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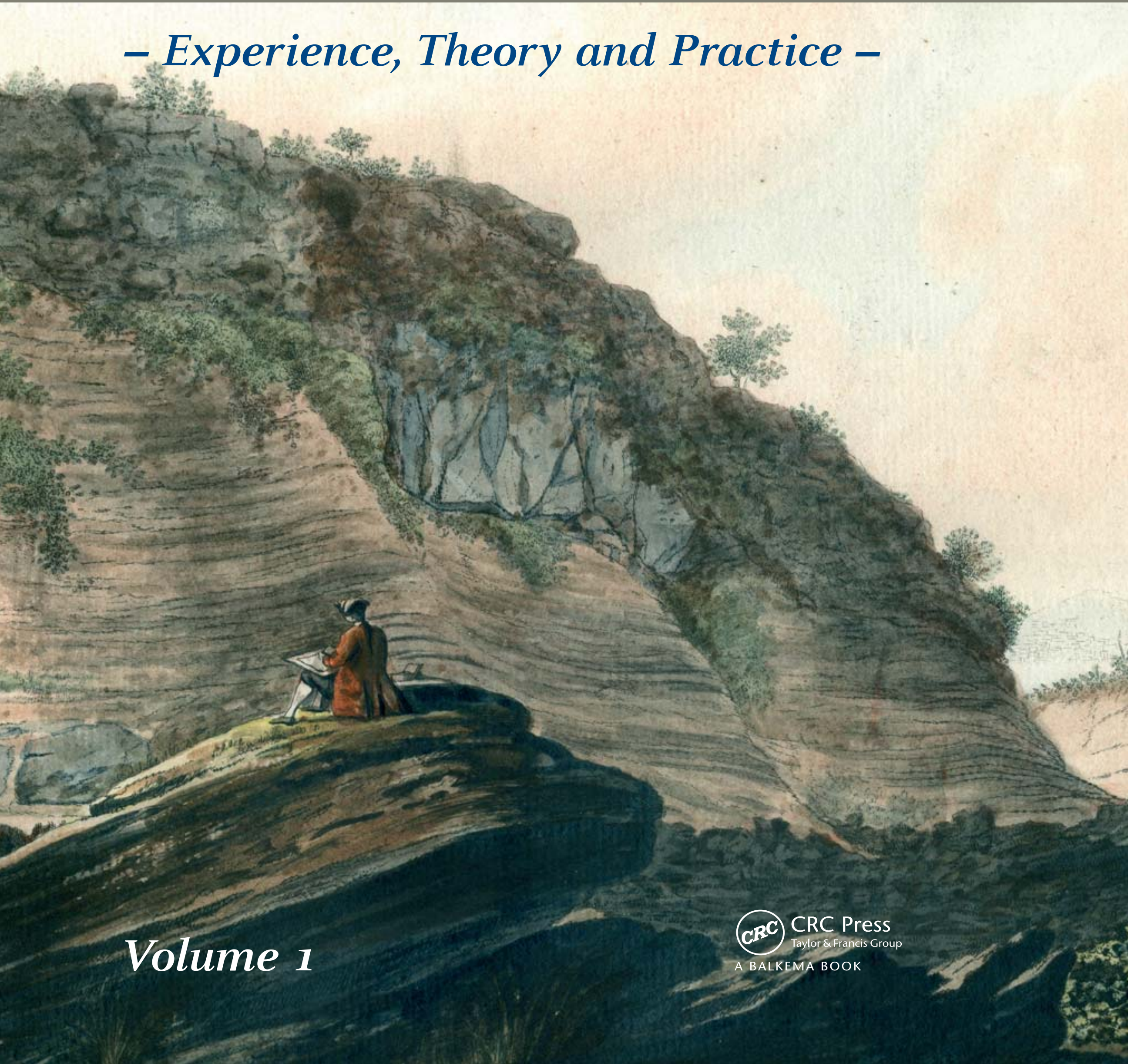
Landslides and Engineered Slopes

