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Capitólio Rockslide in Brazil: Causes, Effects, and Lessons Learned

Giovani Jordi Bruschi[1], Maria Gabriela Batista da Silva[2], Guilherme de Ascenção Silveira [3], Mário Rui Rodrigues Vieira de Castro[4].

Abstract – This article addresses the rockslide that occurred in Capitólio, Minas Gerais, focusing on the geotechnical analysis of the event and its implications. The region, known for its natural beauty and tourism potential, has geological characteristics that make it vulnerable to rockslides, especially during periods of intense rainfall. The event in question caused human and environmental damage, highlighting the urgent need for preventive and mitigation measures. The geotechnical analysis identified that climatic factors, such as excessive rainfall, combined with the fragility of the rock mass and human activity, such as improper land use, may have contributed to the instability. The failure mechanism was characterized by toppling failure with large-volume rock movements. Preventive measures were discussed, including the implementation of geotechnical studies to identify risk areas, structural interventions for ground stabilization, and the establishment of administrative policies, such as regulations and public awareness campaigns. This study emphasizes the importance of integrated planning to ensure public safety, preventing future rockslides and their impacts.

Resumo – Este artigo aborda o deslizamento de rochas ocorrido em Capitólio, Minas Gerais, com foco na análise geotécnica do evento e suas implicações. A região, conhecida por sua beleza natural e potencial turístico, apresenta características geológicas que a tornam suscetível a deslizamentos, especialmente durante períodos de chuvas intensas. O evento em questão resultou em danos significativos, tanto humanos quanto ambientais, evidenciando a necessidade urgente de medidas preventivas e de mitigação. A análise geotécnica identificou que os fatores climáticos, como precipitações pluviométricas excessivas, somados à fragilidade do maciço rochoso e a atuação humana, como o uso inadequado do solo, contribuíram para a instabilidade. O mecanismo de ruptura foi caracterizado por tombamento de bloco com movimentos de rochas em grandes volumes. A partir disso, foram discutidas as medidas de prevenção, incluindo a realização de estudos geotécnicos para identificação de áreas de risco, intervenções estruturais para estabilização do terreno e a implementação de políticas administrativas, como regulamentações e campanhas de conscientização pública. Este estudo destaca a importância de um planejamento integrado para garantir a segurança da população prevenindo futuros deslizamentos e seus impactos.

Keywords – Geological Vulnerability, Intense Rainfall, Rock Mass Instability, Human Activity Impact, Risk Management.

1 Eng., PhD, STATUM Geotecnia, Tel, (54) 98132-5184, giovani.bruschi@statum.eng.br

2 Eng., STATUM Geotecnia, Tel, (37) 99953-6646, maria.silva@statum.eng.br

3 Geo., STATUM Geotecnia, Tel, (31) 97503-8883, guilherme.silveira@statum.eng.br

4 Eng., STATUM Geotecnia, Tel, (31) 98259-0110, mario.castro@statum.eng.br

1. INTRODUCTION

The rockslide that occurred in Capitólio, Minas Gerais, on January of 2022, gained significant attention due to the falling of large rock blocks into Lake Furnas, which hit tourists and caused considerable damage to local infrastructure (see Figure 1). The event resulted in the deaths of several people who were on boats in the area, raising concerns about the geotechnical safety of tourist sites and the impact of human activities on rock stability (G1, 2022).

Figure 1 – Rock rockslide Capitólio, Minas Gerais (Source: G1, 2023).

The Capitólio region is renowned for its striking rock formations, with geological aspects that include quartzites, which are prone to rockslides, particularly during heavy rainfall. The significance of this event is not only linked to its immediate consequences, but also to the pressing need to understand and mitigate the risks associated with rockslides in high-tourist traffic areas (Maciel, et al., 2023).

