Lessons learned from some landslides in Rio Grande do Sul, Brazil

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Abstract

This article presents three cases of landslides that were studied in Rio Grande do Sul state from which relevant lessons on landslide mechanisms in this region have been learned. São Vendelino's case consisted of a series of translational quick landslides that occurred in 2000 during a short rainfall episode. The study focused on one single movement with field and laboratory soil permeability tests, shear strength test and the determination of characteristic curves. The numerical simulations confirmed that only those heavy rains could have caused the landslides. The second case is a landslide in Malhada suburb of the town of Santa Cruz do Sul. The landslide mobilized ~$15x10^6$ m³ of soil and rock comprising a basaltic plateau in successive movements. The movements were observed for some years and they have been studied using field instrumentation and laboratory tests. Its kinematics were well reproduced in the failure models with the mobilization of residual shear strength in a siltstone layer. Siltstone, residual soils of sandstone and basalt were studied to achieve an accurate geomechanical model. The third case is a colluvium deposit in Três Coroas that for many years has had slow movements that caused large lateral deformations on the RS 115 highway. Field investigation identified a thin clay layer at the base of the colluvium which controlled the slope stability. Its operational strength is given by residual shear strength with a friction angle of about 10º. These studies show that only with a good understanding of the geotechnical conditions of a specific area through slope instrumentation it is possible to have reliable risk alerts and possibility of landslide movement prediction. These conclusions must be considered by everyone who needs to predict slope behavior and send risk warnings. Two of the cases also showed the importance of residual shear strength for slope stability.

1 INTRODUCTION

According to Schuster (1996), gravitational mass movements are the largest element of mass movement in the continents. Over time, these processes contribute to the stabilization of lands, resulting in suitable areas for agriculture practice and housing. However, in the short term it becomes hard to see the benefits from gravitational mass movements, wherein the largest of them are frequently treated as natural disasters.

As Turner & Jayaprakash (1996) point out, large gravitational mass movements are not frequent in many regions, and their return time is long if compared to the human life, which ends up creating a false sense of safety in relation to the hazards of these movements.

Gravitational mass movements have been the subject of extensive studies in the world, not only because of their importance as active agents in the evolution of landforms, but also owing to their practical implications and their importance from an economic point of view (Guidicini & Nieble, 1984).

In this sense, it is essential the record and the investigation of the processes that trigger gravitational mass movements, generating knowledge that supports better approach on future problems. Therefore, this article presents some events of landslides that have been studied in the past by LAGEOtec/UFRGS team and discusses some of the main characteristics and that lessons that could be learned from these cases.

2 SÃO VENDELINO

2.1 Event description

On December 2000 an area of 40 km² in the region of São Vendelino registered a concentrated 2 h rainfall. This rainfall was characterized as an isolated event wherein the previous two weeks practically no significant rains were noticed. In Caxias do Sul town, 20 km away, no rain was registered in that day.

This rainfall event, which reached 148 mm/2h (measure taken at the town's headquarters, about 6 km away from the site), caused dozens of shallow landslides in a steep area of the countryside resulting in some important debris flows. Figure 1 shows an aerial overview of failed slope in the region.

Fortunately, there were only 3 fatalities in one of the debris flows routes. And there was considerable damage to the RS 122 highway, municipal roads and some houses. Dozens of debris flows were formed in the main drainages, burying culvert and gullies, destroying small bridges and eroding road embankments. Some roads were closed for months until drainage could be restored. Figure 2 shows the erosion caused in a embankment fill by the overflow of the debris wave in one of the drainage lines.

