An approach to mitigation of landslide hazards in a slum area in São Paulo city, Brazil

OSWALDO AUGUSTO FILHO[1]

[1] *USP-Engineering School of São Carlos. (e-mail: oafilho@sc.usp.br)*

Abstract: The paper presents engineering geology studies for landslide hazard assessment and to support the project of the mitigation civil works in the Jaguaré slum, located in São Paulo city, São Paulo State, southeastern region of Brazil. These studies are part of a landslide hazard mitigation program of the city government comprising a total of 192 slums located in São Paulo city.

The engineering geology assessment was carried out in two main steps: Mapping of the highest landslide hazard slope sectors; Geotechnical characterization of these slope sectors and their failure mechanisms to support the project of the mitigation civil works. The landslide hazard mapping combined Geographical Information System - GIS tools (Arcview 3.2a software) and detailed field surveys. A Digital Terrain Model - DTM, a slope map and a curvature map (convex, flat and concave) were produced of the study area. The interpretation of a high-resolution satellite image (Ikonos) was also used to help the landslide hazard mapping. The work scales in this step were 1:10 000 to 1:1 000.

The geotechnical characterization of the highest landslide hazard sectors used detailed topographic surveys and boreholes standard penetration tests to identify the main slope geotechnical horizons (landfills, transported and residual soils, weathered rock) and their basic parameters (texture, resistance). The groundwater level conditions and the possible slope failure mechanisms are also investigated. The main results are presented using detailed geotechnical slope profiles to support the concept and the layout of the mitigation civil works.

The approach adopted in the study was considered adequate to provide a project of mitigation civil works with a good cost-benefit ratio, which is fundamental in this case, where the economic resources are limited and the landslides hazard areas to mitigate are many.

Résumé: Les présents de papier machinant des études de géologie pour l'évaluation de risque d'éboulement et pour soutenir le projet des travaux civils de réduction à taudis de Jaguaré, situé dans la ville de São Paulo, l'état de São Paulo, région du sud-est du Brésil. Ces études font partie d'un programme de réduction de risque d'éboulement du gouvernement de ville comportant un total de 192 taudis situés dans la ville de São Paulo.

L'évaluation de géologie de technologie a été effectuée dans deux étapes principales: Tracer des secteurs de pente de risque d'éboulement les plus élevés; Caractérisation de Geotechnical de ces secteurs de pente et de leurs mécanismes d'échec pour soutenir le projet des travaux civils de réduction. Le risque d'éboulement traçant le système d'information géographique combiné - outils de GIS (logiciel d'Arcview 3.2a) et enquêtes détaillées de champ. Un Modèle de Terrain de Digital - DTM, une carte de pente et une carte de courbure (convexe, plat et concave) ont été produits du secteur d'étude. L'interprétation d'une image satellite à haute résolution (Ikonos) a été également employée pour aider tracer de risque d'éboulement. Les balances de travail dans cette étape étaient 1:10 000 à 1:1 000.

La caractérisation géotechnique des secteurs de risque d'éboulement les plus élevés a employé des aperçus topographiques détaillés et des essais de pénétration standard de forage pour identifier les horizons géotechniques de pente principale (sols transportés et résiduels de remblais, roche survécue à) et leurs paramètres de base (texture, résistance). Les conditions de niveau d'eaux souterraines et les mécanismes possibles d'échec de pente sont également étudiés. Les résultats principaux sont présentés en utilisant des profils géotechniques détaillés de pente pour soutenir le concept et la disposition des travaux civils de réduction.

L'approche adoptée dans l'étude a été considérée comme proportionnée fournire à un projet des travaux civils de réduction un bon rapport des coûts et rendements, qui est fondamental dans ce cas-ci, où les ressources économiques sont limitées et les secteurs de risque d'éboulements à atténuer sont beaucoup.

Keywords: landslides, risk assessment, geotechnics, geographic information systems, site investigation, protection and environmental urban.

INTRODUCTION

The research of mass movements processes in Brazil, and more specifically in the southeastern region and São Paulo State, have resulted in the accumulation of a significant body of scientific and technical works. This research has tended towards the social and economic importance of these processes. This importance results from the high frequency of mass movements accidents, mainly those related to landslides, in many Brazilian states, controlled by different and specific environmental characteristics.

There are significant areas with very high and high natural susceptibility to mass movements. However, social and economic factors modify this natural susceptibility, resulting on the occurrence of mass movement accidents in areas with middle and middle-low degree of susceptibility as well (Figure 1).