– Experience, Theory and Practice –



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Landslides and Engineered Slopes. Experience, Theory and Practice

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CAMPI PHLEGRÆI
OBSERVATIONS ON THE VOLCANOS OF THE TWO SICILIES
As they have been communicated to the Royal Society of London

By
SIR WILLIAM HAMILTON
HIS BRITANNIC MAJESTY'S ENVOY EXTRAORDINARY, AND PLENIPOTENTIARY AT THE COURT OF NAPLES
To which, in Order to convey the most precise idea of each remark, a new and accurate Map is annexed, with 54 Plates illuminated from Drawings taken and colour'd after Nature, under the inspection of the Author, by the Editor Mr. Peter Fabris.
NAPLES MDCCLXXVI

Private Collection of Prof. Stefano Aversa

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Debris flows occurrence by intense rains at Itaoca city, São Paulo, Brazil: Field observations

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ABSTRACT: In recent years an increase in the occurrence of debris flows has been observed in various regions of Brazil. These mass movements can be characterized by the expressive volume of material mobilized during a relative short period of time, long distances of travelling, high velocity and high transport capacity. On January 13, 2014 an extreme precipitation event produced landslides, debris flows and flash floods in two basins. The study area is located in the "Guarda-Mão" watershed, at Itaoca municipality, which is about 348 km southern of São Paulo city. The basin is lithologically very homogeneous, because the bedrock consists of granitic rocks. The debris flow and flash floods occurred during convective summer storms, with rain intensities of 210 mm in two hours. The damage caused by the occurrence of debris flow included destruction of plantations, houses, bridges, roads, two missing people and 25 deaths.

1 INTRODUCTION

In recent years an increase in the occurrence of debris flows has been observed in various regions of Brazil. These events, which have caused a significant amount of damage to cities, are associated to periods of high rainfall intensities. In Brazil, debris flows are a type of mass movements related to the tropical mountain ranges. These mass movements can be characterized by the expressive volume of material mobilized at relative short period of time, long distances of travelling, high velocity and high transport capacity, including metric rock boulders. All these geomorphological and physical characteristics influence the debris flows triggering processes and the high potential damages related to it.

On January 13, 2014 an extreme precipitation event produced landslides, debris flows and flash floods in two basins. The study area is located in the "Guarda-Mão" watershed, at Itaoca municipality, about 348 km southern of São Paulo city. This catchment has an area of 7,16 km^2. The altitude varies from 150 to 980 m (a.s.l.) and it is 4 km long. The mean annual rainfall is about 2000 mm. As the bedrock consists of granitic rocks, the basin is lithologically very homogeneous, moderately fractured and highly weathered, with presence of large rounded rock blocks. The Itaoca granitoid massif covers an area of about 200 km^2 and is believed to be part of the Ribeira Folded Belt being confined to the Ribeira Valley, at the south-southeast part of the State of São Paulo, southern Brazil. The batholith is intrusive and emplaced into metasedimentary rocks of the Lajeado Sub-Group. The debris flow and flash floods occurred during convective summer storms with rain intensities in the order of 210 mm in two hours. The damage caused by the occurrence of debris flow included destruction of plantations, houses, bridges, roads, two missing people and 25 deaths. Shallow landslides are the type of mass movement more frequent in this region. In spite of this, many recent debris flow events have been registered in the Serra Mar mountain range. The results confirmed the high susceptibility of landslide and debris flow for this region.

2 STUDY AREA

The Serra do Mar mountain range is a set of festooned scarps, presenting a face that dips abruptly toward the ocean, while the opposite face plunges very gently toward countryside. This mountain range extends along the coastline of Brazil, from the Rio de Janeiro state to the Santa Catarina state. In São Paulo state, the Serra do Mar is concentrated within a narrow zone parallel to the coast, with elevation ranging from 100 to 1100 meters above sea level (Gramani & Augusto Filho, 2004). It is composed by metamorphic and igneous rocks, such as granites, schists, gneisses and migmatites, related to Precambrian basement complex.