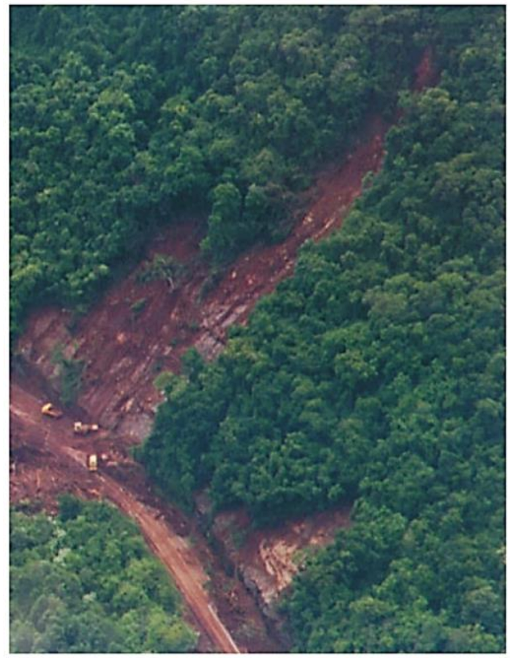

Figure 1. The scar of a landslide typical of the São Vendelino region.

Figure 2. View of the embankment's body erosion caused by a debris flow.

It is interesting that although there were dozens of almost simultaneous landslides during the 2-hour storm, on the following day it was possible to walk almost riskless in the affected areas. No more movements were observed. The problems were related to the remaining debris on the slopes and deposits of mud, boulders and wood logs in the drainage lines.

2.2 Geotechnical aspects of interest

Considering that the landslides were triggered by the rainfall, studies carried out in the area by Martinello (2006), Silveira (2008) and Bressani et al. (2009) aimed to evaluate the geotechnical aspects that influenced the infiltration and flow of water through this material, and also the shear strength. One of the slopes where there were several landslides was chosen for the studies.

The soil mobilized in the landslide presents textural variations along the slope. In general, it is a clayey silt with some fine sand. The color changes from brown in the top of the scar to red in its toe. Table 1 shows the physical indexes of the material sampled in three points along the slope. The three samples studied are composed of soils classified as highly compressible silts (MH).

Table 1. Physical indexes of the studied soils.

Sample	Height 351	Height 360	Height 365
γ (kN/m³)	-	15	16.5
γ_s (kN/m³)	29.5	28.9	29.0
w (%)	32.5	26.6	26.9
e	-	1.44	1.23
Sr (%)	-	53.7	63.3
LL	60	56	54
IP	18	16	20

Note: w, moisture; e, void ratio; Sr, saturation degree.

Silveira (2008) conducted laboratory hydraulic conductivity tests using undisturbed specimens. In these tests hydraulic conductivity coefficients (k) between $2.5x10^{-4}$ and $5.4x10^{-3}$ cm/s have been measured. The results of the direct shear tests resulted in values of cohesive intercept (c') between 4 and 10 kPa and effective friction angle (φ') about 26º (remolded or undisturbed). Triaxial tests in remolded specimens resulted in values of c' between 0 and 10 kPa and φ' between 25.8° and 36°

Martinello (2006) performed in-situ and laboratory hydraulic conductivity tests. He found a wide spectrum of k for these soils. The author used many established techniques for field tests and the results obtained are shown in Table 2.

Table 2. Hydraulic conductivity results acquired by several techniques (MARTINELLO, 2006).

Sample	Minimum K (cm/s)	Maximum K (cm/s)
Guelph permeameter (in situ)	$6.0x10^{-5}$	$1.3x10^{-2}$
Piezometers (in situ)	$1.9x10^{-3}$	$6.2x10^{-3}$
Double ring infiltrometer (in situ)	$1.8x10^{-3}$	$3.1x10^{-3}$
Flexible wall permeameter (lab.)	$2.5x10^{-4}$	$5.4x10^{-3}$

The Guelph permeameter tests (in-situ) resulted in a wide range of values for k. According to the author, this variation is associated with the heterogeneity of the soil and discontinuities of the massif (macrostructure). The tests in piezometers resulted in higher values of k, which may be due to the influence of high hydraulic head necessary for the execution of the tests.

Martinello (2006) performed flow simulations using finite elements. The author simulated the variation of factor of safety related to instabilities assuming a 2 m profile of colluvial soil with $k=3x10^{-3}$ cm/s. The analyses were made in transient condition, with a progressive increase in the water level to simulate the rain intensity (similar to conditions observed). The rocky substrate was considered impermeable.