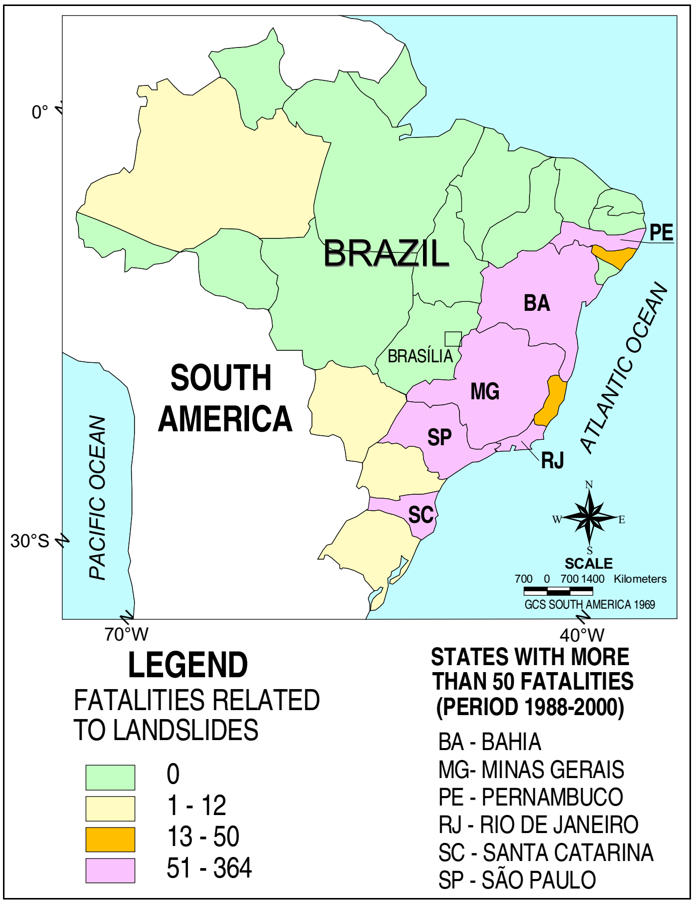

Figure 1. Fatalities related to landslides in Brazil (Augusto Filho 2004).

The increase of the number of mass movement accidents in Brazilian cities, including those located in the São Paulo city, has resulted from intensive urbanization, improper land use and absence of permanent housing programs. These mass movement accidents mainly affect the most impoverished population who often occupy areas with the worst geologic and topographic characteristics. The slums present in the biggest Brazilian urban areas are the typical examples of such terrain.

The paper presents engineering geology studies for landslide hazard assessment and to support the project of the mitigation civil works in the Jaguaré slum, located in São Paulo city, São Paulo State. These studies are part of a landslide hazard mitigation program of the federal and the municipal governments comprising a total of 192 slums located in São Paulo city. The first step of this program was the landslide risk assessment of the slums. The second step involved the detailed engineering geology studies to propose the mitigation civil works.

STUDY AREA

The study area is located in the extreme west region of São Paulo city (Figure 2). It comprises a hill occupied by precarious residences and with low pattern urban infrastructure named Jaguaré slum. There are many historic registers related to landslides accidents in this area. It was select as one of 192 slums located in São Paulo city to receive the landslide hazard mitigation program.

The Jaguaré slum occupies a hill with total amplitude around 60 meters and average declivities above of 30%. This hill is aligned to direction northeast-southwest and it is the divide between the Jaguaré creek and the Tietê River. The Pinheiros River occupies the northeast limit of this hill (Figure 3).

Three main types of geological formations are present in the regional influence area of Jaguaré slum: Quaternary alluvial deposits composed by unconsolidated clays, silts, sands and gravels and related to the depositional dynamics of the major drainage streams; Tertiary sedimentary rocks composed by red claystones, siltstones, mudstones, sandstones and conglomerates related to São Paulo Sedimentary Basin, that is characterized as graben dipping to NNW; and Metamorphic and igneous rocks related to Precambrian basement complex, such as granites, schists, gneisses and migmatites (Figure 3).

The Jaguaré slum occupies an area of 159,304 m^2 located in the northeast part of the hill, where the urban occupation is more precarious and the highest landslides risk situations are predominant. The rocky substratum in this local is composed by migmatites (Figure 3).

