LANDSLIDES IN BELO HORIZONTE, BRAZIL

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ABSTRACT

In Belo Horizonte, landslides are associated with the rainy season that occurs from October to February. In the past recent years, annually, an average of 40 people died due to slope failures that occur in the risk-areas at the city surroundings.
This paper presents the results of two successive rainy-season monitoring carried out in the "Taquaril" slope, located at the "Taquaril" neighborhood. Also, it includes the following slope's studies: stability analysis, geological and geo-morphological characterization. Here, the main goal was to explain why this slope has failed and to identify the main trigger mechanisms.
"Taquaril" slope occupies an area of about 145.2 ha and about 30,000 people live in this risk-prone area located at "Belo Horizonte Complex" geological formation. This terrain is characterized by steeply slopes composed by weathered phyllites and schists, and by unconsolidated colluviums and talus deposits. Shallow rotational slides were observed in "Taquaril Slope", specially, when four-days accumulated precipitation rate reaches or exceeds the threshold rate of 100 mm. Deeper failures that reaches the rock mass occurs when the rock discontinuities are filled with water and the weathering degree of rock mass is high. Anthropogenic actions such as the man-made horizontal and vertical cuts to set up houses in this unstable geological area, associated with high precipitation rates were considered to be the main causes responsible for the landslides triggering.

Key words: landslides, Belo Horizonte.

INTRODUCTION

In Brazil, landslides and erosion have been considered the two main natural hazards. Most of the observed landslides have been triggered by anthropogenic actions, due to human occupancy of geologically risky areas. Every year, the exponential exodus from rural to urban areas had been adding more stress to the risky areas of the big cities surroundings, which are the preferable living places for the low-incoming people coming from rural areas. The lack of infrastructure is evident in those locations: no sewage, no electrical power, and no-treated water systems are implemented in these areas, also called "favelas" - slums. In the case of Belo Horizonte city, with more than 4 million inhabitants, most of the slums are inconveniently located in geologically “risky” areas. On this turn, this illegal soil occupancy adds more negative impacts to the land, due to the vertical and horizontal cuts made in the steeply slopes to build homes. The association of rain and anthropogenic actions are responsible for landslides’ casualties, some of them exceeding the rate of 100 deaths/year.

In January 2003, the precipitation rates were higher than usual and a great number of landslides were reported. In this month, more than 700 hundred families lost their places, sixty-seven persons were injured and among the deaths - nine children were buried alive.

During the landslide’s occurrence, the media reports a huge wave of protests from different segments of the local society, but they seem to evanesce along the rest of the year, in the same way as the promised governmental protective prevention and remediation measures.

It is evident a lack of scientific studies that can support the establishment of future guidelines in how to prevent landslides, which, on its turn, may also contribute to the lack of governmental immediate response to this annually hazard.

This paper has investigated landslides types occurred during two consecutive rainy seasons in “Taquaril” area, which are representative of the diversified geology of the study area, and has established a correlation between precipitation rates and the failure mechanisms observed.

“Taquaril” Slope is located at Taquaril Slum, where 30.000 inhabitants are concentrated in a risk area of 142 ha at Belo Horizonte Complex geological formation (Figure 1.).

The results from this study may contribute to form a database that can be used to develop stabilization techniques and landslides preventive guidelines.

METHODS

The methodology includes field and laboratory testing and the procedures as follow:

- Aerial photographs in 1:5000 and 1:1000 scales, from different years were analyzed to identify the evolution of the sliding processes as well as the anthropogenic actions performed in the area along the years, and the morphological features of the slope.
- The topographic and geological studies. The description of rock mass and the discontinuities was made according to ISRM (1978) instructions.
- Soil sampling and *in-situ* permeability analysis. *In-situ* permeability analyses were made by using the Guelf permeameter.
- Geotechnical laboratory testing on soil as well as to classify the matrix material of talus resting along the slope face.
- Rock Mass Rating – RMR (Bieniawisk, 1989) and limit equilibrium stability analysis according to Hoek & Bray (1981).
- Planar Failure Analysis and Wedge Failure Analysis softwares, developed by Kroeger (1999, 2000a, 2000b) were applied during limit equilibrium analysis of rock masses according to Hoek & Bray (1981), and Xslope software developed by Ballaam (2001) were applied during the limit equilibrium analysis of soil masses according to Bishop (1955). Back analysis from “Taquaril” slope’s landslides were made according to Fontoura *et al*. (1984), Duncan (1996), Augusto Filho & Virgilli (1998) and Abramson *et al*. (2002).

