BACK-ANALYSIS OF A LANDSLIDE THROUGH A DYNAMIC METHOD – STUDY CASE OF ITAGUAÇÚ BEACH, ILHA GRANDE, RJ

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Resumo – Entre março e abril de 2022, o Sítio Paraty-Ilha Grande (RJ), reconhecido como Patrimônio Mundial Misto pela UNESCO, foi afetado por um evento climático extremo, com chuvas intensas por vários dias consecutivos. Isso desencadeou diversos movimentos gravitacionais de massa, impactando vias de acesso, áreas de lazer e comunidades tradicionais litorâneas. Este trabalho apresenta uma retro análise de um deslizamento em área turística, utilizando o modelo dinâmico DAM3D®. Dados locais de chuva foram confrontados com limiares críticos conhecidos para a Serra do Mar, e os resultados demonstram que a modelagem dinâmica é mais eficaz que métodos geométricos tradicionais, como o GIDES, para mapear áreas de risco em destinos turísticos isolados.

Abstract – Between the months of March and April 2022, the Paraty-Ilha Grande UNESCO Site was affected by an extreme rain event, which recorded high levels of intensity rainfalls over consecutive days. This climatic event caused several gravitational mass movements that mainly affected access roads, recreational areas, and traditional populations in the coastline. Aiming to contribute to risk management in this area, recently named a UNESCO Mixed Heritage Site, this work presents a back-analysis of a landslide that happened in a tourism destination. Thus, the local rainfall data were checked by known thresholds in Serra do Mar. The landslide was simulated using the dynamic model DAM3D®, and the results highlight the limitations of geometric methods for hazard mapping. This study emphasizes the applicability of dynamic modeling to improve hazard assessments in isolated tourist areas.

Palavras-Chave – Landslide, dynamic analysis, tourism, hazard analysis, Serra do Mar.

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1. INTRODUCTION

Gravitational mass movements (GMMs) encompass various classifications, typologies, and distinct characteristics (Hungr et al., 2014; Varnes, 1984). Each type is defined by a typical rupture geometry, a specific volume of mobilized material, a characteristic runout distance, and a particular velocity during displacement on sloped terrain (Guzzetti, 2006). GMMs, such as landslides, are influenced by a combination of predisposing terrain conditions, preparatory factors, and triggering mechanisms.

Analyzing the predisposing factors of a specific GMM type helps identify areas with a higher likelihood of occurrence, typically represented in susceptibility maps (Bitar, 2014). Once a GMM is triggered, the displaced material moves and propagates based on its properties and interactions with the terrain (Agliardi and Crosta, 2003), i.e., rheology materials involved control the motion. As a result, hazard maps can be created by delineating impact areas according to movement type, frequency, and magnitude (Fell et al., 2005) (Figure 1a). The level of risk also depends on land use and exposure to hazard. Urban developments, linear infrastructure, and tourism areas often contain vulnerable elements and varying perceptions of geohazards. When these exposed elements coincide with hazard zones, a geological risk scenario emerges with several kinds of consequences based the frequency-magnitude of events, underscoring the need for effective risk assessment and management strategies (Figure 1b).

Given this context, risk management practices in Brazil focus on mitigation, planning, prevention, monitoring, and emitting alerts (Pimentel and Santos, 2018). However, hazard analyses based on geometric methods, such as GIDES, have notable limitations compared to other approaches. While this method may effectively map rockfall events (Monticelli et al., 2025), its primary drawback is the generalization of GMM runout distances, which rely solely on topographic criteria without incorporating historical data, such as inventories. This limitation can lead to either overestimation or underestimation of hazard zones, ultimately reducing the accuracy of risk zone delineation.

