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Article

Saturated hydraulic conductivity of soils in a shallow landslide area in the Serra do Mar, São Paulo, Brazil

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With 9 figures and 1 table

Abstract: The Serra do Mar escarpment, which is located on the southern and southeastern coast of Brazil, is regularly hit by heavy rainfall that triggers numerous mass movements, particularly shallow landslides. Although several studies have investigated the relationship between these processes and the topographic, structural, lithological, and climatic constraints, there are few tests on the hydrological properties that directly influence the stability of slopes. Thus, the main objective of this study is to characterize the spatial distribution of saturated hydraulic conductivity (K_{sat}) and evaluate its influence on the initiation of shallow landslides in the Serra do Mar in São Paulo State (SP). Tests for K_{sat} were performed using the Guelph Permeameter in three scars in an experimental basin in the city of Caraguatatuba-SP, which was strongly affected by landslides in 1967. In each scar, two profiles were excavated (top and center) with tests at six depths up to 2.50 m. To better evaluate the variation in K_{sat}, the particle size and porosity values were used at the same depths. Forty-one K_{sat} values were obtained, and the values varied between three orders of magnitude (10^{-6} to 10^{-4} m s^{-1}), with 80% concentrated between 10^{-6} and 10^{-5} m s^{-1}. In general, the profiles had lower K_{sat} values near the surface with a tendency to increase up to 5 m and significant hydraulic discontinuities between 1 and 2.5 m. It is believed, therefore, that a study of K_{sat} variation can provide important information on the rupture mechanisms within the Serra do Mar and define areas for real-time hydrological monitoring.

Keywords: Hydraulic Conductivity, Shallow Landslides, Serra do Mar, Guelph Permeameter, Hydraulic Discontinuities

1. Introduction

The Serra do Mar escarpment (SM), a geological-geomorphological compartment located along the coast (1,500 km) of the southern and southeastern regions of Brazil, are regularly hit by heavy rainfall, which can reduce the stability of its steep slopes and generate widespread mass movements. Several of these events have caused large numbers of casualties and significant economic losses, including the incidents in Caraguatatuba in 1967 (Fig. 1), Cubatão in 1985, and the Serra do Mar in the states of Rio de Janeiro and Paraná in 2011, which amounted to more than 1,000 fatalities. The victims of all these events, particularly for the states of Rio de Janeiro and São Paulo, have totaled more than 3,200 since 1928. Despite being considered a high susceptibility area, the Serra do Mar has different types of occupation throughout most of its extension, especially urban centers, generating a significant increase in risk areas. Faced with this scenario, since the 1960s, geological-geotechnical and geomorphological studies have been conducted in a more systematic manner (e.g., Meis & Silva 1968, Barata 1969, Costa Nunes 1969, Jones 1973, De Ploey & Cruz 1979, Ipt 1986, Vargas Jr. et al. 1986, Wolle & Hachich 1989, Lacerda et al. 1997, Gabbard et al. 1998, Fernandes et al. 2004 and Kanji et al. 2008). However, despite the fact that there are now more studies available, due to the great variability of soils, rocks, vegetation, and rainfall distribution, there is still a lack of research on the hydrological behavior during intense rainy periods, especially field surveys and long-time monitoring.

Among the properties, soil hydraulic conductivity plays an important role in water movement and may reduce the stability of slopes caused by variation in the soil

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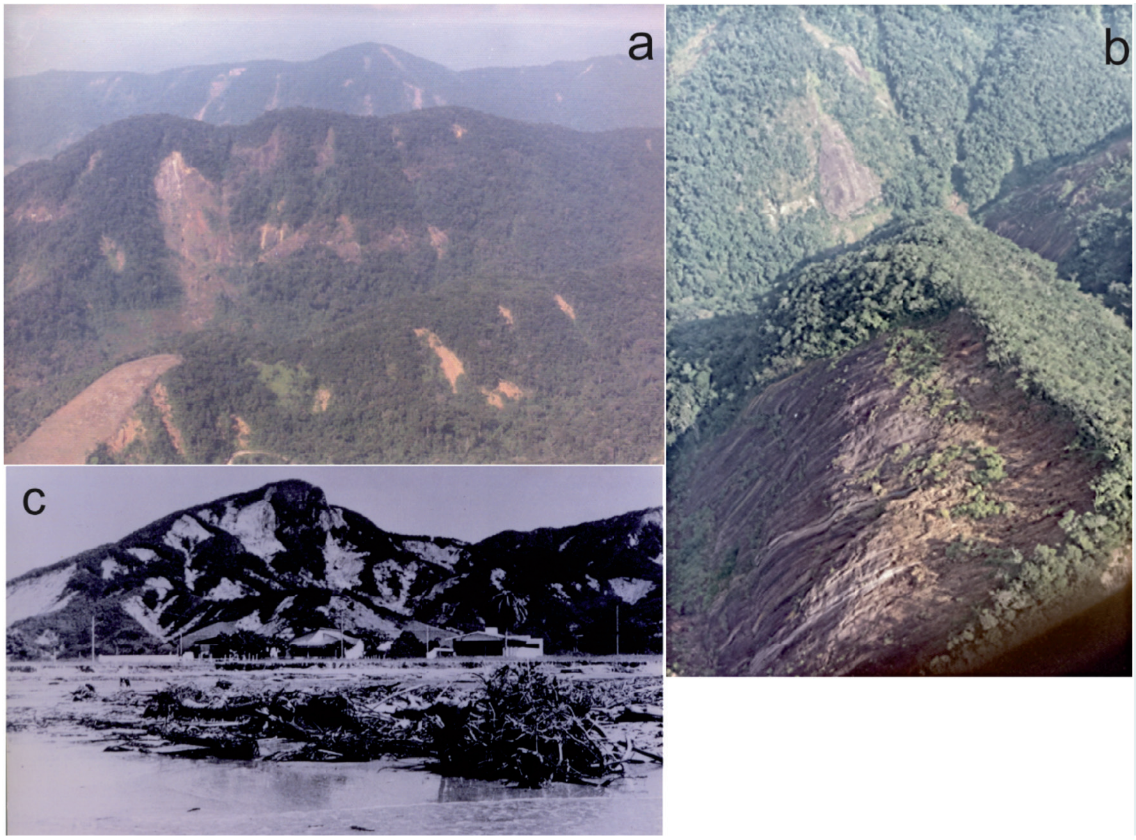

Fig. 1. Landslides triggered in the summer of 1967 in Caraguatatuba City (SP). Figures A and B display scars of shallow landslides that exposed rock surface and mobilized thousands of tons of debris to the valleys; in C, it is possible to observe debris and trees transported by debris flows that reached the adjacent coastal plain. Photograph A and B by Marcelo F. Gramani; Photograph C by the Municipal Archive Caraguatatuba.

profile and/or weathering mantle. Considering the anisotropic and heterogeneous nature of soils, the existence of hydraulic discontinuities significantly influences the failure mechanisms because variations along the pedological profile can generate the rapid increase in positive pore pressure or the decrease in apparent cohesion due to the loss of suction (Anderson & Burt 1978, Dietrich & Dunne 1978, Harp et al. 1990, Campos et al. 1992, Brugger et al. 1997, Terlien 1997, Gerscovich et al. 2006).

