampling, morphological and field structure analysis

To define the vertical and lateral changes in physical properties, three profiles (P1, P2, and P3) were defined in the cut slope (**Figure 2**). The depth range of sampling was 0.1 m to 6.0 m to represent changes in the soil profile (color, texture and structure). Soil color was described using the Munsell Soil Color Chart (2000), and the morphology was described *in situ* using guidelines of (FAO, 2006).

Disturbed soil samples were collected for grain size analysis and undisturbed (cylinder) for pore size distribution. Based on field observations and morphological descriptions, saturated hydraulic conductivity (K_{sat}) tests were performed *in situ* (0.5 m and 1.0 m) with a Guelph Permeameter.

In this paper the terminology saprolite (very altered rock) is used to materials with clear structural features inherited or relict from their parent rock; is the transition between the young residual soil and the rock proper. Young residual soil (or saprolitic soil) refers to saprolite with advanced weathering grade (soil-like material); is more recent than the mature soil and keeps, sometimes, the appearance and structure of the parent rock. The mature residual soil is the upper zone of regolith, relic rock structure is not detectable; corresponding to the pedological horizons (BARATA, 1969; VARGAS, 1985; WOLLE, 1988; BLIGHT, 2012).

2.3 Laboratory analysis

The soil analysis was performed at the Laboratory of Residues and Contaminated Areas of the Institute for Technological Research of São Paulo (LRAC – IPT). Forty-one disturbed samples were collected for grain size analysis and 28 undisturbed samples for pore size.

The particle size analysis was performed by the "IPT – 3852 – Granulometric Analysis" laboratory test based on NBR6502/95, NBR6457/16, and NBR7181/16. Hydrometer and Sieve analysis for samples from each horizon were performed to determine the proportion of gravel, sand, silt, and clay. The Hydrometer test was realized to separate fine fractions (silt and clay) from the sand. Gravel and sand fractions were determined by a set of sieves.

Soil porosity was obtained through the test procedure of "IPT - 3855 - Total Porosity, Effective and Microporosity". Macroporosity and Microporosity were obtained by using the Büchner-funnel method. In this analysis, a suction of 0.8 m H_20 was applied to saturated undisturbed soil samples to eliminate water from the macropores through a leveling tube coupled to the porous plate funnel, for 48 hours. The total porosity is composed by macroporosity and microporosity respectively.

3. Results and discussion

3.1 Morphological characterization of the soil cover

The weathering profile showed wide vertical variation in textural, micromorphological, and macromorphological properties. It was divided into three zones (or layers) (**Figure 3**).