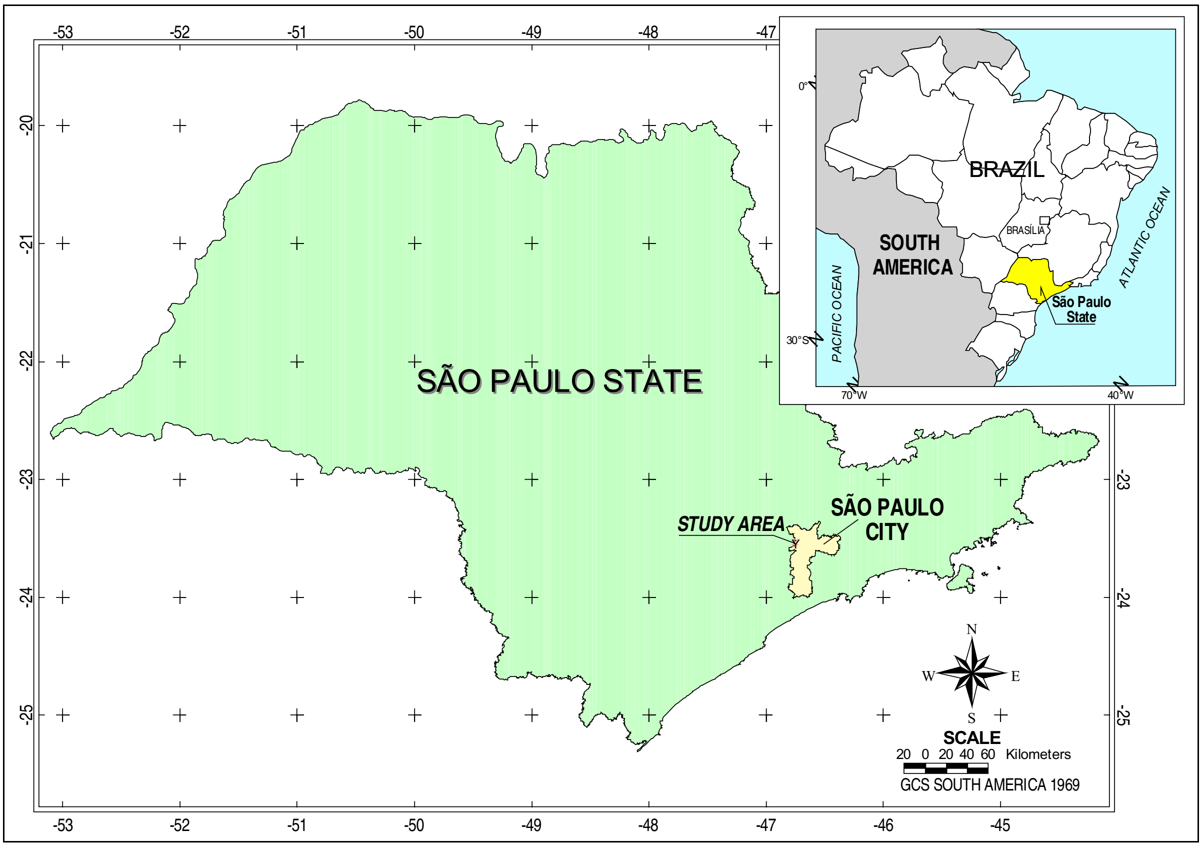

Figure 2. Localization of the study area.