The main contributions of this study are as follows: (*i*) Identification of variations in hydraulic conductivity in soil profiles and sudden changes that may lead to failure during intense rainfall events. (*ii*) Assistance for future real-time water monitoring projects based on the prior identification of these variations along the soil profiles and at different locations of the hillslopes. (*iii*) The use of these K_{sat} values in physically based mathematical models (such as SHALSTAB and TRIGRS) to generate more accurate maps of shallow landslide susceptibility (Gomes et al. 2008, Lopes et al. 2007, Vieira et al. 2010, Silveira et al. 2013, Michel et al. 2014, Nery & Vieira 2014). Thus, *the main goal of this study is to characterize the spatial distribution of the saturated hydraulic conductivity (K_{sat}) and assess its influence in the triggering of shallow landslides at the Serra do Mar (SP)*.

2. Area of study – Guaxinduba Basin, Caraguatatuba (SP)

The rainfall event that hit the slopes in the town of Caraguatatuba during the summer of 1967 displaced approximately two million tons of material (Petri & Suguio 1971). The shallow landslides and debris flows occurred upstream of the urban area, intensely affecting an area of 180 km², mostly on slopes greater than 22°. The disaster prompted research on shallow landslides and their topographical, structural, lithological, climatological, and geotechnical (De Ploey & Cruz 1979) constraints.

This research was conducted in the experimental basin of the Guaxinduba River (24 km²), which is

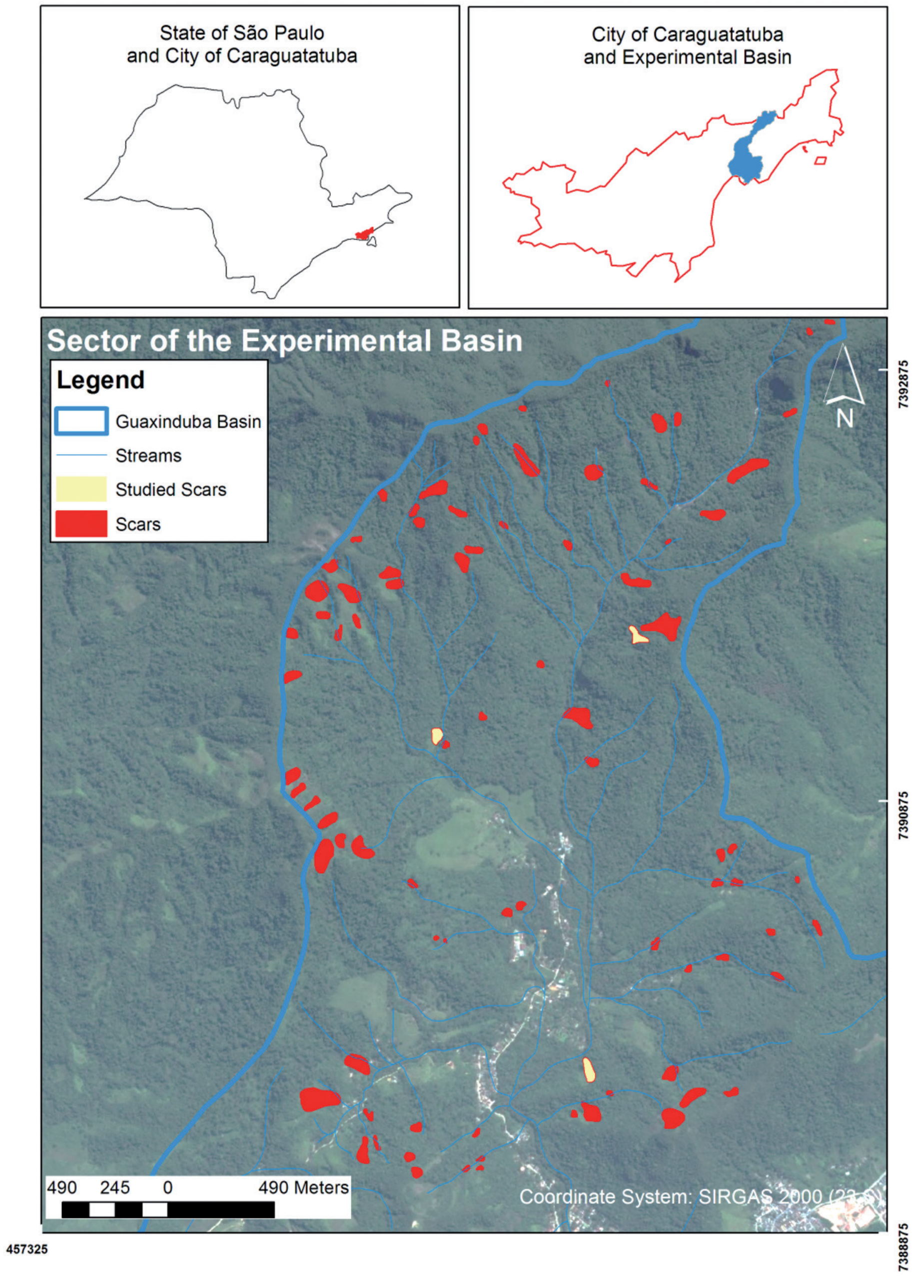

Fig. 2. Location map of the study area.

located in the Serra do Mar in the town of Caraguatatuba (Fig. 2). Several other studies have been conducted in this basin with the goal of understanding the dynamics of mass movements in the Serra do Mar. The basin was selected because of its representation of the geological and geomorphological conditions of the Serra do Mar in São Paulo and especially because of the concentration of scars from shallow landslides triggered in the 1960s. Such scars are currently identified according to their colonization by a pioneer species belonging to the family of *Gleichenias* (Fig. 3). These species have only developed in the scars, which most likely resulted from the presence of extremely sandy saprolite materials and absence of more developed pedological material, inhibiting the restoration of more complex vegetation. In other areas, rain forest covers almost the entire basin, which is primarily a result of the protection provided by Serra do Mar State Park. Areas that had been deforested are currently residential areas in the river terraces and on the gentler slopes of the basin.

Fig. 3. In the upper portion of the figure, it is possible to observe landslide scars from 1967, immediately after the event, whereas at the bottom, the same scars are easily identified due to the difference in vegetation cover (Photo A by Marcelo Gramani and B Tiago D. Martins).

In Caraguatatuba, the landslides were triggered by intense rainfall events during the summer of 1966/1967; rain occurred almost every day that summer and reached 945.6 mm by March 1967 (Fig. 4). The 535-mm rainfall recorded on the 17th and 18th of that month were responsible for the occurrence of hundreds of shallow landslides and debris flows; these events left their mark on the landscape and can still be seen today in the extensive deep scars on the slopes and large deposits of blocks in the slope ruptures (De Ploey & Cruz 1979).

The predominant rock types are leptite and augen gneisses; when subjected to intense biochemical weathering, these rocks produce residual soils that have a silty-sandy matrix and are usually not thick (0.5 to 2.0 m) (De Ploey & Cruz 1979).

The saprolite is thick (up to 50 m), consisting of somewhat inconsistent material that preserves the structure of the parent material and facilitates water infiltration within the massif. According to Wolle & Hachich (1989), such pedological and lithological and structural are crucial for water movement within hillslopes in the Serra do Mar, since the densely fractured saprolite promotes the drainage of the saturation front. This fact shows the predominance of vertical flows over subsurface lateral flows, which is primordial to the stability of such hillslopes.

