ADVENTURE TOURISM ATTRACTIONS IN ANALÂNDIA, SP: IDENTIFICATION AND RISK ASSESSMENT

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Resumo – Este estudo analisa o evento de queda de blocos ocorrido em outubro de 2022 no geossítio Morro do Camelo, em Analândia (SP), que impactou o turismo e o acesso rodoviário. Trata-se do primeiro evento registrado nas Cuestas com dados pré e pós-desprendimento, permitindo uma avaliação detalhada dos processos envolvidos. A análise de risco foi realizada por meio de métodos empírico e geométrico, ambos identificando que a estrada Orlando Teodolini e as áreas turísticas estão em zonas de risco moderado a muito alto. As informações de alta definição obtidas por meio de aerofotogrametria foram cruciais para a execução dos dois procedimentos. Os resultados ressaltam a necessidade de abordagens quantitativas para avaliar o atingimento de quedas de blocos no Brasil, aprimorando modelos preditivos e estratégias de mitigação. Além disso, o mapeamento de risco e a integração entre geologia de engenharia e geoconservação são fundamentais para garantir a segurança em áreas de turismo de aventura.

Abstract – This study analyzes the rockfall event that occurred in October 2022 at the Camelo Hill geosite in Analândia (SP), which affected tourism and road access. It is the first recorded event in the escarpment province with pre- and post-detachment data, allowing for a detailed assessment of the involved processes. Risk analysis was conducted using empirical and geometrical methods, both identifying the Orlando Teodolini Road and tourist areas within moderate to very high-risk zones. High-resolution data obtained with aerial photogrammetry were vital to apply both procedures. The findings highlight the need for quantitative approaches to assess rockfall run-out in Brazil, improving predictive models and mitigation strategies. Also, risk mapping and the integration of engineering geology and geoconservation are essential to ensuring safety in adventure tourism areas.

Keywords – Risk assessment; Adventure tourism; Climbing sites; Corumbataí Geopark; Land-use.

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1. INTRODUCTION

Outdoor recreational areas are gaining popularity worldwide, particularly those associated with adventure tourism activities, such as rock climbing, mountaineering, hiking, ziplining, canyoning, etc. Brazil's diverse geology and landforms provide a wide range of rock outcrops, terranes, and rivers ideal for these activities. For instance, in the state of São Paulo alone, approximately 148 rock-climbing sites have been inventoried. However, around 60% of these sites are in areas classified as highly to very highly susceptible to rockfalls (Monticelli et al., 2025), where accidents and fatalities are not uncommon (Correio Braziliense, 2021).

Due to logistical and financial constraints in conducting detailed risk assessments for all sites (Monticelli, in press), a geoconservation-based ranking method was used to quantitatively evaluate their attractiveness to mountaineers and climbers. For example, at the state level, Pedra do Baú stands out as a major climbing hotspot, while within the Geopark Corumbataí Project (CGP) domain, Cuscuzeiro Hill is the most appealing geosite for this adventure tourism (Figure 1a) (Monticelli et al., 2025). It is worth noting that Cuscuzeiro Hill and its analog, Camelo Hill, are recognized as geosites due to their significance for geotourism, scientific research, and educational activities. Their values are closely tied to geomorphology, rock formations, landscape features, etc., also making them part of the CGP domain (Garcia et al., 2018; Kolya, 2019) (Figure 1e).

Figure 1. Climbing site hotspot of CGP domain: a) Cuscuzeiro geosite, b) rockfall event, c) Camelo geosite, c-d) general elements under risk, and e) panorama view (authors records).

These sites attract tourists, climbers, hikers, and outdoor enthusiasts drawn to landscape views, recreation, and nature experiences. However, such activities can also expose visitors to risk areas, i.e., from stationary to non-stationary elements (Fell et al., 2005) (Figure 1b-e). Moreover, considering recent incidents in outdoor recreational areas across Brazil—such as fatal rockfalls at Capitólio Canyon (Minas Gerais) and Praia de Timbaú (Rio Grande do Norte), as well as flash floods in national parks—there is a clear need for risk assessment standard procedures in adventure tourism areas (Norma ABGE 500, in press).

In parallel, Brazil has strategies for managing natural disasters in urban areas through the National Civil Protection and Defense Policy, established by Federal Law 12.608-2012, which outlines principles, objectives, and tools to address the geological processes (Brasil, 2012). The Institute of Technological Research of São Paulo State developed a foundational methodology for creating susceptibility maps. The Geological Survey of Brazil (CPRM) is responsible for the development, editing, and dissemination of these maps. After the Japan-Brazil partnership, the hazard and risk analysis are also carried out following GIDES reports (Pimentel and Santos, 2018). In other words, guidelines that could and have been adapted for touristic areas examples include studies related to beaches, waterfalls, cliffs, etc. (Dias et al., 2024; Moraes et al., 2023). However, the limitations of these methods are rarely acknowledged by their executors. It is up to the technical and scientific community to present and drive comments and advancements.

