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Relationship between soil physical properties and landslides in Serra do Mar mountain range, Brazil

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Abstract

The Serra do Mar mountain range is a system of escarpments located at the Brazilian coastline. Every year this region is affected by landslides during the rainy season (Dec. to Mar). These processes can be conditioned by several factors such as lithology, geomorphology, and soil physical properties. In general, slope ruptures occur between residual soil and saprolitic soil, where differences of texture and permeability are present. The focus of this research was to characterize some soil physical properties of a weathered granitic profile and understand the relationship with shallow landslides. For this, morphological fieldwork descriptions, grain size analyzes and saturated hydraulic conductivity in situ (K_{sat}) were carried out. Results showed three layers with variation in soil texture and structure: Residual Soil, Saprolite II and Saprolite I. These variations in weathered soil profile can show significant hydraulic discontinuities during an intense rainfall event, which could contribute to the instability of the slope and the triggering of landslides.

1 INTRODUCTION

Serra do Mar mountain range is a system of festooned escarpments located along the Brazilian coastline. It is formed by igneous and metamorphic rocks, with approximately 1,000km of extension (Almeida and Carneiro 1998). Shallow landslides are the most common mass movements in steep and moderate slopes in this region (Cruz 1990).

The physical properties of soils play an important role in slope stability. These properties can influence water movement in the weathered profile (Selby 1993).

In the Serra do Mar, some soil properties were investigated in different sectors of the escarpment (De Ploey and Cruz 1979; Furian et al. 1999; Vieira et al. 2015). These studies highlight the relevance of soil properties to slope instability analyses such as texture, saturated hydraulic conductivity (K_{sat}), structure and porosity.

Every year the region is affected by landslides, causing economic losses, severe damage to infrastructure (urban and rural), and deaths. However, even with the high frequency of these processes, there are a few *in situ* soil investigations available. It's necessary for more detailed investigations of soil physical and hydrological behavior to understand landslides triggering mechanisms in Brazil (De Ploey and Cruz 1979; Wolle and Carvalho 1994). Thus, the main objective of this work was to characterize some physical and hydrological properties of a soil profile and evaluate its relationship with the occurrence of shallow landslides.

2 STUDY AREA

The area is inserted in the south segment of the Serra do Mar in São Paulo state, near to Ribeira de Iguape river valley, southeast Brazil (Figure 1).

Lithologically, the region is on Itaoca granitoid Massif, which has an area greater than 200km² (Mello and Bettencourt 1998). The geomorphological context is characterized by mountainous landforms with tops around 900m and sectors reaching between 1000-1100m (Ross 2002). Rain is frequent during most part of the year, highlighting January as the rainiest month with averages of 200 mm, according to historical precipitation time series from 1962 to 2000 (ANA 2020).

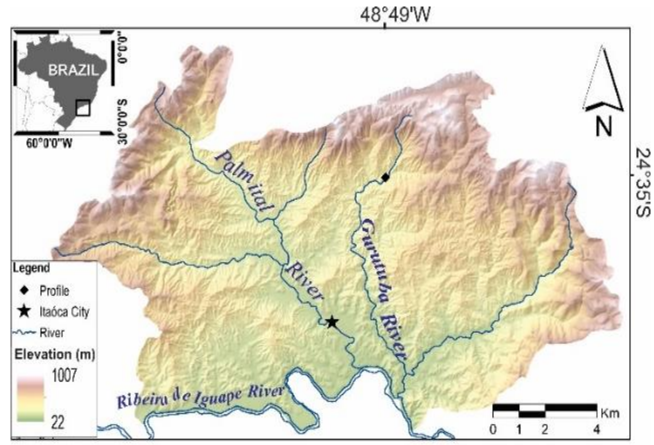

Figure 1. Study area location

In 2014, widespread mass movements were triggered in several watersheds due to intense rainfall. It is estimated that only during this event, the accumulated rainfall was approximately 150 mm in 6.5 hours (Batista and Julien 2019). Shallow landslides occurred mainly at high elevations, in preserved sectors of the slopes (Figure 2A). In one of the watersheds most affected by landslides, 336 scars were mapped (Carou et al. 2017) most of them concentrated between angles 25°-40°(Bonini et al. 2017).

The main drainage was reached by the materials that were mobilized by the landslides, triggering debris flows in some watersheds (Figure 2B). The damage caused includes the destruction of bridges, plantations, houses and roads, mostly due to vegetation mobilization and silting up of many points in the Palmital and Funil rivers (Gramani and Martins 2016).