The aim of this article is to conduct a geotechnical analysis of the rockfall in Capitólio, Minas Gerais, addressing the causes, failure mechanisms, and the impacts resulting from the event. The geological context of the region, the influence of climatic conditions, and human activities are discussed, along with preventive and mitigation strategies that can be implemented to reduce the risk of future rockslides in similar areas. This analysis seeks to contribute to the enhancement of risk management practices and geotechnical safety.

2. CONTEXTUALIZATION

The region of Capitólio, located in the state of Minas Gerais, Brazil, presents geological characteristics that favor the occurrence of rockslides (see Figure 2). The area is primarily composed of quartzites from the Furnas Formation, which are susceptible to sliding processes due to their geological structure, characterized by vertical and horizontal fractures that facilitate the displacement of large rock blocks, especially under saturated conditions. The rocks in the region are prone to weathering, which, combined with heavy rainfall, increases the instability of slopes. The fragility of the rock mass is exacerbated by the presence of geological features such as fractures, which act as natural sliding surfaces (Sun, et al., 2024).

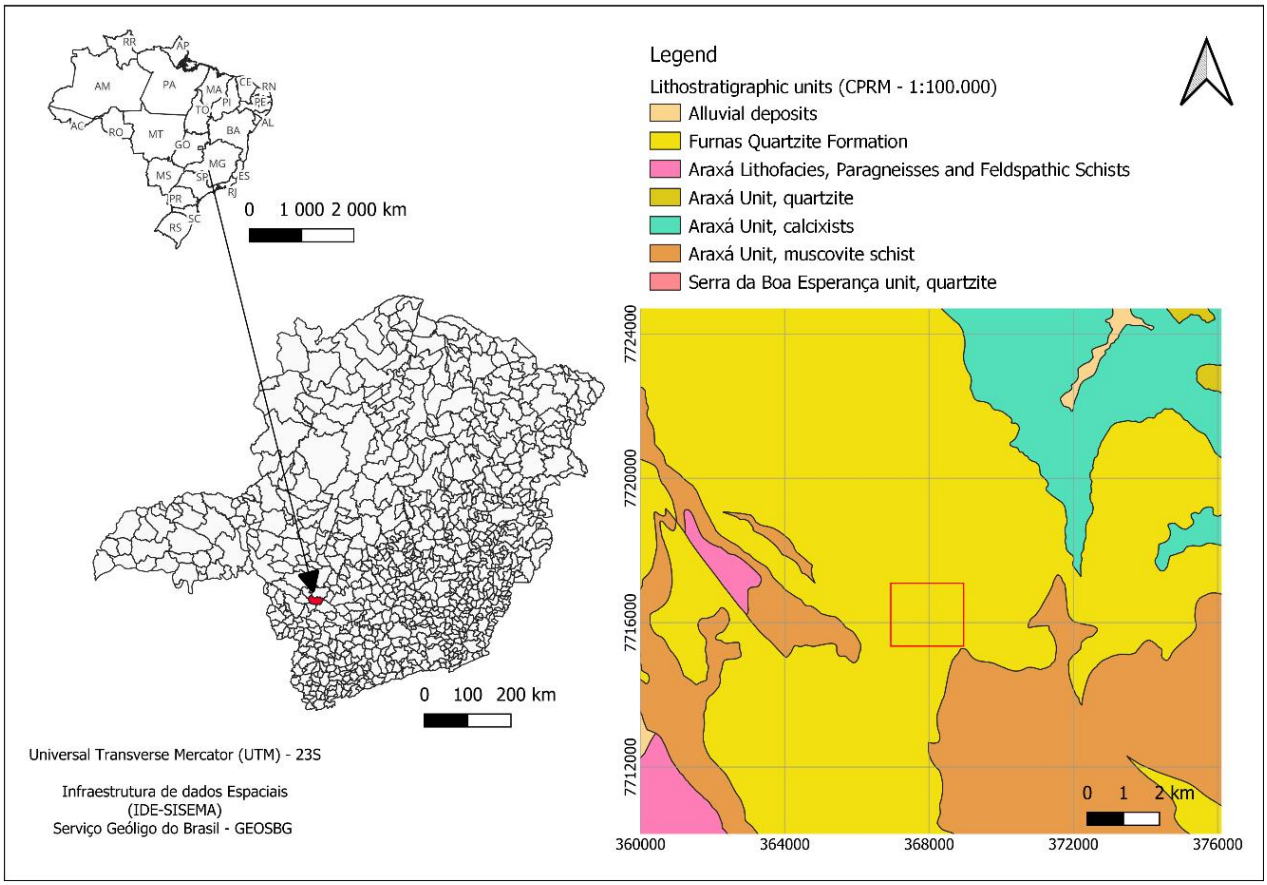

Figure 2 – Study area location and regional geological context.

The importance of tourism in Capitólio is a significant factor for local development, with the region attracting thousands of visitors annually due to the natural beauty of Lake Furnas, waterfalls, and canyons. Tourism is one of the main sources of revenue for the city, but it also places pressure on the local environment. The increased flow of tourists has intensified geotechnical risks, as the construction of tourism infrastructure, such as hotels and restaurants, often occurs without proper consideration of local geotechnical conditions. Uncontrolled tourism in areas with geotechnical risks can further exacerbate the effects of erosion and slope instability (Machado, et al., 2020).

Historically, Capitólio has recorded rockslide events, with several minor incidents over the past decades, especially during periods of heavy rainfall. These events, though not as devastating as the one in 2022, highlight the region's vulnerability to geotechnical instability. The lack of adequate planning and preventive measures in geotechnical risk areas worsens the impact of climatic events, such as the increase in rainfall, which has become more frequent due to climate change (Constantino, 2022).