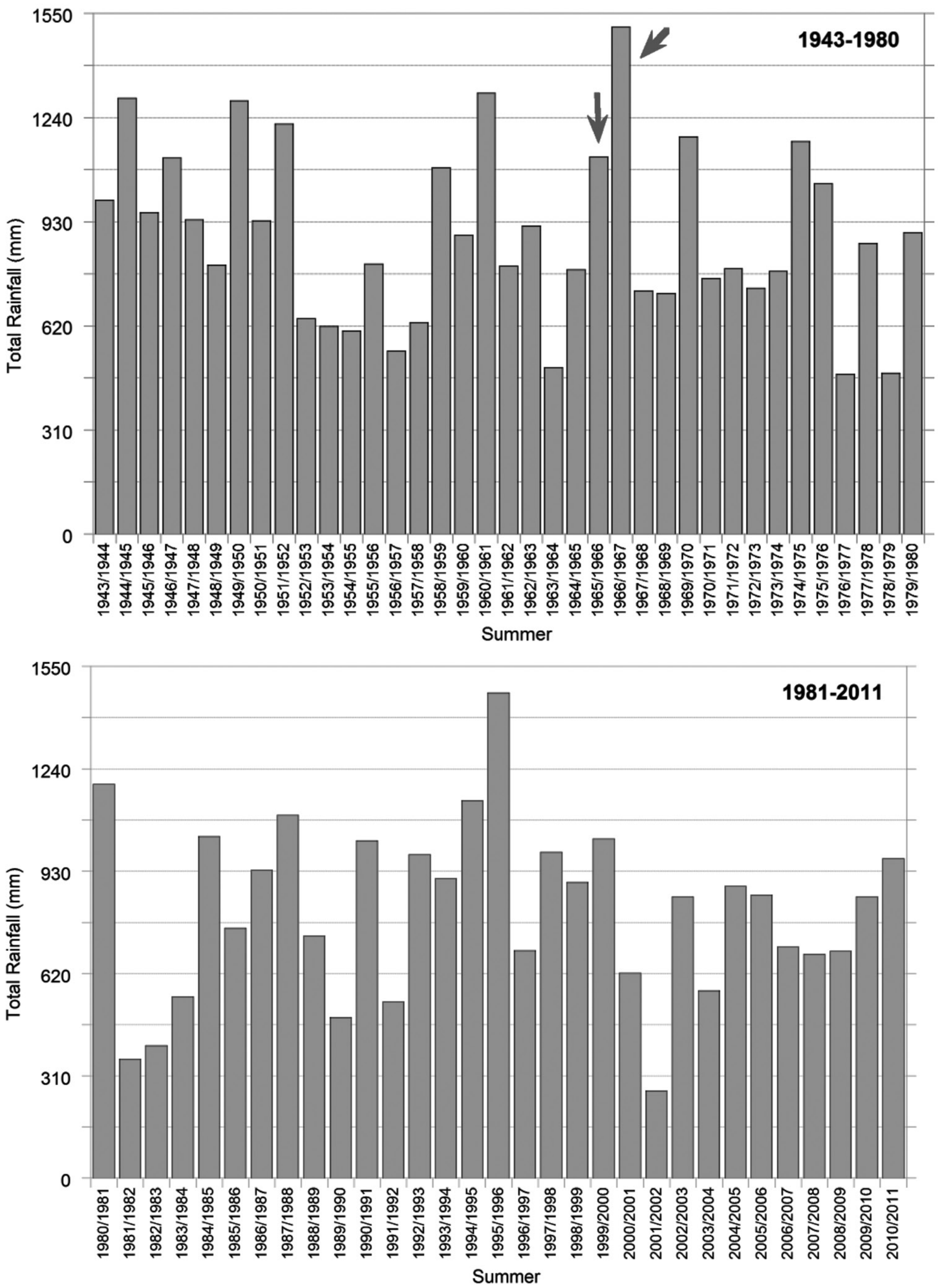

Fig. 4. Rainfall in the summer months (December to March) of 1943 to 2011. Source: Data from Water and Electric Energy Department of São Paulo State.

3. Materials and methods

Three scars from shallow landslides (S1, S2, and S3) were selected based on their well-preserved borders (Fig. 5). To investigate the variation in hydraulic conductivity in the weathering mantles, soil profiles were obtained around (P1) and at the center (P2) of the scar. In each profile, tests were conducted at six depths (0.25, 0.50, 1.00, 1.50, 2.00, and 2.50 m), defined from a morphological characterization of the soils that was conducted in the field based on the changes in texture and structure. The use of two combined profiles (P1 and P2)