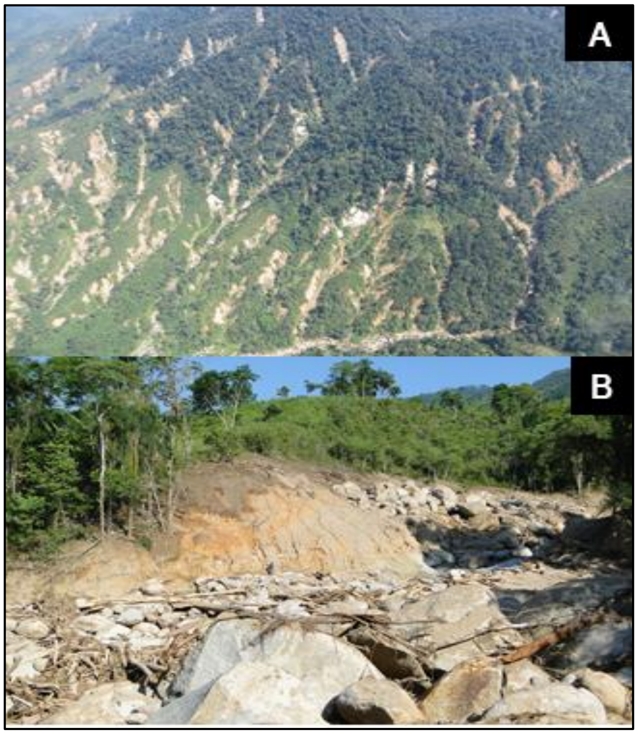

Figure 2. Mass Movements at Itaóca in January of 2014: (A) Shallow Landslides Scar's; (B) Affected area by Debris-Flow. Source: M.F. Gramani

3 METHODOLOGY

A representative profile was chosen in an area affected by landslides in 2014 with approximately 45m long and 12m in high, located over granite lithology (Figure 3). Morphological descriptions were performed (changes in color, texture, and structure) and samples were collected for laboratory analysis. In addition, in situ tests of saturated hydraulic conductivity (K_{sat}) was carried out. The depths of the tests were defined based on the morphological descriptions of the profile, which indicated a change in structure between 0.5m and 1m. In the area, there are significative scars that have rupture surfaces around 1 m depth. This fact also corroborated for the choice of the depths of the permeability tests.

Grain size analyses were made for each layer defined in the fieldwork in the soil profile. Disturbed soil samples were collected according to the visual and textural changes verified in situ. Soil color characteristics were obtained from the Munsell soil chart. For grain size analyzes, the following methods were used: gradation test, to separate the different fractions of sand and gravel; and densimeter, for the separation of fines (silt and clay). Through granulometric analysis, it was possible to quantify and visualize the distribution of soil fractions (sand, silt, and clay) in depth.

The Guelph Permeameter was used to survey the saturated hydraulic conductivity (K_{sat}) in the fieldwork. Measurements were made at the top of the profile (0.5m and 1m).

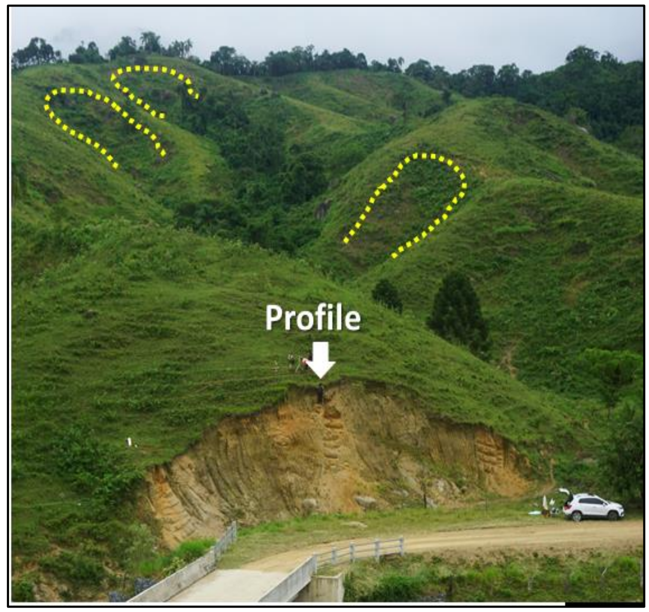

Figure 3: Selected profile near to landslide scars (Yellow dotted line). Source: B. C. Vieira

4 RESULTS AND DISCUSSION

The particle-size analyses, morphological soil descriptions and fieldwork observation allowed the delimitation of 3 main layers: Residual soil (Superficial), Saprolite II (intermediate) and Saprolite I (Deep) (Figure 4).

