

Rockfall hazard assessment using detailed digital surface models at Portão do Inferno/Mato Grosso, Brazil

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Case Study

Keywords

Geotechnical mapping
Gravitational mass movements
Risk mapping

Abstract

This study analyzes the rockfall hazard at Portão do Inferno, located in Chapada dos Guimarães, Mato Grosso (MT), by applying a rockfall risk mapping methodology and its implications for infrastructure work and safety. The objective of the work was to identify areas susceptible to rockfalls and assess the associated risks, considering the local geology and the impacts on highway MT-251. The methodology included Unmanned Aerial Vehicle (UAV)-based aerial surveys, and application of criteria from the Brazilian Geological Service, along with data obtained from the Construction Inspection Report prepared in November 2024. The mapping considered the slope of the terrain to identify critical areas and define hazard zones. The main results indicate that the region has slopes exceeding 50 degrees and fracture systems S1 and S2, which present a high potential for landslides. The study identified unstable blocks that could be removed by highway management and suggested mitigation interventions, including continuous monitoring and the adoption of containment systems. Additionally, it highlighted the importance of vegetation in dissipating the energy of the falling blocks and in stabilizing the slopes. The study concludes that a detailed analysis of geological discontinuities, combined with a continuous monitoring and mitigation system, is essential to reduce risks and avoid high-cost emergency measures. It also reinforces the need to correlate rainfall events with rockfalls to improve prediction and intervention planning.

1. Introduction

Rockfalls are abrupt, downward movements of rock or soil, or both, that detach from steep slopes or cliffs (Highland & Bobrowsky, 2008; Tanoli et al., 2022; Brasil, 2023). The occurrence of rockfalls is a natural phenomenon, but it becomes problematic when it exposes human activities, such as infrastructure and transportation, to risky situations (Dunham et al., 2017; Effgen & Marchioro, 2018; Ferreira et al., 2020; Highland & Bobrowsky, 2008).

As one of the most frequent and destructive types of gravitational mass movement (GMM) (Rosser & Massey, 2022), rockfall hazard mapping is a widely researched subject (Highland & Bobrowsky, 2008). Various methodologies have been employed to better understand the phenomenon and reduce societal exposure to such events (Abbruzzese et al.,

2009). A hazard corresponds to a condition or phenomenon with the potential to cause an undesirable consequence within a given period (Pimentel & Santos, 2018) and differs from risk, which, in addition to the probability of occurrence, includes the magnitude of damage or social and/or economic consequences for a given element, group, or community.

The approaches to estimate rockfall hazard in literature range from the simplest, which are easily applied using qualitative scoring systems (Effgen & Marchioro, 2018; Tanoli et al., 2022) to the use of quantitative methods that include the trajectories in a deterministic (Ferrari et al., 2016) or probabilistic manner (Lanfranconi et al., 2023; Li & Lan, 2015). Other authors employ approaches based on understanding the phenomenon and use geographic information system (GIS) tools to estimate the areas likely to be affected by rockfall (Pimentel & Santos, 2018).

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Submitted on March 25, 2025; Final Acceptance on June 5, 2025; Discussion open until May 31, 2026.

Editor: Renato P. Cunha 

<https://doi.org/10.28927/SR.2026.004925>



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The Rockfall Hazard Rating System (Pierson & Van Vickie, 1993), Modified Colorado Rockfall Hazard Rating System (CRHRS) and Silveira et al. (2024) are examples of methodologies that present an index that ranks areas according to the value obtained based on observations made in field. These methodologies are easy to apply, but they provide localized information. Numerical simulations, depending on the approach, require information related to the materials associated with the GGM and the surface on which it occurs.

Given the importance of the subject, the objective of this study is to present an evaluation of the estimated areas likely to be affected by rockfalls at the site of the natural tourist attraction known as Portão do Inferno, located in the municipality of Chapada dos Guimarães, in the state of Mato Grosso, Brazil, using detailed digital surface models.

1.1 Considerations about rockfall

The movements are extremely rapid, with variable volumes, and they reach the lower slope at angles smaller than the fall angle, resulting in jumps and/or rolls (Highland & Bobrowsky, 2008; Volkwein et al., 2011). The volume of material associated with the rockfall process ranges from individual rock blocks, as the process name suggests, to conglomerates of blocks with dimensions reaching hundreds of cubic meters (Dussauge-Peisser et al., 2002; Highland & Bobrowsky, 2008). The blocks can vary in size and shape, depending on the orientation, spacing, and persistence of the discontinuities present in the rock mass (Da Silva & Santos, 2020), which directly influence both the propagation distance of the blocks and the effectiveness of the vegetation in containing them (Caviezel et al., 2021; Volkwein et al., 2011).