The soil water retention capacity curve was also used, allowing an estimate of hydraulic conductivity as a function of suction (unsaturated condition). Figure 3 shows the pore pressure levels simulated along the slope after 2 hours.

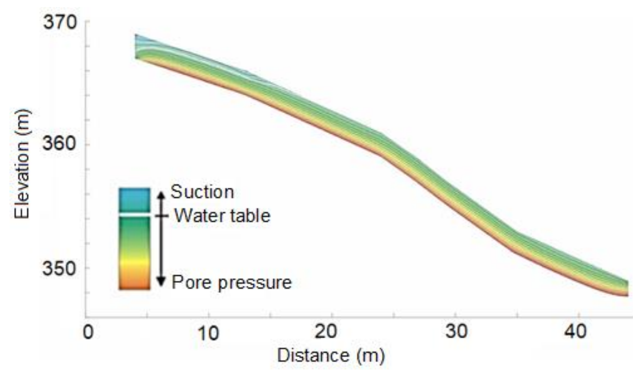

Figure 3. Pore pressure distribution along the slope.

Stability analysis using the results of the flow simulations and the shear strength parameters obtained by Silveira (2008) were performed by Martinello (2006). These analyses were conducted using the infinite slope model considering the failure in the soil-rock interface. As the slope has a variable inclination, the author presents results for inclinations β=26º and β=36º. The results are shown in Figure 4 as a function of the parameter "m", which is the ratio between the water level and the soil thickness measured from the slip surface.

These analyses show that the steepest area of the slope is the most critical one, as the slope inclination results in greater shear stresses, and also because of the fast increase of the water level in this area, as the water comes from the top of the slope.

Using results of the soil permeability and shear strength tests, the stability analyses showed that failure was only possible if a rainfall similar or more intense that the registered in 2000 does happen (Martinello, 2006; Bressani et al., 2009).

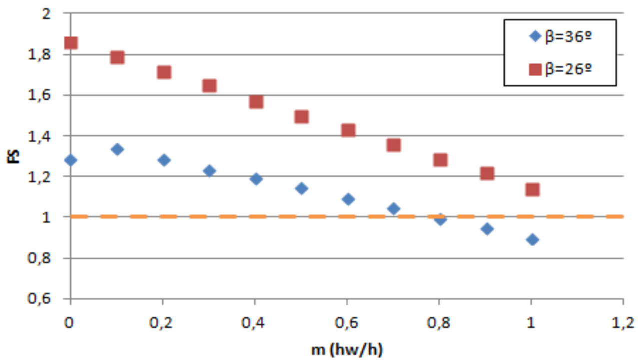

Figure 4. FS variation with the position of the water table (adapted from MARTINELLO, 2006).

It was demonstrated that a good understanding of the geotechnical conditions of this specific area, the use of efficient rainfall record systems it is possible to ensure reliability in the generation of risk alerts and landslide predictions. But it has to be said that the time is very short for any preventive measure to be taken.

3 MALHADA

3.1 Event description

In the central area of Rio Grande do Sul, the occurrence of talus and colluvium deposits is common in the area close to the contact between the Santa Maria and Botucatu Formations. These deposits tend to be heterogeneous with rocky blocks immersed in clayey soil matrix.

A general study about the causes and conditions of rock and soil slips in these circumstances was carried out on the border of Santa Cruz do Sul and Passo do Sobrado towns, locality of Malhada, in the central region of Rio Grande do Sul.

There were a series of movements associated with the displacement of a large mass of soil and rock that detached from the basaltic plateau. The general view of the movement is shown in Figure 5 where it is possible to see the displaced block. Figure 6 shows schematically the movement of the upper crest along some rock joints.

The geomorphological process created a rock scarp close to the edge of the basaltic plateau with circa of 30 m deep, 40 m wide and over 300 m long. Figure 7 shows the outline of the plateau where the rupture starts. The terrain movements are verified in the lower terrain up to the stream. At that point the slipped mass has been eroded through the years causing foot unloading and the conditions for new failures.