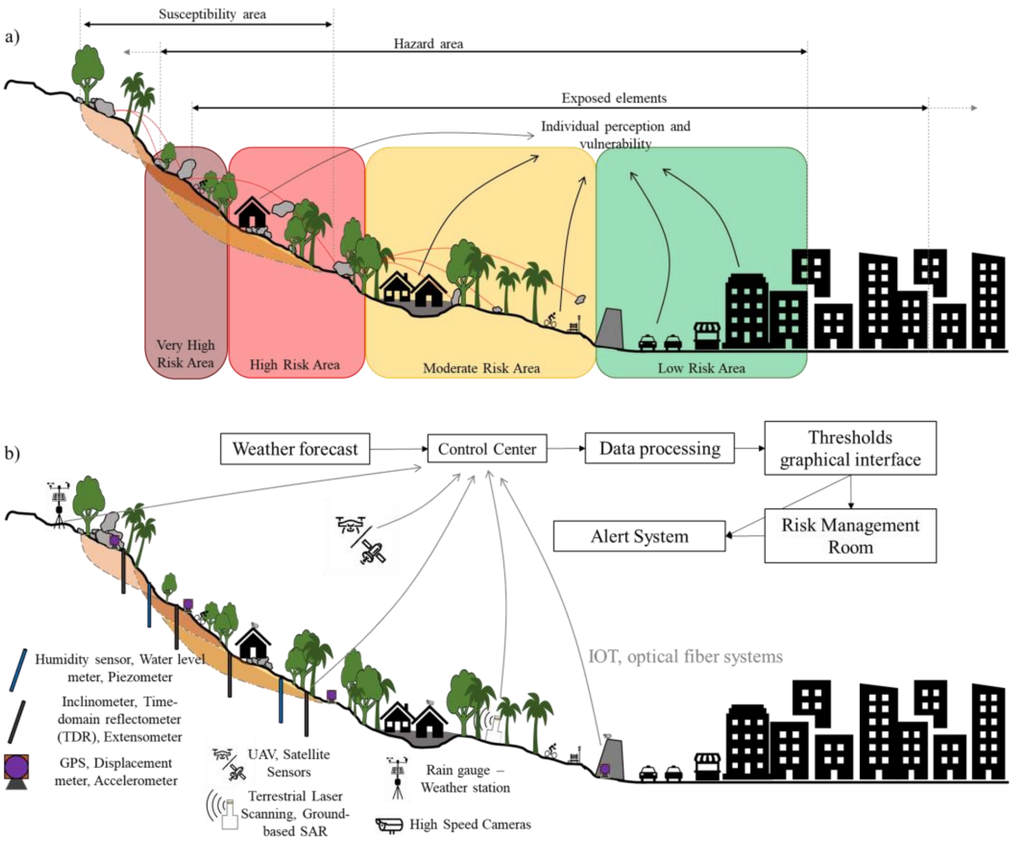

Figure 1. a) Schematic cross section of concepts involved in geological risk for urban, road, and recreational areas and b) slope monitoring applied for risk management plans.

In parallel, dynamic analysis methods provide a more precise approach by accounting for the rheology of material interaction during displacement (Azzoni et al., 1995; Hungr and McDougall, 2009; Revellino et al., 2004). These methods incorporate geological-geotechnical parameters such as physical indices, friction angles, and viscosity, coupling with specific constitutive models to enable more realistic impact estimates. Different types of GMMs, including shallow landslides, deep-seated slides, and debris flows, exhibit distinct behaviors when interacting with the terrain—an aspect that geometric models often fail to differentiate adequately. Consequently, dynamic models refine runout predictions based on the specific behavior of each GMM type (Hungr et al., 1984; Hungr and McDougall, 2009; McDougall and Hungr, 2005).

Research on dynamic analyses that concentrate on GMM travel distance and hazard assessment is still scarce in Brazil. Some existing studies use default parameters from dynamic modeling software (Cabral et al., 2023; Dos Santos Corrêa et al., 2024), while others do not explicitly report them (Veloso et al., 2025). Refining parameter calibration through back-analysis can enhance the accuracy of hazard analysis in the Serra do Mar Mountain Range (SM). Further research on validating and adjusting these parameters would improve the reliability of GMM modeling applied to hazard and risk assessments.

Here, we performed a back-analysis of a shallow landslide that occurred in an adventure tourist area within the Paraty-Ilha Grande UNESCO site. The primary objective of this study was to highlight the limitations of geometric methods in delineating hazard zones associated with high-magnitude events. Also, we reassess the event using dynamic analysis in the Dam3D® software. To achieve this, we compiled rheological parameters for the materials involved with landslide behavior, established relationships between the main parameters, and followed a trial-and-error approach to calibrate them for the landslide deposit area. Additionally, the rainfall event conditions were characterized using rainfall parameters and assessed based on known Brazilian thresholds. Our results demonstrate the feasibility of employing rainfall-based warning systems for isolated risk areas. Furthermore, we identified a reliable range of parameters for landslides within the SM context, suggesting that dynamic analyses can be effectively applied for hazard analysis, offering an alternative to geometric methods. This approach is particularly relevant for isolated tourist destinations prone to summer disasters, where frequently the tourism infrastructures (i.e., buildings, hotels, and camping) are outside the susceptibility area (i.e., source area).

2. THE STUDY AREA AND ITS SHALLOW LANDSLIDE EVENT

The study area is located within the Paraty-Ilha Grande domain, Angra dos Reis, in the state of Rio de Janeiro, Brazil (Figure 2). Notably, this region was awarded the UNESCO World Heritage title in 2019, marking the first global recognition that encompasses both cultural and physical environments. The area is renowned for its attractions, such as the Juatinga trail bypassing Mamanguá Bay and the Atlantic Ocean in Paraty and Lopes Mendes Beach in Ilha Grande, that attract national and international tourists.

However, this region is also situated within the SM, which stretches across several Brazilian states and is known for the occurrences of natural disasters (Figure 2a). In this historical context, we focus on the most recent event, which occurred between March and April 2022. The rainfall event began in late March, and on April 1 and 2, 2022, several GMMs were triggered in the Paraty-Ilha Grande site, including shallow landslides, debris flows, rockfalls, and flash floods. In the Ilha Grande domain alone, approximately 190 scars were identified as being linked to this extreme rainfall event (Figure 2b). Specifically, our study concerns the GMM that occurred at the Itaguaçu Beach in Ilha Grande, which was characterized as a shallow, high-magnitude translational landslide (Figure 3). It is important to emphasize that this scar is part of a comprehensive landslide inventory, including a detailed reconstruction of rainfall conditions from 1963 to 2023—a partnership between Escola de Engenharia de São Carlos-USP, ADDA Consultoria, and Interact—designed to develop and support resilience-focused engineering projects in southeastern Brazil.