Interventions such as deforestation or the absence of vegetation in arid climatic conditions, as well as the indiscriminate cutting of road slopes contribute to triggering the gravitational rockfall movements (Effgen & Marchioro, 2018; Highland & Bobrowsky, 2008). It is worth noting that vegetation has both favorable and adverse effects on the stability of rock slopes (Aqeel, 2018). Vegetation roots contribute to the widening of discontinuities that can lead to failures in rock slopes; however, they function as natural barriers and protect against rockfalls, especially when randomly distributed (Radtko et al., 2014).

The triggering mechanism of gravitational movement may be associated with an increase in stress or with a reduction in the resistance of the discontinuities, with the latter parameter decreasing over time (Wyllie & Mah, 2004), either due to changes in the material of the intact blocks or due to external factors such as rain. The increase in stress may be associated with mass removal, overloading at the crest, dynamic stresses, and lateral pressures due to differential weathering, such as the freeze-thaw cycle and daily or seasonal thermal oscillations (Gomes, 2009; Guidicini & Nieble, 2016).

1.2 Study area

The Portão do Inferno region, between Cuiabá and Chapada dos Guimarães in the State of Mato Grosso, has a history of previous occurrences of rockfall in 2012 and 2021 (G1, 2012, 2023a, b). The recent occurrence in December 2023 led the Mato Grosso Government to declare a state of emergency in the region (Mato Grosso, 2023).

The study area corresponds to the natural tourist attraction, Figure 1, located along the margins of MT-251, which runs through the Chapada dos Guimarães National Park connecting the capital, Cuiabá, to the urban perimeter of the municipality of Chapada dos Guimarães, in the State of Mato Grosso, Brazil.

Thomé Filho et al. (2006) conducted a mapping at a 1:100,000 scale of the Cuiabá, Várzea Grande region and its surroundings. The authors identified a contact, due to erosional discordance, which represents an abrupt change in the geomechanical behavior of the rock masses between the Furnas Formation of the Paraná Group at the highway's foundation and the Botucatu Formation on the natural slopes above the highway level.

Conciani (2024) found that at the foundation of the bridge, 10 meters of sandstones belonging to the Botucatu Formation are observed, followed by the Ponta Grossa Formation for a few meters before reaching the Furnas Formation, as depicted in the scheme shown in Figure 2, estimated from the results of rotary drilling tests.

Figure 3 shows a detail of the area affected by the gravitational mass movement (GMM) of the rockfall type, illustrating the situation in 1959 before the construction of the viaduct and the situation in 2023, immediately after the event.

The Furnas Formation is composed of friable sandstones with structures that indicate anisotropy in the intact rock strength properties due to the formation process and the presence of geological structures. The formation is represented from the base to the top by conglomeratic sandstones that grade into pure sandstones, ranging in color from white to yellowish, and locally purplish, with hummocky cross-stratifications that transition into sandstones with wavy cross-stratifications. In general, they exhibit a medium to coarse grain size with subangular to subrounded quartz grains that are friable, immature, and feldspathic at the base (Thomé Filho et al., 2006; Vieira Júnior et al., 2012).

The Ponta Grossa Formation is composed of siltstones and fine sandstones that, when unaltered, are cream-colored and become reddish and purplish when altered, occurring as discordant, plane-parallel strata overlying the metasediments of the Cuiabá Group. This formation is impermeable to semi-permeable, with water percolation restricted to the fractures (Thomé Filho et al., 2006; Vieira Júnior et al., 2012).

