Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-2535

Mass movements in the "Serra Do Mar" Cordillera, Sao Paulo, Brazil

Movements de Masse dans la "Serra do Mar", São Paulo, Brésil

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ABSTRACT
The paper initially reviews the several phases of investigation of the slides and debris flows that occurred in the lengthy mountain range along the Southeastern Brazilian coast, called "Serra do Mar", in the region of the state of São Paulo, starting with the first observations by Terzaghi (1947), Vargas (1957) and others afterwards. The main conclusions on different studies on the mechanisms and occurrences of mass movements, encompassing landslides in residual soils and in colluvium as well as debris flows, are summarized. The paper presents the latest conclusions on the occurrence and mechanisms of mass movements, differentiating the conditions that lead to landslides and to debris flows, mainly in terms of rains that deflagrate these types of movements.

RÉSUMÉ
Ce travail présente une revision des diverses fases d'investigation des glissements de terrain et des debris flows de la chaine de montaigne denominée "Serra do Mar", qui s'étend au long du littoral sudest Brésilien, dans l´État de São Paulo. On se report aux premières observations par Terzaghi (1947), Vargas (1957) et d'autres en suite. Les principales conclusions des différentes études sur le mécanisme et l'ocurrence des mouvements de masse son résumées. Ce travail présente les dernières conclusions sur ces types de mouvement, avec la différenciation des conditions, qui conduisent aux glissements et aux debris flows, principalement concernant les pluies, qui défragrent ce type de mouvement.

1 INTRODUCTION

The "Serra do Mar" is a mountain range that runs along about two thousand km of the Southeastern Brazilian coast, where the state of Sao Paulo is about the mid portion of this cordillera and the city of Rio de Janeiro in the Northern part. This geomorphological feature was formed as a consequence of the continental drift of the South American plate. The heights of the slopes are usually of about 800 to 1,000m, but can reach almost 2,000m in certain points. The average slope angles are roughly 35^o, being usually higher in the upper parts. It is composed of gneisses and mica-schists, intensely jointed and faulted, with steep schistosity dipping against the slope. Due to the tropical climate, the rock is deeply weathered in most parts, often covered with a very thick mantle of residual soil. At the middle and the lower part of the slopes, colluvial deposits of soils including rounded rock fragments are very common. The stability of both residual soils and colluvium is problematic, originating creep movements and landslides during rainy periods, sometimes developing into debris flows. The region has a high rainfall, reaching 3,000 to 4,000 mm of annual rainfall, mainly in the months of November to March.

The importance of the slope stability study of this region, resides in the fact that several important highways, railroads and pipelines cross the mountain range, linking industrial cities to important ports (mainly São Paulo to Santos and Curitiba to Paranaguá), and the presence of heavy industries settled at the toes of the sierra in Cubatão. This makes the geotechnical investigations significant to understand their mechanisms, to forecast their occurrence and to mitigate their effects.

2 HISTORICAL DEVELOPMENT OF THE INVESTIGATIONS OF THE REGION

Although some geologists and engineers in the 19th century referred generically to the occurrence of slope stability problems in the slopes of the sierra, they were considered natural event, with little consequences since the region did not contain important works. By the end of that century and early 20th century, railroads were built between São Paulo and Santos, with interesting works for drainage and slope stabilization by stone retaining walls, that are preserved up to today. Another railroad was build between Curitiba and Paranaguá, with many high viaducts to avoid being affected by landlides.

The geotechnical modern history of the region can be considered to have started with the visit to Cubatão made in 1947 by Terzaghi due to a large landslide occurred at the excavations at the toe of the sierra for the construction of Unit #1 of the Henry Borden powerhouse. The slide involved a colluvial mass of about 120m high and 250m long. His recommendations (Terzaghi, 1947, in 1967) were to build 3 drainage tunnels and several radial drains from each tunnel. The significant improvement achieved was presented (by means of a graph showing a direct relation between lowering the water table and decrease of the displacements) in his paper on Mechanism of Landslides (Terzaghi, 1950, p.120). He also visited Curitiba by that time.