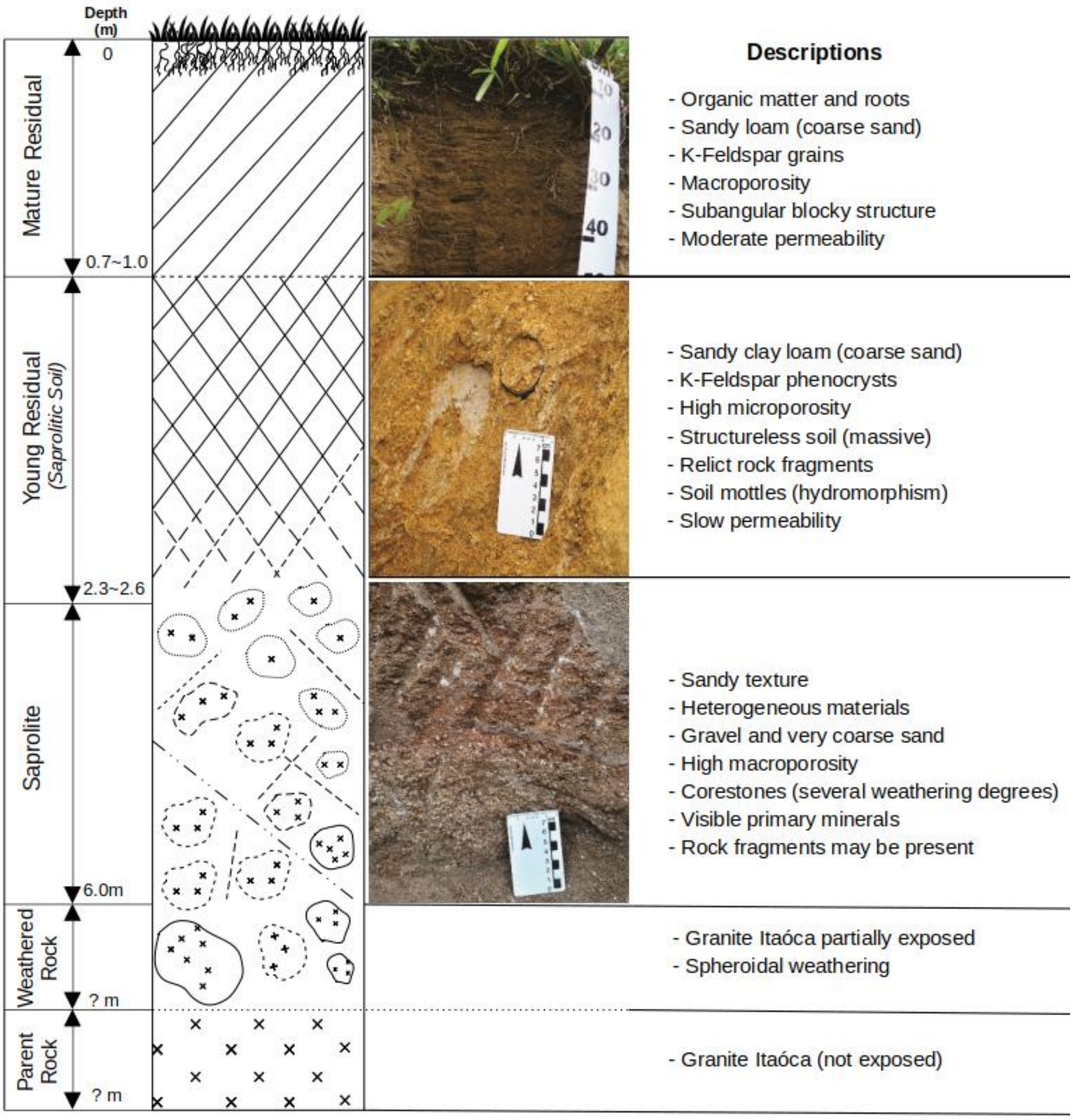

Figure 3: Typical weathering profile in Itaóca granite (Brazil). The profile shows clear differences in soil color, texture, and macrostructure with depth. Three zones were defined: mature residual, young residual, and saprolite.

In general, mature residual and young residual were more clayey than weathered rocks, which contained coarse sand and gravel. Vertical variations in physical and morphological properties likely reveal non-uniform weathering with depth. These variations generated specific geomechanical characteristics for each weathering zone; therefore, each layer responded differently to the infiltration of rainwater. For example, macromorphological characteristics in mature residual (subangular blocky structure) suggested good internal drainage with regard to young residual (massive) (**Figure 4**).