Similarly, the sandstones of the Botucatu Formation, like those of the Furnas Formation, exhibit structures that indicate anisotropy in the intact rock strength properties due to the formation process and the presence of geological

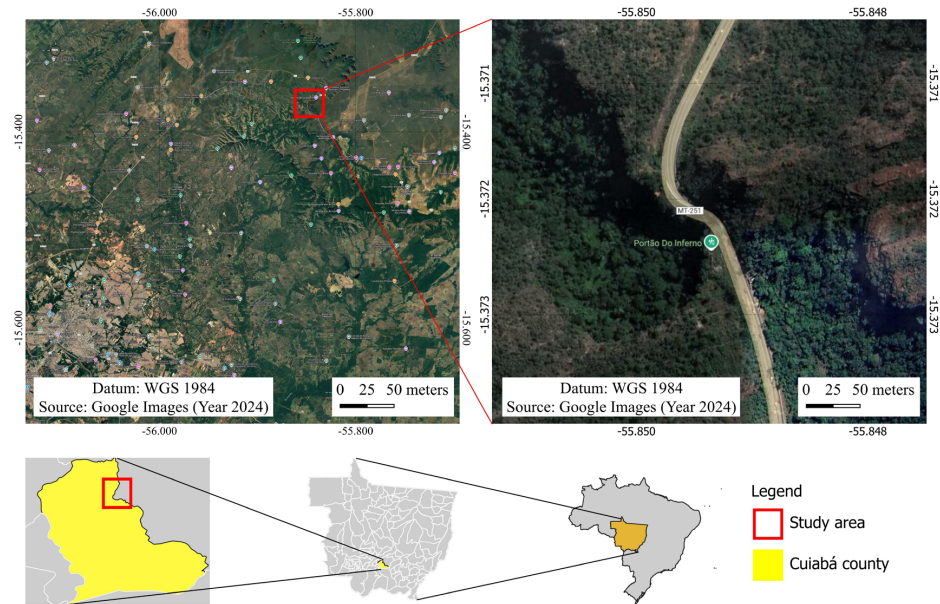


Figure 1. Coverage area of the aerial survey and rockfall hazard mapping.



Figure 2. Aerial view of Portão do Inferno in 2023 and indications of the geological units.



Figure 3. Gravitational mass movement of the rockfall type on highway MT 251 in the Chapada dos Guimarães region, in the State of Mato Grosso, Brazil. (a) Photo of the site before the construction of the viaduct in 1959; (b) Detail of the rock mass in 2023; (c) General view of the Portão do Inferno area in 2023.

structures. This formation is composed of fine to medium, bimodal, red sandstones with well-rounded quartz grains that exhibit good sphericity, a dull surface, and are coated by a ferruginous film, with common siliceous or ferruginous cement (Bertolini et al., 2020, 2021). They display large-scale grooved cross-stratifications as well as tabular cross-stratification, tangential at the base, and plane-parallel stratification (Thomé Filho et al., 2006; Vieira Júnior et al., 2012). The differences in cementation are responsible for the ruineforme relief patterns, where the upper rock layers exhibit greater resistance to weathering, while the degradation of the lower rocks can contribute to triggering the rockfall phenomenon.

Conciani et al. (2024) reports that mass movements only occurred when it rained during the period from December 2023 to February 2024. In exceptional cases, mass movements can also occur in conjunction with thunderstorms and intense winds (Conciani, 2024). This may be related to the stress on the blocks arising from the action of the winds on the vegetation and consequently on the roots that are filling the families of fractures of the rock mass. The study of the daily bulletins reviewed by the author shows that the volume and intensity of rainfall are the triggering mechanisms for these events.

Vandewater (2005) reports that the severity of a rockfall depends on the degree of lithological variation, in terms of strength, and the thickness of the layers. The lithologies of both the Botucatu (Figure 3) and Ponta Grossa formations are sedimentary rocks, which, compared to igneous and metamorphic rocks, exhibit lower intact rock strengths (Marques & Leão, 2023; Min & Moon, 2006; Tsiambaos & Sabatakakis, 2004).

Sandstone from Botucatu Formation can be described as soft rock (Conciani et al., 2024). Nieble et al. (2021) indicates the use of this terminology when it becomes hard to separate rock and soil. The use of the expression soft rock puts the material in a moment of transition between soil and rock, and it may be caused by the alteration of rock or pedogenetic evolution of soil. The Brazilian Department of Transport Infrastructure (DNIT, 1997) classifies a soft rock as that presenting unconfined compressive strength between 10 MPa to 30 MPa. Goulart (2019) verified that the mean unconfined compressive strength for Botucatu sandstone was 16,30 MPa.