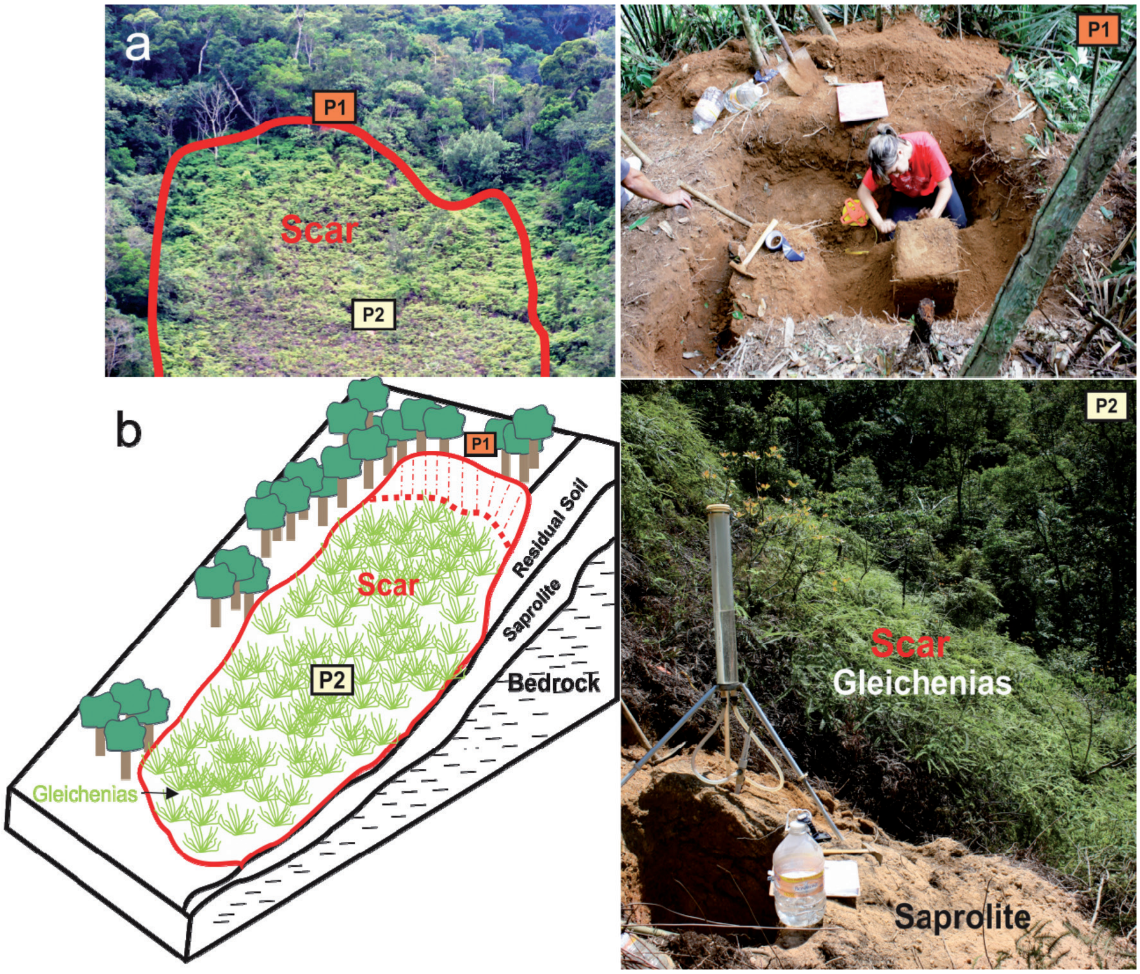

Fig. 5. One of the scars and the location of the pits around and in its center (a). In b is showed the pit that was digged within the residual soil (top profile), in detail in P1, and the other, done in the saprolite (center profile), in detail in P2. The graph shows the profiles' location within the scar, explaining the formation of the complete profile.

allowed obtaining K_{sat} profiles encompassing much more significant depths, in some cases reaching approximately 5 m (e.g., S3).

Particle size and porosity were also studied in the same basin, scars and depths studied herein. Similar particle size distribution patterns were found, with an increased percentage of silt and clay until ~1 m, and a subsequent decrease (Fig. 5). However, the clay fraction exhibited low activity or inactivity. The soils of profiles S1 and S2 are predominantly sandy (with up to 80% sand). S3 shows a particle size distribution that differs from the previous distributions, with high clay content (up to 45%). Colluvial and residual soils yielded high microporosity and total porosity values, with the latter ranging between 50% and 80% in S1 and between 60% and 70% in S2 and S3 (Fig. 6). The micropore distribution followed the total porosity trend, with an increase in S1 and S3, and was more homogeneous in S2 (Ferreira 2013).

The Guelph Permeameter was used to measure K_{sat}, as it has already been used with highly satisfactory results by other authors, such as Campos et al. (1992), Ekanayake & Phillips (1999), Crosta et al. (2003), Ahrendt & Zuquette (2003), Coe et al. (2008), Berti & Simoni (2012), and Kassim et al. (2012). The Guelph Permeameter's structure is mainly responsible for its advantages compared with other instruments: it is light and easily operated by one person, causes minimal disturbances in the soil, uses little water, requires little time, and adapts to steep slopes. However, the main advantage of this device, especially for studies of landslides, is its

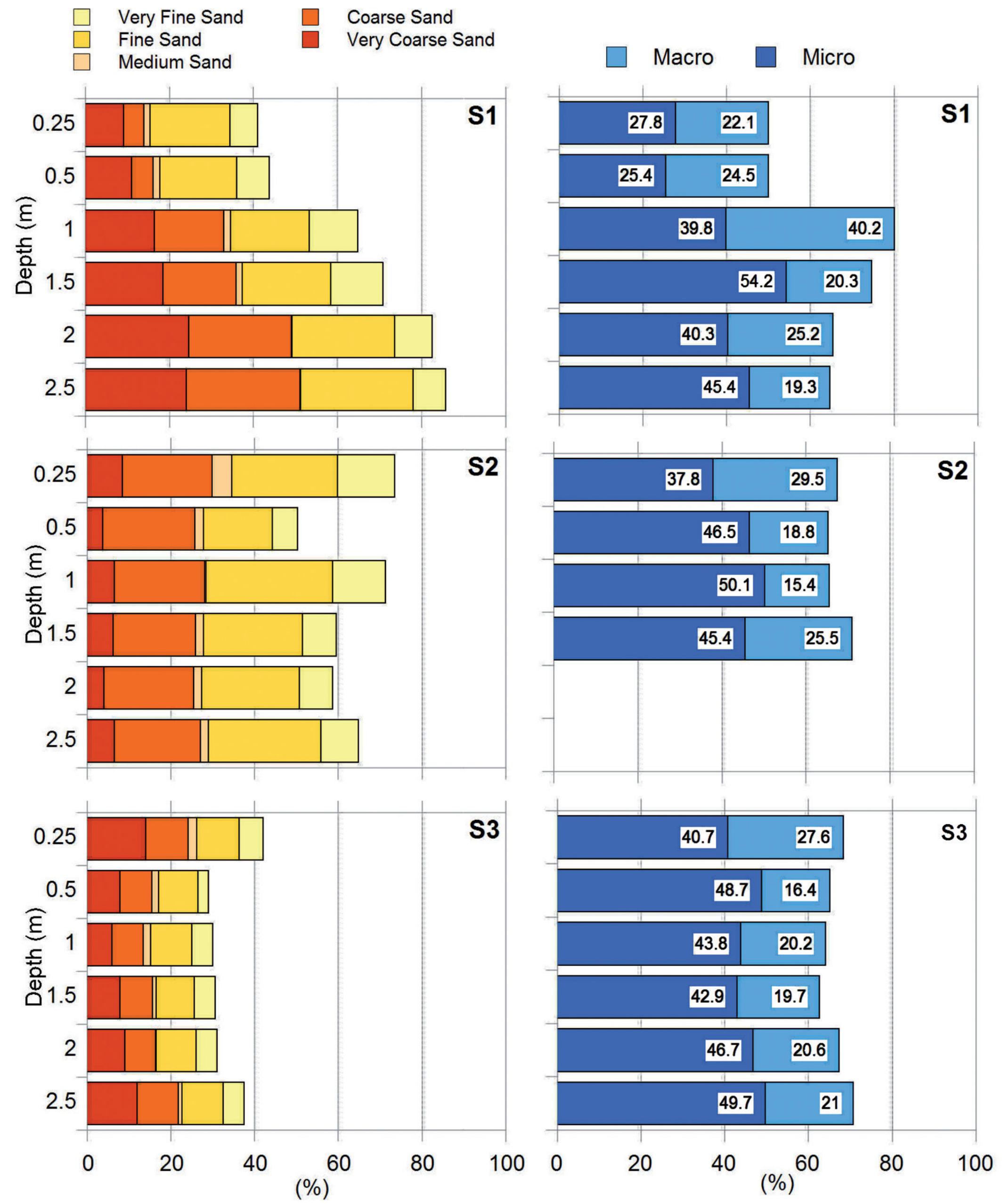

Fig. 6. Depth variation of the sand grain-size and silt + clay percentages in scars S1, S2, and S3 (left) and of macroporosity and microporosity (right). Data from Ferreira (2013).

in situ measuring of thick soil layers, including features such as macropores, which can directly influence the formation of preferential flow within the weathering mantle.