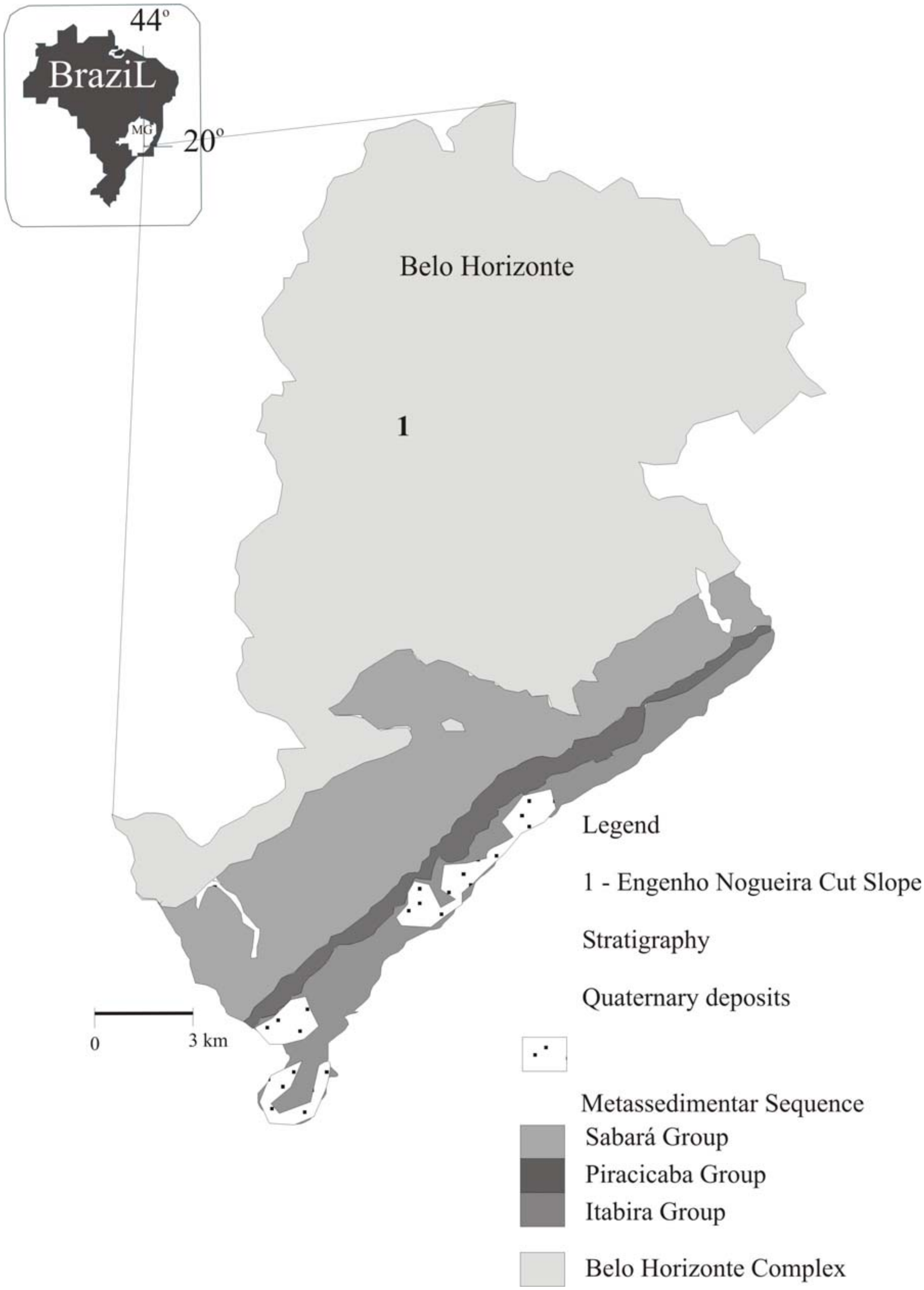

Figure 1.: Geological map of Belo Horizonte City and position of Taquaril Slope within the “Belo Horizonte Complex” geological unit.

GEOLOGY AND GEOMORPHOLOGY

Figure 1. shows the geological map of Belo Horizonte city and the studied area is shown as number 1. The site relief is strongly controlled by existing geological units. In this sense, hills with averaged altitudes of 825m represent the Belo Horizonte Complex area that occupies 70% of the city area. The studied area is located at the Belo Horizonte Complex. The Metassedimentar geological unit corresponds to 30% of the area, and its relief is formed by a sequence of crests and depressions.