Lu & Wong (2008) found that sedimentary rocks have a uniaxial compressive strength approximately 40% lower when wet or saturated, whereas massive igneous rocks may lose up to 10% of their strength. Tang (2018) indicates that the reduction in uniaxial compression strength with increasing water content. Li et al. (2012) reports that a reduction in uniaxial compressive strength (UCS) due to the presence of water has been experimentally observed in many sedimentary rocks and even in some metamorphic rocks. Nieble et al. (2021) also had reported this behavior in Brazilian soft sandstones.

This behavior is typical of unsaturated collapsible soils. Gens & Alonso (1992) had proposed a constitutive model for this kind of material. At this constitutive model, the water content rising with consequent reduction of suction causes the reduction of strength is caused by. This reduction in strength acts as the main triggering mechanism for the mass movements. Yao et al. (2024) proposes a model that can describe the behavior of both wetting-induced swelling and wetting-collapse for unsaturated clays.

Conciani et al. (2024) obtained, through pycnometer method, a grain specific mass value of 2.6 g/cm³ (25.5 kN/m³ – grain specific weight) for the Botucatu Formation sandstones, consistent with 2.71 g/cm³ in São Paulo as reported by Goulart (2019). The apparent specific mass values obtained by the authors ranged from 1.95 g/cm³ to 2.32 g/cm³, like those obtained by Goulart (2019), which ranged from 1.91 g/cm³ to 2.29 g/cm³. Grain size distribution tests with sieve analysis of rotary drilling samples indicated a texture varying from fine to medium sand.

The geological structures associated with the eolian environment of the Furnas Formation (Milani et al., 2007) cause the rocks of this geological unit to exhibit distinct behaviors under the same stresses due to different formation conditions (flooded areas, storm deposits, and wind direction) that are recorded in the intact rock (type and degree of cementation) and in the form of geological structures. Li et al. (2012) observed that, in general, the triaxial compressive strength of rock specimens with transverse bedding planes is higher than those with longitudinal bedding planes.

Silva (2018) conducted a kinematic analysis of the slopes at Portão do Inferno, identifying critical structural patterns for the stability of the rock mass. Through photointerpretation and mapping of discontinuities, the author recognized two preferential lineaments (NE and NW), associated with the tectonic evolution of the Paraná Basin, and three families of discontinuities with specific orientations: northwest (309/83), southwest (244/82), and southeast (154/83), all exhibiting dips greater than 80°. These discontinuities were correlated with potential rupture mechanisms, such as wedge failures (controlled by the intersection of fractures) and planar ruptures (associated with continuous weakness surfaces).

The Work Inspection Report (SINFRA GDEDMG, 2024) complements these findings by identifying two active fracture systems (S1 and S2) that directly influence the current dynamics of rockfalls.

- System S1 (NW-SE, southwest dip): Responsible for rockfalls with trajectories between azimuths 260° and 310°, consistent with the northwest-oriented discontinuities mapped by Silva (2018).
- System S2 (NE-SW, northwest dip): Controls the rupture of rock prisms (azimuths 180°–195°), relating to the southwest and southeast discontinuity families described earlier.

Additionally, the Inspection Report (SINFRA GDEDMG) highlights the differential erosion between

the region's geological formations, emphasizing distinct processes that influence the instability of the rock mass. In the Furnas Formation, piping occurs, a process where the dissolution of cement in sandstones creates linear incisions with a preferred orientation of 120°, leading to the lateral fall of rock columns toward azimuth 190°. In the Botucatu Formation, the interaction between the S1 and S2 fracture systems accelerates block disaggregation, resulting in fragmentation upon reaching the MT-251 highway, thereby increasing risks associated with rock material detachment.

This integration between the S1 and S2 fracture systems and the differential erosion between the region's geological formations demonstrates that the historical structural patterns (Silva, 2018) remain active, underscoring the importance of mitigation strategies aligned with the current geomechanical behavior of the rock mass.

2. Materials and methods

The methodology consisted of the following steps: data collection using Unmanned Aerial Vehicles (UAV) and development of derived products; hazard identification through the methodology of the Brazilian Geological Service (Pimentel & Santos, 2018); synthesis and delineation of affected areas.

2.1 Data acquisition and processing

The aerial surveys were conducted on May 30, 2024, using the MAVIC PRO aircraft, equipped with a 1/2.3" CMOS sensor, with 12.35 effective megapixels (12.71 megapixels in total). The lens has a field of view (FOV) of 78.8°, with a focal length equivalent to 26 mm in the 35 mm format and an aperture of f/2.2. The images obtained have a resolution of 4000 × 3000 pixels. The total post-processing times were significantly long: the combined generation of the sparse and dense point cloud took a total of 8 hours, while the manual editing of the point cloud and the generation of the Digital Elevation Model (DEM) required an additional 2 hours. The creation of the orthomosaic and the digital elevation model (DEM) was created using the free version of Agisoft Metashape.