Herein, we conduct fieldwork and inspections aimed at assessing the risk of the Camelo and Cuscuzeiro Hills geosites. Thus, including climbing sectors, road accesses, recreational areas, and their trails (Figure 1). Hazard and risk mapping were conducted in a GIS environment, applying empirical and geometrical methods. The approach was based on high-resolution orthophotos and topographic data acquired via an unmanned aerial vehicle (UAV) equipped with a post-processing kinematic (PPK) antenna. The cartographic results were then compared for risk analysis and assessments. Additionally, we discuss the assumptions and limitations of these methods in the context of risk analysis focused on adventure tourism areas and also for their access, such as roads and trails. Finally, we propose a contribution to the Brazilian guideline (Pimentel and Santos, 2018), addressing gaps related to rockfall typology.

2. STUDY AREA

The Cuscuzeiro and Camelo Hills geosites are located in the CGP domain, Analândia municipality, state of São Paulo, Brazil (Figure 2). This location is composed of sandstone rocks belonging to the Botucatu Formation from the Paraná River Basin, a Phanerozoic volcano-sedimentary stratigraphic sequence.

Also, the geosites are located in the transition zone between the escarpment and peripheral depression geomorphological provinces. The escarpment province consists of a strip of asymmetrical scalloped cliffs that follow the basin's contours and face the Atlantic Plateau, formed by crystalline rocks of the Brazilian Shield. In Analândia municipality, the escarpment consists of two cliff systems: the lower one supported by basalts and diabases of the Serra Geral Formation and the upper one supported by the Botucatu Formation sandstone (De Abreu and Augusto Filho, 2012) (Figure 2). Thus, kilometers of rock walls with high appeal for tourism development.

Civilians access the geosite by a dirt road and park their cars nearby to enjoy viewpoints, trails, and leisure areas for picnics. In this place, the sandstone emerges as protuberant cliffs that are 30-60 meters high. Due to significant values for the attractiveness of climbing, mountaineering, and (geo)tourism in general (Kolya, 2019; Monticelli et al., 2025), this region was chosen for detailed risk assessment (Monticelli, in press). The attention given and frequent visits along 2021-2022 made it possible to record a natural rockfall event in the Camelo geosite. It seems the first record of rockfall was made after and before by UAV data in CGP and the escarpment landform.

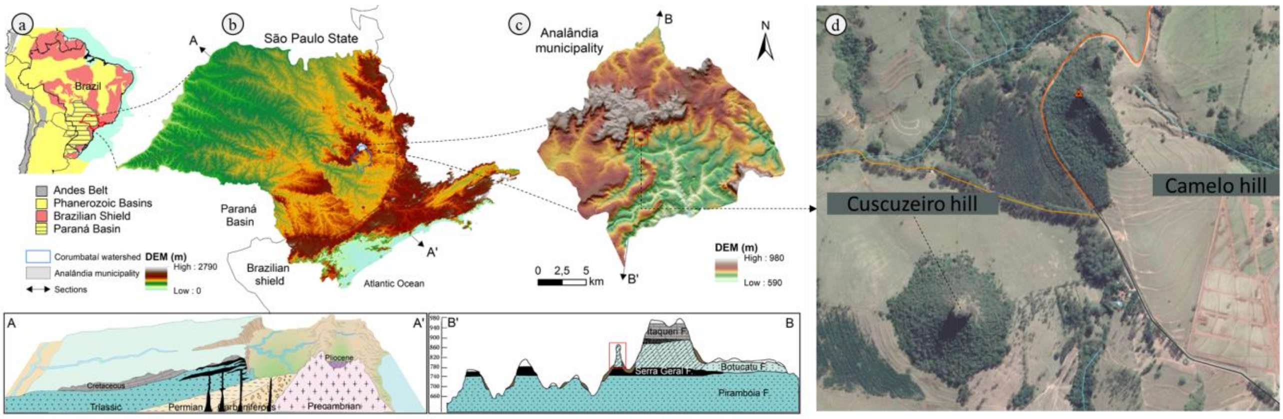

Figure 2. Location map: a) Brazil in the context of South American terrains, b) the state of São Paulo showing the CGP domain, c) the Analândia municipality, and d) the study area for detailed risk assessment in the adventure tourism area (Please check the pdf version with zoom).

3. EMPIRICAL AND GEOMETRICAL METHODS FOR ROCKFALLS HAZARD AND RISK ANALYSIS

Rockfall is a natural process that involves the detachment of the rock from the rock mass and its subsequent free fall, rebound, rolling, sliding, and deposition (Varnes, 1984). The block trajectory often represents the greatest danger to the hitting areas, and its behavior is a great challenge in the evaluation and analysis of this kind of phenomenon (Evans and Hungr, 1993).