Resistant itabirites constitute the materials of the higher crests and they can be founded at the altitude of about 1151m. At the medium altitudes of about 1110 m, quartzites are mostly found; they are alternated with depressions formed by dolomites and phyllites at the altitude of about 950m. The geological features presented by the “Sabará Group” are responsible for the deep valleys due to the inclined schistosity tip of the rock masses.

Local Weather and landslides

The climate of the studied area is semi-humid warm tropical with a pronounced dry season, which has 3 to 4 month duration, from May to August. The main annual precipitation of 1400 mm is concentrated between October and April, whereas January is the wettest month.

November, December and January correspond to the months of more intense precipitation, according to Moreira (2002). Usually, higher precipitation rates occur at the higher altitudes that correspond to the “Metassedimentar Sequence” geological unit’s occurrence.

To monitor “Taquaril” slope, data from local weather conditions were gathered from the meteorological station named “CPRM”.

RESULTS AND DISCUSSION

Geological and Geotechnical Analysis of Taquaril Slope

Taquaril risk area has 30,000 habitants in an area of about 145.2ha and it is located at southeast of Belo Horizonte city, Brazil. This area is considered one of the most risk areas of Belo Horizonte, because over 60% of this area was evaluated as being prone to landslides. About eighty landslides occurrences were registered annually along the years of 1994 to 2000, causing several casualties.

Steep inclined slopes composed by weathered phyllites and schists and also by unconsolidated colluviums and talus deposits characterize the terrain. Discontinuities of rock mass, such as schistosity and fractures sets, may cause wedge and planar failures depending on the cut slope direction and dip. Usually, the inhabitants of Taquaril Slum cut vertical slopes in this risk area to build their houses, which have no foundation and rest over the unconsolidated deposits. Also, the houses are made of low resistant material such as disposal pieces of woods, bricks and even paperboard.

The rock mass is constituted by weathered schists alternated with meta-grey wackes from “Sabará Group”. As the rock mass is exposed to pluvial water the weathering process is accelerated and the schist rock becomes extremely soft and brittle. Generally, superficial deposits are formed by three different materials that cover the slope and are the talus, the colluvium and the garbage (fill).