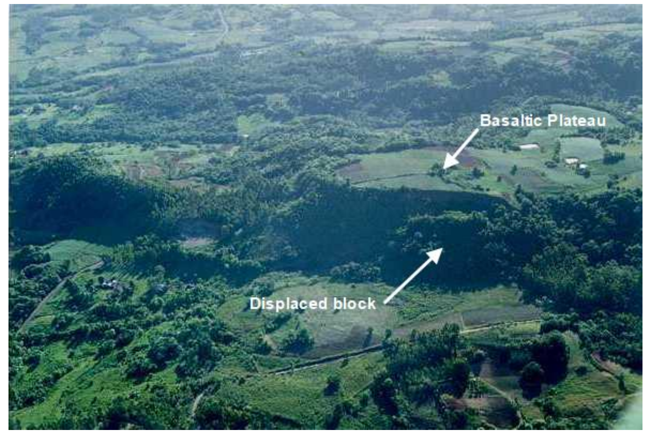

Figure 5. General view of the studied movement area (frontal view).

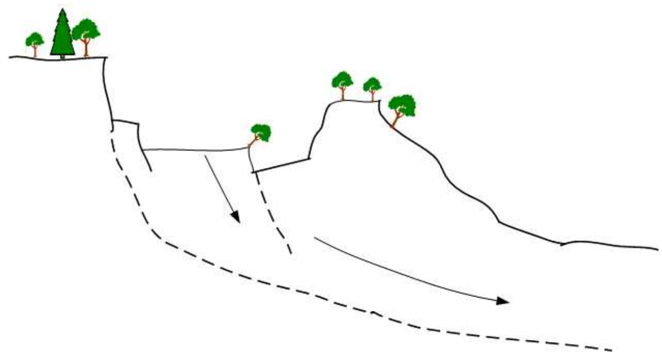

Figure 6. Scheme of the opening sequence of the upper crack and rock fractures.

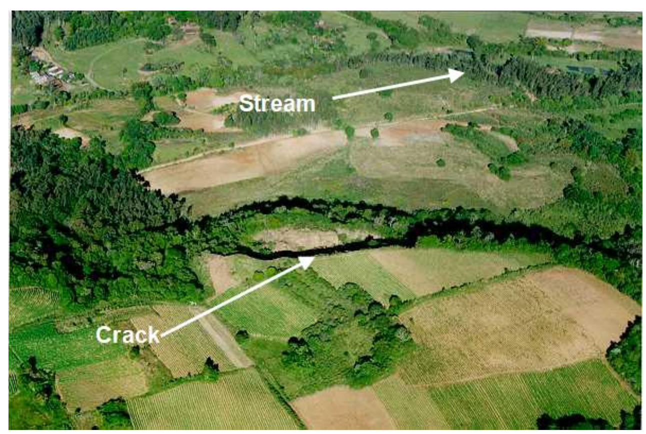

Figure 7. Plateau outline and indication of the moving soil mass.

Pinheiro (2000) divides the rock and soil landslide phenomena into two distinct and contiguous areas. An area is located on the edge of the basaltic plateau, affecting mainly the rocks and secondarily the soil. The other area, in physical continuity with the previous one, is located from the lower third of the scarp, represented by sandstones until the contact with the siltstones, mainly affecting the soil.

Thus, there is a diversity of materials involved in the problem, which makes it quite complex to define average parameters. Pinheiro (2000) studied samples of volcanic rocks (Serra Geral Formation), sandstones (Botucatu Formation) and siltstones (Santa Maria Formation), characterizing geotechnically the residual soil of these 3 lithotypes.

3.2 Geotechnical aspects of interest

Pinheiro (2000) conducted physical and mineralogical characterization tests. Regarding the shear strength, the author presented results of direct shear and ring shear tests.

The siltstone soils profiles have high plasticity, with IP>40%. These soils have a high degree of saturation and are located in the frontal area of the landslides. Soils from silty profiles were classified as CH, CL and ML.