3. SLIDING EVENT

The rockslide in Capitólio occurred on January 8, 2022, in an area of Lake Furnas, in the city of Capitólio, Minas Gerais. The event was marked by the fall of large rock blocks from the upper part of a canyon, striking tourist boats in the area, resulting in the deaths of 10 people and injuring several others. The tragedy caused widespread commotion in Brazil, not only due to the loss of human lives but also because of the intensity of the event and its connection to geotechnical risks in tourist areas (G1, 2022a).

The rockslide took place during a period of heavy rain that affected the region, contributing to the saturation of the rocks and exacerbating instability (G1, 2022a). The rock block that detached was approximately 25 meters long and 15 meters wide, and its fall had a direct impact on the boats, causing significant material damage to the local infrastructure and the tourism industry (CNN Brasil,

2022). The affected area is known for its imposing cliffs and rocky slopes, which are prone to rockslides due to the combination of specific geological characteristics and adverse weather conditions.

Following the event, rescue teams and local authorities mobilized to rescue the victims and identify possible causes of the rockslide. Preliminary investigation indicated that rock instability was exacerbated by climatic factors, such as heavy rainfall, and by the lack of planning for geotechnical risk management in the region, which sees a high tourist influx (G1, 2022a). The incident sparked a debate on the need to strengthen preventive measures in risk areas and raise awareness about the dangers of rockslides (CNN Brasil, 2022).

4. GEOTECHNICAL ANALYSIS

The geotechnical analysis of the rockslide in Capitólio involves identifying the causes that led to slope instability and understanding the failure mechanism that caused the rock block detachment. The event was a combination of factors that resulted in a significant structural failure of the slope. The following details the causes of the slide and the rupture mechanism.

The rockslide in Capitólio can be attributed to a series of climatic and geological factors, amplified by human activities. The primary natural factor contributing to the event was the structure of the rock mass and its geotechnical constraints. There are different types of structurally controlled failure mechanisms that can occur naturally (see Figure 3).