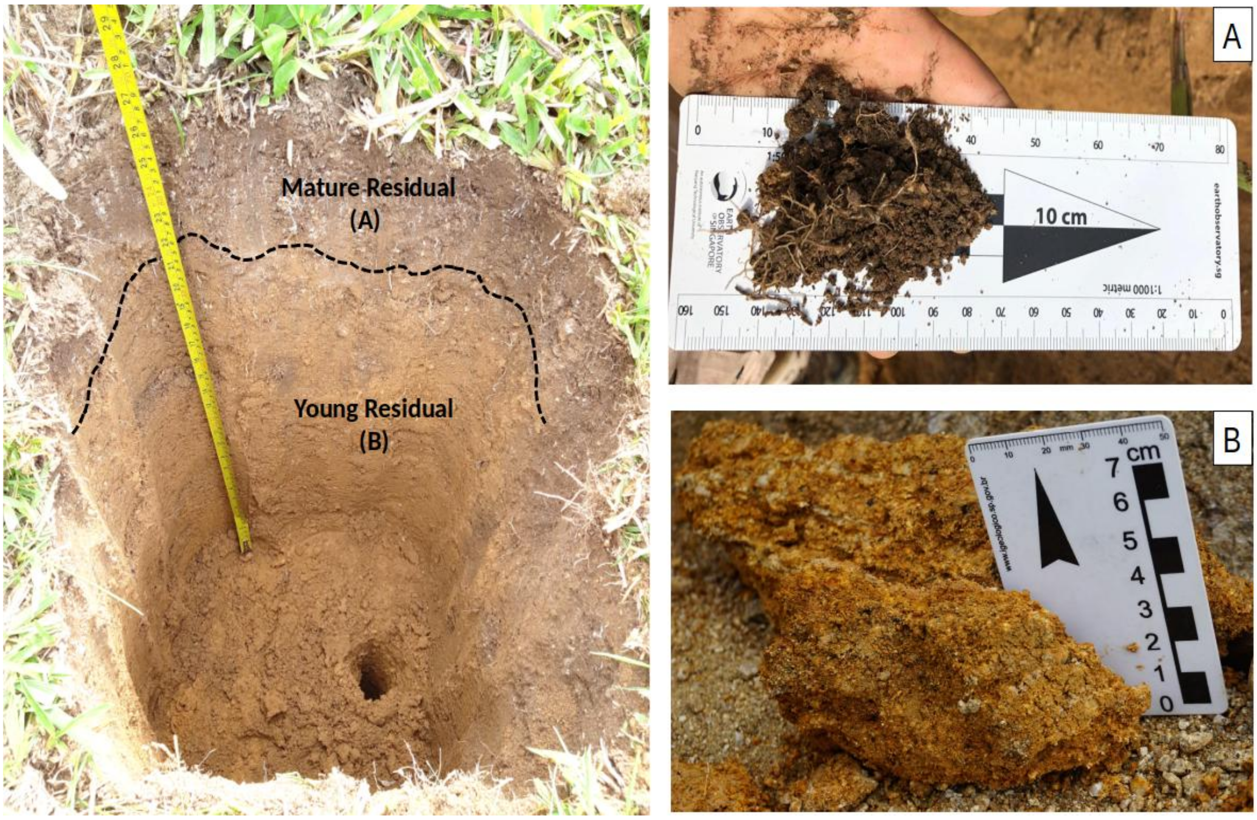

Figure 4: Contact between soil layers with potential rupture zone (black dotted line). Clear differences in soil color and macrostructure (A) Mature residual soil presents a crumb structure and dark color at upper surface and (B) Young residual (Saprolitic soil) presents a massive structure and a light color material.

Mature residual soil contained high concentrations of organic matter and plant roots, in addition to the presence of biological activity, which may have caused the darker color of the material. The dominant hue was 10Y, ranging from dark brown to dark yellowish brown. The crumb structure was concentrated superficially, and the subangular blocky structure predominated in the remaining layer. The soil texture was composed of coarse sand, coarse to very coarse sand, and granules. Primary minerals such as the quartz and K-feldspar were common to the lithology of the study area (MELLO; BETTENCOURT, 1998), and were noticeable to the naked eye.

Young residual (saprolitic soil) has no biological activity, however, it was possible to see capillary roots (rare) that remained only in the upper part, close to the transition zone between the saprolitic and mature residual soils.The dominant vegetation near the cut slope (pasture) may have influenced the limited root depth. The dominant hue was 7.5YR, changing from yellowish brown to reddish yellow (weathered rock limits). The massive characteristics (structureless) predominated, with relict discontinuities and intensely altered corestones in the soil matrix. Soil mottling was observed in saprolitic soil, which also suggested differences in the soil-water regime. The saprolite was composed of intensely altered granite fragments with several alteration grades and primary minerals (increasing in size with depth) involved in the saprolite matrix.

The sharp changes in macromorphology between the mature residual soil and young residual could lead to variations in rainwater flow and retention. Based on the soil structure, water retention occurred in the saprolitic soil, which presented hydromorphism in its matrix. Water percolated vertically through the mature residual soil, which had a block structure, and it was blocked in the young residual, which had a massive clayey matrix.

3.2 Micromorphological and soil physical properties

The weathering profile was texturally sandy (>45%) and showed wide variation in clay with depth. Mature residual soil had an average clay content of 12%, while the young residual had a clay content of 18%, making it the most clayey layer. Saprolite had lower clay contents of approximately 7%. In contrast, the gravel content increased with depth, and the content in the deepest parts of the profile was 31% on average (**Table 1**).

Vieira *et al*. (2015) analyzed landslide scars in Caraguatatuba municipality concluded that superficial soil layers are more clayey than the deepest layer. In addition, the authors pointed out that clay content is directly related to soil microporosity.

Avelar *et al*. (2013) described the granitic materials involved in shallow landslides, where the ruptures were usually within the saprolite (depth of 0.5 m - 2 m). In comparison with the results of Avelar *et al*. (2013), we found that saprolitic soil texture is close to a pink saprolite texture (16% clay, 35% silt, 46% sand, 3% gravel). However, young residual has a higher gravel content and lower silt content, which may be related to differences in lithology (presence of phenocrysts in Itaóca granite) or distinct weathering grades.