3.1. Empirical method

Empirical methods are well-established in the technical-scientific literature due to their simplicity and efficiency in identifying hazardous areas. They typically are used to estimate the travel distance of a falling block and its lateral dispersion in the slope terrain, i.e., the blocks run out. This calculation is frequently based on the reach angle (α) and/or shadow angle (β), combined with the lateral dispersion of the block's trajectory (Azzoni et al., 1995; Crosta and Agliardi, 2003; Copons et al., 2009) (Figure 3).

Essentially, these empirical methods are developed using topographic maps and profiles extracted from a digital terrain model (DTM), i.e., bare earth. Both approaches depended on the inventory of blocks cataloged in the study area. The farthest block is used to calculate, respectively, the reach angle (α) with the source area or the shadow angles (β) with the apex of the talus body. Then the trajectory length is then used to estimate lateral dispersion (Figure 3). In the Cuscuzeiro and Camelo geosites, the farthest sandstone blocks were identified in UAV products and confirmed in field inspection. This task also was useful to identify the most probable block trajectory and its profile.

Given that both geosites consist of landforms that are witness to escarpment retreat, i.e., roughly a cylindrical rock column that is 45 meters high, lateral dispersion was extrapolated to determine the hazardous area. In a conservative approach, it was assumed that the detachment area could release blocks in all directions (Figure 1). Finally, the area under the "shadow/reach" angles has a high possibility of experiencing rockfalls, i.e., a hazard area. In this approach, beyond this limit, there is a very low likelihood of being hit for a block.

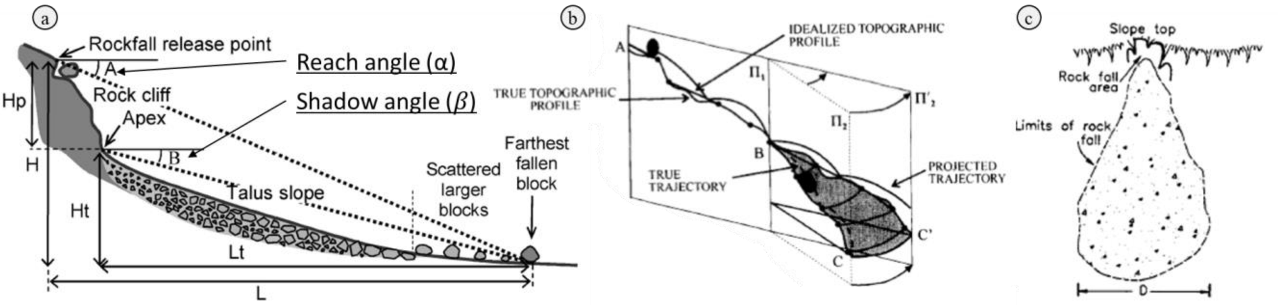

Figure 3. Schemas of the empirical methods procedures: (a) hitting distance (shadow and reach angles), (b) lateral dispersion of trajectories (deviations), and (c) hazard cone delimiting the reach area (modified from aforementioned studies).

3.2. Geometrical method

The CPRM carries out hazard and risk analysis based on the procedures presented in GIDES reports (Pimentel and Santos, 2018), i.e., volume one. Basically, it consists of three phases: data collection and delimitation of the area of interest, the second phase of hazard analysis including one part in the office and another in the field, and the third phase consisting of vulnerability assessment and risk qualification. Figure 4 brings a schematic resume applied for the geosites here studied. For more details, please check the aforementioned reference.

Following geometrical criteria, the source of the block detachment, the critical and dispersion areas, are delimited (Figure 4). These areas represent the hazardous terrains that are qualified in field inspections, where usually they may be evaluated with more accuracy. These tasks are extremely dependent on data input, i.e., topography, as well as the experience of engineering geologists in the recognition of rockfall features, which go from block deposit to rock mass characteristics, such as fracturing index, water presence, detachment scars, deposit of blocks, etc.

In the aforementioned guideline, the hazard and vulnerability qualification in degrees of danger and vulnerable elements are specific for each kind of gravitational mass phenomenon (Figure 5). For rockfall typology specifically, the instability signs that need to be recognized in situ are shown in a chart (pg. 86, Pimentel and Santos, 2018). This task includes, beyond the hazard qualification of the process, the vulnerability assessment of buildings (Pg 89, Pimentel and Santos, 2018).