The landslide occurred along a relief break at the top of the local watershed. Through GIS analysis using CBERs satellite images, the data were compared before and after the event. It is estimated that the source area of the landslide has approximately 15,112.5 m². Assuming the scar is 2.0 meters deep, the initial volume of mobilized material is approximately 30,225.0 m³. The mobilized material traveled about 915 meters before reaching the coastline, where it was deposited on the beach (Figure 3a-b). Based on local newspaper reports and videos, it is estimated that the material accumulated along the coastal line, the buildings, and the tourism infrastructures areas has at least a depth of 2.0 meters. For the buildings, the landslides provoked their partial destruction and the fatalities of seven persons. Additionally, a noticeable change in the color of the seawater across the entire bay was noticed by locals at this event (Figure 3b-c), similar to what happened in 2010 – the Sankay event.

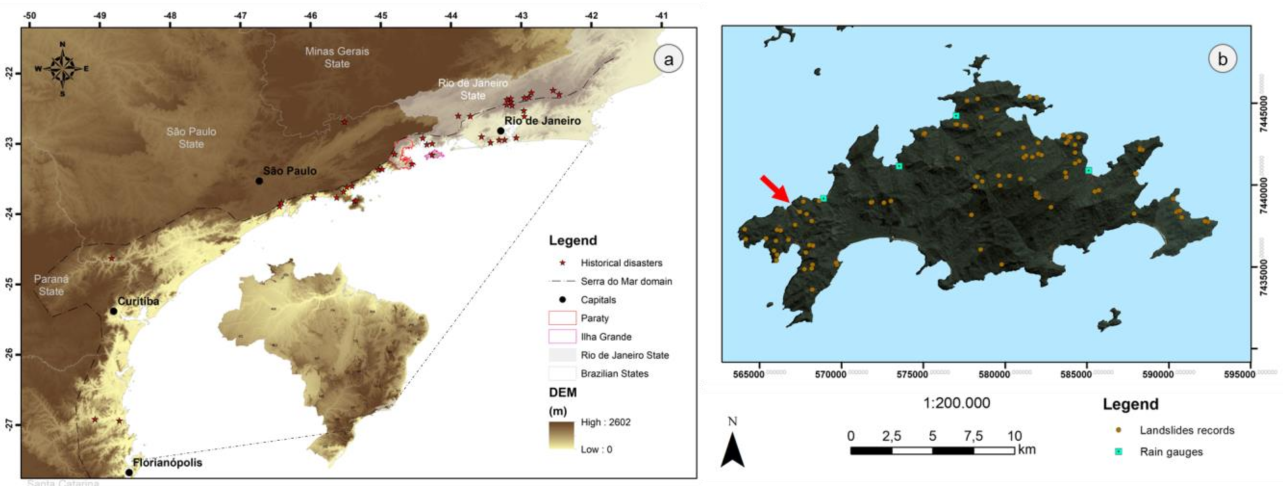

Figure 2. Study location: a) Paraty-Ilha Grande UNESCO domain in the state of Rio de Janeiro; b) landslide records and rain gauges of Ilha Grande. In b), the red-colored arrow indicates the landslide studied.

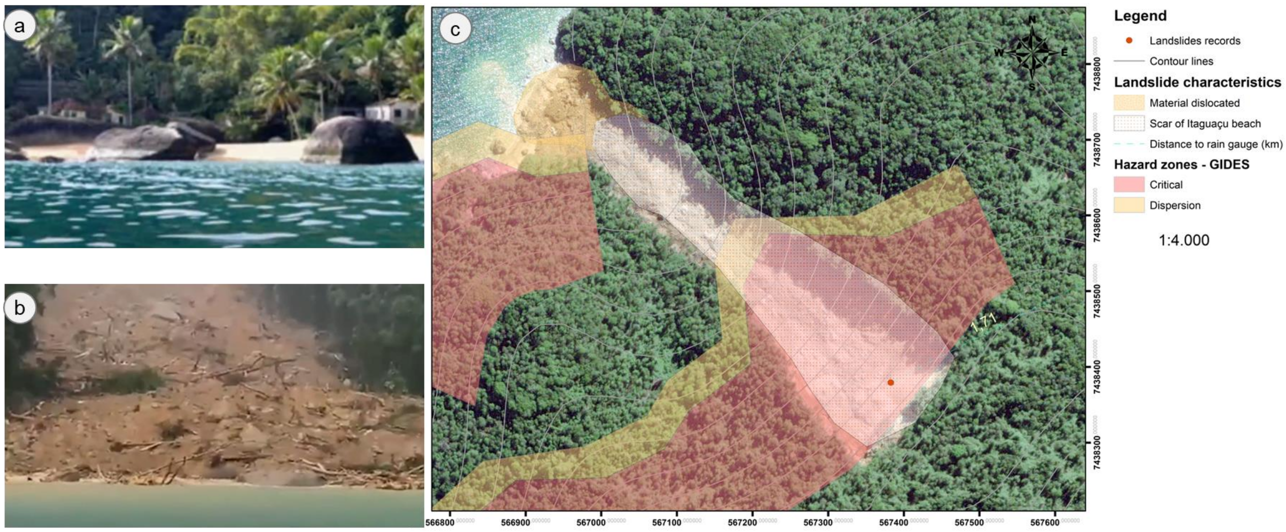

Figure 3. High-magnitude shallow translational landslide of the Itaguaçu Beach: a-b) before and after the event, c) hazard mapping according to the GIDES procedures.