Terzaghi's ideas on landslides also contributed to stabilize another nearby colluvium with slow and continuous slide, activated around 1948 by the construction of the Anchieta highway (linking São Paulo to Santos with its important exportation port). The slide was finally stabilized by the end of the 50's by means of drainage tunnel, deep horizontal drains, and extensive surface impermeabilization with asphaltic emulsion.

The same principle was followed for the stabilization of the Anchieta highway at the 500m elevation, where an area of 200,000m^2 of colluvium was presenting movements of about 1m per month in the rainy season. It had already destroyed a viaduct, retaining walls, and other structures. About one hundred deep horizontal drains were driven in two stages, first up to 30m long due to the intense displacement, and then up to 110m long, achieving total stabilization (Teixeira and Kanji, 1970).

Figure 1: View of the numerous landslides at Serra do Mar in the Cubatão region after the rains of 1985.

Vargas was involved with the slope stability problems of the region due to disastrous landslide of the Monte Serrat hill in the city of Santos, due to heavy rains. Actually, the slide was a reactivation of a former slide in 1928. His paper (Vargas and Pichler, 1957) describes the several types of mass movements observed in the hill slopes, as translational slides, rotational, infinite slope, and rock slides along relief joints.

In the city of Santos and in specific locations of the Anchieta highway some rockslides have occurred during heavy rains, in some cases requiring the construction of tieback anchored walls.

The city of Rio de Janeiro was hit by heavy rains in 1966 and in 1967. A great number of landslides led to severe damage at many sites, as described by Barata (1969) and Nunes (1969).

In between the cities of Rio and São Paulo, two regions of the mountain range suffered catastrophic consequences due to very heavy and intense rains in 1967. The first is the Serra das Araras (state of Rio de Janeiro), with a precipitation of 275mm in 1 day. About 1,200 death was caused both by the landslides and debris flows, but also by the inundation due to the opening of the gates of a water reservoir. The second one, occurred two months later, in the region of Caraguatatuba, caused by rains of 420mm in 1 day and 586mm in 2 days, estimated to correspond to a return period of 2,000 years. It caused 120 deaths and 400 houses destroyed. Hundreds of landslides occurred practically simultaneously, triggering debris flows that traveled tens of km until spreading into the sea.

In the years of 1974 and 1975 the new and modern Imigrantes highway was built linking São Paulo to Santos. In the sierra region it is entirely constructed in a sequence of tunnels and viaducts. Several landslides have occurred induced by the construction, requiring extensive tieback anchored walls.

In the year 1985 the region of Cubatão was hit by heavy rains of 210mm in 1 day and 380mm in 2 days, following a prolonged period of rains (about 550mm in 30 days) triggering hundreds of landslides (Fig. 1) in the hill slopes along the Mogi river. The vegetation of the hill slopes was very much degraded at that time, due to acid rains caused by heavy atmospheric pollution due to emanations from the industrial complex sited at the toe of the sierra (refinery, steel mill, chemicals, etc.), making the occurrence predictable. Debris flows were triggered along the valley, causing its river bed, initially well defined, to enlarge up to 300m, due to the torrent erosion. The total mass was estimated in about $0,5x10^6$ m^3. In 1986 new rains hit the region, but only some isolated landslides occurred.

New landslides have occurred in the city of Rio de Janeiro in 1988, caused by rains varying from 100 to 229mm in 1 day, with consequent damages and fatalities. In 1996 new rains caused about 60 deaths, most of them due to landslides at the hill slopes occupied by houses of poor construction. At the valleys of the Quitite and Papagaio creeks the rains were of about 400mm in 1 day, and triggered a debris flow with an estimated volume of about 0,15 $x10^6$ m^3.

Figure 2: View of the landslide transformed in debris flow at km42 of the Anchieta highway.