The materials of the Santa Maria Formation are the weaker in the area. Pinheiro (2000) measured peak effective cohesive intercept (c'_p) between 1.5 and 22 kPa and peak effective friction angles (φ'_p) between 18º and 37º. In the ring shear tests, these materials presented a residual friction angle of about 16º.

The results are important since the residual mechanism seems to be fundamental in understanding the movement that occurs in the contact of the siltstones of the Santa Maria Formation with the sandstones of the Botucatu Formation. Optical and electronic microscopy images showed the occurrence of strong orientation of clay particles.

Residual sandstone soils are non-plastic with a fine sandy texture, classified as SM (silty sands). These soils have very high shear strengths, especially the friction angles. Due to this, the material behaves as soft rock or stiff soil being sensitive to the stresses generated by the massif weight. The parameters obtained from the weathered materials of this formation are: c' = 0 to 9 kPa and φ'_p = 33-48º.

Residual volcanic rock soils were obtained from points that characterize two different magma flow events. The characterization showed soils with different properties being important the individualization of these structures for proper determination of geotechnical parameters.

The soil from the first magmatic flow showed a variable texture between clayey sand and medium to coarse sand. The samples from the second flow characterized this material as a saprolite soil with a clayey silt texture. This soil has weathered minerals with the presence of sand-sized particles made up of primary minerals in several weathering stages. These are ML and CH soils. It is also interesting the occurrence of expansive minerals verified in X-Ray diffraction analyses.

The weathered soils of the Serra Geral Formation presented c'_p values between 0 and 21 kPa and φ'_p between 32-54º. Ring shear test resulted in the following values: c'_r=0 and φ'_r=17º, however, the presence of failure surfaces in these materials with the mobilization of residual shear strength have not been verified.

To determine the initial pre-failure conditions of the top of the slope Rinaldo (2000) made analyses in which the vertical discontinuities observed, mainly in volcanic flows, were simulated as tension cracks. In this analysis it was considered that the siltstone layer controls and conditionate the rupture surface. Parameters of peak, post-peak and residual shear strength were adopted in order to investigate which ones best reproduced the field situation.

The safety factors obtained in the analyses are shown in Table 3, in order to illustrate the importance of determining the operational shear parameters.

Table 3. Safety factors obtained in the stability analyses for the upper slope.

Spencer			Morgenstern-Price			Siltstone strength
Circle	Spiral	Block	Circle	Spiral	Block	
1.67	2.01	2.20	1.69	1.81	1.95	Peak[1]
1.42	1.65	1.78	1.43	1.46	1.56	Post-peak[2]
1.16	1.35	1.40	1.14	1.07	1.16	Residual[3]
1.11	1.21	1.26	1.03	0.93	0.88	Residual[4]

Note: [1,2,3] mean values; [4] minimum values.

The FS values closest to 1,0 were obtained when shear strength parameters were adopted in residual condition for the residual soil layer. This indicates that the massif movements can cause a reduction of shear strength and consequently the triggering of the landslide.

Figure 8 shows the result of the stability analysis for the upper part of the slope, considering the circular movement, indicating the most critical rupture surface obtained with the Spencer model.

Pinheiro (2000) also carried out stability analyses for the lower portion of the slope. In this analysis the author considered that the red siltstone layer controls and conditionate the rupture surface. The combination of FS close to the 1,0 and surfaces befitted with the field observation was only obtained when residual shear strength parameters are adopted for the layer of residual soil of siltstone.

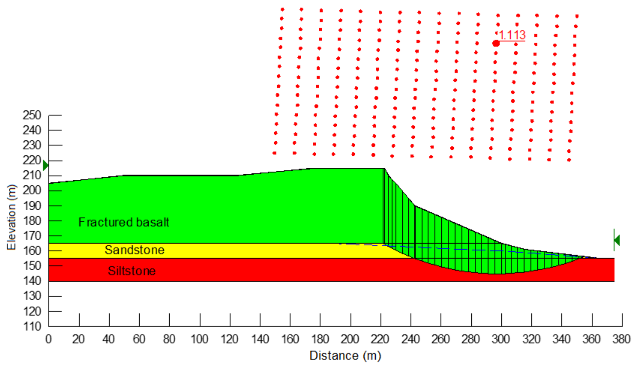

Figure 8. Stability analysis performed for the upper slope using the Spencer model.