The climate in the Serra do Mar region is tropical humid, with the average annual rainfall ranging from 1500 to 2500 mm. Rain is mainly concentrated in summer months, from December until March.

The region of Serra do Mar, specifically the segment in São Paulo State, presents catchment basins with physiographic characteristics favorable to the occurrence of landslides phenomena, sudden floods and debris flows. This is mainly related to their dimensions (shape and area), topographical unevenness, drainage profile and materials subject to mobilization (Cruz & Massad, 1997; Cruz *et al.* 2000; Kanji *et al.* 1997; Kanji *et al.* 2000; Massad *et al.* 1997).

Figure 1. Study area location.

Figure 2. Panoramic view of Guarda-Mão creek. Observe the landslides scars and the severe river bank erosion.

The area affected by the debris and mud flows presented in this work, is located at Itaoca city, in the south of São Paulo state, southeast Brazil. The area is inserted in the Boa Vista Mountain Range (local name), a relief marked by cliffs, ridges and small drainage areas like amphitheaters. The main stream associated to the flows is Guarda-Mão creek. It forms a drainage basin located about 4 km NW from the center of Itaoca (Fig. 1), with a rounded shape, which extends over an area of 7 km^2, and an elevation difference of about 800 m. The main channel has an average slope of 22^o. The stream travels about 4 km before it flows into the Palmital River, a major stream in the region. The climate is humid and the average annual rainfall varies between 1,000 and 4,000 mm. The less rainy (drier) season occurs between June and August in winter times. Temperatures range between 11^o and 32^o.

Figure 2 shows the rugged relief configuration, landslides scars and severe river bank erosion in Guarda-Mão creek.

3 GEOLOGICAL AND GEOMORPHOLOGICAL ASPECTS

The Guarda-Mão creek basin is located south of the Boa Vista Mountain Range, a syncline that exposes the metasedimentary and metacarbonate sequence of the Lajeado Sub-Group. These rocks occur in a Precambrian terrain named Ribeira Belt that outcrops in the south-southeast of São Paulo and northeast Paraná (Ribeira River Valley), as part of the southeastern Brazil folded belts (Fig. 3). The Guarda-Mão creek flows over Itaoca Unit, consisting of intrusive rocks sin to tardi-orogenic (Mello and Bettencourt, 1998), characterized by monzogranites, quartz-monzogranites and locally by porphyritic and isotropic quartz-syenites (Faleiros, 2008). This Itaoca granitoid massif has an area greater than 200 km^2.

Lithologically, the Guarda-Mão basin is very homogeneous, as the basement is mainly composed of granitic rocks, moderately fractured and weathered. There are many blocks of rounded rocks present in the drainage channel and in the weathered soil of the area.

There are rock slopes in the upper portion of the basin, partially vegetated, with dips in the order of 70^o and heights of 10–15 m. The rock masses can be classified as classes I and II (Bieniawski, 1989), little to moderately fractured. The weathering profile (from surface to the rock) is typical of the region, prevailing surface soils (2 m depth), saprolite soils