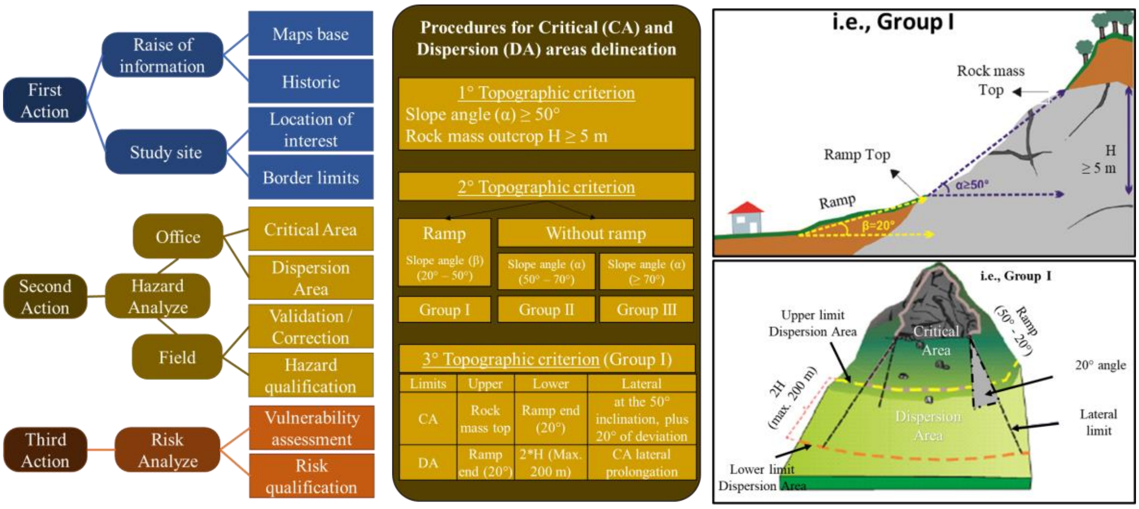

Figure 4. Resume of the geometrical method procedures (modified from Gides).

In the correlation matrix, hazard (i.e., P1 to P4) grades are chosen based on the identification of signs of instability in rock mass and in the terrain within the hazard zones, critical and dispersion areas (i.e., P3c or P2d). Nevertheless, it is known dense forest vegetation could mitigate certain magnitudes of blocks during movement (Dorren and Berger, 2006), but no comment was made regarding it. Here we made a schematic drawing representing hazard and vulnerability degrees according to the presence of vegetation and land use, in this case, the adventure tourism area and its activities (Figure 5).

Four risk classes, ranging from R1–Low to R4–Very High, can be defined for each typology according to the guideline (Pg 92, Pimentel and Santos, 2018). The risk classes (R1 to R4) are defined by using a correlation matrix between hazard and vulnerability. The hazard and vulnerability also grade from P1 to P4 and V1 to V4, i.e., from low to very high hazard or vulnerable element under risk (Pg 93, Pimentel and Santos, 2018).

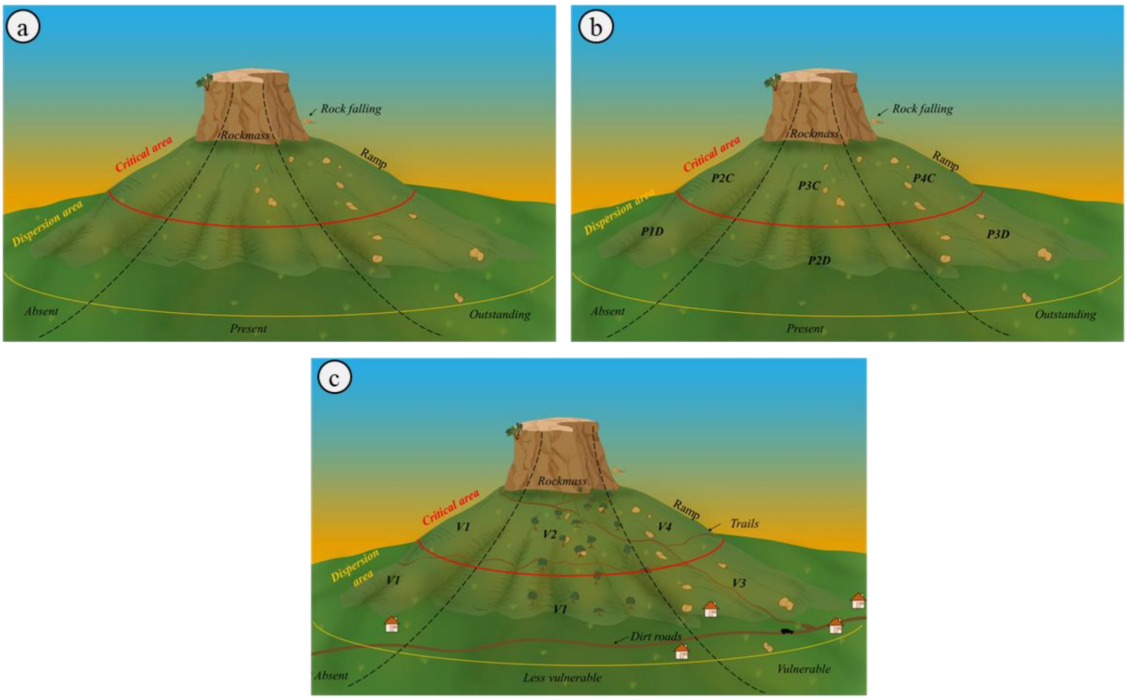

Figure 5. Contribution to GIDES procedures covering hazard classification (this study). (Please check the PDF version with zoom).