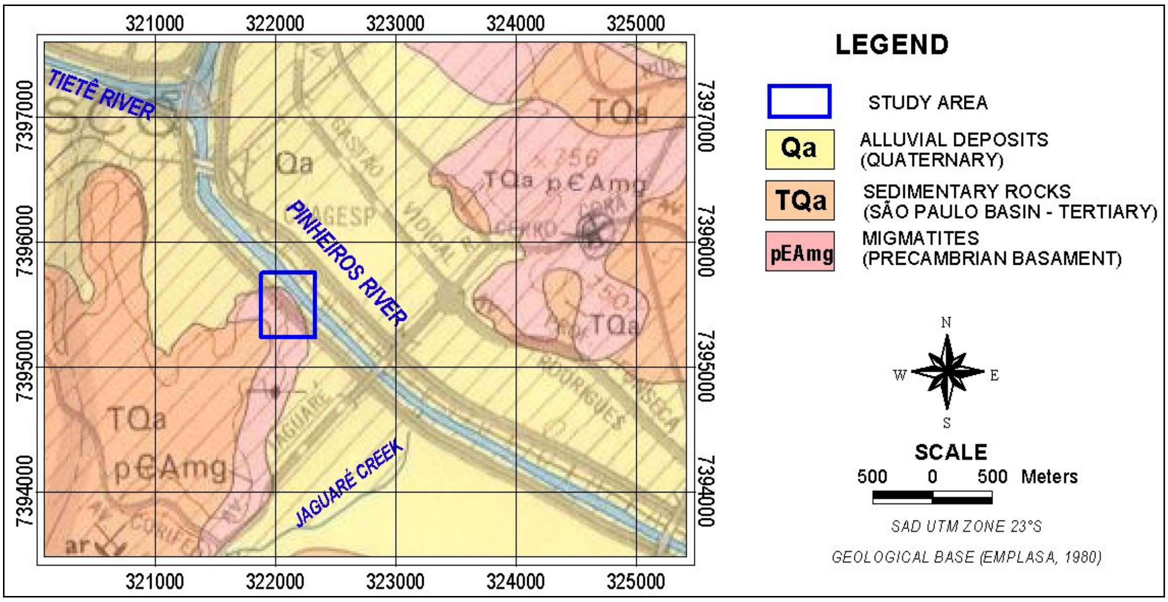

Figure 3. Main geological formations and the study area.

METHOD AND ACTIVITIES

The approach of the study was based on the following general principles:

- All steps are based on the knowledge of the agents, causes and triggering mechanisms of the mass movements occurred or with potential to occur in the study area;

- The methods of investigation and characterization of the mass movements used ranged from the more simple to those more complexes and expensive. All methods employed are adapted to the Brazilian environmental conditions and technical capabilities;
- The different steps of investigation and characterization of the mass movements were oriented by the formulation of qualitative and quantitative models and considering the methods of analysis proposed by Turner & Schuster (1996); Working Group Committee on Risk Assessment (1997); Jibson et al (1998); Campbell et al (1999) and Augusto Filho et al (2002);
- The use of the Geographic Information System (GIS) environment was encouraged in all steps of the study.

The geological and geotechnical characterization was based on the analysis of the previous works developed in the study area and the new data obtained with specific surface and subsurface investigations. These geotechnical investigations comprised detailed topographic survey, field mapping and boreholes standard penetration tests (SPT).

The main steps and activities of the study were:

- To research and to collect the previous data comprising geological map, landslides hazard map, aerial photographs and high-resolution satellite image (Ikonos);
- To produce a spatial database using the GIS tools, the topographic map at 1:10,000 scale and the high-resolution satellite image (Ikonos);
- To produce the digital terrain model (DTM), the slope map and the curvature map using GIS tools and the spatial base of the previous step;
- To analyse the results of the preliminary investigations and to define the highest landslide hazard sector to be investigated with more detail;
- To realize the new and detailed surface and subsurface investigations in the highest landslide hazard sector;
- To analyse the data collected in the previous steps, to define the main types of mass movements with potential to occur in the highest landslide hazard sector and to present the conclusions to support the project of the mitigation civil works.

RESULTS

Identification of the highest landslide hazard sector

The high-resolution satellite image dated from January of 2001 (*Ikonos*) was draped on the digital topographic map at scale 1:10.000 (contour intervals of 5.0 meters) using geometric correction procedures available in the GIS environment *(*Arcview 3.2a software). This digital cartographic base was used to store and to realize the preliminary analysis of the surface data collected during the initial steps of the study.

The preliminary investigations were based on the field surveys to collect data related to the slope stability factors such as, the presence of instability indicators (cracks and steps affecting the terrain and edifications), the geometry of the slopes, including the cuts and the landfills, the characteristics of the weathering profiles and human modifications related to inadequate urban occupation. They were also involved the analysis of the slope and curvature maps, obtained by processing and modelling of the digital cartographic base at scale 1:10.000.

The analysis of these preliminary investigations resulted on the identification of the highest landslide hazard sector present in the Jaguaré slum. It is located in northeast region of the slum and comprises an area of 5,000 meters, occupied by 56 houses. This sector can be subdivided into three main segments considering the landslide hazard situations: top, slope and base (Figures 4 and 5).

The topographic map was used to create the digital terrain model (DTM) with a grid presenting a cell size of 1.0 meter. The interpolation method named *Topogrid* (Arcinfo 7.1.2 software) was applied to generate the DTM. It is specifically designed for the creation of hydrologically correct digital elevation models from comparatively small, but well selected elevation and stream coverages (Hutchinson 1996).

The slope map was produced using the DTM previously described and considering the following degree slopes intervals: 0^{o} to 10^{o}; 10^{o} to 20^{o}; 20^{o} to 30^{o}; 30^{o} to 45^{o} and greater than 45^{o} (Figure 6). The declivity is a fundamental factor in the slope stability analysis. Many studies conducted in the Brazilian territory showed that the frequency of the shallow landslides increases exponentially to declivities upper to 20^{o} and it hits the maximum for declivities values between 30^{o} to 45^{o} (Augusto Filho *et al*. 2002). Table 1 presents the percentile distribution in area of these slope classes considering all the initial study area and the highest landslide hazard sector only.