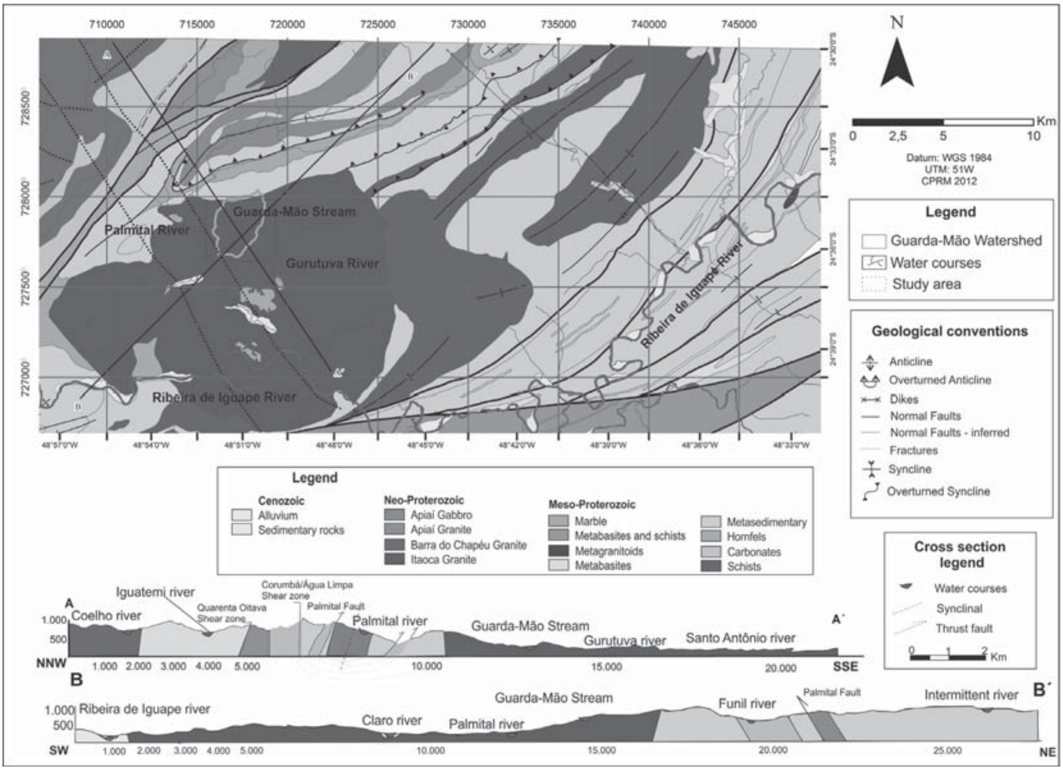

Figure 3. Geologic map of study area (after Perrota *et al.*, 2006, modified).

and saprolite. Besides the weathered soil, there are also colluvium and talus deposits. The study area is in the geomorphological context of the Serra do Mar Mountain Range. It is characterized locally by elongated relief, prevailing convex tops with narrow and deep valleys with steep slopes—30–60% (IPT, 1990). In these slope sectors, the influence of inclination triggering landslides is remarkable. IPT studies indicate that the 45º slope class has levels of relative susceptibility about 30 times higher than the slope class below 10º in similar mountainous areas. The concentration of shallow planar landslides is also much higher in the group above 35º.

4 TRIGGERING FACTORS

Rainfall precipitation values that triggered mass movements in the study area, reached values that can be classified as "extreme rain event".

The debris flow and sudden floods occurred during convective summer rainfall with high intensity and short duration. The obtained values are estimated from radar data, and reach the order of 210 mm in two 2 hours. According to reports from residents, the rain started around 21h, weakly, and reached its peak around 23h 15.

Figure 4 shows the correlation between cumulative rainfall (mm) and the time (hours) for different occurrences of landslides and debris flows in Brazil and in other countries (modified after Gramani, 2001 and Kanji *et al.*, 2008). The TL line indicates the conditions for triggering landslides; GL line represents boundary conditions in which widespread landslides occur with greater probability of debris flows generation; and the CE line indicates the occurrence of extreme events, as debris flows. Note that the rain registered in the mountain range near Itaoca, were extremely intense, inserting this case above the CE line.

