Application of the SHALSTAB model for the identification of areas susceptible to landslides: Brazilian case studies.

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ABSTRACT

Since the 1960s, catastrophic and generalized events of hazardous mass movements caused millions of dollars in economic losses and resulted in thousands of fatalities and homelessness in Brazil. To understand these processes and attempt to predict them, mathematical models have been utilized world-wide describing the physics of the process through mathematical equations. The objective of this study was to present two areas widely affected by shallow landslides where the SHALSTAB model was applied to understand the process and to predict potentially unstable areas in several hydrographic basins. Simulations utilized the types of distinct data that were available in each area. From both areas, geotechnical data collected in the field, topographical data from digital topographical maps and Digital Terrain Models (DTM) from Light Detection and Ranging (LiDAR) were utilized. Susceptibility maps were validated using two indexes, scar concentration (SC) and landslide potential (LP), based on landslides that occurred in 1985 and 2011. Both indexes showed satisfactory results given that the unconditionally unstable category described more than 45% of the landslide events, and the LP index displayed the highest values for the most unstable categories.

KEYWORDS

Serra do Mar; LiDAR; Landslide Potential; Natural Disasters

1. Introduction

Landslides in Brazil occur predominantly in steep slopes associated with high rainfall indexes, particularly in summer. Between 1988 and 2015, 4,000 fatalities were recorded as a consequence of 773 events in 243 municipalities (Macedo and Martins, 2015). These authors also showed that the states of Rio de Janeiro, São Paulo, Minas Gerais and Santa Catarina had the highest number of fatalities. Starting in the 1960s, important events considered catastrophic were recorded, resulting in millions of dollars in economic losses, thousands of fatalities and homelessness. A few events marked the history of Brazil, particularly in the years 1966, 1967, 1985, 1988, 1995, 2008, 2009, 2010, 2011 and 2014 (Fig. 1).

Figure 1 (a) Mass movements at Serra do Mar near the municipality of Caraguatatuba in 1966/1967, at Santa Catarina in 2008, at Rio de Janeiro in 2011 and at São Paulo in 2014. Sources (a) Caraguatatuba municipality archives, (b) and (d) photo credits: Marcelo Gramani, and (c) personal archives

2. Serra do Mar and Study Areas: Copebrás Basin and Bom Brinquedo Basin

The Serra do Mar mountain range in southern Brazil is a geological-geomorphological compartment that extends for 1,500 km. It is characterized by frequent mass movements associated with the rainy season between December and March when 60% of the annual mean precipitation of 3,300 mm occurs

(Meis and Silva, 1968; Fúlfaro *et al.*, 1976; de Ploey and Cruz, 1979).

One of the largest events occurred in the municipality of Caraguatatuba, São Paulo State, where precipitation reached 947 mm in March 1967, with 115 mm on the 17th and 420 mm on the 18th of that month. This triggered numerous landslides and debris flows across a radius of 15 km resulting in 440 fatalities (de Ploey and Cruz, 1979).

On January 23rd and 24th, 1985, 380 mm of rain over a 48 h period, corresponding to 40 to 60% of the typical January monthly rainfall in the area, caused severe shallow landslides that reached the main drainage network at Serra do Mar in the municipality of Cubatão (state of São Paulo), and caused a highly destructive debris flow (Massad *et al.*, 2000; Kanji *et al.*, 2003).

On January 11th and 12th, 2011, rainfall reached approximately 300 mm/48 h and more than eight municipalities in the Serra do Mar region located in Rio de Janeiro were affected by 3,562 landslides that caused more than 1,500 deaths and serious damage to urban and rural infrastructures due to heavy preceding rainfall (Coelho Netto *et al.*, 2011).

In view of this, efforts have been made to comprehend mechanisms that trigger these processes and to integrate factors related to the soil, topography, morphometry of relief and drainage, rainfall volume, and hydrological monitoring (Fernandes *et al.*, 2004). Furthermore, particularly after the 2011 mass movement events, the Brazilian government passed a law related to the production of susceptibility maps, particularly regarding landslides and flooding, to ensure the production of maps that indicate areas with higher or lower degree of susceptibility focused on hydrographic basins.

To exemplify the application of the SHALSTAB model, two areas in Serra do Mar that were widely affected by shallow landslides in different periods were selected, one located in the state of São Paulo and one in the state of Paraná (Figures 2 and 3).