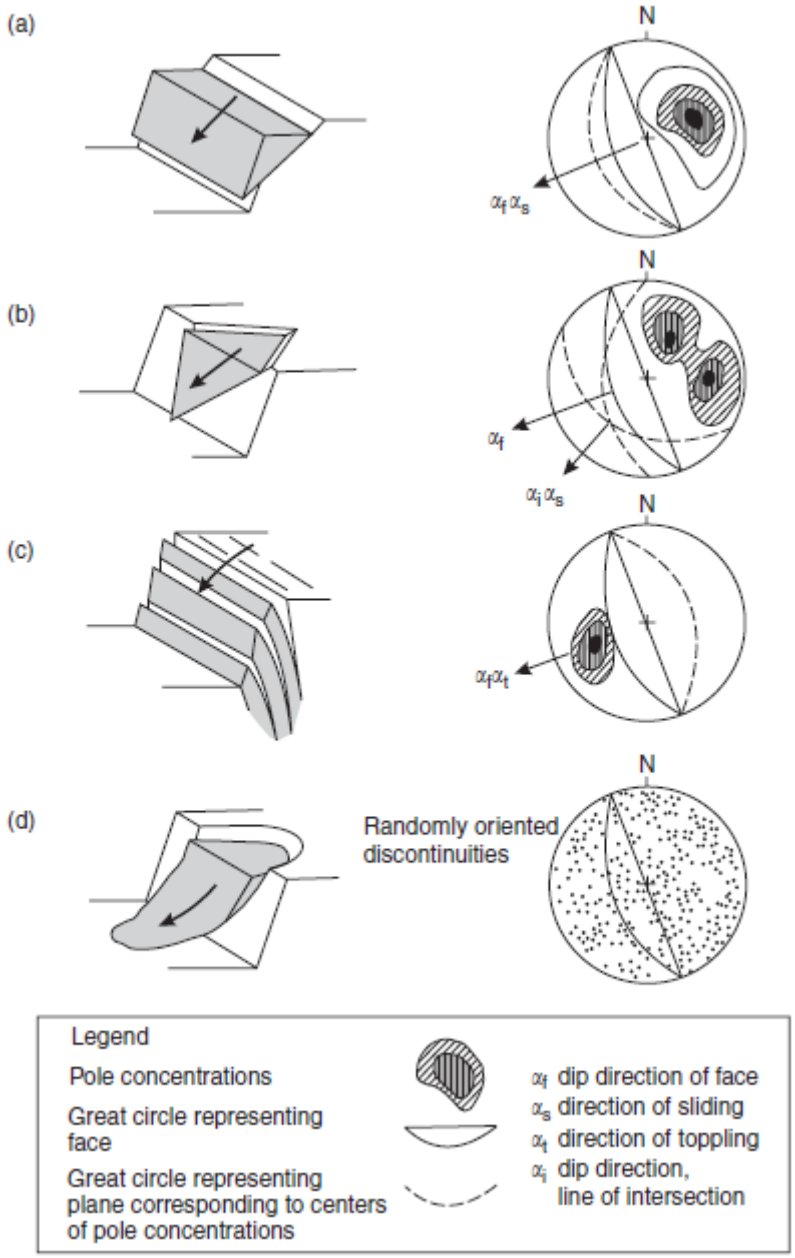

Figure 3 – Four main types of block failures in slopes: (a) plane failure; (b) wedge failure; (c) toppling failure; (d) circular failure. (Adapted from Wyllie & Mah, 2017).

The Capitólio region is characterized by numerous fractures in the quartzites, making the slopes vulnerable to rockslides during periods of excessive rainfall (Maciel, et al., 2023). These quartzites outcropping in the region have vertical and horizontal fracture systems that delineate rocks segments, leading to block toppling failures (see Figure 2c). These structures act as slip planes, allowing large rock blocks to move easily when the material's integrity is compromised.