5 GUARDA-MÃO DEBRIS FLOW

The phenomenon observed in Guarda-Mão creek basin was characterized as a debris flow, following definition of Hungr *et al.* (2011). These authors describe this process as "very rapid to extremely rapid surging flow of saturated debris, in a steep channel", with a "strong entrainment of material

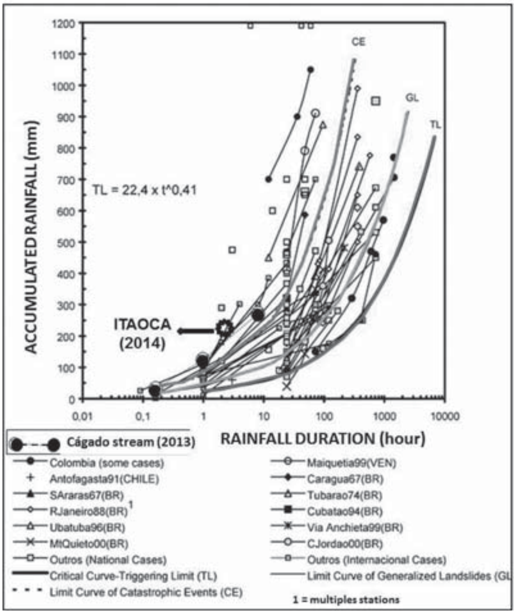

Figure 4. Accumulated rainfall graph (mm) versus time (hours) of some major events involving slips and debris flows (modified after Kanji *et al.*, 2008). In this case, the plotted values estimated were about 210 mm accumulated in two hours of rain, for the disaster occurred in the Itaoca region.

and water from the flow path". Debris flow events often occur simultaneously with floods.

The field work and fly-over operations in the area sought to characterize the sedimentary features generated by this process (type of transported material, grain size, stratigraphic profile and arrangement of coarse sediments), range, flow path, impact, physiographic aspects of the basins and recurrence of this type of process in the region. The main observations collected in this initial phase of the work were: (1) intense bank erosion, especially in the upper third of the main drainage channel; (2) large amount of rock blocks and boulders transported, both rounded, forming side and central ridges (levees), at specific points of the channel; (3) predominance of sandy matrix suporting the new deposits, (4) intense mobilization of plant material; and (5) large distance range (Ogura & Gramani, 2000; Znamesky & Gramani, 2000).

5.1 *Model of debris flow*

The model of debris flow adopted, presented by Gramani & Augusto Filho (2004), considers two main sectors of the basin during the triggering and developing of the debris flow processes: slopes and drainage. The main debris flow events registered in the Brazilian territory, and particularly in São Paulo state, show that these processes start in the slopes of the basins, triggering many landslides in a short period of time (Figs. 5–6). Sometimes, a large debris slide also starts the debris flow proc-

Figure 5. View from the upper portion of the slopes of the Guarda-Mão stream basin. In this sector, predominated soil and rock slides with variable size and shape. Observe the vegetation cover present in this upper portion of the slope and the materials present in the streambed.

Figure 6. Overview of the Guarda-Mão creek basin, especially the stretch where there was intense bank and stream bed erosion.

esses, such as the debris flows events occurred in 1999 and 2013 in the Pilões River (Gramani, 2013) and in 2010 in Rio de Janeiro state (Coelho Netto *et al*. 2011; Avelar *et al.* 2011).

The material provided from many landslides or a single large slide is conveyed to the drainage system, where it blends with different water volumes and forms a viscous mass. The viscous mass incorporates debris material by erosion of the aluvial-colluvial deposits existing along the drainages. The record of recent debris flows shows an additional component: formation of natural and temporary dams along the stream. Disruption of these dams amplifies the mobilization of the material downstream, and therefore, the distance range of masses. It is noteworthy that the choices of parameters and data regarding the drainage basin characteristics depend on the generation model adopted for the triggering and development of debris flows

5.2 *The drainage basin subdivision*

The Guarda-Mão creek basin was subdivided into three sections, according to the methodology proposed by VanDine (1985). This work proposes the division into: i) an Initial Zone (T1) with slopes greater than 25º; ii) a Transport Zone (T2), where predominates partial erosion, with slopes of approximately 15º; iii) and a Alluvial Fan Deposition Zone (T3), with slopes lower than 10º. This approach assumes that it is a channelized debris flow, according to the classification proposed by Pierson and Costa (1987), and that the gradient may vary depending on the relative channel confinement, geology (which determine the composition and gradient of the deposit), and the water/sediment ratio of the flow (VanDine, 1985).