The device consists of a Mariotte bottle installed after the excavation of a soil boring of known diameter. A hydraulic head H is applied until the stability of flow Q [L^3T^{-1}] is achieved. Subsequently, to obtain the K_{sat} value, equations are used, as described by Reynolds & Elrick (1985), Elrick et al. (1989), among others. Due to the most satisfactory results found by these authors, Equation 1 was used in the present study; this equation, proposed by Elrick et al. (1989), incorporates a parameter α [L^{-1}], representing the texture and structure characteristics of the soil:

$$K_{sat} = \frac{CQ}{\left[2\pi H^2 + C\pi a^2 + \left(\frac{2\pi}{\alpha}\right)\right]} \quad \textbf{(1)}$$

where C is a parameter associated with the H/a ratio (hydraulic head/borehole radius) and a secondary dependence on the soil characteristics, Q [L^3T^{-1}] is the constant flow obtained in the field, H [L] is the water level in the borehole (hydraulic head), and α [L^{-1}] is the parameter that represents the texture and structural characteristics of the soil.

4. Results and discussion

Forty-one K_{sat} values were obtained, ranging between three orders of magnitude (10^{-6} to 10^{-4} m s^{-1}), with 80% concentrated between 10^{-6} and 10^{-5} m s^{-1} (Fig. 7), thereby corroborating other studies that have attempted to explain the hydrologic control of shallow landslides (De Ploey & Cruz 1979, Avelar & Coelho Netto 1992, Campos et al. 1992, Boogard & Van Asch 2002, Vieira & Fernandes 2004).

This small variation in K_{sat} can be associated with (i) errors in the measurement execution, such as the sealing of the borehole wall during its excavation; (ii) the equations for conversion of the K_{sat} values, which may result in underestimated, overestimated and negative values (more details can be found in Reynolds & Elrick 1985 and Elrick et al. 1989); and (iii) the spatial variability of the physical properties of the materials. It is believed that, even considering the uncertainties of the measurements, the K_{sat} variation has a close relationship with the variation in the physical properties in this study, given that the variations in the sand and clay content, as well as total porosity, could explain the K_{sat} variation (Table 1).

With respect to vertical variation, authors have noted that K_{sat} tends to decrease with depth in soils under forests. Harr (1977) and Dykes & Thornes (2000), who performed studies in Oregon (West Coast of the United States) and Brunei, respectively, found values of approximately 10^{-6} and 10^{-3} m s^{-1} in surface horizons, 10^{-9} to 10^{-5} m s^{-1} in the subsurface, and up to 1.0 m on average. In the present study, this behavior was also observed, with lower K_{sat} values near the surface and reducing up to 1 m. However, an increasing trend occurred up to approximately 5 m, which can be explained by the approach of the C horizon and weathered fractured rock (e.g., leptite and augen gneisses); in many slopes of the Serra do Mar, this horizon can reach between 15 m and 50 m in depth (Cruz 1974).

Thus, the presence of significant hydraulic discontinuities was noted between 1 and 2.5 m with trends for increased K_{sat} with depth, which has been described. In studies conducted in the city of Rio de Janeiro in coastal massifs that were strongly affected by shallow landslides, Campos et al. (1992) and Vieira & Fernandes (2004) also identified discontinuities at the same depths.

4.1. Scar 1

In this scar, which is located on a hillside covered with a *deposit of talus overlying saprolite*, the profile showed values between 10^{-6} and 10^{-4} m s^{-1} (Fig. 7). In the talus, even with a low amplitude (7.3×10^{-5} to 1.7×10^{-4} m s^{-1}), the values were high because of the presence of centimetric to decimetric blocks immersed in a sandy loam matrix and high levels of total porosity (65%), with 40% macropores and a high void ratio (1.7). Avelar et al. (2011) found similar values for void ratios (up to 1.6) in colluvial soils in the Serra do Mar region in the state of Rio de Janeiro, which was hit by 3,562 landslides (most of which were shallow) in the summer of 2011. De Ploey & Cruz (1979) found significantly lower K_{sat} values in

Table 1. Correlation analysis of saturated hydraulic conductivity and physical parameters of soils.

Correlation analysis	**Landslide Scars**			**General**
	S1	**S2**	**S3**	
K_{sat} × Microporosity	0.641431	–0.04036	–0.6816	0.024915
K_{sat} × Macroporosity	0.520504	0.617432	0.596873	0.572563
K_{sat} × Total porosity	0.880852	0.498755	–0.42152	0.510892
K_{sat} × Clay content	0.419555	–0.29337	–0.58535	–0.21448
K_{sat} × Silt content	0.594928	–0.6338	–0.15998	0.053063
K_{sat} × Sand content	–0.51099	0.492172	0.740809	0.110611

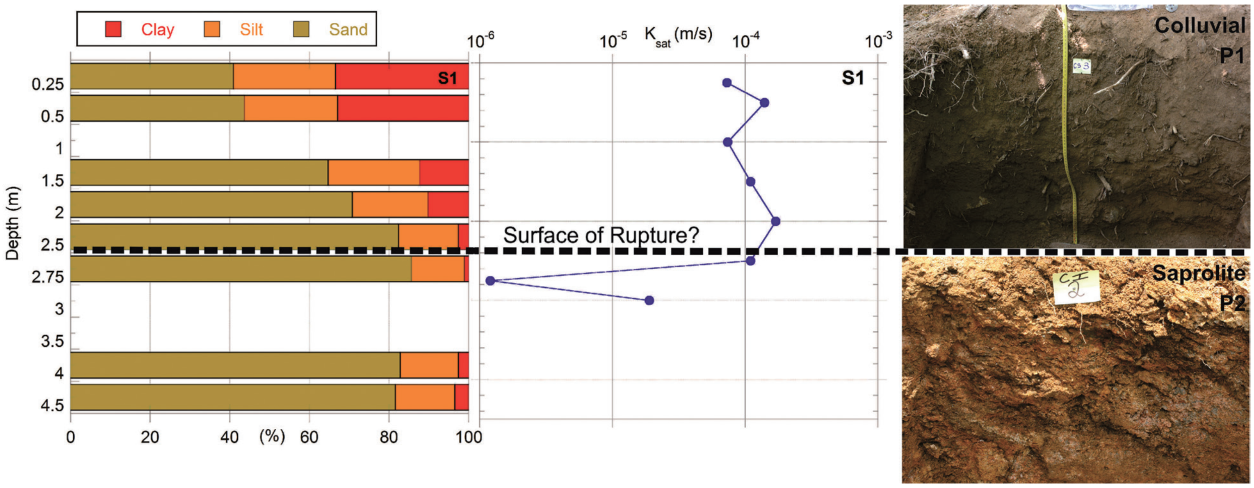

Fig. 7. K_{sat} variation in depth within scars S1. Note the reduction of K_{sat} between 2.5 and 2.75 m (from 10^{-4} to 10^{-6} m s^{-1}), and the gradual increase of sand fraction.

