THE NUMERICAL MODELING AS AN INSTRUMENT FOR ASSESSING THE POTENTIAL OF DEBRIS FLOWS: AN APPLICATION IN THE SERRA DO MAR IN SÃO PAULO STATE, BRAZIL

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Resumo – Fluxos de detritos são processos hidrogeomorfológicos que se desenvolvem ao longo de redes de drenagem e envolvem fluidos geralmente densos, compostos por materiais de diferentes granulometrias, além de madeira e quantidades variáveis de água. Por sua capacidade de percorrer longas distâncias e atingir altas velocidades, sua ameaça e risco é maior do que outros processos geodinâmicos. Matematicamente, podem ser descritos como um fluido monofásico composto por um líquido intersticial e um fluido granular que constitui a fase sólida e possui propriedades reológicas adequadas. Assim, este trabalho tem como objetivo mostrar os resultados da simulação numérica com o modelo *RAMMS* (*Rapid Mass Movement Simulation*) dos eventos de fluxo de detritos que ocorreram em 1967 em uma área montanhosa na Serra do Mar na região de Caraguatatuba (SP) utilizando *inputs* calibrados (viscosidade, MDT - Modelo Digital do Terreno, cicatrizes de escorregamento como áreas de lançamento do material, densidade do material do fluxo de detritos, duração do processo de fluxo de detritos, informações relativas à erosão promovida pelo processo e ortofotos). As simulações dos diferentes cenários revelaram que os materiais mobilizados pelos escorregamentos nas escarpas dos tributários dos rios Santo Antônio e Guaxinduba foram canalizados nos talvegues e avançaram à jusante, onde prevalecem declividades menores que 5º. Em geral, os resultados mostraram uma boa correlação entre a área e a espessura de deposição modelada e observada, e o trabalho de campo e os estudos de retroanálise revelaram que os fluxos de detritos da Serra do Mar têm um fluxo reológico predominantemente granular.

Abstract – Debris flows are hydrogeomorphological processes that develop along drainage networks and involve generally dense fluids, composed of materials of different grain sizes, wood, and variable amounts of water. Their threat is greater than other geodynamic processes because they can cross long distances and reach high speeds. Mathematically, it can be described as a one-phase fluid composed of an interstitial liquid and a granular fluid that constitutes the solid phase and has proper rheological properties. Thus, this work aims to show the results of the numerical simulation with the *RAMMS model (Rapid Mass Movement Simulation)* of the debris-flow events that occurred in 1967 in a mountain area in the Serra do Mar in Caraguatatuba region (São Paulo State, Brazil) using calibrated input parameters (viscosity, DEM, landslide scars as release areas, the density of the debris-flow material, duration of the debris-flow process, erosion information, and orthophotos). The simulations of the different scenarios showed that the materials mobilized by the landslides in the escarpments of the tributaries of the Santo Antônio and

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Guaxinduba rivers were channeled in the thalwegs and advanced downstream, where slopes lower than 5º prevail. In general, the results showed a good correlation between the area and thickness of deposition modeled and observed. The fieldwork and the retro-analysis studies revealed that the Serra do Mar debris flows have a predominantly granular rheological flow.

Palavras-Chave – *Software* de simulação; Modelo *RAMMS*; Processos hidrogeomorfológicos; Serra do Mar.

1. INTRODUCTION

The debris flows are hydrogeomorphological processes characterized by their high erosive capacity and with a large volume of water in their flow, capable of mobilizing materials of different compositions and dimensions during their trajectory, which behave are highly viscous, dense, and concentrated to hyperconcentrated fluid. They are often initiated by heavy rainfall and/or landslides.