A rain of 60mm in 1 hour after preparatory rains occurred at the slopes behind a large Petrobras refinery in Cubatão, in February, 1994. About 100 landslides occurred almost simultaneously, generating debris flows that hit the refinery, causing sev eral damage to utilities. As a result the operations of the refinery were interrupted for 2 weeks, with a loss estimated in 44 million US dollars. The total volume mobilized was roughly 0,3 $x10^6$ m^3, calculated both by the volume removed by trucks and by air photo interpretation. In 1996 another debris flow occurred in the same place, under a rain of 40mm in 1hour, but without damage, since some emergency works were already done. Detailed descriptions of these events and the protection works undertaken were reported by Massad et al (2003), Cruz et al (2003) and Kanji et al (2003).

At the extreme South of the mountain range (Serra Geral) the geologic constitution correspond to basalt flows. There are notices of the occurrence of debris flows in that region but they were not studied or reported. One exception is a huge debris flow that occurred near the town of Timbé do Sul, in the limits of the states of Rio Grande do Sul and Santa Catarina. In December 1995 an exceptionally heavy rain of about 500mm in 1 day hit some valleys, causing extensive landslides. Their area is estimated in about 25% of the total area affected. The generated debris flow, occurred in pulses, involved a calculated volume of $3x10^6$ m^3. The number of deaths was limited to 26, since the area is agricultural and far from the local towns.

In December 1999, again heavy rains caused a landslide very close to the Anchieta highway, forcing the traffic interruption. The slide, involving soil and weathered rock, was of about 0,3 $x10^6$ m^3. The slide developed into a debris flow, running more than 3 km downwards the hill slope, as shown in Fig. 2.

Several papers review the history of mass movements and discuss the landslide mechanisms in the Serra do Mar, mainly those by Wolle (1988, 1989) and Vargas (1997 and others) in natural slopes, and Lacerda (2004) in colluvial soils. Gramani and Kanji (2001) present and inventory of past debris flows.

3 RAINS TRIGGERING MASS MOVEMENTS

It is well known that rains that can trigger mass movements in a certain region may not affect another, due to differences in topography, geology, types of soils, climate, etc. This is confirmed by the several existing criteria expressed by various authors for triggering rains, each one developed for its own region.