At the bottom of the slope where the silty sediments of the Santa Maria Formation advance towards the stream, several failure processes occur, mainly involving these materials. Most of the time the surface ruptures develop in approximately circular shapes.

4 TRÊS COROAS

4.1 Event description

This landslide mobilizes a colluvium located between km 23+300 and 22+600 of the RS-115 highway, as shown in Figure 9. The material consists of a slope deposit, formed by layers of slightly cohesive materials that came from weathering of 2 distinct types of lithologies: the volcanic rocks of the Serra Geral Formation and the sandstones of the Botucatu Formation.

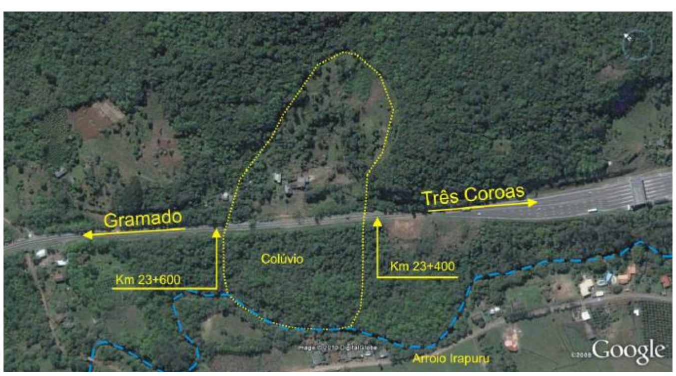

Figure 9. Delimitation of the displaced soil mass.

The colluvial deposit is formed by materials intensely weathered with blocks of basaltic rocks immersed in the soil. Clay and sandy layers are also found. The colluvium is limited at southeast by a sandstone scarp and to the north by a talus deposit composed of basaltic rocks. In the other directions the colluvium is not confined allowing the dispersion of the materials in a fan-shaped pattern. The mobilized material is deposited in the downstream area. Evidences of the movement were initially recorded in 1998 and until 2011 deformations were still occurring (Nichel, 2011).

4.2 Geotechnical aspects of interest

This slope suffered creep processes for many years. The triggering agents are the intermittent supply of groundwater through joints and fractures in the rocks located upstream of the slope and the decrease in the shear strength of the soil due to alignment of clay particles that exists at the base of the colluvium.

The slope movements started to be noticed, and maybe accelerated, with the construction of the road embankment. This embankment started to exert an overload onto the unstable mass and to hinder the water runoff over the slope increasing the volumes of superficial infiltration.

Bobermin (2011) carried out physical characterization and shear strength tests in the soil that constitutes the colluvium. The soil contains 68% of boulders and sand and 32% of silts and clays. The soil has IP=20 which characterizes this material as very plastic.

Direct shear tests performed on undisturbed specimens resulted in a friction angle of 31.5º and the cohesive intercept of 3.5 kPa. However, the construction of a suitable geomechanical model for this landslide has shown that the shear strength parameters must be lower than these, and that was investigated by Nichel (2011).

During geotechnical investigations in the area, the presence of a very clayey thin layer was detected at the base of the colluvium, in the transition to the sandstone. Disturbed sampling of this clay was carried out using the SPT apparatus. Figure 10 shows the appearance of the deformed samples taken from the bottom of the colluvium.

Figure 10. Soil samples from the bottom of the colluvium.

Ring shear tests carried out on this colluvium contact material indicated a low shear strength - a residual friction angle of 10º was measured. The low residual friction angle can be explained by the presence of montmorillonite clay mineral in the soil as pointed by Scanning Electron Microscopy and X-Ray diffraction tests (Nichel 2011).