Based on the geometric method for hazard and risk mapping presented in GIDES, volume 1 (Pimentel and Santos, 2018), the critical and dispersion areas of the shallow landslide event were delimited. The results are shown in Figure 3c. The raster ALOS PALSAR, with a 12.5 m resolution, was used for this task and also for DAM 3D modelling. We opted to present a hazard map without qualification (i.e., P4c or P3d). Once, it is evident that the geometric method fails to characterize the impact area of this high-magnitude shallow landslide.

While the source area was roughly identified as a critical zone, the dispersion area was underestimated by the GIDES method. The landslide run-out and its deposit extended much farther than indicated by the Brazilian method (Figure 3c). Although the maximum length of 50 meters was used according with the guideline, the houses hit by landslide event would not be mapped as a hazard area, thus without risk. This result may be partly due to the low-resolution topography, but the universal topographic criteria and its rules undoubtedly play a significant role in this outcome.

This example underscores the limitations of geometrical methods for risk mapping, revealing that reports on the number of elements in at-risk areas in Brazil are often misleading and inaccurate, especially for touristic destinations such as the Paraty-Ilha Grande UNESCO site. Aspect particularly relevant for natural slopes, where elements at risk are typically located along the coastline, near the beaches, and therefore at a considerable distance from the potential GMM source areas.

3. TRIGGERS CONDITIONS INVOLVED WITH THE SHALLOW LANDSLIDE EVENT

The SM is well known for frequent shallow landslides triggered by intense rainfall. In particular, the Ilha Grande site has experienced tragic events in the past, i.e., the Sankay landslide in 2010. During the 2022 event, the Paraty-Ilha Grande region once again witnessed widespread landslides and debris flows. The most affected areas included highways, urban centers, and tourist infrastructures such as campsites and hotels along the river and beaches closest to slope terrains.

Understanding the triggering mechanisms behind landslide initiation is crucial for the development of effective landslide early warning systems (LEWS), particularly regarding rainfall patterns (Figure 4). In this study, we focused the analyses on the triggering conditions associated with the landslide at Itaguaçu Beach. Precipitation data were obtained from rain gauges on Ilha Grande covering the period from March to April 2022.

To establish reliable correlations, the distance between the rain gauge and the landslide scar must be minimal, ideally less than six kilometers (Silva et al., 2022). Accordingly, the Araçatiba rain gauge station, located 1.57 km from the landslide, was selected. For comparison, data from the Abraão station, located 4 km away, were also collected (Figure 4). Both rain gauges are operated by the National Center for Monitoring and Alerts for Natural Disasters, and their data are publicly available online (CEMADEN, 2023).

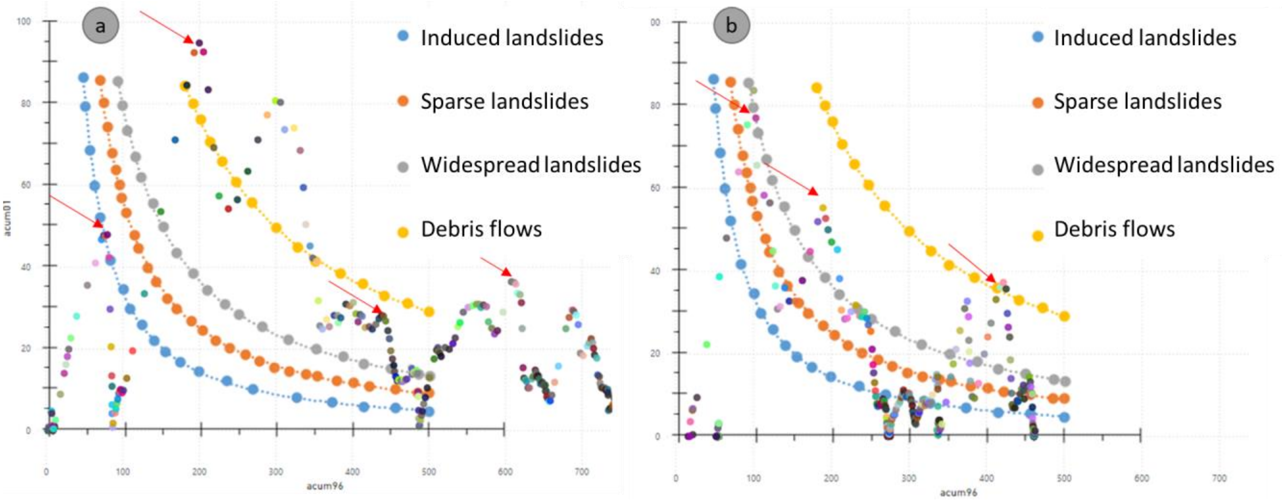

Figure 4. Triggering conditions of the landslide at Itaguaçu Beach: a) Araçatiba and b) Abraão stations. Thresholds accordingly with Tatizana et al. (1987) showing in detail the rainfall peaks (red arrows).