The curvature map was also produced using the DEM. The curvature function is a processing tool of Arcinfo 7.1.2 software. The curvature of a surface is calculated on a cell-by-cell basis. For each cell, a fourth-order polynomial is fit to a surface composed of a 3x3 window. From an applied viewpoint, output of the curvature function can be used to describe the tendency of the hillsides to concentrate or to disperse the superficial water flow. This characteristic is very important factor that acts on the triggering mechanisms of the mass movement processes.

A positive curvature indicates that the surface is upwardly convex at that cell. A negative curvature indicates that the surface is upwardly concave at that cell. A value of zero indicates that the surface is flat. The curvature map identified the slopes presenting the convex, flat and concave shapes. The concave curvature is considered more unfavourable to slope stability (tendency to concentrate the superficial water flow), following by the flat and convex curvatures. Table 2 presents the percentile distribution in area of these three basic curvatures shapes of slopes considering all the initial study area and the highest landslide hazard sector only.

The highest landslide hazard sector presents the highest frequencies in area of slopes with inclinations between 30° and 45°, if we to compare with the all area of the Jaguaré slum. In relation the curvature shapes, the highest landslide hazard sector presents the highest frequency in area of slopes with convex shape. The slope and base segments of the highest landslide hazard sector can be characterized as presenting the highest relative vulnerability degrees. They have the houses with the worst construction characteristics. Many inadequate geometry modifications on the natural slopes resulted from the implementation of cuts too high/steep and landfills without any compacting control. In this situation, shallow landslides or small slope failures can result on highest social damages, including fatalities.

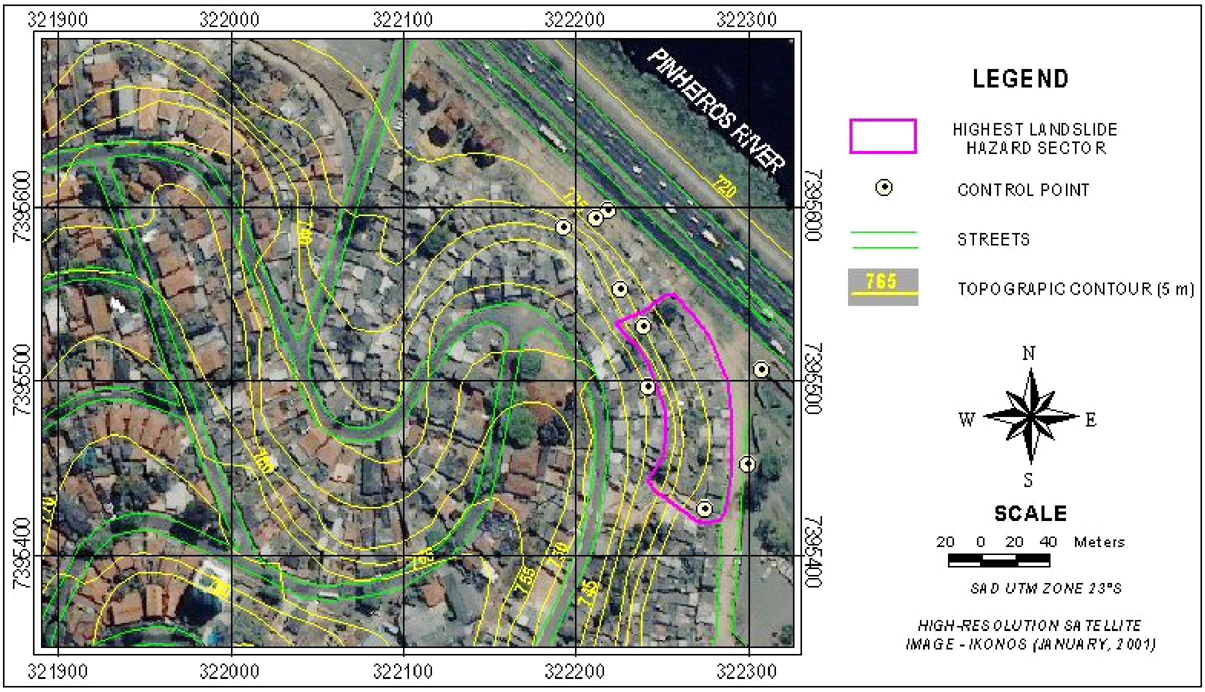

Figure 4. The highest landslide hazard sector located at the digital cartographic base used during initial steps of the study.