Table 1: Grain size analysis in 3 granitic weathering profiles.

	Profile 1				**Profile 2**				**Profile 3**			
Depth (m)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)
0.1	11	15	47	27	13	16	52	19	13	14	52	21
0.2	13	19	52	16	10	11	52	27	8	17	61	14
0.3	16	22	46	16	10	14	54	22	11	16	51	22
0.5	9	14	49	27	17	11	51	21	8	13	57	22
0.7	10	18	47	26	9	9	54	28	11	13	52	25
1.0	7	16	52	26	17	10	49	24	15	11	44	30
1.3	12	22	49	17	18	15	48	19	13	10	48	29
1.5	-	-	-	-	16	14	47	23	-	-	-	-
2.0	18	15	47	20	15	15	42	28	9	6	52	33
2.3	18	15	44	23	23	16	41	212	12	6	50	32
2.6	15	17	44	24	10	12	53	5	9	9	52	30
3.0	2	7	50	41	9	9	48	34	8	8	52	32
4.0	4	6	47	43	5	10	56	29	2	4	58	36
5.0	2	5	45	49	9	7	53	31	8	10	68	14
6.0	-	-	-	-	2	6	54	38	-	-	-	-

Carou (2019) found the following trend in the topmost 1 m-thick layer: the sand content increased (62% to 71%) with increasing depth, and the clay content (12% to 7%) decreased with increasing depth. Furthermore, this trend was observed only in the mature residual soil; in the young residual soil layer, there was an inverse trend with an increase in clay and a decrease in sand. In addition, the author indicated a predominance of subangular blocky soil structures in the superficial horizons, while massive structures predominated at greater depths.

The clay content associated with other physical properties (texture, structure, and porosity) allowed the development of changes in permeability, directly affecting water flow in the horizons. Soil texture and microporosity differences could cause instability during the rainy season and, consequently, landslides (WATAKABE; MATSUSHI, 2019).

In landslide-prone areas in the Serra do Mar, Mendes *et al*. (2015) analyzed soil mantles and highlighted that water retention is not directly linked to mineralogical and textural soil features, but it is linked to aspects such as the distribution of macroporosity and microporosity in the soil matrix.

Pore size typology and distribution can influence in water-dynamics and water retention in soil mantles (SIDLE; BOGAARD, 2016). Soil macropores predominated the mature residual soil (27% to 34%), and micropores were dominant in young residual soil (26% to 32%) (**Figure 5**); this characteristic of saprolitic soils may be linked to the high rates of clay associated with massive structures. Similar studies on landslide scars have identified macropore predominance in the upper zones of the weathering profile and micropore predominance in the lower zones (DE PLOEY; CRUZ, 1979; CERRI *et al*., 2020). Microporosity provides the development of low permeability in the soil matrix, decreasing rainwater infiltration and facilitating landslide triggering.