Residual Soil (0.1m to 0.7m) has an average content of 12% clay and 53% sand (Table 1). Soil structure is crumbs, which can possibly have a relation with biological activity and the presence of roots (fine to very fine roots) (Figure 4A). The surface presented dark colors in comparison to the other layers of the profile, which may be due to the presence of organic matter at this layer. Dominant hue is 10Y (Munsell color chart), ranging from dark Bruno to dark yellowish Bruno. In the transition to Saprolite II, structure varied between sub-angular blocks in shape to the absence of a soil structure (apedic). The K_{sat} in this layer showed values $10^{-7}ms^{-1}$ (0.5m), indicating a very low K_{sat}, which may be associated with the amount of clay at this depth (about 17%) (Table 1).

Saprolite II (1m-2.3m), presented the highest average of the clay content (18%), and the lowest average of the sand (around 45%) (Table 1). The dominant hue is 7.5YR, changing from yellowish brown to reddish yellow (layer boundary). There is no defined structure (massive), a characteristic that is reinforced by high concentrations of clay (Figure 4B). At a depth 1m, the layer is slightly gravelly which can explain the K_{sat} values, $10^{-6}ms^{-1}$, about 10 times greater than the residual soil layer.

Saprolite I (2.6m-6m) is located at the base of the alteration profile. The lowest clay content was found in this layer, (7%), and the highest concentration of sand (53%) and gravel (31.4%) (Table 1). Clear relict features were observed in Saprolite I, varying in color between pink, yellow, orange, white and gray (Figure 4C).

The clay showed wide variability in depth, increasing from Residual Soil (12%) to Saprolite I (18%), and decreasing from Saprolite I (18%) to Saprolito II (7%), with the remaining fractions maintaining a constant percentage (Table 1). The highest average of this fraction is found in the layer Saprolite II, with its peak concentration (23%) at 2.3 m. The occurrence of this high percentage average, in addition to the lack of structure of the soil, can make it difficult to water percolation in the profile. Such characteristics (morphological and textural) could contribute to possible slope instability.

Figure 4: Weathering Profile: (A) Residual Soil; (B) Saprolite II; (C) Saprolite I.

Table 1. Grain size in weathering granite profile

Depth (m)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Layer
0.1	13	16	52	19	Residual Soil
0.2	10	11	52	27	
0.3	10	14	54	22	
0.5	17	11	51	21	
0.7	9	9	54	28	
Averages	11,8	12,2	52,6	23,4	
1.0	17	10	49	24	Saprolite II
1.3	18	15	48	19	
1.5	16	14	47	23	
2.0	15	15	42	28	
2.3	23,2	15,5	40,8	20,5	
Averages	17,8	13,9	45,4	22,9	
2.6	10	12	53	25	Saprolite I
3.0	9	9	48	34	
4.0	5	10	56	29	
5.0	9	7	53	31	
6.0	2	6	54	38	
Averages	7	8,8	52,8	31,4	

In the case of an instability situation, a rupture zone would occur between the Residual Soil (superficial) and Saprolite II (intermediate layer). This rupture would occur mainly due to differences in permeability, which may reflect the different textures and soil structure. Intense rain events can cause the more permeable overlying layer (Residual Soil) to rapid loss of apparent cohesion (suction) and consequently rupture. De Ploey and Cruz (1979) also found some ruptures between the contact of the mature residual soil and the saprolitic material (young residual) in scars from landslides in the Serra do Mar.

The existence of a less permeable layer just below a more permeable one can corroborate the rupture models in the Serra do Mar. According to Wolle & Carvalho (1994), in situ studies at the area, some landslides are associated with the reduction of K_{sat} in depth with the formation of temporary water tables and an increase in the positive pressure load.

5 CONCLUSION

Soil structure played an important contribution to this work. At saprolite II, massive character (apedic) in association with high clay content can generate significant textural and permeability differences between Residual Soil and Saprolite II, allowing slope instabilities.

The physical properties evaluated can't explain K_{sat} variation. However, the low K_{sat} values may be associated with the clay content and soil structure in profile.

In order to complement this research, studies will be carrying out, including porosity (macro and micro), moisture content and bulk density, soil water characteristic curve, aiming to analyze their influence on slope stability.

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