Kang and Lee (2018) highlight that because they can cross long distances and reach high speeds, the threat of debris flows is greater than other geodynamic processes. In general, these processes are characterized by a movement in the form of flow, involving generally dense fluids, composed of coarse material and fine material, as well as plant remains and varying amounts of water, behaving as, highly viscous, dense, and concentrated to hyperconcentrated fluids (Ni and Wang, 1990). Due to these characteristics, added to its high range, even in flat areas, high speeds, and high peak flows, the debris flows have a high capacity of erosion and impact force, which give them great destructive power, and, therefore, are classified as high-risk factor processes, which can cause loss of life and considerable physical damage to infrastructure and the environment (Downling and Santi, 2013; Kang and Lee, 2018).

Mathematically, debris flows can be described as a one-phase fluid composed of an interstitial liquid and a granular fluid that constitutes the solid phase and has proper rheological properties (Iverson, 1997; Rosatti and Begnudelli, 2013; Liu et al., 2017). This represents a simplification of a debris-flow process where the main components are water and solid material consisting of a wide range of grain sizes (Rickenmann et al., 2006). Thus, several numerical models have been elaborated in the last years, to measure, identify, predict, and monitor debris-flow processes with more accuracy, such as FLO-2D, KANAKO 2D, and MassMov2D (Pudasaini, 2005; Wu et al., 2012). One of these models is RAMMS (*Rapid Mass Movement Simulation*), which uses a single-phase model, that doesn't distinguish between fluid and solid phases and the material is modeled as a bulk flow. This model describes the frictional behavior of debris-flows movement using the Voellmy relation (Christen et al., 2010).

Due to these characteristics, the phenomenon occurs naturally in mountainous regions, usually associated with high rainfall (Gramani, 2001; Takahashi, 2014). Collins and Znidarcic (1997) point out that in tropical and coastal areas mass movements in the form of rapid debris flows are common, causing enormous destruction in their trajectory involving different types of soils and geological environments.

In Brazil, the area's most susceptible to its occurrence are those located at the foothills of the Serra do Mar, Serra da Mantiqueira, and Serra Geral (Gramani, 2001). In the municipality of Caraguatatuba, on the northern coast of São Paulo State, on March 18, 1967, one of the most expressive mass movements recorded in the State and Brazil occurred, caused by heavy rains that devastated the region, associated with the escarpment relief of Serra do Mar, causing significant social, economic, and environmental damage, with many losses of human lives (Cruz, 1974; Gramani, 2001). An accumulated rainfall of 586 mm in 3 days triggered widespread landslides on the slopes of the hills and Serra do Mar escarpment, whose materials reached numerous drainages and generated debris-flow processes in the urban area of Caraguatatuba city, destroying 400 houses, and killing 120 people (Cruz, 1974; Gomes et al., 2008a).

In February 2023, in the neighboring municipality (São Sebastião, SP - Brazil) widespread debris-flow processes and landslides were triggered by accumulated rainfall that reached more than 600 mm in 48 hours. Due to population growth, disorderly occupation, and the current climate change scenario, debris-flow occurrence has increased in Brazil in recent years, especially in mountainous areas, which requires extensive knowledge about the factors that trigger these processes (Kobiyama et al., 2010).

Studies involving modeling of debris flows both, retro- and forward analysis are recent in Brazil. The pioneering work of Alvarado (2006) used the Discrete Element Method (DEM) to simulate the debris-flow process and in last year's Lopes and Riedel (2007), Gomes et al. (2008b), Polanco (2010), Bueno et al. (2013), Gomes et al. (2013), Sakai et al. (2013), Silva et al. (2013), Conterato (2014), Pelizoni (2014), Rocha et al. (2014), Sancho (2016), and Silva-Filho (2016) also included in their scope studies of Brazilian debris-flow cases involving mathematical modeling.