It is important to emphasize that this methodology focuses primarily on qualitative risk estimation for poorly constructed buildings in urban centers and does not account for linear infrastructure such as roads and railways. Moreover, they overlook the touristic appeal of adventure tourism areas and the major non-stationary activities that are time- and space-dependent (Fell et al., 2005). For example, activities like walking on a trail next to sandstone cliffs, taking a boat tour through a canyon, or swimming in a waterfall prone to flash floods. In this sense, herein we tried to represent these kinds of elements under risk for adventure tourism areas of Cuscuzeiro and Camelo geosites (Figure 5c). A suggestion regarding the vulnerability (V1-V4) grades that could vary according to vegetation cover, integrity, and strength, as mentioned in Dorren and Berger (2006).

4. UAV-PPK FLIGHTS AND PHOTOGRAMMETRIC PROCEDURES

Satellite topographic data offers a significant advantage in terms of coverage; however, high-resolution data with public access is rare in Brazil, making its use on a detailed scale unfeasible. In this sense, we used the UAV DJI Phantom 4 PRO®, equipped with the antenna PPK of Guandalini®.

The main advantage of using UAVs equipped with PPK is that they ensure high-precision georeferenced images with agility in taking information. In PPK mode, raw GNSS data is recorded during flight and later processed to refine the positioning accuracy of photos, reducing the need for many ground control points. The corrections received from a base station or GNSS network (i.e., Brazilian Network for Continuous Monitoring of GNSS Systems - RBMC) are usually processed after two to seven days (Figure 6a). Also, the method is useful in areas with unstable signals or where real-time corrections are not feasible, i.e., Real-Time Kinematic.

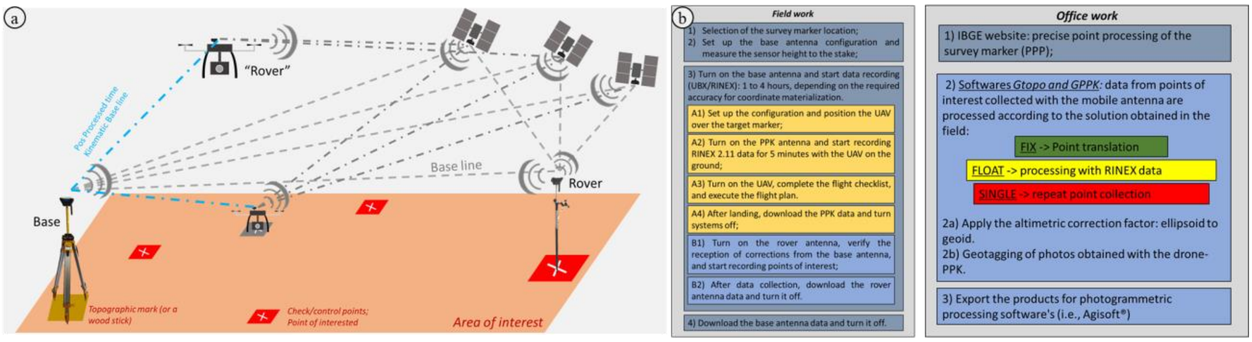

Figure 6. Schematic illustration: a) UAV-PPK mode and b) workflow. (Please check with zoom).

The flights were supported by the EMLID® RS2 geodesic antenna for data position corrections during PPK-UAV flights. Our campaigns were carried out in August 2021 and November 2022, i.e., before and after the rockfall event (Figure 1b). The horizontal flight plans were elaborated using DroneDeploy® software, while vertical flight plans were elaborated with Litchi®. Following IBGE guidelines (IBGE, 2023), PPPs were materialized for five topographic marks in the study area, around the geosites and along the dirt road (Orlando Teodolini). The installation of marks aimed to help cover adjacent flight plans at the same place of landing and delay. The UAV-PPK mode and PPP workflow can be seen synthesized in Figure 6b. For more details about PPP, please check the aforementioned reference.

Geotagged photos were then processed in Agisoft®, a photogrammetric software, which served to generate the cartographic products, i.e., dense clouds, digital elevation models of terrain and surface, and orthophotos. These products were elaborated with 0.2- and 1-meter resolution for risk analysis. Finally, ArcGIS® software (GIS environment) was then used to carry out the procedures involved with the empirical and geometrical methods. For more details about photogrammetric workflow, please check (Viana et al., 2019).

5. RESULTS AND DISCUSSION

The 2022 rockfall event at the Camelo Hill geosite in Analândia municipality, which disrupted road access and tourism for several weeks, is detailed in this study for the following reasons: i) It is the first recorded rockfall in the escarpment province with data both before and after detachment; ii) it impacted linear; iii) tourism infrastructures directly; and iv) it relates to ABGE standard procedures #400 (under discussion) and #500 (in press). For more details, please visit the ABGE website.