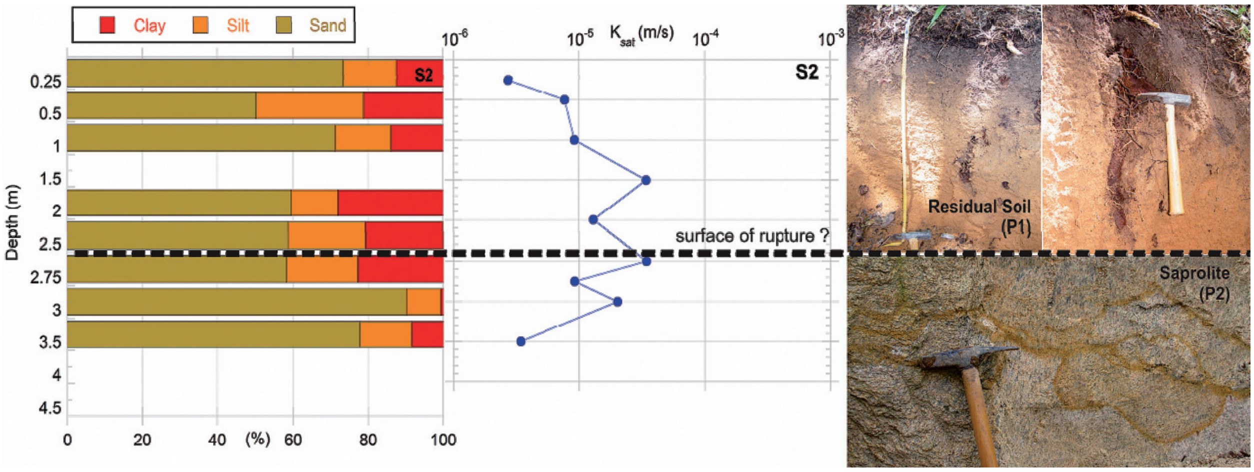

Fig. 8. Particle size distribution, K_{sat} profile, and the weathering mantle within scar S2, where we note the predominance of sand fraction along the profile, and K_{sat} profile did not present significant hydraulic discontinuities.

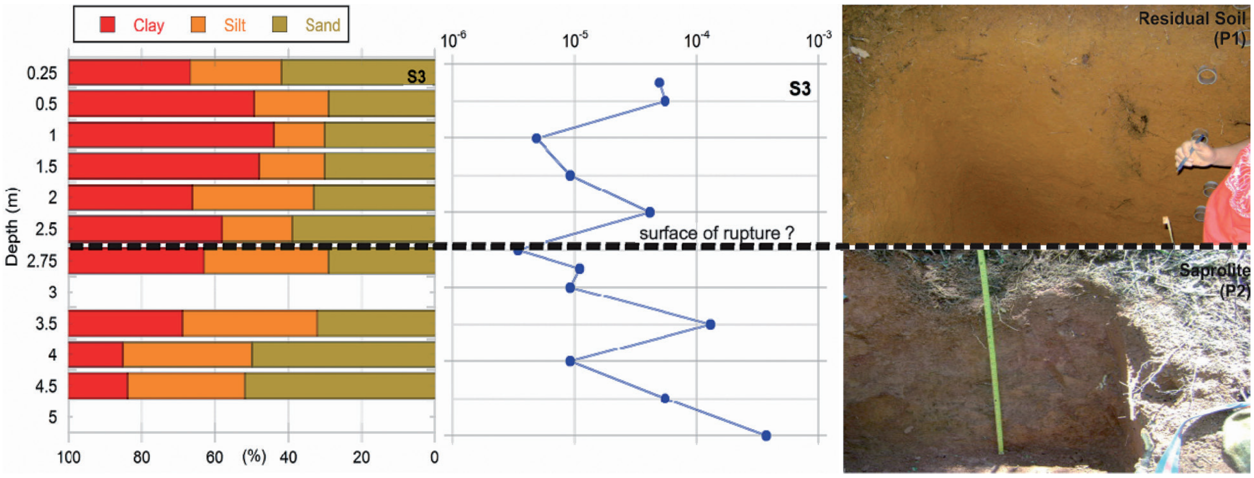

Fig. 9. Particle size distribution, K_{sat} profile, and the weathering mantle within scar S3. Note the trend of increase of K_{sat}, but the existence of hydraulic discontinuities, especially between 1 and 2.5 m.

the colluvium (between 10^{-7} and 10^{-6} m s^{-1}) in a basin contiguous to Guaxinduba.

Between 2.0 m (talus) and 2.5 m (more weathered saprolite and ± 70% sand), the value of K_{sat} remained high (1.1×10^{-4} m s^{-1}). However, at 2.75 m, less weathered saprolite (with ± 80% sand) was present, and the K_{sat} values were significantly lower by approximately 100-fold (10^{-6} m s^{-1}). This variation might have led to the formation of a perched groundwater level and increased pore pressure above this depth (2.75 m).

4.2. Scar 2

In this scar, which is located on a hillside covered with *residual soil overlying saprolite* (Fig. 8), the K_{sat} profile yielded values of between 10^{-5} and 10^{-6} m s^{-1} and had less pronounced hydraulic discontinuities. In the residual soil, there was an increasing trend with depths from 10^{-6} m s^{-1} (0.25 m) to 10^{-5} m s^{-1} (2.5 m) and further reduction up to 3.5 m in the saprolite. This increase in residual soil was also accompanied by higher percentages of macroporosity (from 18% to 29%), total porosity (from 60% to 67%), and sand content (from 40% to 57%). However, between 3 and 3.5 m, the sand content underwent a small reduction (approximately 15%) accompanied by a slight reduction in K_{sat}.

According to Gerscovich et al. (2006), these less pronounced discontinuities would not prevent the creation of saturation zones. However, the average values of K_{sat} for the entire profile could enable advancement in the face of saturation, and thus depths could be reached where the shear strength is lower. Rao (1996) and Matsushi et al. (2006) stated that where the angle of friction is smaller than the angle of the slope, the increased humidity at depths can lead to a rupture because of the loss of apparent cohesion, although it does not promote the development of positive pore pressures. Similar to what was found by Ferreira (2013), the values of these parameters were similar in this scar, wherein the angle of friction of 36.8° was exceeded by the angle of the slope (~40°).

4.3. Scar 3

In this scar, which is located on a hillside covered with *residual soil overlying saprolite with a high degree of alteration* (Fig. 9), the K_{sat} profile had values between 10^{-6} and 10^{-5} m s^{-1}, showing an increasing trend with depth. However, three significant hydraulic discontinuities were indicated at depths of 1 m, 2.5 m, and 4 m; the first two discontinuities can be explained by the decrease in porosity from 28% to 16% and from 20 to 13%, respectively. For the discontinuity at 4 m (reduction of approximately 20 times), however, no direct relationship with the values of the material's physical properties was found. The discontinuities that can be explained as possible rupture zones (1 m and 2.5 m) were also identified by Wolle & Hachich (1989) in areas that are subject to shallow landslides in the Serra do Mar and by Wakatsuki et al. (2005) in soils derived from gneiss in South Korea that had physical, chemical, and hydrological properties similar to those discussed here.

4.4. Saturated hydraulic conductivity variation and shallow landslides

The lower values near the surface and higher values at depth may hinder the rapid increase in positive pore pressure and complete saturation of the weathering mantle. However, hydraulic discontinuities were also found in all scars, with a noteworthy sharp decrease between 1 and 2.5 m in S1 and S3. The behavior observed here is inconsistent with the hypothetical model of the failure mechanism established as prevalent in the Serra do Mar in São Paulo State. According to Wolle & Hachich (1989), this mechanism indicates a progressive increase in K_{sat} with no discontinuities and decrease along the profile due to the presence of saprolites and fractured rocks that facilitate the vertical drainage.