Based on the investigation database the geotechnical profile shown in Figure 11 was defined with emphasis on the clayey layer at the colluvium bottom.

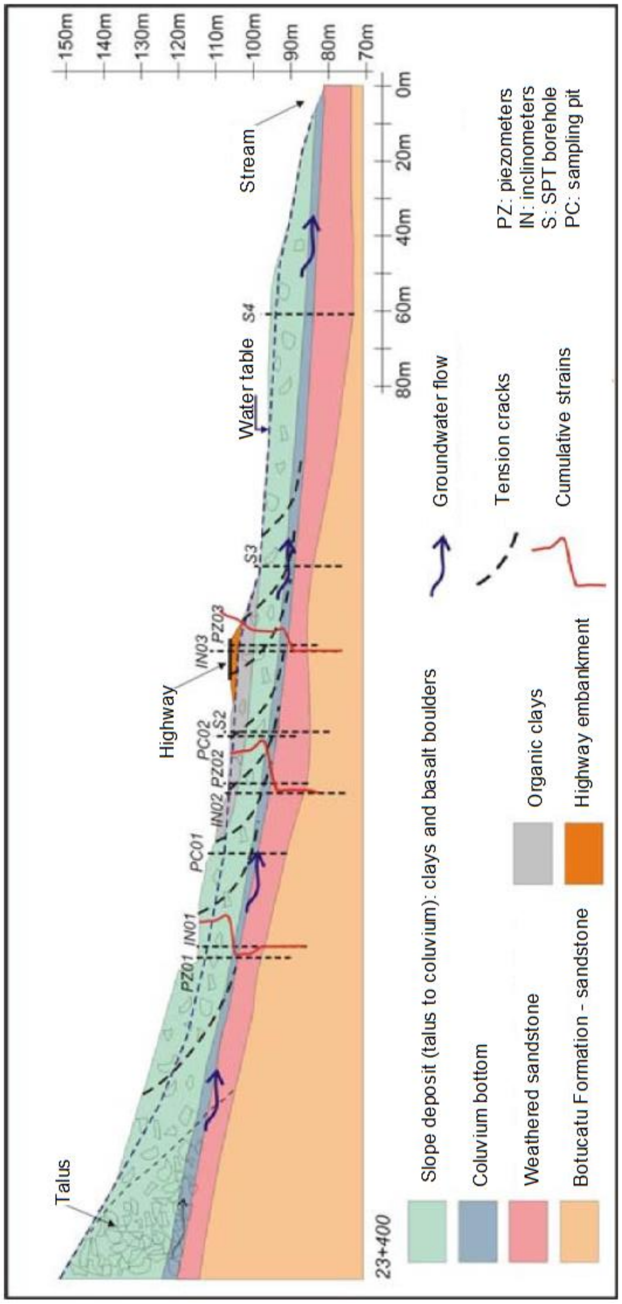

Figure 11. Geotechnical profile of the studied slope (NICHEL, 2011).

The relation between rainfall and excess pore pressure was also commented by Nichel (2011). Records of a pluviometer installed close to the area were compared with pore pressure measurements made with an electric piezometer. Figure 12 shows the pluviometry records at a spot close to the studied area and the pore pressures measured along the time.