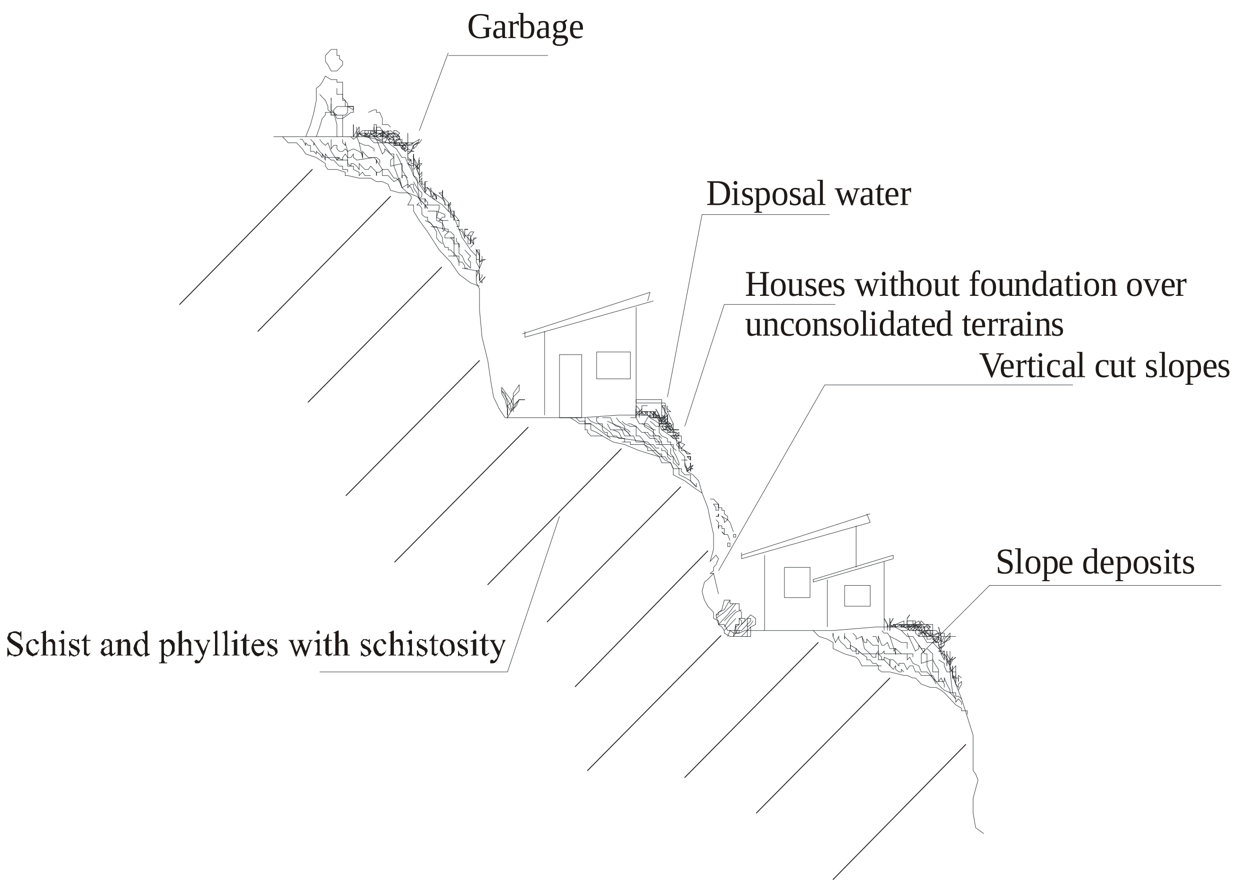

Figure 2.: Typical land-uses at “Taquaril “Slum.

Topography is usually being modified and heaps of garbage and waste material from constructions are daily thrown along the slopes and drainages, creating piles of waste deposits placed in unstable conditions, as shown in Figure 2.
Figure 3. shows a photo of the landslide that occurred in January 2003 and before this failure the slope has showed evident moving signs and small slide scars, which had characterized the imminent risk of failure.

Stability Analysis of Taquaril Slope

The kinematic analysis shows that the rock mass may fail after two different mechanisms: wedge failure and planar failure. The geotechnical slope stability analysis was performed under two different conditions: (i) the discontinuities were considered to be totally filled with pluvial water; (ii) the discontinuities were considered to be dry. In the first case, the safety factor for wedge and planar failures were 0 and 0.7, respectively, that means both are below 1 and then, unsafe.

Figure 3.: Taquaril Slope after the landslide occurred on January/2003.

In the second case, the safety factor for wedge and planar failures were 1.4 and 1.5, respectively, both above 1.3 – and then, they could be considered safe.
During the two-years monitoring period not all the expected failure types had occurred. However, shallow rotational failures have occurred in talus deposit that rest along the slope face. It appears that the talus works like a protection against the full rock mass saturation. Rain-water infiltration, preferentially, will percolate in the superficial deposit, which has a hydraulic conductivity of about 10^{-4} cm/s, before reaching the rock mass deposit.
A representative 25 m slope in this area was closely investigated and it is shown in Figure 4. "Taquaril" slope has an inclination of 50^0 at the first 15m of height (from the bottom of the slope) and turning to 36^0 near the top of the slope.
Also, during the monitoring period two rotational landslides had occurred in the site. The first one is located at the slope upper face and the second one, at the slope bottom face, as shown in Figure 4. Both failures have occurred at talus deposit.

A back analysis was performed in order to investigate the geotechnical conditions that might have been acting in the slope, at the moment of the failure. Among the geotechnical parameters used during this analysis are the values of friction angle obtained by direct shear test on inundated samples of the matrix talus. Also, for the back analysis it was used the same geometry of the failure surface as given by topographic analysis, performed before and after the failure occurrence. Thus, Figure 5. shows the slope geometry and the failure surface used for the back-analysis calculations.
Pore pressure values were obtained by the use of the coefficient r_u in accordance to Bishop & Morgenstern (1960) and expressed as follows:

$$r_u = \frac{u}{\gamma \cdot h} \qquad (1)$$

where,
u = water pore pressure;
γ = soil mass weight
h = failure surface depth

The software Xslope, based on Bishop's Slice Limit Equilibrium Method (Bishop, 1955), was used during back analysis and the input data were established according to the following:

- A surface failure depth, h=1.5m was adopted,
- The r_u values were changed until the safety of factor equal 1 was reached,
- Cohesion values in the range of 0-10 kPa,
- Friction angle values in the range of 28-34 degrees, and they were obtained from direct shear testing.

Table 1.: Parameters obtained from Back- Analysis of Taquaril Slope.