Serra do Mar is one of the most relevant orographic features in the Atlantic coast of the South American continent, and it is known for

having the most “Tormented” relief in Brazil due to its slopes, tectonic processes and faults. It is an outstanding feature in the Brazilian terrain for its grand geomorphological features and its role on human occupation from the colonial period to present (Almeida, 1953).

Geomorphological features in the São Paulo State portion of Serra do Mar display several natural features, primarily those associated with lithological, structural and climatic conditions. Geologically, the main escarpments of this unity are associated with the most resistant rocks such as granite, granite gneiss, alkaline and basic intrusions and quartzite. Thus, natural processes of mass movement are common in this area, which is subjected to high annual mean rainfall and long-lasting rainfall events. Some stretches display the highest volumes of rain in Brazil, together with the Amazon region, where approximately 5,000 mm/year has been recorded.

where the main petrochemical companies in the country are hosted. Migmatite and schists are the predominant rock types, 60% of the escarpments are convex and concave at 30 to 40 degree angles, and a large portion faces the southeast, south and southwest (Vieira *et al.*, 2010).

The *Bom Brinquedo Basin* extends for 0.16 km² and is located north of the urban perimeter of the Antonina municipality (state of Paraná). In March 2011, the municipality was affected by generalized mass movements triggered by 98.6 mm of rainfall on the day of the occurrence and an accumulation of 263 mm between March 1st and March 11th, 2011. In this basin area, porphyritic granite is the predominant rock type, interspaced by diabase dikes, with the slopes most affected by landslides having an inclination of 20° to 30° and predominantly concave (Martins *et al.*, 2017b).

Figure 2 Location of the two basins in the states of São Paulo and Paraná related to Serra do Mar.

The *Copebrás Basin* in São Paulo state extends for 3.6 km² and was affected by approximately 400 shallow landslides on January 23rd and 24th, 1985. The basin is located in a heavy-traffic highway network through which a large portion of Brazilian exports are transported to the port of Santos. The Cubatão Industrial Park is also located in this region,

3. Methods and Materials

3.1 Model

One of the methods used to predict shallow landslides in susceptible areas employs physics-based mathematical models, which physically describe the processes through mathematical equations and disregard the subjective or direct opinion of the researcher. Beginning in the 1990s, two important physics-based mathematical models were developed: the *Distributed, Physically Based Slope Stability Model* (dSLAM), created by Wu and Sidle (1995), and the *Shallow Landsliding Stability Model* (SHALSTAB) of Montgomery and Dietrich (1994). In the late 1990s and early 2000s, three additional models were developed: *Stability INDEX MAPping* (SINMAP) by Pack *et al.* (1998); Pack *et al.* (2001); *Transient Rainfall Infiltration And Grid-Based Regional Slope Stability* (TRIGRS) and *Shallow Landslides Instability Prediction* (SLIP) by Montrasio and Valentino (2008).

SHALSTAB was developed from propositions by Montgomery and Dietrich (1994), Montgomery *et al.* (1998) and Dietrich *et al.* (1998) that spatially represent the potential susceptibility of shallow translational landslide occurrences for a given hydrographic basin with the compilation of a slope

stability model and a steady-state hydrological model, which is analyzed based on the topography. The combined models provide a ratio between the precipitation and soil transmissivity that can lead to slope failure (Equation 1). The first model is based on the slope stability model that uses the infinite slope equation, which defines a ratio between the support tension and material destabilization. The second model is based on the propositions by O'Loughlin (1986), who considers the ratio between the concentration and transmissivity of water in the soil, providing the spatial standard of soil saturation equilibrium, defined by an upstream source area. The combined model may be expressed in terms of the critical ratio of rainfall to soil transmissivity necessary to cause a landslide:

$$\text{Log} \left(\frac{q}{T} \right) = \frac{\text{sen} \theta}{\left(\frac{a}{b} \right)} \left[\frac{C'}{\rho_w g z \cos^2 \theta \tan \phi} + \frac{\rho_s}{\rho_w} \left(1 - \frac{\tan \theta}{\tan \phi} \right) \right]$$

where,

q = critical rainfall to cause rupture [mm/day]

T = soil transmissivity [m^2/day]

a = contribution area [m^2]

b = length of cell contour [m]

θ = slope angle [$^\circ$]