Figure 7 shows the topographic profile along the Guarda-Mão creek, reconstructed from the Digital Terrain Model, indicating the sections (T1, T2 and T3).

The area selected for morphological and sedimentological characterization comprises the portions T2 and T3, represented in Figures 7 and 8. The sections and the main features observed are also presented in those figures.

The segment 1 (T1) is the steepest portion of the channel, whose average slope is 35º. This interval is characterized by the predominance of landslides, rock slides and erosion of the channel by the passage of the flow. From the comparison of aerial photographs taken before and after the event, it is noted that this section has large areas of erosion in marginal slopes and various landslides scars on the slopes facing the channel.

The segment 2 (T2) has an average slope of 10º and predominance of channel and banks erosion. In this section the deposition of boulders

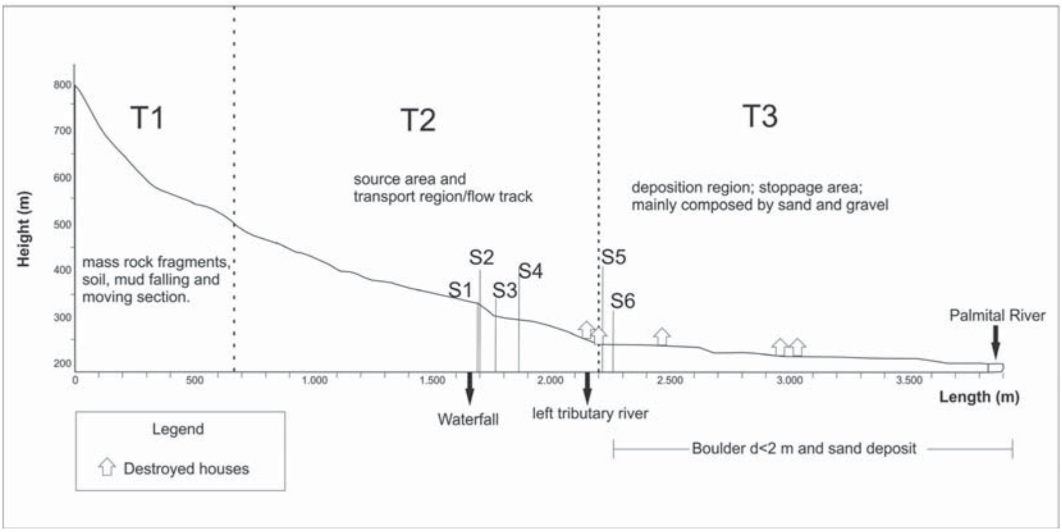

Figure 7. Profile of Guarda-Mão Creek Basin, reconstructed from the Digital Terrain Model, subdivided into three sections: T1 corresponds to the area of landslides and rock slides (θ ~ 30º); T2 the portion where θ <15º, in which there is intense lateral erosion and remobilization of the river bed, with deposition of boulders; T3, portions whose inclination is θ ~ 3º, in which predominates the deposition of gravel and sand (Gramani & Arduim, 2015).