Figure 5. Partial overview of the highest landslide hazard sector identified in the Jaguaré slum.

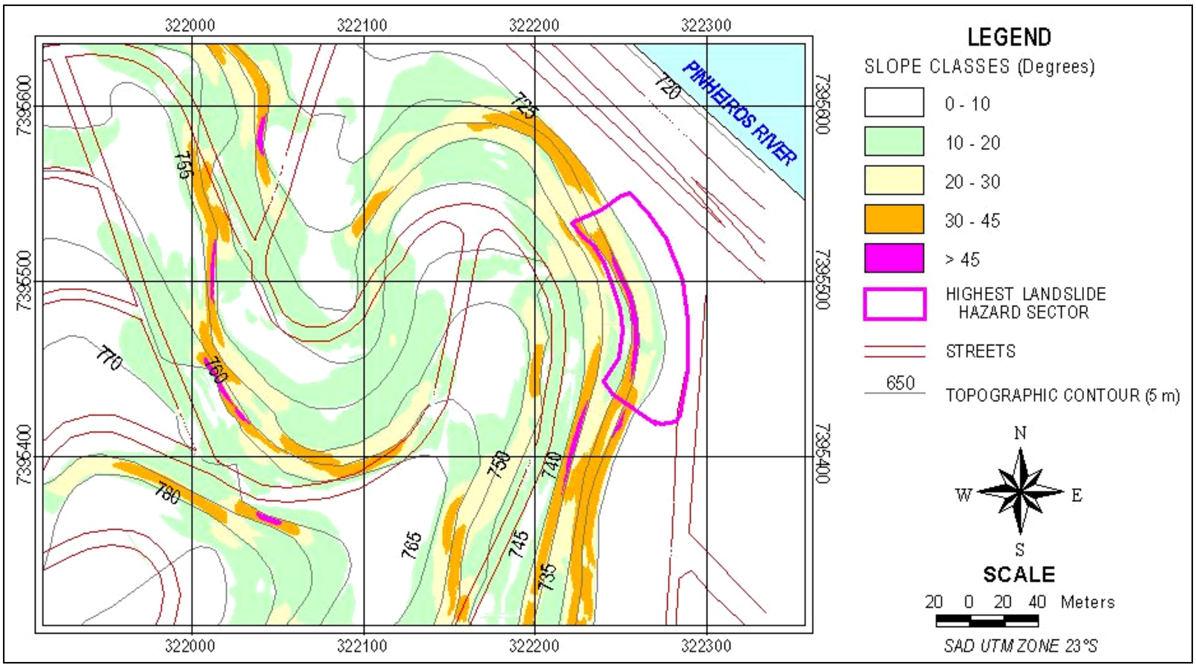

Figure 6. Slope map and highest landslide hazard sector identified in the Jaguaré slum.

Table 1. Distribution in area of the slope classes.

Slope Classes (degrees)	Percentage of Total Area (%)	
	Jaguaré slum	Sector*
0 to 10	42.2	0.0
10 to 20	35.6	30.7
20 to 30	14.6	43.2
30 to 45	7.0	18.3
Upper to 45	0.5	7.9

*The highest landslide hazard sector without its base area.

Table 2. Distribution in area of the slope curvatures.

Slope Curvature	Percentage of Total Area (%)	
	Jaguaré slum	Sector*
Convex	59.0	75.9
Flat	24.4	14.4
Concave	16.6	9.7

*The highest landslide hazard sector without its base area.

Detailed surface and subsurface investigations

The surface investigations comprised detailed topographic survey and new field surveys. The detailed topographic survey was carried out at a scale of 1:1,000 with topographic contours of one meter. The newly identified hazard areas were mapped to improve the eventual reallocations of land within the implementation of the mitigation civil works. New fieldwork was carried out to characterize the typical weathering profiles present in the highest landslide hazard sector, to identify the geological structures and its potential influence on the triggering mechanisms of slope processes and to observe the human modifications that act on the slope susceptibility degree (points of concentration of pluvial and served water, inappropriate cuts and landfills, structural fragility of the edifications and others, (Figure 7).

Some outcrops of rock occurred in the extreme north of highest landslide hazard sector. They expose a migmatite with gneissic paleosome very weathered and fractured, middle texture, cataclastic foliation and presenting pink to orange colours with dark grey horizons (paleosome). The main foliation presents strikes ranging from E-W to N70^{o}W and dips 60^{o} to 70^{o} S or SW. A fracture family with attitude N-S/sub-vertical was also identified. The slope of highest landslide hazard sector dips manly to E and NE, therefore, the main foliation and the fracture family do not influence the slope stability.