ρ_w = water density [g/cm^3]

g = gravity acceleration [m/s^2]

z = soil thickness [m]

ρ_s = global density of saturated soil [g/cm^3]

ϕ = angle of internal friction [$^\circ$]

c' = effective soil cohesion [kPa]

In Brazil, most studies utilize mainly the SHALSTAB (Guimarães *et al.*, 2003; Fernandes *et al.*, 2004; Zaidan and Fernandes, 2009; Vieira and Ramos, 2015; Martins *et al.*, 2016) and SINMAP models (Lopes, 2006; Michel *et al.*, 2014; Nery and Vieira, 2014) and, to a lesser extent, the TRIGRS model (Rabaco, 2005; Vieira *et al.*, 2010). Thus, the objective of this study was to present two areas widely affected by shallow landslides in Serra do Mar where the SHALSTAB model was applied to understand the process and to predict unstable areas in hydrographic basins of distinct dimensions.

Figure 3 (a) Generalized landslides in Serra do Mar near the Copebrás Basin. Source: Institute for Technological Research of São Paulo and (b) landslide in the Bom Brinquedo Basin. Source: personal archives.

3.2 Topographic Data

To evaluate the landslide susceptibility, simulated scenarios were created using data available from each area. For the Copebrás Basin, a 5 m resolution Digital Terrain Model (DTM) was used from a topographic contour map at a 1:10,000 scale.

For the Bom Brinquedo Basin, the 1 m resolution DTM was obtained from an airborne LiDAR system using an OPTECH 2050 device. Raw data from LiDAR were processed in ArcGIS Desktop version 10.3 (<http://desktop.arcgis.com/en/arcmap/10.3/get-started/quick-start-guides/arcgis-desktop-quick-start-guide.htm>). First the LiDAR data was filtered to include only data corresponding to the terrain using the *LAS Dataset* toolbox, subsequently it was applied the Natural Neighbor interpolator to

generate a raster surface. While these settings were appropriate to generate the DTM, limitations were identified caused by the data point density corresponding to terrain and, consequently, the interpolation of these points in a continuous surface. These limitations tend to directly affect the grid quality and, thus, the spatial resolution of the cells. These limitations are discussed in the literature for quite some time, e.g., Cowen *et al.* (2000), who evaluated the effects of forest canopy density on the number of points corresponding to terrain, estimating that between 10% and 40% of the laser pulses will reach the terrain surface in an area of 80% and 90% of forest coverage.

3.3 Geotechnical Data

To generate susceptibility scenarios for both basins, field data collected in other studies were used. For the Copebrás Basin, geotechnical data by WOLLE and CARVALHO (1989) were used, who collected and analyzed field data near one of the scars (Table 1). This was one of the main *in situ* geotechnical and hydrological surveys that aimed to understand infiltration of pluvial waters in non-saturated soils and its effect on triggering shallow translational landslides by the elimination of suction pressure. In this study, two pilot areas in Serra do Mar located on steep ($>30^\circ$), linear slopes were selected, one of which is near the Copebrás Basin.

Table 1 Topographic and geotechnical data used in both basins.

Parameters [unit]; Basin	Copebrás	Bom Brinquedo
DTM	topographic map (1:10,000 scale)	LiDAR
Soil cohesion (c) [Pa]	1000	0
Internal angle of friction (Φ) [$^\circ$]	34	31
Total unit weight of soil (ρ_s) [g/cm^3]	1.7	2.6
Soil maximum thickness (z) [m]	3.0	1.0

For the Bom Brinquedo Basin, detailed *in situ* geotechnical data were obtained by Lopes (2013) for soil physical properties (angle of friction, cohesion, natural relative specific weight and saturated relative specific weight) to correlate soil

thickness and the water table level within unstable areas of the slopes.

3.4 Validation of the Susceptibility Maps

To validate the susceptibility maps, two indexes were used based on scar maps of landslides that occurred in 1985 in the Copebrás Basin and in 2011 in the Bom Brinquedo Basin: scar concentration (SC), defined as the ratio between the number of cells from each category affected by scars and the total cells affected in the basin; and landslide potential (LP), defined as the ratio between the number of cells from each category affected by scars and the total number of cells from the corresponding category.