2.2 Field mapping

Based on regional geology, a preliminary structural mapping of the discontinuities in the rock mass was carried out following specifications of Hudson & Ulusay (2007), examining their aperture, infill, persistence, roughness, degree of alteration, orientation (direction/dip) and other relevant characteristics for the qualitative assessment of the discontinuities' behavior. The Equation 1 represents volumetric joint count (J_v) proposed by Palmström (1982) which is used to estimate of the size of the blocks using Equation 2 (Palmström, 1995).

$$J_v = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \dots + \frac{Nr}{5} \quad (1)$$

where Nr = the number of random joints.

$$V_b = \beta + \left(\frac{1}{J_v} \right)^3 \quad (2)$$

where β = block shape factor, recommended to use a common value of 40, and V_b block volume (m^3).

2.3 Rockfall hazard mapping

According to Volkwein et al. (2011), hazard mapping should consider the probability of block fall occurrence, the probability that it will reach the dispersion area, and the intensity. In this stage, where the product is a hazard map, the criteria defined by Dutra et al. (2018) and Pimentel & Santos (2018) were used to identify the potential hazard and to delimit the critical areas where triggering may occur, as well as the areas of block dispersion related to the gravitational mass movement of block falls.

The authors (Dutra et al., 2018; Pimentel & Santos, 2018) define the critical block fall area, meaning the area with the highest probability of triggering gravitational mass movements, as locations with slopes of 50° or more and heights greater than five meters. Areas with slopes of less than 20° and limited to the height of the slope under analysis are considered dispersion areas, defined as areas subject to the deposition of material mobilized during a gravitational mass movement. Intermediate areas, with slopes between 20° and 50°, are categorized as ramps, where the influence on the block's reach and trajectory is significant. Areas defined as the upper limit, occurring above the critical area, are locations that may provide blocks for the movement.

The descriptions of the hazard classes defined by the Brazilian Geological Service are presented in Table 1. All classes consider that the topographic conditions and/or criteria for delineating the impact of gravitational mass movements are met.

3. Analysis and results

The Digital Elevation Model (DEM) that was developed clearly displays the escarpment boundary to the west of the study area, with values exceeding 70°. The analysis considered four slopes near MT-251, two corresponding to Portão do Inferno both of which have faces with NW–SE orientation, dipping southwest, and exhibit slopes greater than 50°. Two other slopes, farther from MT-251 but still within the coverage area exhibit a NW–SE orientation, dipping southwest, and a NE–SW orientation, dipping northwest. Areas with slopes greater than 50° present potential for block falls, according to Pimentel & Santos (2018).

Table 1. Hazard classes defined by the Brazilian Geological Service.

Hazard	APE	APC	Signs of instability	Potential energy of the movement	Records of past gravitational mass movements or deposits	Likelihood of the occurrence of gravitational mass movements during a normal rainy season
P1	AD	P1d	No signs	Dispersed	No	Low
P2	AC	P2c	Isolated cases may occur	Concentrated	Isolated	Moderate
	AD	P2d	Few unstable conditions	Dispersed	Isolated	Moderate
P3	AC	P3c	Evident signs of instability	Concentrated	Possible	High
	AD	P3d	Evident signs of instability	Dispersed	Possible	High
P4	AC	P4c	Evident signs of instability	Concentrated	Possible	Very high

Legend: see List of Symbols. Source: Adapted from Pimentel & Santos (2018).

Based on the structural survey of discontinuities at the site, four fracture sets were observed with mean orientations of 279/76 (S1), consistent with Silva (2018) and SINFRA (SINFRA GDEDMG, 2024); 149/15 (S2), like the S2 system identified by SINFRA (SINFRA GDEDMG, 2024); and two additional sets with orientations of 50/84 (S3) and 86/67 (S4). The persistence of discontinuities varies between 0.5 and 4 meters in length, moderately spaced (2.5 to 10 mm) to very closed (< 0.1 mm) and with smooth to rough wavy roughness. The S1, S2, S3 and S4 families have discontinuity spacings of 1.5 m, 1.80 m, 0.3 m and 0.4 m, respectively. The estimated volumes of the blocks were 0.1 m^3 , compatible with those observed in Figures 4.