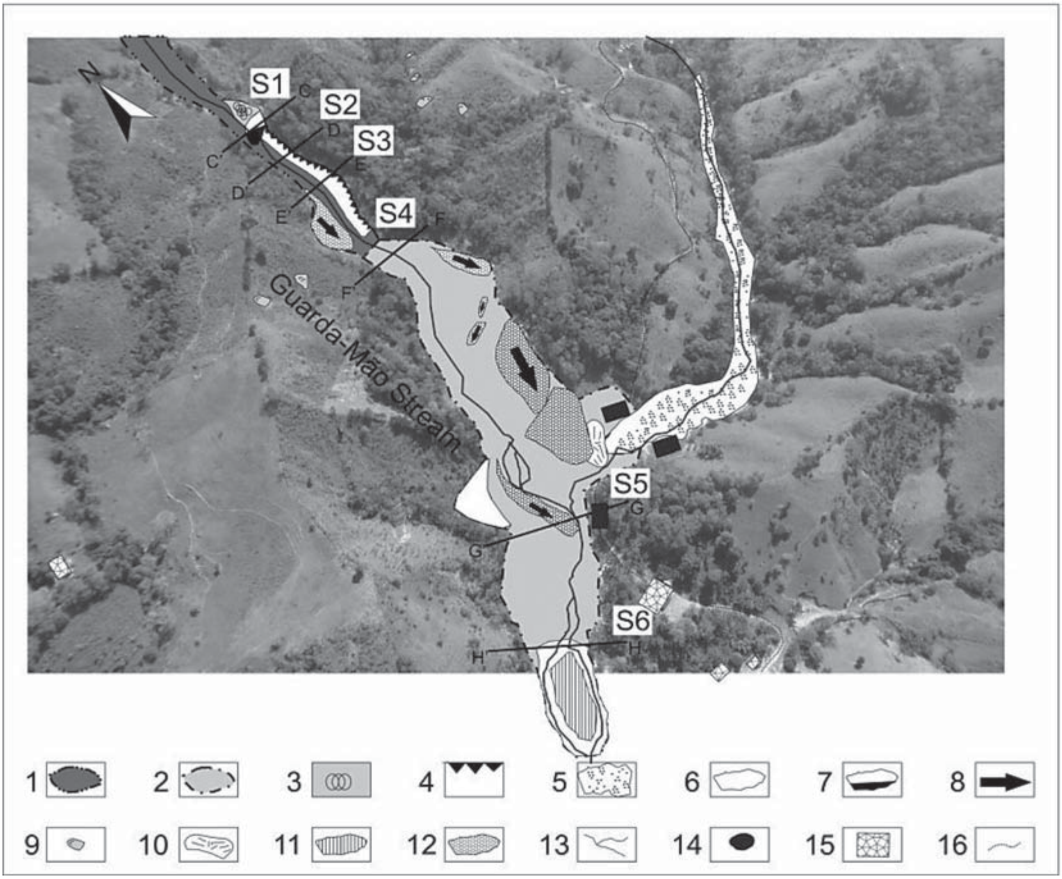

Figure 8. Schematic bird eye view of the Guarda-Mão basin, with traces of the cross-sections performed in the field; (1) T2 - stretch of intense lateral erosion and mobilization of riverbed; (2) T3 - stretch of intense deposition, predominantly gravel and sand; (3) accumulation of boulders upstream of the waterfall; (4) lateral erosion; (5) flood debris deposit; (6) gravel and coarse sand deposit; (7) waterfall; (8) deposition flux; (9) erosion scar; (10) accumulation of plant debris; (11) deposit of boulders with a diameter <2 m; (12) bars or levees; (13) Current waterway; (14) dwellings destroyed at the event; (15) housing; (16) earth track.

with approximately 2 m in diameter also begins. The channel modeled by the passage of the flow is observed from the intermediate to the final portion of this section. This section presents evidence of the flow path, indicated by the points of deposition and erosion in marginal slopes. Sections 1 to 4 individualized in this work, as well as sand/gravel bars, are representative of the deposits found in this section.

In the segment 3 (T3), where slope is less than 3º, the deposition of sand and gravel grain size sediments dominates, setting the debris flow range of deposition. The sections 5 and 6 give details of the deposit in the distal portion of T3.