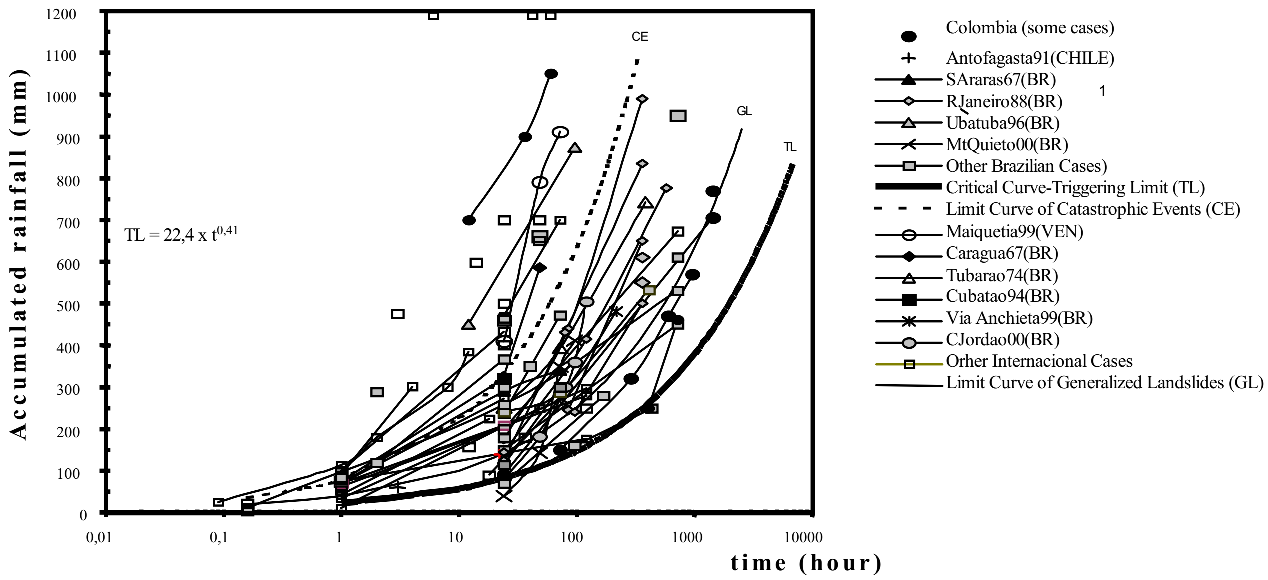

Figure 3: Accumulated rain precipitation with time, showing triggering curve for landslides and curves for different degrees of severity.

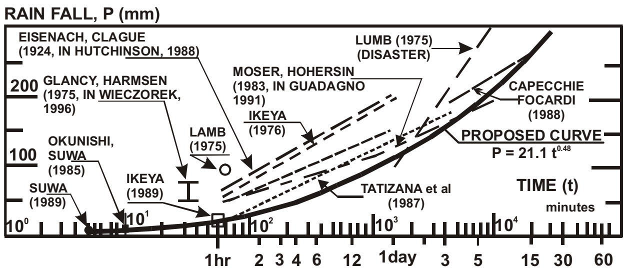

Figure 4: Accumulated rain precipitation with time: comparison with other Brazilian and international criteria.

Various studies searched a correlation between rains and landslides in the different regions of Serra do Mar. Guidicini and Iwasa (1977) considered the accumulated rains during the whole year, in comparison to the historical average annual accumulated rains, producing stability charts for different regions. Tatizana et al (1987) considered the rain intensity and the accumulated rains in the preceding 4 days, plotting one against the other, obtaining a curve clearly separating data with and without landslides.

In the region of the city of Rio de Janeiro other correlations were made, also in different terms and criteria, mainly by GEORIO, the public authority responsible for slope hazards and stabilization. Their experience, reported by Feijó et al (2001) is that landslides in Rio can occur if the rains reach average values of 26mm in 1 hour, 67mm in 1 day and 99mm in 4 days.

A simple type of graph, considering the accumulated rain (mm) during the rainy event with the logarithm of time (hrs), where several recorded events were plotted, allowed the recognition of a zone where no landslides occur, limited by a tentative curved "critical line" or "triggering limit", above which the rains causes landslides, as shown in Fig. 3 (Kanji et al, 2003). In this figure, the different points correspond to recorded rains where landslides have occurred. The start of the time count occurs as soon it starts raining after a certain periods of no rains (usually several days). Based on the type and consequences of the plotted slides, it was possible to zone the graph with respect to the severity of the events, as follows:

(a) above the "triggering limit-TL" curve the landslides are probable, more probable the higher it plots above the line;
(b) above the "GL" curve the slides are generalized within the affected region, with possible occurrence of debris flows:
© above the "CE" curve the rains cause landslides and debris flows, of catastrophic damages.

The comparison between the Triggering Limit proposed in Fig. 3 with other Brazilian and international criteria is presented in Fig. 4 (first attempt with only slight difference), where it is shown that the Triggering Limit curve encompasses all other criteria and is practically coincident with the previously mentioned work by Tatizana et al (1987), as well as is practically coincident with the criteria expressed by Feijó et al (2001) for Rio de Janeiro. Some differences should be accounted to the regional differences already mentioned.

4 MECHANISMS OF THE MASS MOVEMENTS.

As a brief summary, the mechanism involved can be described as follows.

In the upper part of the slopes of the mountain range, where the slopes are steeper (35 to 45^o), the slides are long and translational, being shallow, reaching about 1m thickness. In that region usually the permeability increases with depth, so the water table is very deep. This is confirmed by in-situ permeability tests and by loss of grout for anchors cementation. The rain water percolation is vertical, causing loss of suction due to the saturation. Wolle and Carvalho (1989) calculated the amount of rain required for failure, concluding that a rain of 180mm after preparatory rains is enough to saturate 1m of soil and promote failure, for the common soil parameters encountered. This condition doesn't require any positive pore pressures to produce the landslides. Rarely it can be found that even in the higher parts of the slope thicker residual soils occur, so rotational slides can be observed in these cases. Monte Serrat slides in 1928 and 1956 are an example (Vargas and Pichler, 1957).