The Copebrás Basin scar map was generated from an aero-photogrammetric survey (color diapositive infrared films) performed by the National Institute of Spatial Research in August 1985 at a 1:25,000 scale. Mapping was based on a visual analysis using the absence of vegetation and the slope position as the primary criteria. Slope position was defined from other studies performed in the Serra do Mar in São Paulo State, showing that ruptures of shallow translational landslides occur in the upper third portion of the scar.

The scar map for the Bom Brinquedo Basin was obtained by Martins *et al.* (2017a) by evaluating previous studies and producing a new map based on the terrain morphology characteristics, such as slope inclination and curvature associated with the contribution of the basin area.

4. Results and Discussion

4.1 Copebrás Basin

Class frequency (F) showed that 30% to 40% of the basin area was classified as unconditionally unstable (**Figures 4 and 5**). The area corresponding to the other categories decreased dramatically, remaining fairly constant until the class $\log(Q/T) > -2.2$. The unconditionally stable category occupied less than 7%.

Figure 4 Copebrás Basin susceptibility map.

The evaluation of SC showed that the unconditionally unstable category characterized approximately 66% of the scars. However, considering the cumulative percentages of this index in each class, 76% of the landslides were in the $\log(Q/T) < -3.1$ category, 82% in the $\log(Q/T) < -2.8$ category, and 89% in the $\log(Q/T) < -2.5$ category. These results are similar to those reported by Montgomery and Dietrich (1994) and Dietrich *et al.* (1998) in studies in the Western United States, for which 83% to 100% of the scars were characterized by $\log(Q/T) < -2.5$. Slightly lower cumulative percentages were obtained by Dietrich *et al.* (1998), who identified that only 54% of the landslides correspond to $\log(Q/T) < -3.1$, 68% correspond to $\log(Q/T) < -2.8$ and 90% correspond to $\log(Q/T) < -2.5$.

Such variability in scar concentrations, considering the cumulative percentages and the limits of $\log(Q/T)$, is a function of the quality and resolution of the DTM grids. According to these authors, to obtain more than 60% of the scars in a 30 m² grid, a $\log(Q/T) < -2.5$ limit is needed. For a 10 m² resolution grid, a $\log(Q/T) < -2.8$ limit may be more appropriate and for high resolution DTM, the limit can be $\log(Q/T) < -3.1$.

Figure 5 Susceptibility class distribution (F), scar concentration (SC) and landslide potential (LP).

The LP analysis reveals a better agreement between the SHALSTAB predictions and the scar map. The highest LP indexes were recorded in the unconditionally unstable category, decreasing dramatically in the $\log(Q/T) < -3.1$ category and then gradually until the $\log(Q/T) > -2.2$ category. The lowest LP values were identified in the unconditionally stable category.

4.2 Bom Brinquedo Basin

In contrast to the previous basin, the highest frequency values were obtained for the two most stable categories (unconditionally stable and $\log(Q/T) < -2.2$), which together represented almost 80%, followed by the unconditionally unstable category, which corresponded to approximately 20% (Figures 6 and 7).

The four intermediate classes had very low values that altogether accounted for less than 1%, and two categories had null values ($\log(Q/T) -2.8$ to -2.5 and -2.5 to -2.2). However, in the SC index, the unconditionally unstable category had the highest value, nearly 45% of the scars, and the two most stable categories together accounted for 55% of the scars.

Notably, scars occurred in all areas defined as unconditionally unstable, which is considered a positive model output. Although there are areas belonging to this category that were not involved in the 2011 event, they can still be considered susceptible to slope failure given that the model does not provide a timeframe for the occurrence of landslides. Thus, it is not feasible to interpret an overestimation of the model in that regard.

Intermediate categories also displayed null values or values lower than 0.12% for this index, which was reflected in the LP and, in turn, had the

highest values for the unconditionally unstable (24.80%) and the $\log q/T < -3.1$ (20%) categories. The two most stable classes displayed values similar to the previous scenarios, together accounting for nearly 16% of the basin area. The classes $\log q/T < -3.1$ and -3.1 to -2.8 had high values for this index despite being less relevant when the frequency and scar concentration results were analyzed.

The distribution of values and particularly the null values in some of the categories are similar to results previously reported by (Martins *et al.*, 2017a), including null values for the same categories. These authors analyzed the effects of data in the generation of the Digital Terrain Model, comparing models generated from contours and from LiDAR, using the SHALSTAB in a basin adjacent to the Bom Brinquedo Basin.

Figure 6 Bom Brinquedo Basin susceptibility map.

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