5.3 *Impact and morphology of the deposit*

Six sections were performed perpendicular to the channel, from upstream to downstream, predominantly located in the T2 section. In each section, the marginal slope was characterized and measurements of the dimensions of the deposit and the grain size were done. The levees, identified in field works in sections 2 and 3, were also analyzed and subdivided, thus complementing the description of the deposit (Fig. 8).

Figures 9 and 10 show images of fly-over in the Guard-Mão Basin (December, 2014), highlighting the different sections with a predominance of ero-

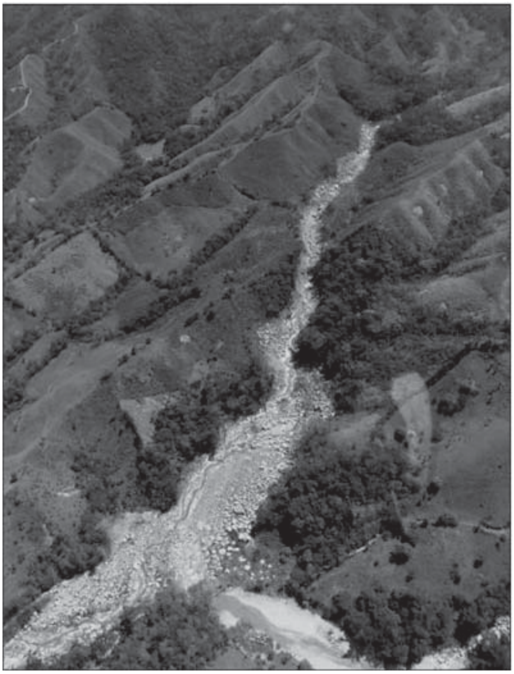

Figure 9. Aerial view photograph of December, 2014: View from downstream of the T2 section, highlighting the erosion and deposition areas along the channel under confined flow conditions.

Figure 10. Aerial View of the transition area T2 / T3, from upstream: notice number and size of materials deposited in the stretch. The drainage in this part had a width of about 2 m before the passage of the flow.

sion and deposition areas along the channel under confined flow conditions.

Figures 11–16 illustrate the social and environmental impacts, caused in the area: a total of

Figure 11. General view of the stretch intensely affected by the debris flow. This is the limit between the boulders and sandy deposition.

Figure 12. Debris flow deposits in a stretch where predominates sediments of boulders (> 2 m) proportions.

Figure 13. Debris flow deposit. The frontal portion is composed of big rock blocks, imbricated and orientated according to the main flow direction.

Figure 14. From upstream to downstream, general view of the intense sand deposition and boulders disperse along the Guarda-Mão creek.

Figure 15. Intense deposition and imbrication of big rock blocks, at the left Guarda-Mão river bank. There was a home in this place.

Figure 16. View of the levee formed in the left Guarda-Mão river bank.

22 deaths were recorded, eight destroyed houses, intense vegetable mobilization, increasing the width of the drainage from 2 m up to 70 m, plantation destruction and siltation of drainage paths.

6 CONCLUSIONS

The results obtained by field surveys confirm the high natural susceptibility to mass movements in the region of Serra do Mar. The landslides and debris flows are the highlighted phenomena, followed by flash floods in small hydrographic basins

Shallow landslides are the class of mass movements with more frequency within this scenario. 22 landslides scars were recorded in the basin of Guarda-Mão creek. The debris flow was enhanced by a natural dam located in the intermediate slope section. The transport of coarse sediments was predominant in the upper third and in the middle sections of the basin. Sedimentary features such as particle size inversion, concentration of large blocks and boulders, in the front portion of the transported material, that are isolated by sandy matrix can confirm the debris flow.

The rains were sudden with high intensity and short duration. They were very concentrated in one small area, regarding the geographical distribution.

The negative impact of this debris flow was big because it has killed 22 people in this basin.

It is necessary to establish a methodology that allows identification of hazards and prediction of run out distance and trajectory of the flows based on the estimated volumes and typology of transported materials.

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