The eight boreholes standard penetration tests were realized distributed on three sections perpendicular to the slope of the highest landslide hazard sector (Figure 8). The typical weathering profile of the highest landslide hazard sector presents the following geotechnical units from the surface:

- Debris deposit: not compacting landfill with 0.5 to 1.5 meters of thickness, heterogeneous texture (clay, silt and sand) including trash materials (plastic, residues of civil construction, etc.), dark grey to heterogeneous colours and SPT values less than 2 (very soft);

- Lateritic or superficial soil: until 2.0 meters of thickness, homogenous and porous structure, cohesive behaviour, clay sand texture with granules of quartz, yellow to orange colours and SPT values ranging from 2 to 4 (soft);
- Residual soil (migmatite): thickness variable, foliate structure, sand silt texture with clay, mica, granules of quartz and feldspar, pink colours and SPT values ranging from 8 to 30 (firm to very stiff);
- Very weathered rock (migmatite): texture, structure and colours similar to the saprolitic soil and SPT values upper to 30 (hard to impenetrable).

The main geotechnical units and the groundwater levels identified by the subsurface investigation were represented on detailed geotechnical sections (Figure 9). The analysis of the results obtained with the detailed geological and geotechnical investigations pointed to the following main conclusions to support the concept and the layout of the mitigation civil works:

- There are shallows debris deposit and lateritic soil horizons with reduced shear strength (SPT values less than 2) covering all slope of the highest landslide hazard sector;
- The boreholes located on the base of the slope indicated that the bedrock presents depths less than 4.0 meters in this region. This is compatible with the outcrops of rock observed also in the base of slope in the extreme north of the area;
- There is a debris deposit located in the base of geotechnical section 1 probably related to an ancient landslide;
- The bedrock tends to become shallow from the south (section 1) to the middle of the area (section 2) and it becomes deeper again from the middle to the north of the area (section 3). The ground water surface has a similar behaviour;
- The slope instability processes more probable to occur are the shallow landslides involving the debris deposit and the lateritic horizons. The large and deep debris slides (soil and weathering rock) controlled by geological structures seem unlikely to occur.

Figure 7. Typical occupation presents in the highest landslide hazard sector.

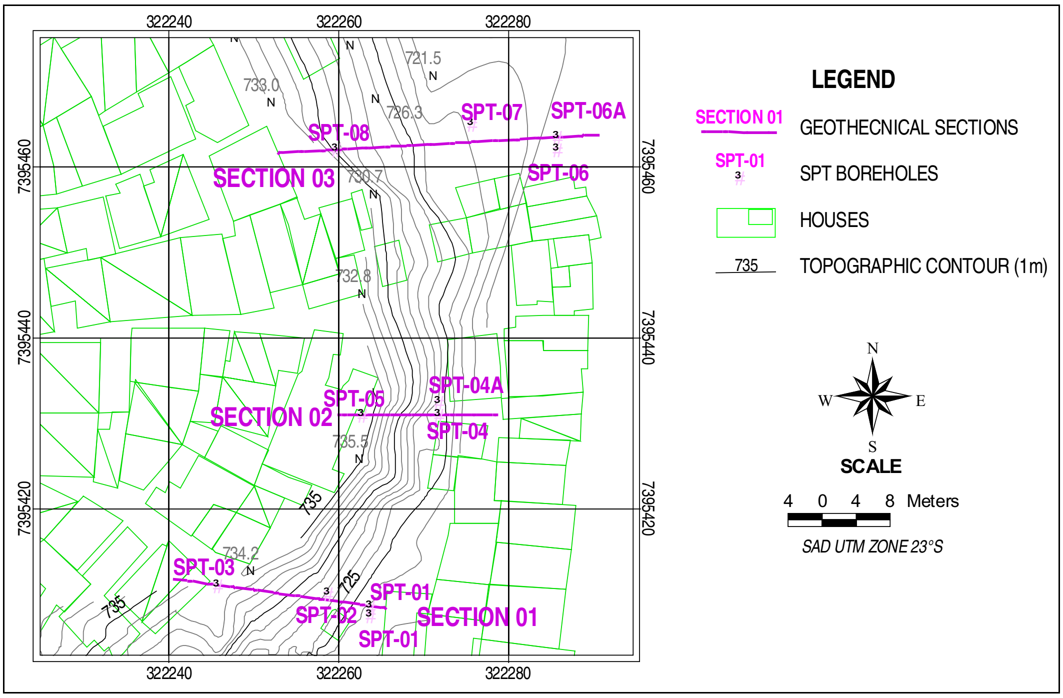

Figure 8. Localization of the SPT boreholes and the geotechnical sections (detailed topographic survey).