Material	**Cohesion**	**ϕ**	**r_u**	**γ**	**h**	**Pore pressure**	**SF**
Rupture surface in superior slope face							
Talus	4 kPa	33^0	0.47	15 kN/m^3	1.5m	11 kPa	1
Rupture surface in inferior slope face							
Colluvium	7 kPa	28^0	0.47	14 kN/m^3	1.5m	10 kPa	1

The values given by back analysis are shown in Table 1. The back analysis results have shown that pore pressure values of 10-11 kPa might been acting in talus deposit during rainy seasons. These values are considered too high. However, it is important to point out that failures had occurred simultaneously to heavy precipitations; the one that had occurred in January 16th, when precipitation rates were exceptional too high, varying from 217mm (one day) to 282mm (accumulated for 4 days), as shown in Table 2. Apparently, pore pressures seem to act mainly along the contact surface between the talus and the rock mass, and landslides are shallow due to the short depth of talus deposit (1.5m). Lower than 10 kPa pore pressure values may induce shallower landslides scars and creep.

Table 2.: Landslides occurrences and precipitation rates during two consecutive rain seasons: October/01 to January/02 and October 02 to January/03.

Landslides date	Daily precipitation rates (mm)	Precipitation rates in three days before (mm)	Precipitation rates accumulated in four days (mm)	Landslide Type
30/12/2001	59.30	59.30	118.60	Shallow rotacional
08/01/2003	83.5	137.4	220.9	Shallow rotacional
16/01/2003	217.5	65.4	282.9	Shallow rotacional

The geotechnical analysis results are shown in Table 3 and they describe that the talus matrix texture is mainly silt, followed by clay and fine sand, respectively in colluvium and talus samples. The soil void index is high, although hydraulic conductivity is medium - 10^{-4} cm/sec. This value range agrees with those values obtained by Ortigão (1995) and Terzaghi & Peck (1967) for silty soils. In Taquaril slope, the soil permeability depends mainly on the percentage of micaceous constituents as well as on the soil structure. The soil granulometry - in the range silty fine sand, together with the medium value of soil permeability, may induce the soil to fail under undrained conditions, upon saturation. Also, the loss of suction under unsaturated conditions and the increase in the pore-water pressure, at the contact surface between rock mass and talus should be considered, when performing a slope stability analysis.

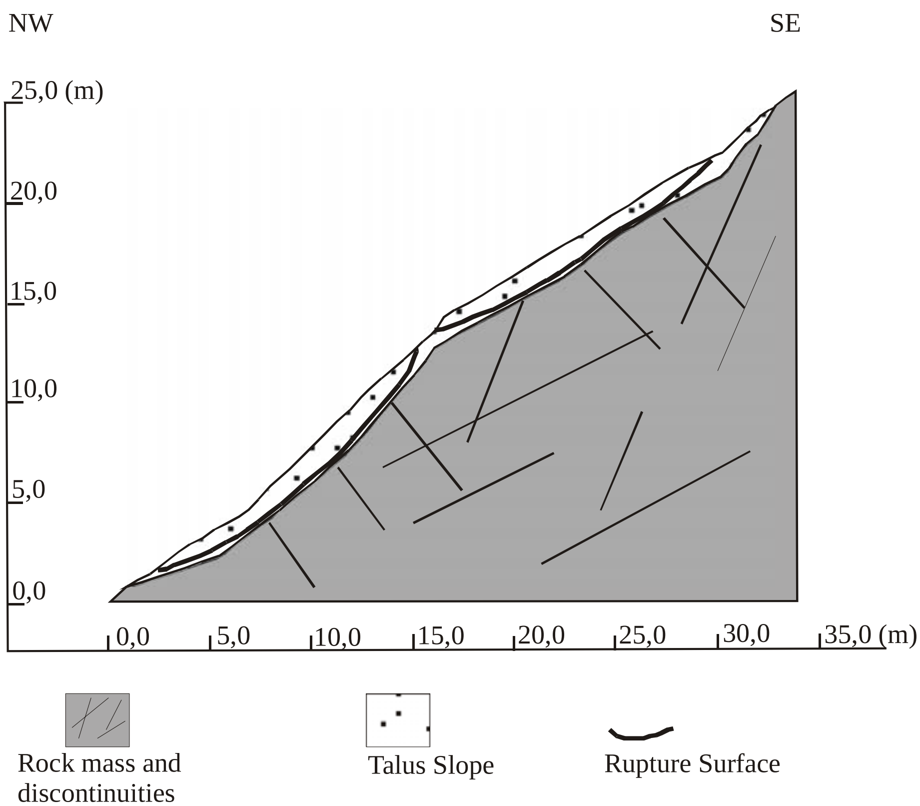

Figure 4.: Typical Taquaril Slope profile showing the two failure surfaces that have occurred