Research indicates that the majority of shallow landslides have a failure plane between 1 and 2.5 m, mainly due to the presence of these discontinuities (Wolle & Hachich 1989, Campos et al. 1992, Vieira & Fernandes 2004, Gerscovich et al. 2006). Considering the rainfall characteristics (that is, the high-intensity rains, reaching up to 120 mm/h in the summer (Cruz 1974)), it is believed that the K_{sat} decrease at these specific depths can cause a rapid increase in positive pore pressures, partly because the rainfall in the summer is long lasting, mostly due to the occurrence of cold fronts in the region. In the summer of 1966/67, the total recorded rainfall was approximately 2,600 mm/4 months (509 mm/December, 645 mm/January, 507 mm/February, and 960 mm/March), of which 586 mm was recorded on March 17 and 18.

The location of the profiles on the lower third of the slopes (S1 and S3), associated with the sharp K_{sat} decrease, may also have increased instability due to higher previous moisture content, conditioned by the greater water volume coming mainly from subsurface flows. As for S2, the small hydraulic discontinuities and the progressive increase in K_{sat} (values of approximately 10^{-5} m s^{-1}), may have favored the vertical drainage, hindering the development of positive pore pressures. Some authors associate this behavior with the ruptures by loss of apparent cohesion in situations where there is increased moisture where the angle of friction is lower than the slope angle (Rao 1996 and Matsushi et al. 2006).

In scar S2, the friction angle was 36.8°, surpassed by the slope angle.

When the K_{sat} profiles were analyzed along with other variables, a hypothesis was raised about the mechanisms responsible for triggering the three scars, which might have been the rapid increase in pore pressure (S1 and S3) and the loss of apparent cohesion (S2). However, such behavior can only be confirmed with the hydrological monitoring of the soil during rains.

5. Final considerations

- K_{sat} showed little variation compared with the large spatial variability of this property, and no pattern was found for the different profiles. However, significant hydraulic discontinuities were identified between 1 and 2.5 m, which coincide with those observed in other studies in the Serra do Mar.
- The variation found in K_{sat} at depth does not enable us to define a rupture model for shallow landslides in the Serra do Mar (loss of suction or increase in positive pore pressures), although some studies consider the disruptions to be a result of advanced saturation and reduced suction.
- Profiles with an increased number of hydraulic discontinuities were considered favorable to the rapid development of positive pore pressures, which was primarily because they yielded high K_{sat} values above the discontinuity.
- Although certain studies of the Serra do Mar might seek to evaluate the hydrological dynamics of slopes through geotechnical testing and correlations between rainfall and landslides, there is still a need for an improved understanding of the behavior of water and its direct influence in initiating shallow landslides.
- Therefore, it is believed that studying K_{sat} variation can provide important information on the rupture mechanisms in the Serra do Mar and define areas for real-time hydrological monitoring. However, it is important that more measurements be conducted to verify the influence of this property in the Serra do Mar landslides, such as the retention curve, cohesion, and friction angle.

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References

Ahrendt, A. & Zuquette, L.V. (2003): Triggering factors of landslides in Campos do Jordão city, Brazil. – Bull. Eng. Geol. Environ. 62: 231–244. DOI: 10.1007/s10064-003-0191-8

Anderson, M.G. & Burt, T.P. (1978): The role of topography in controlling throughflow generation. – Earth Surf. Proc. and Land. 3: 331–344. DOI: 10.1029/WR014i006p01123

Avelar, A.S. & Coelho Netto, A.L. (1992): Subsurface water flow associated to hollows (in portug.). – In: 1st Brazilian Conf. on Slope Stability, Rio de Janeiro, v. 2: 709–720.

Avelar, A.S., Coelho Netto, A.L., Lacerda, W.A., Becker, L.B. & Mendonça, M.B. (2011): Mechanisms of the recent catastrophic landslides in the mountainous range of Rio de Janeiro, Brazil. – In: Proc. of 2nd World Landslide Forum, Rome.

Barata, F.E. (1969): Landslides in the tropical region of Rio de Janeiro. – In: 7th International Conference on Soil Mechanics and Foundation Engineering, Mexico: 507–516.

Berti, M. & Simoni, A. (2012): Field evidence of pore pressure diffusion in clayey soils prone to landslides. – J. Geophys. Res. 115 (F3): 2187–2205. DOI: 10.1029/2009JF001463

Boogard, T.A. & Van Asch, W.J. (2002): The role of the soil moisture balance in the unsaturated zone on movement and stability of the Beline Landslide, France. – Earth Surf. Proc. Land. 27: 1177–1188. DOI: 10.1002/esp.419

Brugger, P.J., Ehrlich, M. & Lacerda, W.A. (1997): Movements, piezometric level and rainfall at two natural slopes. – In: 2a Conferência Brasileira sobre Estabilidade de Encostas – COBRAE & 2nd Pan American Symposium on Landslides, Rio de Janeiro, v. 1: 13–20.

Campos, T.M.P., Vargas Jr, E.A. & Eisenstein, Z. (1992): Considerações sobre o processo de instabilização de encostas em solos não-saturados no Rio de Janeiro, (in portug.) – In: 1ª Conferência Brasileira sobre Estabilidade de Encostas, Rio de Janeiro: 741–755.

Coe, J.A., Kinner, D.A. & Godt, J.W. (2008): Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central Colorado. – Geomorphology 96: 270–297. DOI:10.1016/j.geomorph.2007.03.017

Costa Nunes, A.J. (1969): Landslides in soil of decomposed rock due to intense rainstorms. – In: Proc. 7th Int. Conf. on Soil Mechanics and Foundation Engineering 2: 547–554.

Crosta, G.B., Dal Negro, P. & Fratinni, P. (2003): Soil slips and debris flows on terraced slopes. – Nat. Hazards Earth Sys. 3: 31–42. DOI:10.5194/nhess-3-31-2003

Cruz, O. (1974): A Serra do Mar e planície na área de Caraguatatuba-contribuição à geomorfologia litorânea tropical (in portug.). – Série Teses e Monografias, 11, IGEOG/USP: 181 p.

De Ploey, Y. & Cruz, O. (1979): Landslides in the Serra do Mar, Brazil. – Catena 6: 111–122. DOI: 10.1016/0341-8162(79)90001-8

Dietrich, W.E. & Dunne, T. (1978): Sediment budget for a small catchment in mountainous terrain. – Z. Geomorphol. N.F. Suppl. 29: 191–206.

Dykes, A.P. & Thornes, J.B. (2000): Hillslope hydrology in tropical rainforest steeplands in Brunei. – Hydrol. Processes 14: 215–235. DOI: 10.1002/(SICI)1099-1085(20000215)14:2<215::AID-HYP921>3.0.CO;2-P

Ekanayake, J.C. & Phillips, C.J. (1999): A model for determining thresholds for initiation of shallow landslides under near-saturated conditions in the East Coast region, New Zealand. – J. Hydrol. 38: 1–28.

Elrick, D.E., Reynolds, W.D. & Tan, K.A. (1989): Hydraulic conductivity measurements in the unsaturated zone using improved well analyses. – Groundwater Monitoring Review 185: 184–193. DOI: 10.1111/j.1745-6592.1989.tb01162.x

Fernandes, N.F., Guimarães, R.F., Gomes, R.A.T., Vieira, B.C., Montgomery, D.R. & Greenberg, H. (2004): Topographic controls of landslides in Rio de Janeiro: field evidence and modeling. – Catena 55: 163–181. DOI:10.1016/S0341-8162(03)00115-2

Ferreira, F.S. (2013): Análise das propriedades físicas do solo na deflagração dos escorregamentos translacionais rasos na Serra do Mar (SP), (in Portug.). – Dissertation, University of São Paulo; 112 p.