Thus, this work aims to show the results of modeling of a debris-flow process that occurred in 1967 in a mountain area in the Serra do Mar in the Caraguatatuba region (São Paulo State, Brazil) (Figure 1) with RAMMS numerical simulation, using parameters calibrated as input, obtained by retro-analysis of the event. In recent years, there has been an increase in the occurrence of these phenomena in Brazil, which demands a better understanding of their conceptual model. The region stands out in the Brazilian scenario being an area where there are important highways that connect the upland to the coast, seaports, railways, pipelines, and industries, in addition to being currently in the process of urban expansion and attracting a large annual flow of tourists, which increases the risk factor for debris-flow movements.

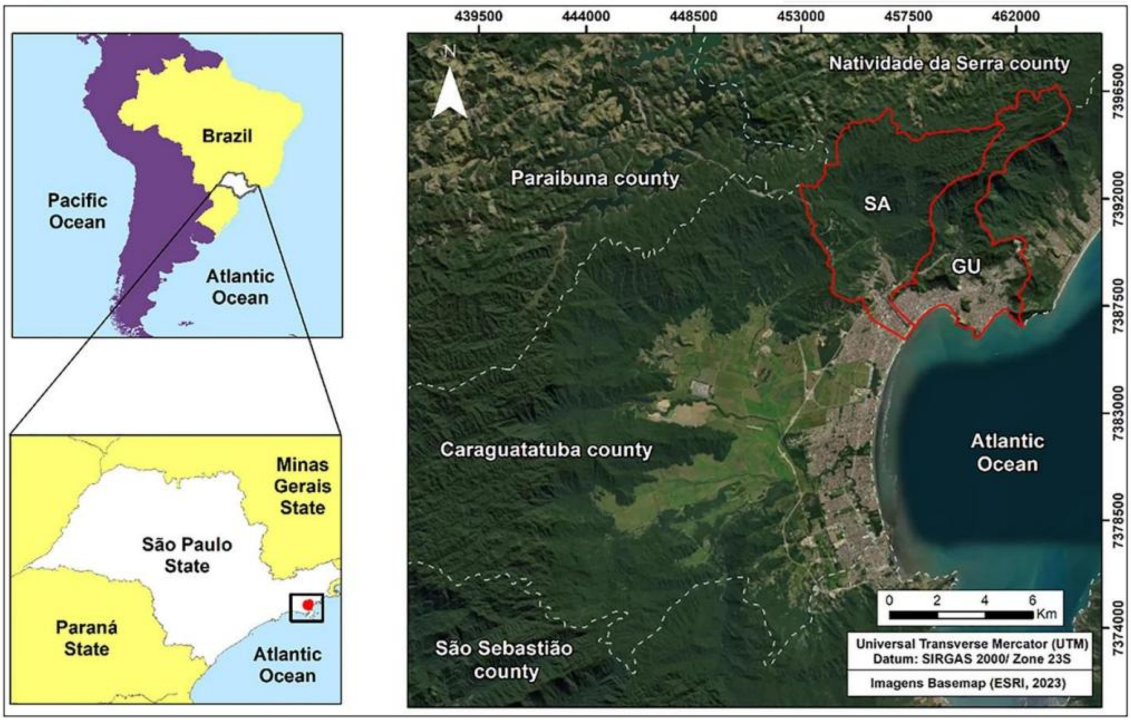

Figure 1. Map of the study area location (highlighted in red). Elaborated by authors (2023).

2. METHODOLOGY

For the study area, the assessment of the potential to debris-flow occurrence was based on the premise that its triggering is closely related to the morphometric parameters, past occurrences of these processes, and the anthropic intervention (Jakob, 1996; Kanji et al., 1997; De Scally et al., 2001; Wilford et al., 2004; Kobiyama et al., 2010; Chen and Yu, 2011; Takahashi, 2014; Cerri et al., 2018).

For the cartographic base, the Caraguatatuba topographic chart (SF-23-YD-VI-1) (IBGE, 1974) was used at a scale of 1: 50,000. In addition, the geological map at 1: 50,000 scale of the Caraguatatuba sheet (CPRM, 1982) was used to subsidize the step of geomorphological and the debris-flow deposit mapping.