This natural condition of rock mass, combined with saturation of rocks, caused by the intense rain that occurred in the period preceding the event, played a crucial role in the occurrence of the failure. When water penetrates existing fractures, it reduces cohesion between rock particles, lowering the material's strength and facilitating the movement of rock masses (Liu, et al., 2024). Additionally, the weathering of rocks, a natural process caused by the action of water, wind, and temperature variations, contributes to the weakening of rock structures, making them more susceptible to failure (Heather, et al., 2018).

Another factor was the influence of human activities. The increasing construction of tourism infrastructure near the slopes may have contributed to rock instability, as vegetation removal and

increased surface load on the slopes can exacerbate the erosion process and weaken the cliffs (Philips et al., 2006). The lack of proper geotechnical assessment in risk areas aggravates this vulnerability.

The detachment of the rock block was likely triggered by the combination of climatic and geological factors. The accumulation of water in the structure and subsequent loss of strength caused a failure at a critical point of the slope, resulting in a large-scale rock toppling (Jin, et al., 2024). The fracturing process was accelerated by the combination of rock weathering and the additional load imposed by water, leading to the fall of a large rock block approximately 25 meters in length (G1, 2022).

5. IMPACTS

The rockslide in Capitólio generated several impacts that affected both the local population and the ecosystems and economy. The human impact was undoubtedly the most severe. The rockslide resulted in 10 confirmed deaths and left several others injured, most of whom were tourists aboard the boats struck by the falling rocks. Additionally, the tragedy created a climate of insecurity among the local population, which relied on tourism as a source of income for many years (G1, 2022; CNN Brasil, 2022). The shock and concern about the possibility of new rockslides disrupted the daily life of the city, with many people seeking safety alternatives. The loss of lives and the sense of vulnerability in risk areas, such as the surroundings of Furnas Lake, created a strong demand for preventive measures and reassessment of the geotechnical conditions of the tourist areas.

The rockslide also had environmental impacts, mainly through the destruction of vegetation areas and the alteration of the natural habitat of local species. The fall of large rock blocks affected the fauna and flora in hard-to-reach areas, compromising regional biodiversity (Geertsema, et al., 2009). Although the rockslide occurred in a region already impacted by human activity and tourism, the event highlighted the need to consider the interactions between geology and the environment for more sustainable planning of tourism and urban activities.

Moreover, the alteration of the terrain's morphology and the potential contamination of Furnas Lake's waters by materials from the rockslide, such as rock debris and waste, are also environmental issues that need long-term monitoring. These changes can affect water quality, directly impacting aquatic fauna and local fishing activities (Parkash, 2023).

The economic impacts were felt both in the short and long term. Tourism, one of the city's main sources of income, experienced an immediate downturn after the disaster. The fear of new rockslides led to a decrease in the number of tourists visiting the region, affecting local businesses and job creation. The impact on tourism-related businesses, such as travel agencies, restaurants, and local commerce, was severe, with many services facing revenue drops due to the decline in visitors (Diário do Comércio, 2024).

Additionally, the costs of rescue operations, medical assistance, and the reconstruction of affected areas also represented a significant economic burden for the region, requiring public and private investments to ensure safety and rehabilitation of the area. The event also underscored the importance of risk analysis and the implementation of preventive policies, which, although initially costly, can prevent even higher costs in the future should new rockslides occur (G1, 2022b).

6. DISCUSSION

Several preventive and mitigation actions can be discussed as potential measures to prevent similar disasters and minimize the impacts on high-risk areas. The proposed strategies include geotechnical risk assessments, structural interventions, and administrative measures aimed at ensuring greater safety for the population and the region's tourism activities, as summarized in Table 1.

Table 1 – Preventive and mitigation measures for high-risk areas.