The rainfall data were processed to calculate rainfall parameters, including intensity (mm/h) and 96-hour accumulation (i.e., I – E_{96h} parameters) (Figure 4). To characterize the event, we applied rainfall thresholds for induced, sparse, widespread landslides and debris flows (Tatizana et al., 1987). Analyzing the peak values in the reconstructed rainfall trajectories allows for important observations. Notably, using a rain gauge within a close radius provides more accurate insights into the conditions that triggered the landslide studied. For instance, the rainfall trajectory recorded at the Araçatiba rain gauge indicated that the debris flow thresholds were exceeded much earlier than at the Abraão rain gauge. Surprisingly, around 800 mm of rain accumulated during 55 hours of rain in Araçatiba.

In summary, the rainfall conditions leading to the back-analyzed landslide rank among the most extreme, surpassing the landslide and debris flow thresholds. This analysis suggests that the GMMs affecting the SM, particularly in the Paraty-Ilha Grande UNESCO site, can be anticipated through critical rainfall threshold exceedances. The findings strongly support the implementation of an LEWS for this UNESCO site. Nevertheless, while the Angra dos Reis municipality has a management plan in place based on rainfall monitoring, Paraty still lacks one. Furthermore, based on this event, it seems that isolated areas at risk, such as Ilha Grande, are unlikely to be covered by public risk management plans.

4. DYNAMIC ANALYSIS METHODS

Dynamic analyses can be used to calculate the travel distance, expected GMM path, energy, height, discharge, velocity, and impact forces involved in landslide, debris flows, soil creep, rock debris, and avalanches (Hungr et al., 1984; Crosta and Agliardi, 2003; Revellino et al., 2004; McDougall and Hungr, 2005; Hungr and McDougall, 2009). Among hazard and risk analyses, some outputs like impact forces and energy are used to design mitigation. It is one of many advantages in relation to GIDES guidelines.

Many software programs are available commercially, such as Rocfall® for rockfall and RAMMS® modules and DAM3D® for several typologies. While the first software is specified for the typology, the second and third are more flexible; for example, they permit modelling a shallow translational landslide, its achievement in a drainage, and the respective transformation into debris flows. Herein, we used the Dynamic Analysis Modelling software – DAM3D® – for back-analysis of the Itaguaçu Beach landslide. In this program, it is assumed that the mobilized material is a fluid equivalent (Hungr and McDougall, 2009).

Four constitutive models can be assumed based on the rheology of GMM, including friction (Coulomb), friction and pore pressure, plastic (Bingham), and turbulent (Voellmy) models. Generally, dynamic analysis modeling can represent the vast majority of typologies of geological-geotechnical and hydrogeological threats, as the landslides presented in Figures 1-2 (Hungr et al., 1984; Crosta and Agliardi, 2003; Revellino et al., 2004; McDougall and Hungr, 2005; Hungr and McDougall, 2009). The main input data in this program are topography, source area (location where a landslide will occur or occurred), depth of the rupture surface, erosion of the layers, etc. Based on the materials involved in the rupture, the movement, and the conditions at the time of the deflagration, the constitutive model and rheological parameters can be defined to represent the typology of the threat and its interaction with the terrain. For instance, the friction angles and density of material are the main parameters for the Coulomb model, while the friction and turbulence coefficients are for the Voellmy model (Dos Santos Corrêa et al., 2024), i.e., for landslides to debris flows modelling.

Herein, the back-analysis and its calibration started with a survey in literature of constitutive models and their main parameters (Hungr et al., 1984; McDougall and Hungr, 2005; Hungr and McDougall, 2009). This task was carried out considering local to international scale studies involving rock avalanches, landslides, and debris flow typologies (Hungr et al., 1984; McDougall and Hungr, 2004; Revellino et al., 2004; McDougall and Hungr, 2005; Hungr and McDougall, 2009; Revellino et al., 2008; Sosio et al., 2012; Cabral et al., 2023; Dos Santos Corrêa et al., 2024).

For this step, various observed characteristics of GMM can be compared to modeled outputs, including velocity, entrainment, discharge, or the depth of deposited material. While some of these parameters require monitoring technologies, depth is often easier to estimate through field investigations and reports (Graf and McArdell, 2011). Because of this accessibility, deposit depth is commonly used to evaluate the influence of input parameters. In this study, the normalized mean absolute error (nMAE, %) was adopted as the calibration metric. This index measures the average absolute difference between observed and simulated values, normalized by the observed data, enabling a scale-independent assessment of model accuracy. In this case, lower nMAE values indicate a better fit, while high values indicate poor modelling parameter adjustment.

It is important to emphasize that the reports, scar and deposit characteristics observed in satellite images and triggering conditions involved with the event also were helpful in this analysis.