The attractions of the Camelo geosite were identified through field surveys and conversations with visitors on both weekdays and weekends to determine its primary recreational uses. Although privately owned (a ranch/farm), its viewpoints, trails, and climbing sector are easily accessible, located near the Orlando Teodolini dirt road. The exposure areas of stationary and non-stationary elements are shown in Figure 7a.

Approximately 780 detached rock blocks were inventoried at this geosite. To streamline characterization, they were assumed to be spherical. Their dimensions were analyzed using an orthophoto from an aerial survey, with the average elongation of each block used to estimate volume (Figure 7b). The total estimated rockfall volume was 5,523.3 cubic meters, or approximately 14,000 tons. Dense point clouds were then used to verify some of these results.

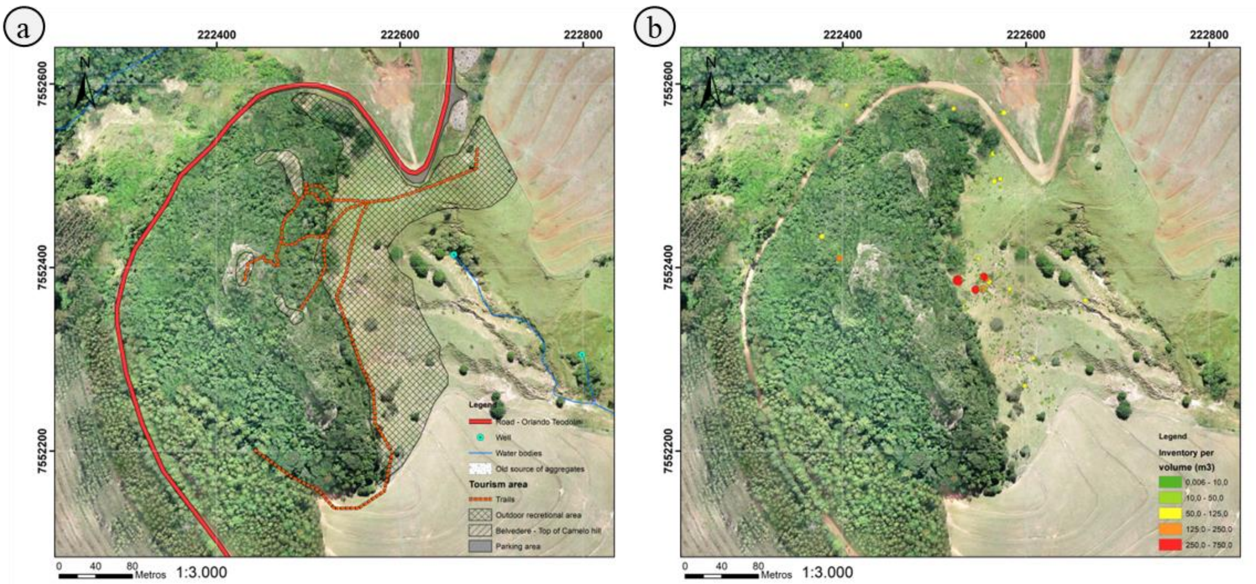

Figure 7. Camelo Hill geosite: a) attraction and elements exposure, b) inventory based on volume (Please check with zoom).

The rockfall deposits at the Camelo geosite range from extremely small to large (Stock et al., 2013). The most frequently inventoried blocks, about 55%, are classified as very small, measuring between 0.5 and 5.0 m^3 (Figure 8a). Alternatively, blocks most commonly deposited range from 0.1 to 10.0 m^3, accounting for nearly 80% of the inventory (Figure 8b) (Wang et al., 2013).

Blocks around 1.0 m^3 tend to be found farther from their source areas (Figure 8c), though some may have been remobilized by the movement of other blocks within the talus bodies due to erosion processes. This suggests two possible groups of blocks: recent rockfall deposits and remobilized blocks. A significant portion of the area is covered by vegetation, limiting direct observation and a complete block count. As a result, the inventory does not represent the totality of the rockfall deposit at the Camelo Hill geosite, but we believe that it is sufficient for the analyses conducted herein.

Regarding hazard analysis, the reach angles obtained from the inventory range around 38.6°, while for the event, the farthest block obtained a value of 43.4°. Depending on characteristics involved in the rockfall process and the landforms and terrain itself, reach angles may vary between 35 and 55° (Azzoni et al., 1995; Crosta and Agliardi, 2003; Copons et al., 2009). From the top of the cliff, the point where the sightline—defined by the reach angle—intersects the topography marks the maximum energy line of a generic block, representing the farthest potential deposition area. This maximum energy line was mapped to delineate the hazard zone based on the empirical method (Figure 9a).

According to the geometrical method, critical and dispersion areas were determined using topographic criteria. Field inspections then identified and classified instability evidence, applying the same approach to assess hazard and vulnerability. Many features could be addressed related to rockfall features (Figure 1). Regarding vulnerability analysis, taking what was proposed (Figure 5), the areas with Cerrado vegetation near the cliff were considered more vulnerable, whereas the dense Eucalyptus vegetation was deemed less vulnerable to rockfalls. This distinction resulted in slight differences in the final risk map (Figure 9b). Nevertheless, dynamic analysis is required to check the previous indication (Figures 5 and 9).