As for the remote sensing data, orthophoto images from Emplasa (Paulista Metropolitan Planning Company) (2011) were used at a scale of 1: 10,000 and aerial photographs from 1973 at a scale of 1: 25,000, and high-resolution images from Google Earth Pro® platform were used also, to get more updated information on the land use in the region. Google Earth (GE) was launched in 2005 and has since become one of the most popular virtual globes, with wide use for teaching and research in Geosciences, mainly in studies of landscape forms and processes (Boardman, 2016).

In a GIS environment (ArcGIS 10.8), the respective contour lines and the drainages of the Caraguatatuba topographic chart were georeferenced and incorporated into the digital database as well as the geological map, whose lithological units have been vectorized. From the contour lines the Digital Elevation Model (DEM) and the slope map were created, which helped the geomorphological mapping and the calculation of the morphometric parameters.

2.1. Back-analysis studies of the 03/18/1967 debris-flow processes

The back-analysis studies included the historical retrieval of the variables that involved the debris-flow processes in the Santo Antônio and Guaxinduba watersheds in March 1967, the extraction of the landslide scars, and the mapping of the deposits and their respective thicknesses (Gregoretti et al., 2016). The causes of the debris-flow occurrence were investigated through bibliographical research on reference works, including photographic and cartographic registration.

For the landslides scars extraction aerial photos in 1: 25,000 scale with 1.5 x 1.5 m spatial resolution of the VASP (São Paulo Airway) aerial photogrammetric survey (1973) were selected for the respective procedures. The extraction was performed using photointerpretation techniques in a GIS environment so that the size, the vegetation, the texture, and shape were the criteria considered for the identification (Loch, 1984; Marchetti and Garcia, 1986; Barlow et al., 2003; Guzzetti et al., 2012). The deposit mapping and their respective thicknesses were also carried out in the GIS environment using photointerpretation techniques (Vandine, 1985; Van Steijn, 1996), complementing information with bibliographical data and fieldwork.

2.2. The RAMMS model

RAMMS (Rapid Mass Movement Simulation) is a numerical 2D simulation model developed by the WSL Institute for Snow and Avalanche Research SLF and the Swiss Federal Institute for Forest, Snow and Landscape Research WSL. The physical model of RAMMS uses the Voellmy-Salm continuous flow model (Salm et al., 1990; Salm, 1993) based on Voellmy friction law (1955) and describes debris-flow processes as a continuous model of medium depth. This model divides frictional resistance into two parts: a dry-Coulomb-type friction (coefficient μ) that scales with the normal stress and a velocity-squared drag or viscous-turbulent friction (coefficient ξ). Thus, the friction resistance S (Pa) is defined as (Equation 1):

$$S = \mu\rho Hg\cos(\emptyset) + \frac{\rho g U^2}{\xi} \tag{1}$$

where ρ is the density, g the gravitational acceleration, ∅ the slope angle, H the flow height and U the flow velocity. The normal stress on the running surface, $\rho Hg\cos$ (∅), can be summarized in a single parameter N. RAMMS uses a single-phase model, so we cannot distinguish between fluid and solid phases and the material is modeled as a bulk flow. Regarding the entrainment of bed materials, the version v1.5 does not consider the erosion effect, so it is not possible to predict the increase in volume of the debris-flow material as it travels along the channel. The input parameters of RAMMS are the total volume of the debris flow and the resistance parameters μ and Ɛ. As output data, the program provides values (for each grid cell) of flow height, flow velocity, flow pressure, impact forces, and profiles of height, velocity, and flow pressure at certain locations for projecting structures (Bartelt et al., 2013).

2.3. Debris-flow modeling

Before numerical modeling in RAMMS, the program input parameters were listed and modified according to the model's needs. Thus, the topographic data from the DEM was converted to ASCII format. Moreover, the calculation domain and the release area were transformed into the shapefile format, and the release height was inserted in the program/ imported into the shapefile attribute table of the release areas. The debris flow duration, material density, and μ/ ξ parameters were obtained from bibliographical data (Table 1).