As shown in Figure 4, and assuming that the rain trajectory's peaks represent the moment of triggering, we can conclude that the landslide formed under extreme conditions. As a result, the mobilized material's rheology may exhibit fluidized behavior. Also, the beach deposit area has a gentle slope of approximately 5 degrees. However, a significant portion of the mobilized material accumulated at the base of a steeper section, where the slope ranges from approximately 10 to 15 degrees (Figure 3b). Overall aspects that elucidate the bunch of initial parameters that can be used in the back-analysis (VanDine, 1996).

5. LANDSLIDE EVENT BACK-ANALYSIS

Several scenarios were developed for Coulomb and Voellmy rheological models. The main parameters analyzed were the friction angles and the turbulence coefficient, since they majorly control the height, deposition, and speed of the landslide (Revellino et al. 2008; Sosio et al; 2012; Bezak et al. 2020). Other parameters, such as specific weight (19.0 kN/m³), internal friction angle (28°), maximum eroded depth (2.0 m), number of particles (3,000), and erosion rate (0.01 m/km^{-1}), were adopted equally during the back-analysis.

The simulation time is rarely discussed in dynamic analyses studies. But it is something that needs to cover the period between the detachment of the soil-rock mass, its displacement in space, and final deposition, i.e., the return to the resting state. Roughly, a total dissipation of kinetic energy is recommended. In SM, the worst cases of debris flows took about 40 minutes (Jones, 1973) to 45 minutes (Gramani, 2001). In Canada, rock avalanches took around 2.5 minutes from the release point to final deposition (Hungr et al., 1984; McDougall and Hungr, 2005; Hungr and McDougall, 2009). However, for landslides, the duration is still a geotechnical challenge, usually being adapted for each case studied. Herein, we assumed that the event took place in about 300 seconds, i.e., five minutes.

For the Coulomb model, only the residual friction angle of the mobilized material was varied between 5° to 23° (S1: 5°, S2: 8°, S3: 11°, S4:14°; S5: 15°; S6: 16°, S7:17°; S8:18°; S9:19°; S10:20°; S11:23°). For landslide back-analysis, deposit thickness was estimated based on field evidence. The spatial positions of two impacted houses were used as reference points for model calibration based on nMAE, house-0 and house-1, with a deposit thickness ranging between 1.0 to 2.5 meters. Note for this calibration process, among eleven scenarios modeled with the Coulomb model, the most successful were S5, S6, and S7. Based on direct observation of the simulated (Figure 5a) and the nMAE values (Figure 5b).

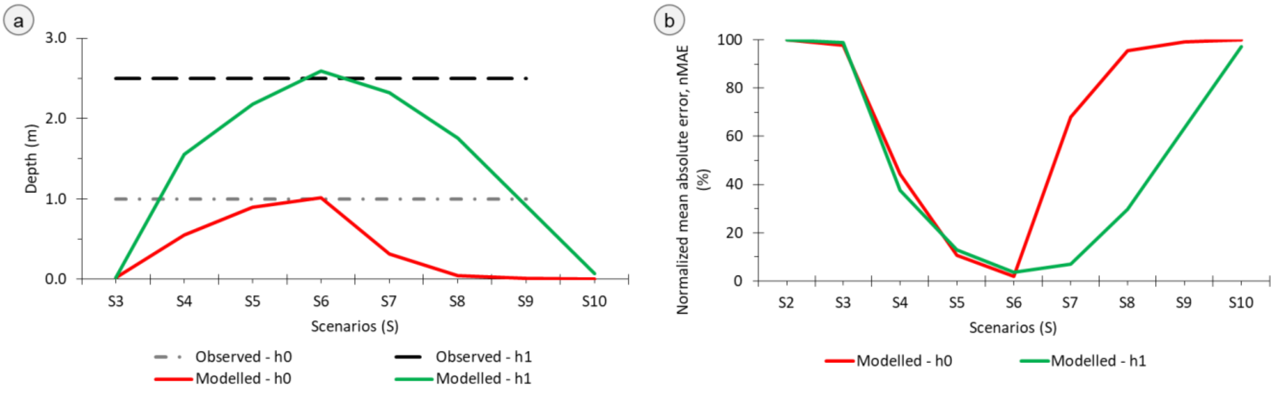

Figure 5. Checking calibration using the Coulomb model: a) landslide deposit depths observed versus modelled, b) normalized mean absolute error.

In Figure 6, some results of dynamic analysis using the Coulomb model for Praia do Itaguaçu landslide back-analysis were presented. Indeed, the S5-S7 scenarios are quite representative of the real deposition area of the landslide (Figure 6b-c), while others overestimated (Figure 6a) or underestimated (Figure 6d) the landslide behavior. In other words, in 300 seconds of simulation, the mobilized material in S1 crossed the entirely coastline and stopped in the middle of the Ilha Grande Bay (Figure 6a), or the mobilized material in S9 could not reach the known impacted area (Figure 6d). Therefore, the residual friction angles used in scenarios S5-S7 ranging between 15°-

17°, with a nMAE less than 20%, are quite satisfactory for the representation of a high-magnitude shallow landslide herein studied.