Due to the fracturing pattern, it may be necessary to remove larger volumes of rock than just isolated blocks. The blocks in the critical areas and upper limit that are unsupported would need to be removed, as shown in Figure 4. It is observed that none of the blocks in Figure 4 can be identified in the aerial survey but only through site visitation. The rock mass exhibits discoloration of intact rock and discontinuity surfaces slightly weaker externally than in its fresh condition. The surface can be peeled off with difficulty using a knife, leaving small marks with firm blows from the tip of a geological hammer.

If containment structures are not installed, the blocks will continue to impact the roadway since it is integrated into the ramp and the mapped dispersion zone. Occurrences of rock block falls should be continuously monitored, and the blocks found in the dispersion area and on the ramp should be recorded to update the dispersion zone indicated in Figure 5.

For the area covered by the aerial survey, zones with a very high risk of block falls in the critical zones and a high risk in the ramp and dispersion zones have been identified (Figure 6). Pimentel & Santos (2018) recommend that in

the absence of vulnerability data, a medium vulnerability be assigned until a more detailed evaluation of the situation is conducted, which, when associated with the mapped danger areas, implies a very high risk of block falls in the critical zones and a high risk in the ramp and dispersion zones.

In the case of artificial slopes along road corridors, vulnerability assessments should consider the vulnerability of civil structures and vehicles. Sight distances, the effectiveness of containment structures, visibility distance for decision-making in the event of a gravitational mass movement, and the roadway width (Aqeel, 2018; Da Silva & Santos, 2020; Rosser & Massey, 2022) must be considered in this analysis.

It is observed that the entire rock mass has been categorized as a very high-risk area, as has the section of the highway used as an observation area. Based on the hazard mapping and the ortho-mosaic, locations have been identified where blocks must be inspected and removed if they are isolated or unsupported due to the fall of lower blocks, or if they are separated from the rock mass by open discontinuities—with or without infill—as shown in the examples presented in Figure 7.

The mapping process can be validated through continuous monitoring of the site. Figure 8 shows an example of rock blocks falling over the highway. This is the real risk predicted by the model showed before. Damage to infrastructure is just one of the several issues caused by slope instability in the region. The actual trouble is the possibility of accidents involving people.

The blocks indicated in Figure 9 were identified from the aerial survey, but they should not be considered the only ones to be removed. The presence of vegetation and the angle of the aerial survey prevent the identification of unsupported blocks solely through imagery. The Inspection Report (SINFRA GDEDMG, 2024) indicates that block removal was carried out by rappelling by the company that



Figure 4. Examples of unsupported blocks in a wedge rupture scar following a fall related to the lower layer of the sedimentary rock (Conciani, 2024).