The modeling step in the RAMMS version 1.5 program was performed through the establishment of a simulation routine, based on different release heights, material density, and viscosity (ξ).

3. RESULTS AND DISCUSSIONS

Before the modeling step in RAMMS software, the input parameters were adjusted according to their requirements (Table 1).

Table 1. Input parameters, data source, and numerical parameters required in the RAMMS model. Organized by authors (2023).

Input	Source	Numerical parameter
Topographic data	DEM (1:10,000 scale)	Grid of 8 meters
Release area	Landslide scars from aerial photos (1973)	----------
Release height	Back analysis and fieldwork observations	1.0, 1.3 and 1.5 meters
Calculation domain	Santo Antônio and Guaxinduba catchments	----------
Erosion information	Back analysis	5 meters
Debris-flow duration	Back analysis	45 minutes (2.700 seconds)
Material density	Back analysis	1,700; 1,800; 1,900 and 2,000 kg/m^3
μ (dry Coulomb-type friction coefficient)	Back analysis	0.05
$\mathcal{E}$ (viscous–turbulent friction coefficient)	Back analysis	190 and 200 m/s^2

The simulations of the different scenarios showed that the materials mobilized by the landslides in the escarpments of the tributaries of the Santo Antônio and Guaxinduba rivers were channeled in the thalwegs and advanced downstream, where slopes lower than 5º prevail (Figure 2A and 2B). The debris-flow fan could not be represented by the simulations due to the Digital Elevation Model used (1979). The limitation of DEM is that there are no older topographical bases for the place, since the first aerophotogrammetric surveys in the region date back to 1974 and correspond to the 1:50,000 scale.

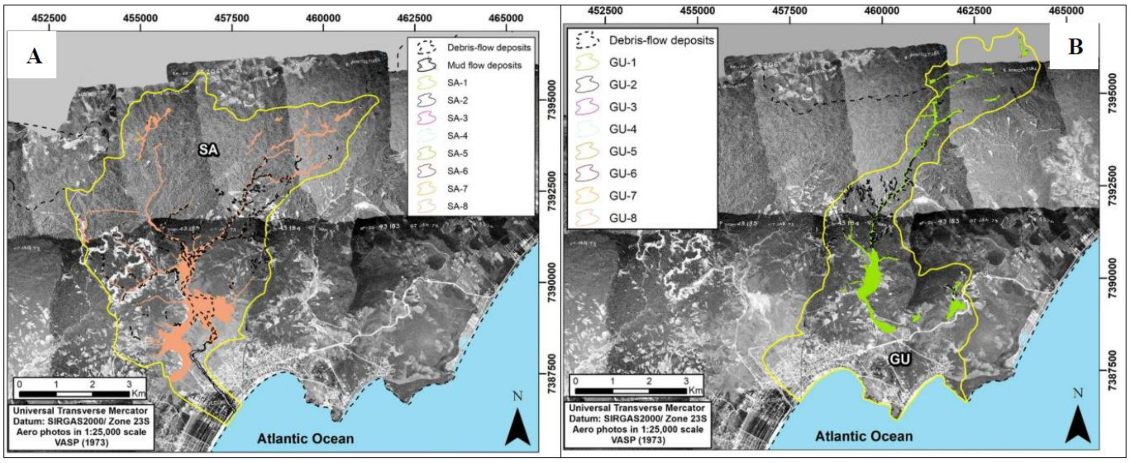

Figure 2. Deposits produced by the RAMMS model from a release height of 1.0 meter vs. deposits mapped on 1973 aerial photographs. (A) Santo Antônio catchment; (B) Guaxinduba catchment. Elaborated by authors (2023).