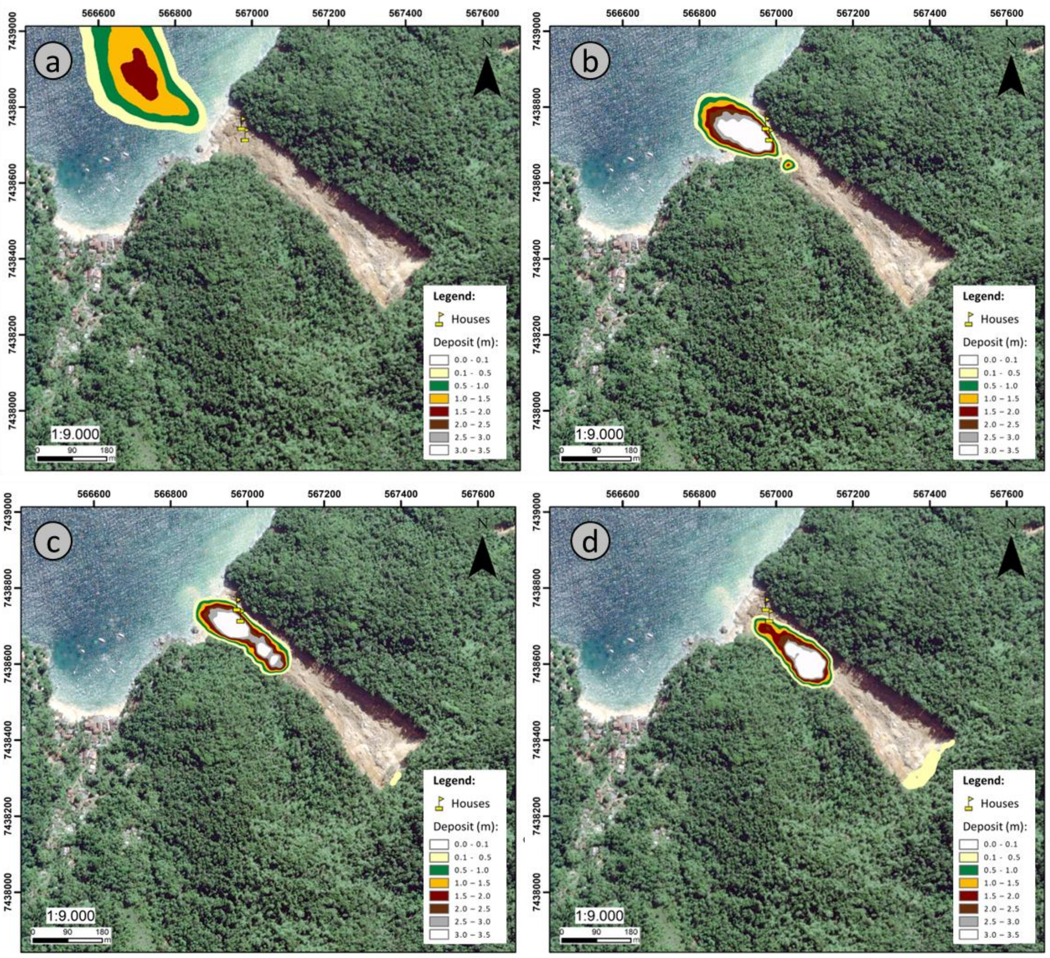

Figure 6. Examples of back-analysis with the Coulomb model. Residual friction angles of a) S2 – 8°, b) S4 – 14°, c) S6 – 16°, and d) S10 – 20°.

For the Voellmy model, a quite more complex set of parameters was defined, and the best previous range of residual values was tested (i.e., 15°-17°). In this case, the turbulent coefficient was varied between 1 and 200 m/s^2 (S1: 15°-1m/s^2; S2: 15°-3 m/s^2, S15: 16°-1 m/s^2, etc.). Around forty scenarios were modeled. Then, to check the performance of the landslide back-analysis, the deposit depths observed versus modelled were analyzed for the scenarios idealized (Figure 7).

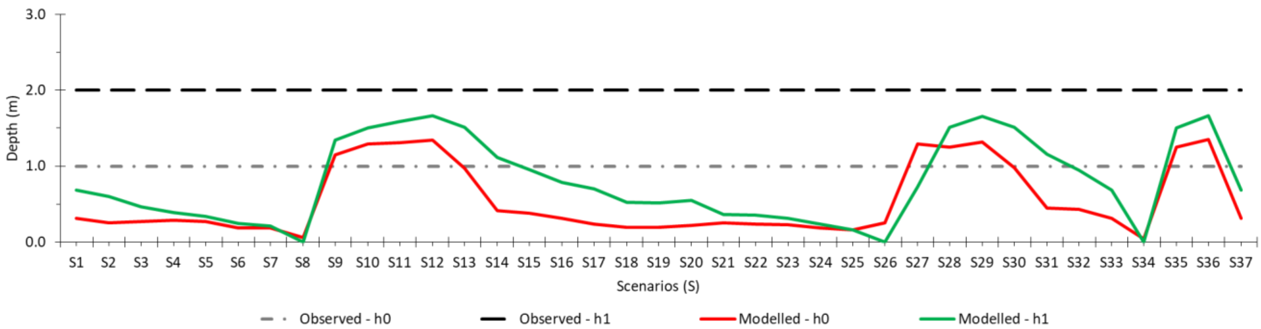

Figure 7. Checking calibration using the Voellmy model: landslide deposit depths observed versus modeled.