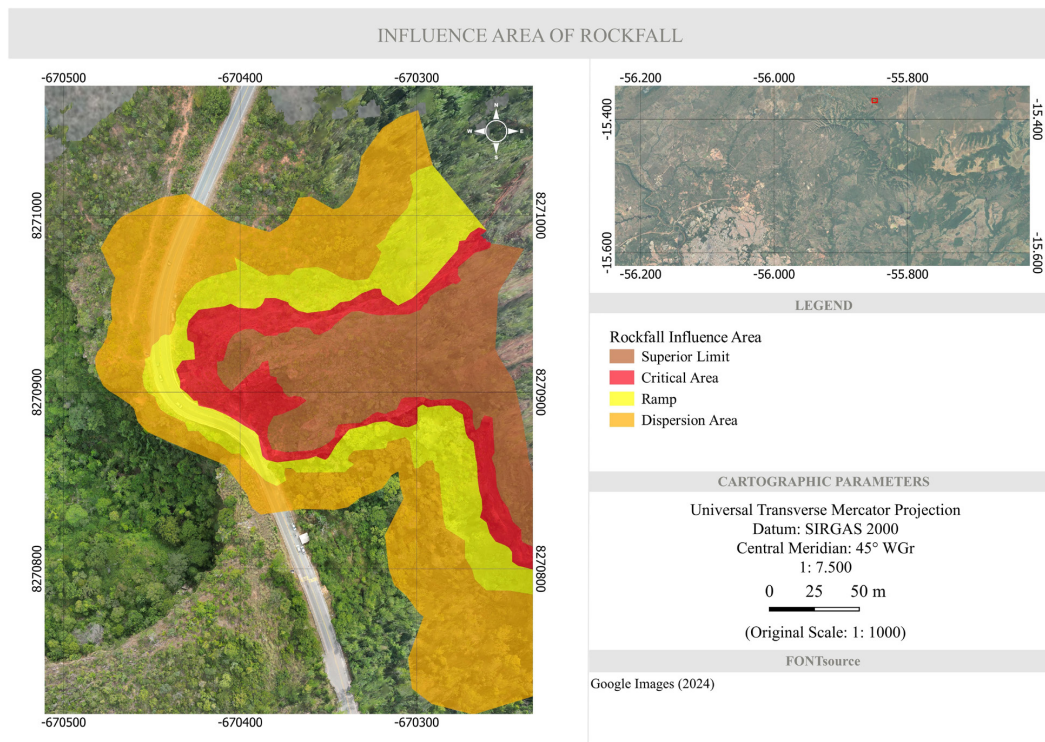


Figure 5. Mapping of the critical areas, dispersion zones, and ramps related to gravitational mass movements of the block-fall type.

manages the highway, predominantly displacing submetric blocks, most of which disintegrated during their fall to the highway level. However, the report does not specify which

blocks were removed, making it impossible to directly correlate the blocks identified in the aerial survey with those already removed from the area.

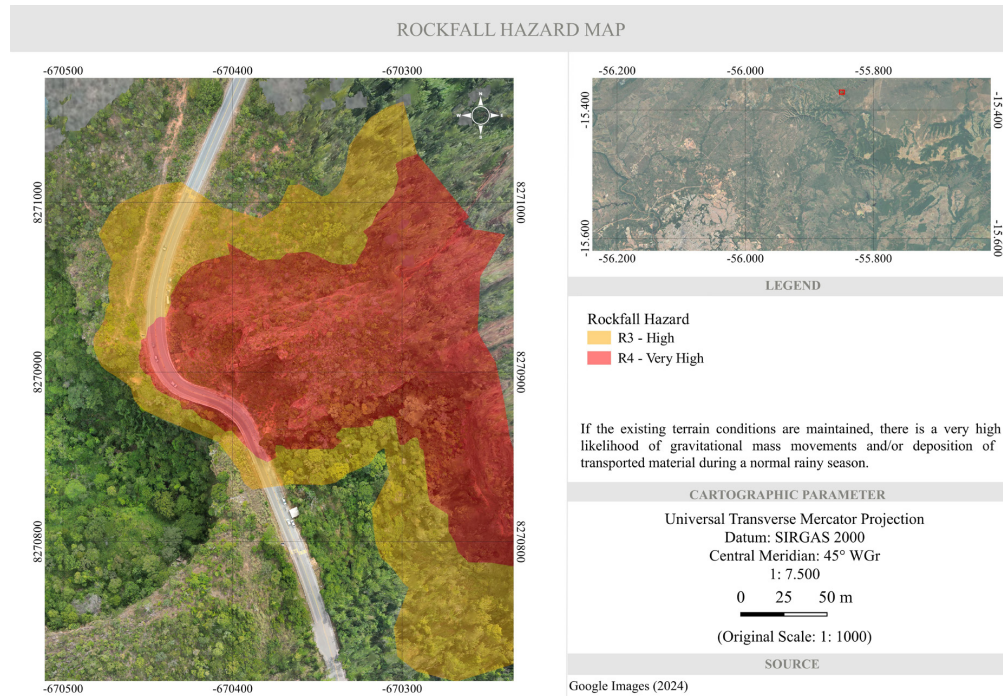


Figure 6. Mapping of the risk of block falls within the scope of the aerial survey.



Figure 7. Examples of unsupported blocks are likely to be removed (Conciani, 2024).



Figure 8. Rock blocks fallen over the highway as a validation of the mapping work (Conciani, 2024).

