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Mechanisms of the recent catastrophic landslides in the mountainous range of Rio de Janeiro, Brazil

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Abstract Catastrophic mass movements occurred in January 2011 in a mountainous area of Rio de Janeiro leaving more than 1,500 dead people and large destruction. Heavy thunderstorms occurred on January 11th (~100 mm/day) and 12th (~150mm/day) and triggered thousands landslides on steep slopes with trees and block rich debris materials converged into the river channels, hence avalanches down valley. Through fieldwork, mainly translational slides and debris flow types were observed, as well as some rotational slides and rock fall. Initial studies show that translational slides occurred in saprolite soil with 1 to 3 m depth and on more than 30-degree slopes. Debris flows initiated in small catchments with very steep slopes and run out along the valley bottom where colluvial soils are present. This study focuses geological analysis and correlation between soil properties and geotechnical behavior in order to explain this catastrophic slope movement mechanisms and processes.

Keywords shallow landslides, intensive rainfall, direct shear test, Rio de Janeiro

Introduction

On January 11th and 12th, 2011, 3,562 landslides occurred in the mountainous region of Rio de Janeiro State (RJ). These caused more than 1,500 deaths and severe damage to the urban and rural infrastructure of the municipalities of Nova Friburgo, Teresópolis, Petrópolis, Sumidouro and Bom Jardim. These landslides were observed in a regional band of around 20 x 80 km, where intense rainfall reached 325 mm within 48 hours (Fazenda Mendes Station\CPRM). Precipitations over 24 hours at various stations within the area with most destruction showed values of 200mm over 24 hours (more details on this can be found in Coelho Netto et al., 2011).

Although considered the most destructive landslides ever registered in Brazil, similar characteristic events already occurred in RJ in 1966, 1967, 1988, 1996 and 2010 (Meis & Silva, 1968; Barata, 1969; Jones, 1973; Lacerda, 1997, 2007; Coelho Netto et al., 2009). In this 2011 event, the majority of landslides were of shallow translational type with many occurrences of debris flows and few rotational slides or rock falls. The most extensive debris flows moved along the most significant valley bottoms of the region and produced a trail of destruction of houses, farms, factories, roadways, bridges, drinking water networks, electricity and telecommunications. They were formed by the junction of diverse shallow translational slides occurring on slopes adjacent to rivers and originating from hollows in mountainous zones.

The geology of the State of Rio de Janeiro is associated with an ample fold belt from the Proterozoic Era, mainly composed of rocks with high metamorphic grades (gneisses) with well defined foliation in the SW-NE direction and fractures in diverse directions. Sin-tectonic igneous (granitoid) rocks, generated by anatexis also occur and are oriented in the same way as metamorphic rocks. The geomorphology of the State presents a predominance of hills and coastal plains with isolated rocky massifs, however the mountainous region of Rio de Janeiro contrasts sharply with this group.

Figure 1 Aerial view of some landslides which occurred on January 12th, 2011 in the mountainous region of Rio de Janeiro State where shallow translational landslides were dominant.

In the mountainous region, granites (post and tardi-tectonic), migmatites and gneisses with little foliation compose a province of highly weathering-resistant rocks which regionally produce a mountainous geomorphology called the Serra dos Orgãos. In this mountainous region of Rio de Janeiro, the valley bottoms are narrow and develop along persistent tectonic fractures in which only the larger-sized rivers are able to generate even fluvial deposits where the majority of the population is located. Adjacent to these valleys, escarpments with rocky outcroppings and steep slopes (more than 35 degrees) are common; these can present deposits of talus or colluvium rich in rock blocks at the base. On the other hand, in the Serra dos Orgãos landscape, there are also many areas where intramontane hills grade to slopes of slighter declivity (between 15 and 35 degrees). In these areas the regolith are composed by thick saprolitic and colluvial deposits that together can reach until 10 meters in depth. Oly in few areas at Serra dos Orgãos range occur deep weathering profiles (saprolites) up to 50 m in thickness.

Colluvial soils in southeast Brazil have characteristic geotechnical features with high void ratio between 1.2 and 2.2, and frequently show a friction angle between 28 and 32 degrees with a cohesion intercept of 2 to 10 kPa (Silveira, 1993; Avelar, 1996; Lacerda, 2004). Saprolitic soils have variable geotechnical parameters according to the parent rock and the degree of weathering; however ,for saprolites originating from Rio de Janeiro granites described in the literature, a void ratio varying from 0.6 to 1.1, with a friction angle between 30 and 37 degrees and cohesion intercept between 6 and 30 kPa are mentioned (Fonseca et al., 2004; Lacerda, 2004). These soils also generally show highly saturated hydraulic conductivity with values between 10^{-2} to 10^{-4} $cm.s^{-1}$ (Avelar & Coelho Netto, 1992).