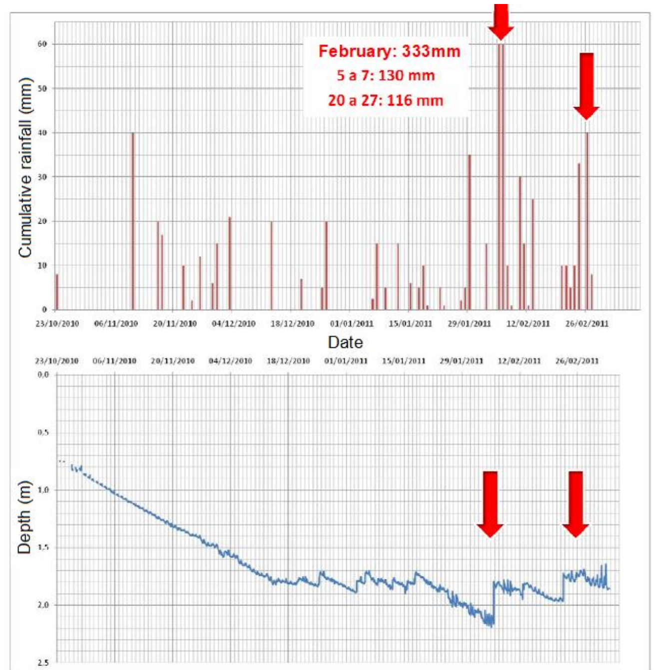

Figure 12. Records of precipitation close to the studied area and pore pressure levels measured on the slope.

February 2011 was the rainiest month of the monitored period with 333 mm rainfall in 28 days (arrows in Figure 12). In three days, 130 mm of rainfall have been recorded close to the historical monthly average of 165 mm.

This 3-day concentrated precipitation represented an increase in the piezometric level inside the colluvial mass of approximately 40 cm (data obtained from the electric piezometer).

Nichel (2011) concluded that the groundwater levels verified in the colluvial mass are ruled primarily by discharges from regional aquifers that emerge near the base of the basaltic layers located upstream from the slope. Local precipitations have only a secondary role in the definition of pore pressure levels.

5 CONCLUSIONS

The São Vendelino's series of landslides were caused by an intense but localized rainfall (148 mm/2h). Water flow simulations using finite elements were performed adopting a value of $k=3x10^{-3}$ cm/s, considered representative of field conditions, in the transient condition. In the FEM the progressive increase of the water level was observed while simulating the real rainfall.

Using the results of soil shear strength and flow simulations stability analyses indicated failure conditions for rainfalls of similar characteristics to those observed in the region at that time which demonstrates the importance of understanding the water infiltration and flow for the comprehension of landslides triggering.

The Malhada case involves successive movements caused by the displacement of a large mass of soil and rock that was separated from the regional basaltic plateau causing the appearance of a scarp 300m long at the edge of the rocky plateau.

The movement involved basaltic rocks and weathered rocks of the Santa Maria Formation overlaid by residual soils and colluviums. Pinheiro (2000) conducted analyses of the probable initial failure mechanisms considering tension cracks in the volcanic layers (field discontinuities). It was found that the siltstone layer controls the failure surfaces, whether adopting peak, post-peak or residual shear strength parameters. The most representative FS values were obtained adopting residual shear parameters which indicates that there was a progressive degradation of shear strength with cumulative movements.

The colluvium located between km 23+300 and 23+600 of the RS-115 highway has been moving for many years (Nichel, 2011). It is constituted by soil deposits originated from rocks of the Serra Geral Formation and sandstones of the Botucatu Formation.

Direct shear tests performed on representative undisturbed specimens of the colluvium resulted in a friction angle of 31.5º and a cohesive intercept of 3.5 kPa. However, these values were not consistent with the geomechanical models developed for the slope. Orientated geotechnical investigations detected a thin clay layer at the base of the colluvium which was sampled and tested in ring shear equipment obtaining a residual friction angle of 10º.

The pore pressure and rainfall monitoring in the region allowed the conclusion that the groundwater level verified in the colluvium primarily reflects the regional aquifers discharges, at the base of the basaltic layers, with local rainfall having a secondary role.

In these studies it was demonstrated that the interpretation of landslide phenomena is only reliable if the geotechnical conditions of each specific area are fully understood. This sometimes requires slope monitoring over a period of months and also the use of in-situ pluviometry recording systems. These conclusions must be considered by everyone who needs to predict slope behavior and, in particular, by those responsible for establishing risk alerts levels.

The studies of two of the cases also showed the importance that the residual shear strength of some soils had in the overall slope stability - that appears to be repeated in many other situations in Southern Brazil (and South America).

6 ACKNOWLEDGEMENTS

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