Measure	Action	Description
Risk Assessment	Detailed geotechnical studies	Identify and map unstable slopes and risk areas around Furnas Lake, analyzing factors such as local geology, rainfall, and vegetation.
	Continuous weather monitoring and early warning systems	Install monitoring systems to detect extreme weather impacts and provide early warnings, ensuring safety for tourists and locals.
	Stability studies of slopes and escarpments	Analyze areas affected by human activity (construction, roads) to assess slope stability and define intervention measures.
Structural Intervention	Slope stabilization (e.g., retaining walls, drainage systems)	Implement structural measures like retaining walls, drainage, and slope reinforcement to prevent rockslides.
	Geotechnical monitoring systems (e.g., piezometers, inclinometers, ground-penetrating radar)	Use real-time monitoring tools to detect soil conditions and potential slope movements to mitigate risk.
Administrative Measure	Risk zones and access restrictions	Define geologically unstable areas as restricted zones to prevent access and reduce risk.
	Land-use control and regulation of tourist activities	Control land use and tourist activities in vulnerable areas to prevent overload and minimize risk exposure.
	Awareness campaigns	Educate both locals and tourists about the risks of rockslides to promote safer behaviors.
	Integrated emergency response system	Develop a collaborative system between civil defense, environmental agencies, and security forces to ensure effective disaster response.

The first mitigation measure involves conducting detailed geotechnical studies to identify and map risk areas. In Capitólio, identifying unstable slopes, especially in the tourist areas around Furnas Lake, is essential to prevent new rockslides. Analyzing factors such as local geology, rainfall patterns, rock structure, and vegetation is fundamental for understanding risk dynamics. Continuous monitoring and the installation of early warning systems are crucial for mitigating the impacts of extreme weather events and ensuring the safety of tourists and the local population.

Furthermore, studies on the stability of slopes and escarpments, with special attention to overload zones created by human activities such as construction and roads, are also critical for planning control and intervention measures.

Structural interventions aim to stabilize risk areas and protect against rockslides. In Capitólio, slope stabilization works, such as constructing retaining walls, drainage, and slope reinforcement,

are essential to mitigate the risk of new rockslides. Additionally, using monitoring systems such as piezometers, inclinometers, and ground-penetrating radar allows real-time monitoring of soil conditions and detecting potential movements before they become disastrous. Another important measure is the controlled removal of rock blocks that pose an imminent risk of detachment, preventing unexpected failures and enhancing overall slope safety.

Administrative measures involve establishing regulations and implementing public policies aimed at risk reduction. In Capitólio, creating risk zones with restricted access to geologically unstable areas is an effective prevention measure. Land-use control and regulation of tourist activities are essential to minimize the overload on vulnerable areas. Moreover, awareness campaigns about the risks associated with rockslides and the importance of environmental protection should be conducted for both the local population and tourists to raise awareness of the dangers and encourage responsible behavior in risk areas

Finally, creating an integrated emergency response system involving civil defense, environmental, and security agencies is essential to ensure a swift and effective response in the event of new disasters.

7. FINAL REMARKS

The rockslide in Capitólio, Minas Gerais, was a tragic event that underscored the importance of effective geotechnical management in tourist regions with geological instability. The geotechnical analysis of the incident revealed that intense rainfall, combined with the specific geological characteristics of the region, may have contributed to triggering the disaster. Additionally, human activity, particularly tourism and construction in vulnerable areas, may have increased the risks.

The preventive and mitigation measures discussed in this work, such as conducting detailed geotechnical studies, implementing structural stabilization interventions, and developing administrative policies, are essential for reducing the risk of future rockslides. Continuous monitoring of geotechnical conditions and raising awareness among both local residents and tourists about the dangers of inappropriate land use in high-risk areas are crucial actions to ensure the region's safety and sustainability.

It is imperative that local authorities and tourism managers adopt an integrated approach involving the assessment and continuous monitoring of geotechnical conditions, along with stricter land-use regulations. Environmental education and public awareness should also be prioritized to mitigate the impacts of future events and protect both human lives and the region's natural resources.

In conclusion, the Capitólio tragedy serves as a stark reminder of the need for more rigorous geotechnical planning and management in vulnerable areas, with particular attention to the impact of human activities and the effects of climate change on terrain stability.

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