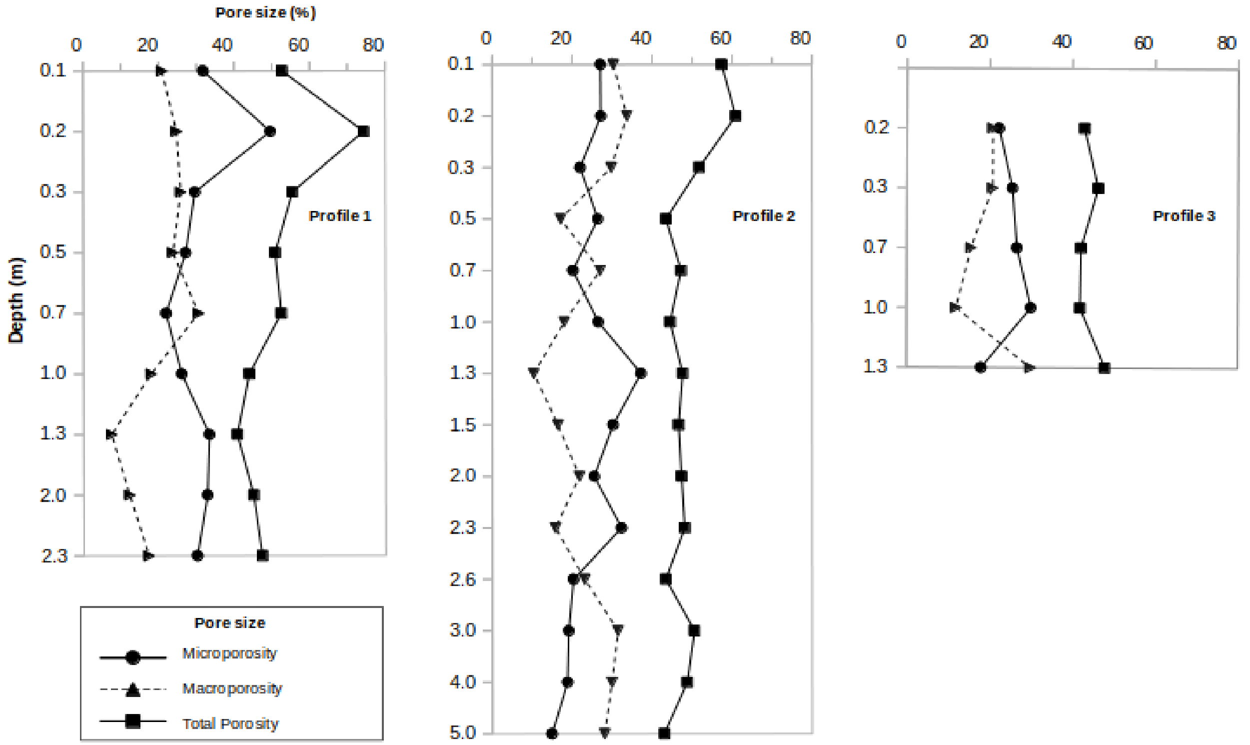

Figure 5: Soil porosity distribution in weathering granitic profiles 1, 2, and 3. Changes in microporosity and macroporosity distribution can be linked to clay content. Total porosity is not affected by clay content.

In this research, saturated hydraulic conductivity (K_{sat}) was lower than 10^{-7} ms^{-1} (0.5 m) and $10^{-6}ms^{-1}$ (1m), which can be linked to high clay content at both measurement points (17 %) in profile 2. Furian *et al*. (1999) pointed out that changes in soil permeability between soil horizons can be related to landslide initiation in the Serra do Mar mountain range. Gomes and Vieira (2016) found significant hydraulic discontinuities between 1 m and 2.5 m depth in landslide scars, demonstrating a direct relationship between porosity and soil texture. In one scar, the increase in K_{sat}, from 10^{-6} ms^{-1} (0.25 m) to 10^{-5} ms^{-1} (2.5 m) was followed by an increase in macroporosity (18% to 29%) and sand content (from 40% to 57%).

In Serra do Mar, slope ruptures occurred mainly because of differences in soil texture, structure, and geomechanical discontinuities in the boundaries between different layers. Based on field observations and laboratory analysis, these differences in soil properties also corresponded with local landslide rupture, where landslide scars were recognized up to 1 m in depth. In addition, studies carried out in the Serra do Mar also identified that the rupture surface was along the contact between the well-developed material (mature residual soil) and the underlying material (young residual soil) (DE PLOEY; CRUZ, 1979; FURIAN *et al*., 2002; LACERDA, 2007).

4. Conclusions

The shallow landslides in Itaóca are dependent on several factors, and soil physical properties are useful for distinguishing between weathering layers and defining the rupture zone. In this study, the weathering profile presents three distinct layers: mature residual soil, young residual soil (saprolitic soil), and saprolite. The different weathering zones may be linked to changes in the physical and morphological soil characteristics.

Young residual soil characteristics (clayey matrix, microporosity, and structureless) contribute to water accumulation in the subsurface, which favors slope rupture resulting from increased pore-water pressure. During intense rainfall, rapid rainwater infiltration into the mature residual soil followed by slow infiltration in the young residual soil can initiate positive pore-water pressure or loss of suction, which may enhance soil slip rupture in hillslopes.

In addition, this study demonstrates the influence of soil texture on pore size distribution. The total porosity is not affected by texture; however, the macropores and micropores are strongly linked to the clay content.

A potential slip surface occurs between the mature residual soil and young (saprolitic soil), mainly due to the textural, macromorphological, and micromorphological features that cause changes in permeability. This work adds to the understanding of granite weathering profiles in landslide-prone areas in tropical environments and can inform future soil studies in the Serra do Mar mountain range.

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