The region was originally covered continuously by the Atlantic rainforest, which was significantly removed and resulted in the vegetable plantings, grasses (pastures) and urban centers due to human occupation. Some parts with the original forest remain and, in various locations re-colonization by secondary forests occurred due to the impracticability of agricultural activity. These regenerated forests permit the entry of water into the soil, however they do not present deep root anchoring to increase soil resistance on the slopes. During the enlargement of urban and rural activity, cuts into the slopes were made to implant roadways and residences. Such factors increased vulnerability to landslides, as observed in various situations of this type.

The goal of the present work is to understand the geological, geomorphological and geotechnical mechanisms and processes related to the landslides located in the municipality of Nova Friburgo. In Teresópolis and Sumidouro the study focused the images interpretation.

Methods

Mapping the landslides in large portions of Nova Friburgo, Teresópolis and Sumidouro was undertaken by interpreting colored satellite images with a spatial resolution of 0.5 m, in a rectangle of 27.0 x 15.5 km (421 km^2). The landslide contours extracted from these images were entered into a topographic base of 1:50,000-scale over which a DEM was elaborated with a 20 x 20 m grid for later morphometric analyses using GIS. Using this map, fieldwork was undertaken to register the types of landslides which occurred according to the Varnes (1978) classification, and the characteristics of forms, especially length, width and depth of ruptured surfaces. Also the materials involved were observed.

After noting that there were materials which predominated in the landslides, 04 types of soil were selected for geotechnical characterization and realization of direct shear tests: grey saprolite, pink saprolite, slope colluvium and valley bottom colluvium.

The direct shear tests were performed on circular samples of 63.5 mm in diameter and 25.8 mm in height, submerged in water for around 20 hours and placed in a ShearTracII Geocomp apparatus with a horizontal displacement rate of 0.05 $mm.min^{-1}$. Since the rupture surfaces of the majority of the landslides observed reached up to 2m in depth, the values adopted for the initial normal vertical stress in the tests were 25, 50 and 100 kPa. At the end of the tests, the samples reached 12 mm of horizontal displacement representing an almost 18% deformation. This deformation is enough to cause a rupture in the samples since the slope soils in southeast Brazil tend to reach failure near to 3% deformation (Silveira, 1993; Avelar, 1996; Fonseca et al., 2004). In diagram σ (kPa) *versus* τ (kPa), the linear interpolation defined the equation of the failure envelope for each studied soil.

Results

The interpretation of the satellite images permitted observing the 3,562 landslides, in the rectangular area of 421 km^2, yielding an average density of 8.46/km^2. The GIS analyses enabled establishing landslide size classes (Tab. 1) grouped into large (from 20,000 to 100,000 m^2); medium (from 5,000 to 20,000 m^2) and small (from 32 to 5,000 m^2), for respective frequences of 3.9, 17.0 and 79.1 %.

Slopes and landslides morphology

Analyzing the DEM with GIS, it was also possible to extract the slope declivities both in the landscape and where landslides occurred (more details are in Coelho Netto et al., 2011). In the landscape, it was noted that there is a normal distribution of slope declivity classes with an average of 17.2 degrees and a standard deviation of 9.8 (Tab. 1). In the same way, for the slopes with landslides an average declivity of 18.9 degrees and a standard deviation of 10.9 were observed.

Moreover, the mode of slope declivities in the landscape was verified to be 17.3 degrees (Tab. 1) with a relatively narrow declivity range as indicated by the second quartile (Q2) and third quartile (Q3) with angles between 9.6 and 24.5 degrees. In the same way, the values for slopes with landslides were seen to be close, with a mode of 19.8 degrees and an interval of Q2 and Q3 between 11.7 and 29.7 degrees. This analysis treats landslides in general; however three size classes were considered and it was noted that large landslides show a mode (21.0 degrees) slightly larger than medium (19.8) and small (17.6). This indicates that for a landslide to produce a larger area (or volume), it needs to be on a steeper declivity on the slope. However, in addition to the declivity, its association with slope materials is important.

Table 1 Statistical distribution of the slopes angles (degrees) obtained from DEM associated with landscape and landslides.