It is important to highlight that noticeable differences were observed in the Santo Antônio River thalweg, which was originally meandering; after the event, whose date is not precise, the thalweg underwent a process of channelization (Figure 3). The limitation of the DEM is that there are no older topographical bases for the place since the first aerophotogrammetric surveys in the region date back to 1974 and correspond to the 1:50,000 scale. We decided not to use them because the elaboration of a DEM from these data would hinder and reduce the quality of the results.

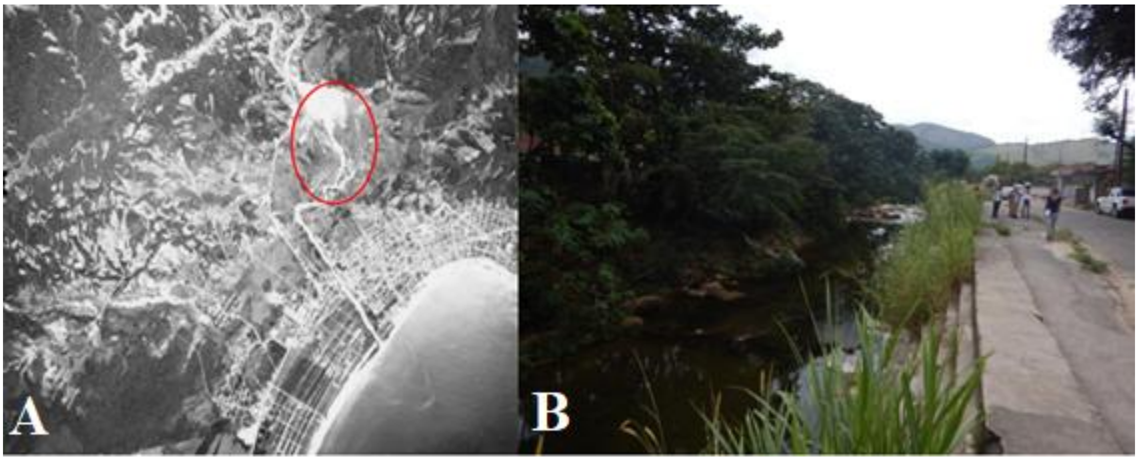

Figure 3. (A) Aerial photo of 1973 showing the unchannelized canal in the plain of the Santo Antônio catchment (marked in red); (B) Channelized sector of the Rio Santo Antônio in the plain (photo from 2016).

The model did not simulate large leakages of the rectified channel of the Santo Antônio River for all the scenarios and the mud flow and mud flood processes in the Guaxinduba River valley, and in this sense, the simulated debris thicknesses inside this watercourse were higher than those observed in the back-analysis step. Although the mapped deposit considered aerial photographs of 1973, 6 years after the event, it is notorious that the debris-flow deposit area that the limitation of the DEM (based on 1979 topographic data) influenced the result calculated by the model, especially concerning the river Santo Antonio in plain area, which was channeled some years after the 1967 event. Hussin et al. (2012), when performing debris-flow modeling in the French Alps in 2003, also verified that changes in channel morphology directly influence the results produced in the simulations in the RAMMS.

4. CONCLUSIONS

The debris flows that occurred in the Santo Antônio and Guaxinduba catchments (Caraguatatuba region, São Paulo State, Brazil) on 03/18/1967 were triggered by widespread landslides on the slopes of the Serra do Mar, which, upon reaching the drainage channels, generated hyperconcentrated flows of a strictly granular nature and with a large volume of material mobilized.

The results of the retro-analysis and modeling showed that landslides occurred preferentially in slope classes from 20 to 350. However, other factors were decisive, mainly the high rainfall ratios that affected the region.

Even though the simulations have not been able to adequately reproduce the geometry of the debris-flow deposits related to the 1967 event in the Santo Antônio basin, they suggest that future debris-flow events are unlikely to form debris cones due to the channeling of the Santo Antônio River.

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