In general perspective, both methods indicated that a section of the Orlando Teodolini dirt road lies within the risk area, with a hazard level ranging from moderate to very high. In case of new detachments, the exposure to the block propagation trajectory is likely to happen. Likewise, parts of the recreational area's parking lot and access trails leading to the viewpoints are also within the risk scenario, classified as very high in the geometrical method (Figure 9b).

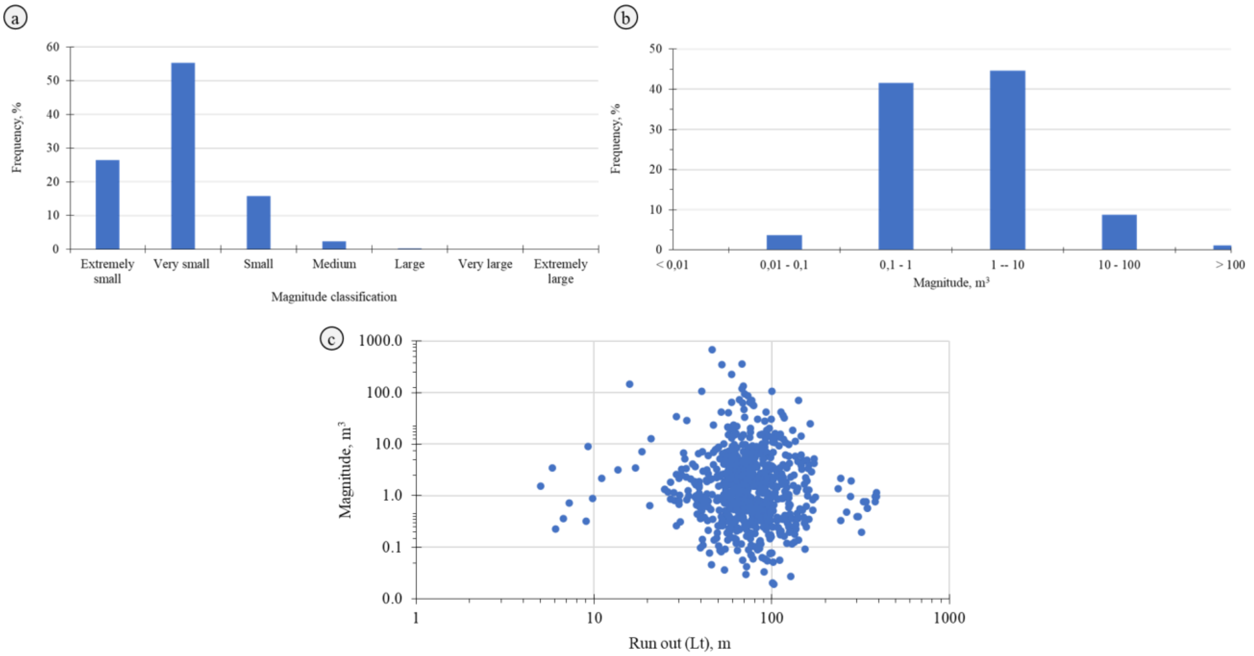

Figure 8. Magnitude classification: a) USA Geological Survey, b) Wang et al., (2013), c) magnitude versus travel distance.

In the event that occurred in October 2022, the blocks detached from the slope had an estimated volume of about 240 m^3. This initial volume fragmented shortly after the first impact with the talus at the base of the escarpment, causing a spreading of block trajectories in a semi-radial pattern. Five block trajectories were recorded radiating from this impact zone, totaling 54.2 m^3 of rock. These blocks rolled down the slope through the vegetation. Some were stopped by the vegetation, while three blocks, totaling approximately 22.5 m^3, reached the dirt road (Figure 9). Of the volume that detached, about 9% represented a hazard to road users, i.e., civilians and tourists (Figure 1c-d). Vegetation was responsible for retaining approximately 13% of the block volume, while rock fragmentation upon initial impact was the main factor in energy dissipation and block propagation.

It was expected that both methods managed to capture the essence of this event. That is, the impact zone of the 2022 event was contained within the previously mapped hazard area. For the empirical method, it is because, in a simplistic way, the reach angle obtained from the event is higher than the value from the inventory, i.e., block deposits catalogued have the data of higher travel distance. So, the inventory is something mandatory to be done prior to this method application.