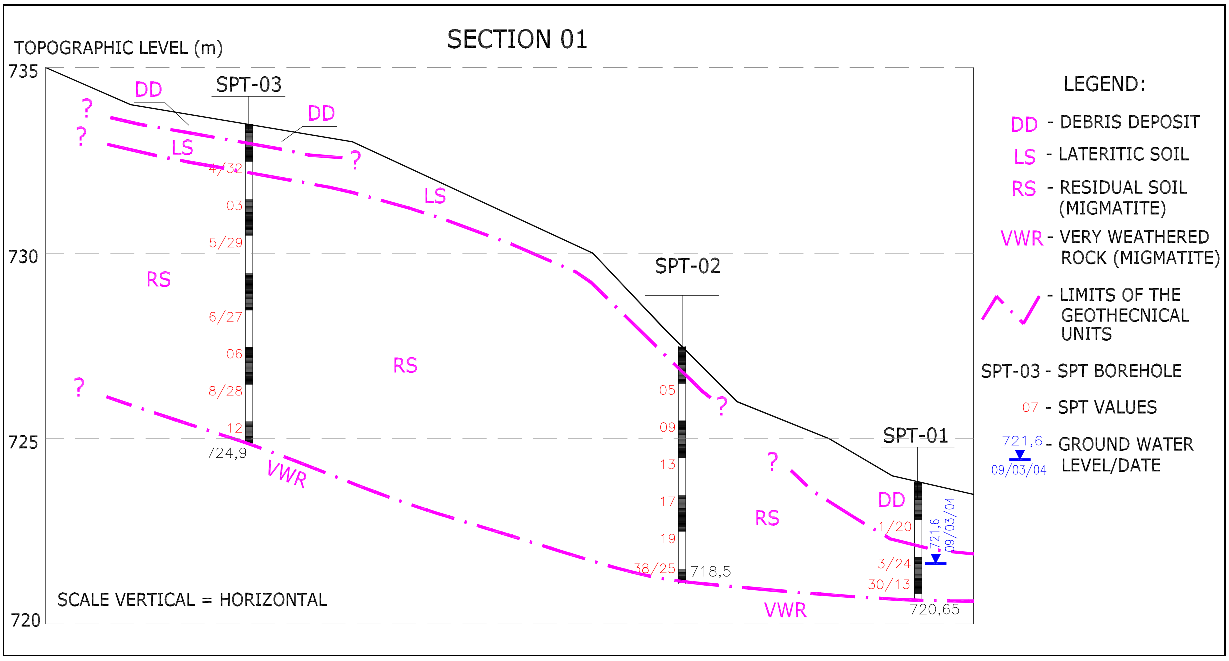

Figure 9. Typical profile mapped along the geotechnical section 1.

CONCLUSIONS

- The approach adopted in the study was considered adequate to provide a project of mitigation civil works with a good cost-benefit ratio, which is fundamental in this case, where the economic resources are limited and the landslides hazard areas to mitigate are many;
- The consideration of different scales of work using the GIS tools, the detailed surface and the subsurface investigations together provided the knowledge of the main geological, geotechnical and occupation parameters present in the study area;
- It was possible to identify the highest landslide hazard sector inside the Jaguaré slum and to point to it the detailed investigations maintaining a compromise between cost and the need to provide the necessary parameters to the concept and the layout of the mitigation civil works;

- The shallow landslides involving the debris deposit and lateritic horizons are the slope instability processes more probable to occur in the highest landslide hazard sector of the Jaguaré slum. The large and deep debris slides (soil and weathering rock) controlled by geological structures seem unlikely to occur;
- Considering the conclusion above, the mitigation civil works proposed will involve mainly small excavations to remove the deposit of debris and to improve the geometric conditions of the slope, the implementation of an adequate surface drainage system on all sector, the implementation of slope protection by vegetation and to move some houses to more favourable areas.

Corresponding author: Dr Oswaldo Augusto Filho, USP-Engineering School of São Carlos, Av. Trabalhador São-carlense, 400, São Carlos, São Paulo, 13560-970, Brazil. Tel: +55 16 3373 8268. Email: oafilho@sc.usp.br.

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