Gabbard, D.S., Huang, C., Norton, L.D. & Steinhardt, G.C. (1998): Landscape position, surface hydraulic gradients and erosion processes. – Earth Surf. Proc. Land. 23: 83–93. DOI: 10.1002/(SICI)1096-9837(199801)23:1<83::AID-ESP825>3.0.CO;2-Q

Gerscovich, D.M.S., Vargas, E.A. & Campos, T.M.P. (2006): On the evaluation of unsaturated flow in a natural slope in Rio de Janeiro, Brazil. – Eng. Geol. 88: 23–40. DOI:10.1016/j.enggeo.2006.07.008

Gomes, R.A.T., Guimarães, R.F., Carvalho Jr, A.O., Fernandes, N.F., Vargas Jr, E.A. & Martins, E.A. (2008): Identification of the affected areas by mass movement through a physically based model of landslide hazard combined with an empirical model of debris flows. – Nat. Hazards 45: 197–209. doi:10.1007/s11069–007–9160-z

Harp, E.L., Wells, W.G. & Sarmiento, J.G. (1990): Pore pressures responses during failures soils. – Geol. Soc. Am. Bull.102: 428–438. DOI:10.1130/0016-7606(1990)102<0428:PPRDFI>2.3.CO;2

Harr, R.D. (1977): Water flux in soil and subsoil on a steep forested slope. – J. Hydrol. 33: 37–58; DOI: 10.1016/0022-1694(77)90097-X

Instituto De Pesquisa Tecnológicas Do Estado De São Paulo (1986): Indicação preliminar de áreas prioritárias para recomposição da cobertura vegetal na Serra do Mar afetadas por poluição na área de Cubatão (in Portug.),São Paulo. – Relatório nº 24: 293.

Jones, F.O. (1973): Landslides of Rio de Janeiro and the Serra das Araras escarpment, Brazil. – US Geol. Survey Prof. Papers 697: 42 p.

Kanji, M.A., Cruz, P.T. & Massad, F. (2008): Debris flows affecting the Cubatão Oil Refinery, Brazil. – Landslides 5: 71–82. DOI 10.1007/s10346-007-0110-3

Kassim, A., Gofar, N., Lee, L.M. & Rahardjo, H. (2012): Modeling of suction distributions in an unsaturated heterogeneous residual soil slope. – Eng. Geol. 131–132: 70–82. DOI: 10.1016/j.enggeo.2012.02.005

Lacerda, W.A., Ehrlich, M. & Santos Jr, O.F. (1997): Efeito das variações de poro-pressão sobre a estabilidade de encostas em solos residuais. – In: 2a Conferência Brasileira sobre Estabilidade de Encostas – COBRAE & 2nd Pan American Symposium on Landslides, Rio de Janeiro, v. 1: 381–388.

Lopes, E.S.S., Riedel, P.S., Bentz, C.M. & Ferreira, M.V. (2007): Calibração e validação do índice de estabilidade de encostas com inventário de escorregamentos naturais na bacia do rio da Onça, na região da Serra de Cubatão, SP (in Portug.). – Geociências 26: 83–95.

Matsushi, Y., Hattanji, T. & Matsukura, Y. (2006): Mechanisms of shallow landslides on soil-mantled hillslopes with permeable and impermeable bedrocks in the Boso Peninsula, Japan. – Geomorphology 76: 92–108. DOI: 10.1016/j.geomorph.2005.10.003

Meis, M.R.M. & Silva, J.X. (1968) Considerações geomorfológicas a propósito dos movimentos de massa ocorridos no Rio de Janeiro (in Portug.). – Revista Brasileira de Geografia 30: 55–72.

Michel, G.P., Kobiyama, M. & Goerl, R.F. (2014): Comparative analysis of SHALSTAB and SINMAP for landslide susceptibility mapping in the Cunha River basin, southern Brazil. – J. Soils Sediments 14: 1266–1277. DOI 10.1007/s11368-014-0886-4

Nery, T.D. & Vieira, B.C. (2014): Susceptibility to shallow landslides in a drainage basin in the Serra do Mar, São Paulo (Brazil): predicted using the SINMAP mathematical model. – Bull. Eng. Geol. Environ. 73: 01–15. DOI: 10.1007/s10064-014-0622-8

Petri, S. & Suguio, K. (1971): Características granulométricas dos materiais de escorregamentos de Caraguatatuba, São Paulo, como subsídio para o estudo da sedimentação neocenozóica do Sudeste Brasileiro (in Portug.). – 25° Cong. Bras. Geol., Bol. Esp. São Paulo, n. 1, 203 p.

Rao, S.M. (1996): Role of apparent cohesion in the stability of Dominican allophane soil slopes. – Eng. Geol. 43: 265–279. DOI: 10.1016/S0013-7952(96)00036-1

Reynolds, W.D. & Elrick, D.E. (1985): Measurement of field-saturated hydraulic conductivity, sorptivity and the conductivity-pressure head relationship using the "Guelph Permeameter". – In: Proceedings, National Water Association Conference on Characterization and Monitoring of Vadose (Unsaturated) Zone. Denver, Colorado-EUA, 25 p.

Silveira, C.T., Oka-Fiori, C., Santos, L.J.C., Sirtoli, A.E., Silva, C. & Botelho, M.F. (2013): Soil prediction using artificial neural networks and topographic attributes. – Geoderma 195–196: 165–172. DOI: 10.1016/j.geoderma.2012.11.016

Terlien, M.T.J. (1997): Hydrological landslide triggering in ash-covered slopes of Manizales (Colombia). – Geomorphology 20: 165–175. DOI: 10.1016/S0169-555X(97)00022-6

Vargas Jr, E.A., Oliveira, A.R.B., Costa Filho, L.M. & Campos, L.E.P. (1986): A study of the relationship between the stability of slopes in residual soils and rain intensity. – In: International Symposium on Environmental Geotechnology. Envo Publishing: Leigh, USA: 491–500.

Vieira, B.C. & Fernandes, N.F. (2004): Landslides in Rio de Janeiro: The role played by variations in soil hydraulic conductivity. – Hydrol. Process. 18: 791–805. DOI: 10.1002/hyp.1363

Vieira, B.C., Fernandes, N.F. & Augusto Filho, O. (2010): Shallow landslide prediction in the Serra do Mar, São Paulo, Brazil. – Nat. Hazards Earth Sys. 10: 1829–2010. DOI:10.5194/nhess-10-1829-2010

Wakatsuki, T., Tanaka, Y. & Matsukura, Y. (2005): Soil slips on weathering-limited slopes underlain by coarse-grained granite or fine-grained gneiss near Seoul, Republic of Korea. Catena 60: 181–203. DOI: 10.1016/j.catena.2004.11.003

Wolle, C.M. & Hachich, W. (1989): Rain-induced landslides in southeastern Brasil. – In: Proceedings of 12th International Conference Soil Mechanics and Foundation Engineering. Rio de Janeiro, v. 3: 1639–1642

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