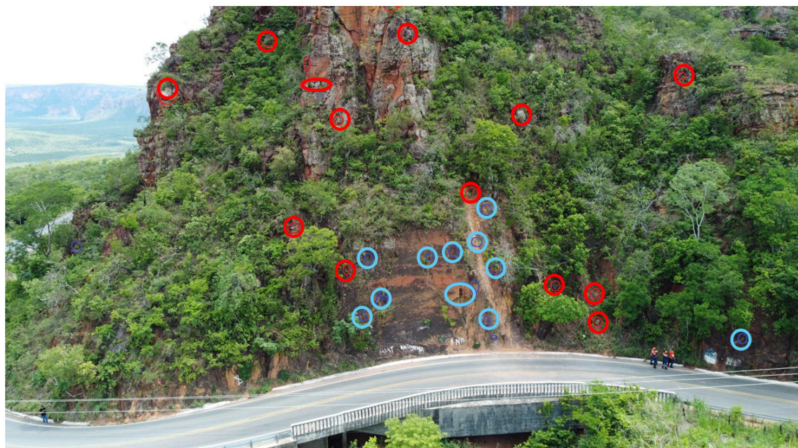


Figure 9. Occurrences of blocks to be inspected/removed in the field, on site. Red circles indicate large blocks, and blue circles indicate small blocks (Conciani, 2024).

4. Conclusion

This research provides an ongoing assessment of rockfall-susceptible zones at the Portão do Inferno natural tourist attraction. Preliminary results reveal two previously unreported discontinuity sets, expanding the structural understanding of the area. Parameters such as aperture, persistence, and degree of alteration were evaluated, and block sizes were estimated closely with previously documented dimensions. For each identified set, the authors recommend quantitative estimates of shear strength under different conditions should be performed using Barton Bands rupture criterion, for example.

The Inspection Report mentions the natural benches B1 and B2, recommending that they be used as containment platforms to prevent blocks from reaching the highway, probably based on the observation of terrain morphology. Benches B1 and B2 are located, respectively, in the critical area and at the upper limit of East-West faced north slope on Figure 5, both considered by the authors a source area for falling block material. Based on the adopted methodology, both locations are classified as very high-risk areas, but this does not exclude their effectiveness in containing blocks originating from higher elevations.

The aerial survey revealed vegetation cover in the ramp and block dispersion zones, with the exception of the MT-251 highway corridor. It is recommended by the authors to include the monitoring of vegetation developing along the discontinuities of the rock mass, located in the critical very high-risk area, in the monitoring strategy, and to maintain the vegetation in the ramp area to help mitigate the impacts of falling and rolling blocks. As it is a federal conservation unit, it is not possible to change the preexisting vegetation species on the slopes, even if the roots contribute to the opening of the fractures.

The areas identified as very high risk on the block-fall hazard map coincide with the recorded block-fall events. The methodological approach proposed by Pimentel & Santos (2018) is commonly applied at scales between 1:25,000 and 1:10,000. In this study, mapping was carried out at a 1:1,000 scale using a digital surface model derived from UAV airborne surveying. The delineation of critical areas, dispersion zones, and ramps associated with gravitational mass movements is more precise but may be subject to errors if the influence of vegetation is not removed during the airborne survey processing. The generated dataset supports future simulations of block-fall trajectories for improved hazard prediction.

Finally, it is recommended to adapt the hazard classification system by considering rainfall events and the history of previous occurrences in order to define a robust and efficient system that can be continuously implemented and that allows for the prioritization of areas requiring containment solutions—thus avoiding unforeseen costs and emergency interventions.

It is also recommended that occurrence records, whenever possible, be correlated with rainfall events to establish an inventory of area occurrences and refine the proposed mapping. The Inspection Report (SINFRA GDEDMG, 2024) showed an indication of a relationship between both variables. The authors also recommended performing rotary drilling under technical supervision, followed by optical logging to estimate RQD values and enable the application of geomechanical classification systems such as Slope Mass Rating.

Acknowledgements

The authors would like to thank the Mato Grosso Infrastructure Secretary and ICMBIO for giving them access to the region to carry out this research.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Bruno Rodrigues de Oliveira: conceptualization, data curation, visualization, writing – original draft. Fabiani Dalla Rosa Barbosa: conceptualization, writing – review & editing. Wilson Conciani: conceptualization, writing – review & editing.

Data availability

All data produced or examined during the current study are included in this article.

Declaration of use of generative artificial intelligence

This work wasn't prepared with the assistance of generative artificial intelligence (GenAI).

List of symbols and abbreviations

AC	Critical area
AD	Dispersion area
APC	Field survey
APE	Office work
Nr	Number of random joints
P1	Low hazard
P2	Medium hazard
P3	High hazard
P4	Very high hazard
V_b	Block volume
β	Block shape factor

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