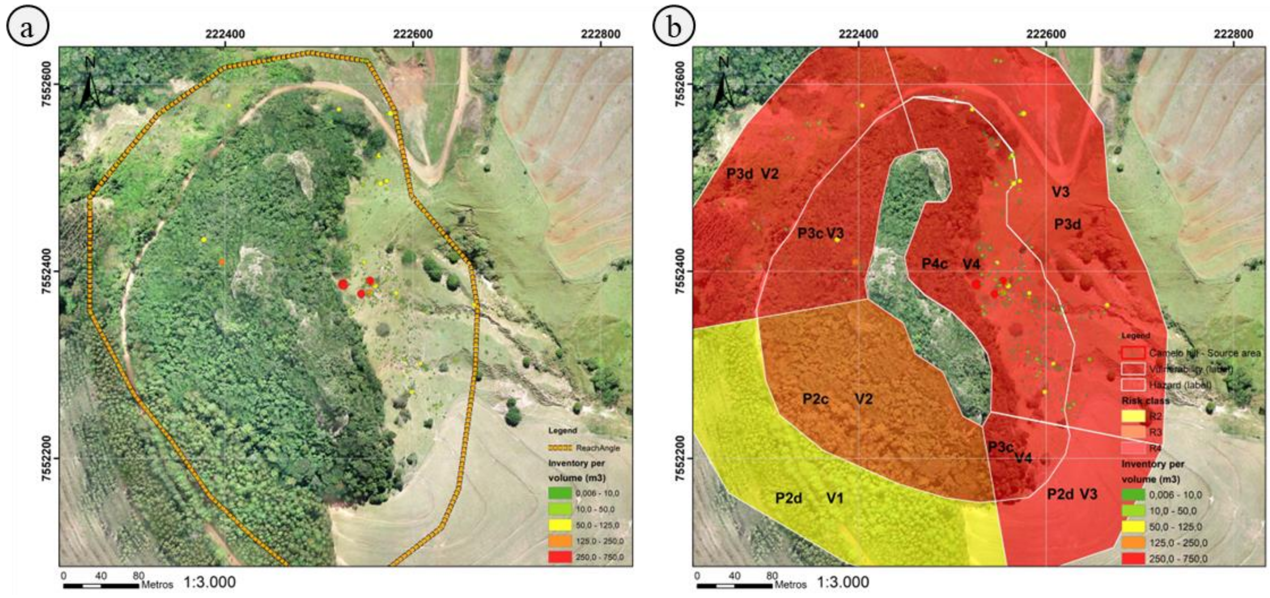

Figure 9. Risk map of Camelo Hill geosite by a) empirical and b) geometrical methods.

Concerning the geometrical method, it seems that it incorporates the concepts of reach angle in some essence but is slightly conservative with the use of dispersion area. These aspects are related to the lack of information concerning rockfall inventories. Resulting in a risk area larger than the previous method. For instance, the reach angle produces a risk area of 152531.6 m^2, and the geometrical method is 162840.0 m^2, around 6.5% higher. For the Brazilian method, the GIDES procedures do not allow for predicting block trajectories, calculating block interactions with the terrain surface or the presence/absence of vegetation, nor do they suggest solutions. According to the authors, research on the rockfall topic is still in its early stages, making it difficult to indicate definitive conclusions about the procedures, thereby favoring a conservative approach.

In this case, we believe that a numerical value could be addressed to represent the runout of Brazilian geological-geomorphological formations as reach and shadow angles. These values can be compared between rock outcrops, as well as serve to calibrate parameters in dynamic analyses in more complex conditions, aiming at indicating structural mitigating measures. Finally, it seems to be a constant that Brazilian methods are always qualitative; they never aim to take a step towards quantitative.

6. CONCLUSIONS

In this study, we conduct a risk assessment of the adventure tourism area of Camelo Hill, Analândia. A geosite within the Corumbataí Geopark Project domain in São Paulo State, Brazil. The primary goal was to apply empirical and geometrical methods to hazard and risk zonation in the recreational areas and its access roads and trails. The key findings are summarized as follows:

The hazard assessment methods effectively captured the rockfall event, demonstrating their applicability in similar escarpment environments. Both empirical and geometrical methodologies proved useful, with the first method requiring a detailed rockfall inventory for hazard calculation, while the latter, though more conservative, does not rely on prior data. High-resolution input data remains essential for both approaches;

The Orlando Teodolini Road, connecting Analândia to São Carlos, lies within a Moderate (R2) to Very High (R4) risk zone for rockfalls. Furthermore, the tourist attractions within the Camelo Hill geosite domain, including the parking lot, trails, and recreational spaces, also present significant risks, ranging from High (R3) to Very High (R4).

Future risk research should focus on defining numerical parameters for rockfall run-out in Brazilian geological landforms, allowing for improvements of predictive models and more effective mitigation planning, rather than relying solely on qualitative analyses without meaning for comparative purposes or decision-making.

Integrating engineering geology and geoconservation is critical for ensuring visitor protection in geosites vulnerable to natural disasters, such as the rockfall process. Special attention is required to improve user safety in these areas. Risk mapping remains an important tool for raising awareness, guiding appropriate land use, and promoting responsible practices in adventure tourism areas.

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