The lower part of the slopes, with inclinations usually less than 25^o is frequently covered by colluvial deposits sitting on less permeable soil. Under this circumstance the seepage is mostly parallel to the slope. As a result, creep problems are very common and when slides occur, they are more of the rotational type and greatly affected by pore pressures due to the water level (WL) rise. However, in some portions (as at el.200m of the Anchieta highway), when the colluvium lies on more permeable stratum it is well drained and the deposit is stable. A detailed description about the behavior of colluvial masses in Serra do Mar was recently presented by Lacerda (2004).

Translational slides caused by pore pressures due to WL rise can also be observed when soil strata rest on impervious rock, as found in some areas, but not frequently. Cases of this type were observed in Rio de Janeiro and São Vicente cities.

Table 1: Ratio L/B as a function of slope inclination

ELEVATIONS (m)	MEAN SLOPE	RATIO L/B
500 – 750	37°	3
300 – 500	30°	2
70 - 300	12°	1

The shape of the slides as a function of elevation is confirmed by a photo interpretation of the failed slopes after heavy rains behind the Petrobras refinery, as shown in Tab. 1 by the ratio length (L) to width (B).

When the ground consists of structured residual soils or weathered rock, the geological features and weakness planes play the most important role, including the effect of cleft water pressures, which usually depend on the occurrence of intense rains to fill the fractures and not so much on preceding rainfall.

The large slide at km 42 of the Anclieta highway, occurred in December 1999, was conditioned by a series of local geological features for its occurrence: a layer of soil underlain by weathered rock with 3 sets of joints, one of them dipping about 30° to the slope, plus a diabase dike that inhibited drainage after heavy rains, explaining its transformation into debris flow (Wolle et al, 2001).

With respect to debris flows, the experience shows that preceding preparatory rains are necessary, followed by intense rains, of a minimum of 40mm in 1 hour for their deflagration. A great number of slides occur on these circumstances, temporarily damming the creek or river bed, promoting the deflagration of successive surges of debris flows, which also incorporate deposits from the bottom and the banks, greatly increasing their flow rate.

A relationship between slid area and rainfall has been found by Massad (2002), shown in Fig. 5, considering 1m thick translational slides, as mentioned above.

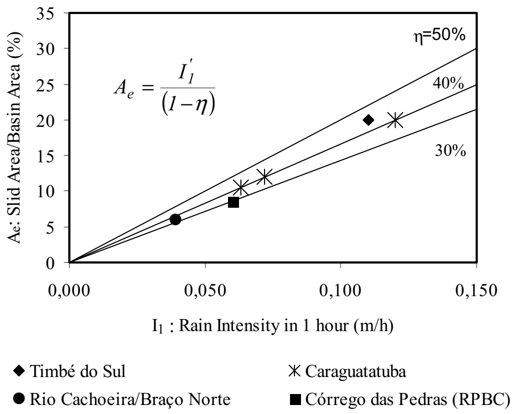

Figure 5: Relationship between slid area as a percentage of total basin area (Ae), rain intensity in 1 hour (I'_1) and soil porosity (η).

5 CONCLUSIONS.

Considering the high and steep slopes of the mountain range, covered by tropical residual soils and colluvium, the main triggering factor of landslides and debris flows is the rainfall. A criteria for determining triggering rains is proposed, with correspondent levels of severity. The landslides are mainly translational and due to loss of suction in the upper part of the slope, and mainly rotational and dependent on positive pore pressures in the lower part. The direction of seepage is greatly dependent on the substratum permeability. Debris flows are relatively common, depending on the hourly rain intensity, provided preparatory rains occur. The 1hr rainfall has a relationship with the area of slides with respect to the basin area.

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