Note for this calibration process, among several scenarios modeled with the Voellmy model, the best adjustments are represented by S9-S13, S27-S30, and S35-36 (Figure 7). In these scenarios, the landslide deposit was average for both residences, slightly overestimated for one and slightly underestimated for the other, but reasonable for a dynamic analysis. For example, the scenario 27, modelled with the residual friction angle of 16° with turbulence coefficient of 2 m/s^2, could represent adequately the landslide deposit (Figure 8b). While the scenario S25 didn´t simulate well the deposition zone and its thickness (Figure 8a).

These results emphasize the sensitivity of the Voellmy model to both the residual friction angle and turbulent coefficient. Small variations in these parameters led to considerable differences in runout and deposit thickness, particularly in the lower part of the slope. This reinforces the need for careful calibration using observed field data when applying dynamic models. It also highlights the model's robustness in capturing subtle differences in mobility behavior between similar scenarios, which can be critical for realistic hazard assessments.

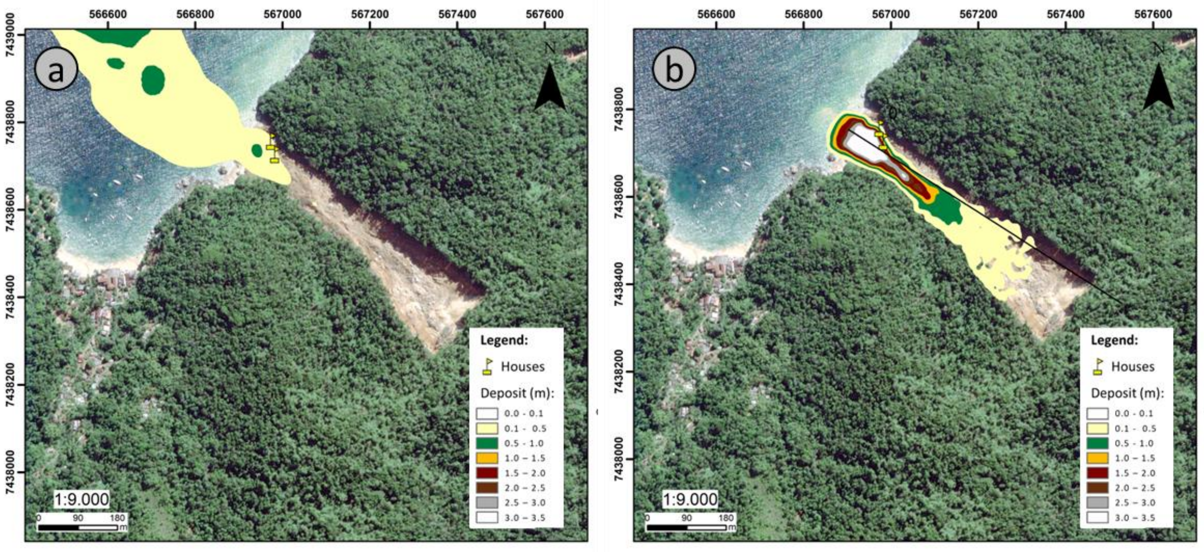

Figure 8. Examples of back-analysis with the Voellmy model: a) S25: 15° - 200 m/s^2 and b) S27 – 16° - 2.0 m/s^2

6. CONCLUSIONS

In this study, we conducted a back-analysis of the shallow landslide that occurred at Itaguaçu Beach, within the Paraty-Ilha Grande UNESCO Site, in the state of Rio de Janeiro, Brazil. The main objectives were to calibrate parameters for a high-magnitude landslide using the dynamic modeling tool DAM3D® and to enhance hazard zonation. The analysis focused on improving the understanding of landslide behavior in coastal areas of the Serra do Mar Mountain Range, which are increasingly exposed to extreme weather events.

The results showed that hazard analysis based solely on geometric methods was not sufficient to delineate the full dispersion area of the landslide. In contrast, the dynamic approach successfully reproduced key features of the event, including the extent of the deposition zone, using the same topographic data. This demonstrates the superiority of dynamic modeling in complex natural terrains, especially in scenarios involving shallow landslides triggered by intense rainfall.

A reliable range of parameters was defined for high-magnitude landslides within the Serra do Mar context, supporting the use of dynamic analysis as a practical alternative to geometric methods in Brazil. This is particularly relevant for remote tourist destinations that are frequently affected by summer rainfall disasters. The integration of physically based models into hazard assessments can lead to more accurate delineation of risk zones and strengthen land-use planning and disaster preparedness.

Finally, the findings support the feasibility of implementing early warning systems for landslide-prone areas in isolated coastal locations. However, the effectiveness of such systems depends on their proper operation by local civil defense authorities, such as those in Angra dos Reis and Paraty. In areas with limited public services, as seen in the Itaguaçu Beach case, civil protection strategies should also consider structural solutions, including robust shelters, to safeguard both residents and tourists during extreme events.

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