Spatial element	total	Q1 0-25%	Q2 25-50%	Q3 50-75%	Q4 75-100%	mean	st. dv.
Slopes on the landscape		0 - 9.5	9.6 - 17.3	17.4 – 24.5	24.5-71.1	17.2	9.8
Slopes with Landslides	3,562	0-11.6	11.7-19.8	19.9-29.7	29.8-65.5	18.9	10.9
Landslides 20,000 to 100,000 m^2	140 (3,9%)	0-12.9	13.0-21.0	21.1-27.7	27.8-58.4	20.0	11.1
Landslides 5000 to 20.000 m^2	606 (17,0%)	0-12.1	12.2-19.8	19.9-26.7	26.8-65.5	19.2	10.8
Landslides 32 to 5,000 m^2	2,816 (79,1%)	0-9.5	9.6-17.6	17.7-24.8	24.9-54.9	17.1	10.6

Geology and landslides types

The survey of types of slope movements show that for the majority of shallow translational slides, debris flows also occur (mainly at the bottoms of large valleys) with few rotational slides and rock falls. In this way, it was possible to trace a typical geological profile for the predominant type (Fig. 2). The fieldwork indicated that the predominant rock in the region is an equigranular granite with grain between 3 and 5 mm, basically composed with quartz, k-feldspar and biotite. This rock is of Proterozoic Age and it is inserted in the regional geological maps as the Serra dos Orgãos Batolite and Nova Friburgo Granite units (DRM-RJ, 1982).

Observations on the materials involved in the shallow translational slides showed 04 types of different soils: (1) saprolites with grey coloring, representing the initial stage of granite weathering; (2) saprolites with pink coloring, which are in the most advanced stage of weathering; (3) colluvium of red coloring and intense laterization which cover the slope and (4) chestnut-colored colluvium with blocks of rounded rock filling the valley bottoms, generally in the hollows.

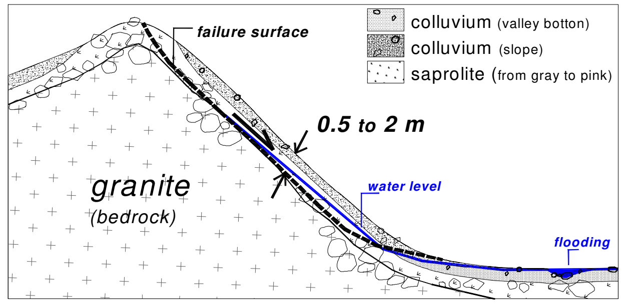

Figure 2 Typical geological profile associated to the shallow translational slides.

These predominant landslides present a rupture surface with a depth between 0.5 and 2.0 m, generally located within the saprolites (Fig. 3). In other cases, rupture surfaces were observed within the slope colluvium, with a depth of up to 1.0 m (Fig. 4). Also, they were observed ruptures along the soil-rock contact (Fig. 4b), with a small quantity mass of soil mobilized due to the thinness of this layer.

Figure 3 Shallow translational slide with failure surface on saprolite derived from granite.

(a) (b)

Figure 4 Landslides with failure surface in colluvium (a) and along soil-rock boundary (b).

Geotechnical behavior of materials

The four soil types found in the landslides represent differentiated geotechnical characteristics and behaviors (Tab. 2 and Fig. 5), there are only similarities in the specific gravity of the grains. The void ratios clearly differentiates the saprolites from the colluvial. The saprolites present similar void indexes, varying between 0.77 and 1.03, which contrast significantly with the colluvium where the variation ranges from 0.97 to 1.61.

The grey-colored saprolite has elevated presence of biotite which indicates that is a slightly weathered soil and, hence, close to the unweathered rock limit (granite). Among the soils studied, it compared as being very sandy

(69%) and more resistant to shear stress, behaving as a granular material with a friction angle of 36.7 degrees and a cohesion of 25 kPa. The pink-colored saprolite was similar to grey saprolite, especially in so far as the friction angle of 38.6 degrees. This behavior pointed that pink saprolite is a material which suffered more chemical weathering, denoted by the transformation of biotites for the generation of clay minerals and iron oxides/hydroxides which influence its coloration and also reduce the sand content to 46% and increase the clay fraction by 16%. This chemical weathering action also reduces the cohesion intercept to 25 kPa.

The red colored colluvium presents less sand percentage than the other soils, with only 25%, moreover, it does not present an increase in the clay content, which only reaches 17%. These characteristics significantly affect the shear strength behavior of this soil which, despite presenting a friction angle of 38.3 degrees, near to the saprolite values, shows zero cohesion intercept.

Table 2 Soil types and properties.

soil type	gravel (%)	sand (%)	silt (%)	clay (%)	specific gravity	void ratio
valley botton colluvium	2	52	19	27	2.693	0.97 - 1.21
slope colluvium	0	25	58	17	2.664	1.16 - 1.61
pink saprolite	3	46	35	16	2.858	0.77 - 0.80
gray saprolite	2	69	25	4	2.650	0.95 - 1.03

The valley bottom colluvium shows a clear difference in relation to the previous soils, especially due to its grain size characteristics and resistance to shearing. It is a soil with high content of sand (52%) and clay (27%) which give it a larger friction angle than the others, with 42.0 degrees and a small value for the cohesion intercept with only 6 kPa.