Table 3.: Geotechnical parameters of superficial deposits that cover Taquaril Slope

Sample	**material**	**ρ_s**	**ρ_{nat}**	**ρ_d**	**LL**	**LP**	**e**	**n**	**c**	**φ**	**Texture %**					
		g/cm^3	**g/cm^3**	**g/cm^3**	**%**	**%**		**%**	**kPa**		**Clay**	**Silt**	**Fine sand**	**Medium sand**	**Coarse sand**	**Gravel**
Taq-1	talus	2.79	1.38	1.21	40	18	1.31	57	0	34^O	25	35	14	6	6	15
Taq-2	talus	2.78	1.38	1.21	40	18	1.30	57	----	----	21	33	10	4	4	28
Taq-3	Landfill	2.77	1.34	1.22	41	26	1.27	56	----	----	29	35	13	4	5	14
Taq-4	Saprolite	2.82	1.74	1.55	34	14	0.81	45	24	16^O	13	37	18	5	5	22
Taq-5	Talus	2.75	1.48	1.33	33	NP	1.07	52	6	33^O	4	25	13	7	4	47
Taq-6	Colluvium	2.76	1.38	1.33	40	21	1.08	52	----	----	26	44	16	4	2	7
Taq-7	Talus	2.78	1.48	1.33	40	13	1.09	52	----	----	11	36	12	5	8	29
Taq-8	colluvium	2.77	1.48	1.25	42	NP	1.22	55	----	----	10	60	28	1	1	0
Taq-9	Talus	2.80	1.48	1.25	36	NP	1.24	55	10	28^O	6	45	23	3	4	19

ρ_s – grain specific weight LL – liquid limit LP – plastic limit NP - non plastic
ρ_{nat} – natural specific weight c – cohesion φ - friction angle
ρ_d – dry specific weight e – void index n - porosity

DISCUSSION

Although just two rainy seasons are insufficient to run a statistical analysis about precipitation and landslides, it was possible to observe that rain effect, associated with the physical properties of slopes terrains, contributes to favor the type of landslide that probably will occur.
At Taquaril Slope, shallow rotational landslides from talus only have occurred after 100mm precipitation rates accumulated during 4 days. Precipitation rates lower than 100 mm may cause creep and small intensity slumps. It was observed that the superficial deposits exert a protective effect against the underneath rock mass saturation and deeper failure.
It was possible to observe that pluvial water exert different effect on the geological materials analyzed such as:

- The stability analysis of the Taquaril slope has shown that the discontinuities dip and direction are favorable to slide, wedge, planar and toppling failures from the rock mass. However, water saturation conditions of the discontinuities seems to determine the type of failure that may occur;
- Pluvial water also cause runoff and induce erosion, which may expose discontinuity planes;
- Although weathering process of the rock mass occurs under longer periods of time, water is responsible for its acceleration. Schists and phyllites, when exposed to pluvial water action, became soft and brittle and became favorable to landslides;
- In talus, colluvium and residual soils, pluvial water is responsible for suction reduction, and for pore pressure increase, which can act mainly along the contact zone between soil and rock mass.

CONCLUSIONS

It was observed that pluvial water can induce different landslides types depending on the physical characteristics of geological materials, and the anthropogenic actions at the studied site. The rock mass weathering conditions, cut directions, discontinuities dip and direction, the shear resistance parameters, the presence of relict structures in soils, among many others, are important factors that must be associated with pore-water parameter for slope stability analysis.
Specific engineering techniques and prevention plans must be employed in the risk areas to mitigate landslides hazards. At Taquaril Slope is recommended the removal of all families that are living there.
Also, the remediation techniques must consider a drainage system for the rock mass. More studies are needed for the talus deposits. The complete removal of the talus material may be considered as an engineer sound solution to stop debris flows; or, at least they must be covered with iron meshes depth anchored in a not weathered rock mass. Finally, erosion control should be reinforced to keep the A and B-horizons in place.
Finally, anthropogenic actions such as the man-made horizontal and vertical cuts to set up houses in this unstable geological area, associated with high precipitation rates were considered to be the main causes responsible for the landslides triggering.

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