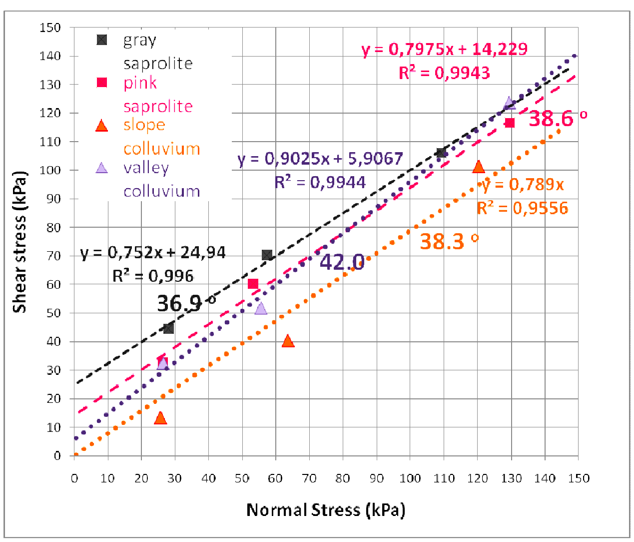

Figure 5 Shear strength envelope for the 04 soils studied.

Conclusions

The occurrence of granite in the mountainous region of Rio de Janeiro makes the action of weathering processes difficult and permits the stability of steep slopes, which oftentimes present outcroppings of large-sized rocks. This situation was revealed in the statistical data on slope declivity with an average value of 18.9 degrees and standard deviation of 10.9. On the other hand, with the geological time action and progressive increase of chemical weathering, in general more accentuated with granite fractures, the parent rock mass gives way to saprolitic soils with a gradation of weathering effect which will reduce the real cohesion (cementation) and generate rupture during prolonged rainfall events or during intense rainfall. In all, rock is not always completely weathered, as the occurrence of 'in situ' rounded rock blocks produced by spheroid exfoliation is common in the region.

In the recent landslides, as the saprolite soils present higher actual cohesion, in order for them to rupture in these soils it is probable that an initial saturated zone was formed during the rainy season after December, 2010. The infiltration gradually promoted expansion in the saturation zones into these soils with slowly increase of pore-pressure on the regolith-rock boundary. At the same time there was a moisture increase in the upper part of these soils (unsatured zones) and the suction was gently reduced. On January 11th and 12th, with the advent of intense rainfall, a sudden elevation of the phreatic level should have occurred and there was an rapid increase of pore-pressure with consequent significant reduction in effective stresses. This produced the failure conditions in the saprolites. Fig. 2 represents a synthesis of this dominant slope failure mechanism.

The shallowest ruptures occurring in the colluvial soils could have been different. Due to the lack of true cohesion in the colluvium located on the region's slopes, it is probable that during the intense rainfall of January 11th and 12th 2011, there was sufficient infiltration to increase soil moisture, hence without creating a saturated zone. This increase in soil moisture could have caused significant reduction in suction and consequent soil rupture process.

Once the valley bottom colluvium was shown to be more resistant to shear stress than that located on the slopes, the conditions for its rupture also should have been different. The destruction at the valley bottoms in the area analyzed appears very similar to debris flows, however, due to the mechanical shear strength behavior of this soil, it seems that the destruction of these valley bottom soils relate to erosive effects produced by the passage of flows with high concentration of suspended solids. These concentrated flows would come from the superficial outflow generated by intense rainfall, added to the sediment available by shallow translational landslides, originating from the slopes of hollows and steep slopes adjacent to the channels. Few cases in the studied region are debris flows originating in the slope areas or in the bottoms of steep valleys, that is, in these soils phenomena related to the sudden pore-pressure increase induced by sub-surface water flows were not common. It is possible that this erosive effect with debris flow appearance is more connected to phenomena of flood waves in the valley bottoms, due to outflow produced from rocky slopes located in the hollows.

Acknowledgments

We would like to thank the Brazilian Research Council (CNPq), Rio de Janeiro Research Foundation (FAPERJ), Posgradute Program Foundation (COPPETEC), Hydrological Fund (CT-Hidro), Agriculture Fund (CT-Agro), and Brazilliam Science and Technology Institute for Geo-Rehabilitation (INCT-Reageo CNPq-FAPERJ) for their financial support and study grants. The authors would like to thank the students who participated in the different stages in the field and in the laboratory: Anderson Sato, Gabriela Vianna, Ingrid Araujo, Vitor Costa, Natália Lacerda, Ana Carolina, Pedro Lima, David LaCroix, George Teles, André Bastos and Matheus Leal. We would also like to than engineer Sérgio Iorio and technician Luis Carlos Oliveira.

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