Soils and Rocks
An International Journal of Geotechnical and Geoenvironmental Engineering
www.soilsandrocks.com
ISSN 1980-9743
ISSN-e 2675-5475

Geological-structural mapping of rock slopes applied to stabilization projects: case study of Serra das Antas, BR-470, Rio Grande do Sul

Gabriela Macedo Miranda[1#], Fernanda Castells Vidaller Laurino[2], Marcos Saito de Paula[3], Ricardo José Mirisola Rodrigues[4]

Article

Keywords:
Structural geological mapping
Geomechanics
Geological-geotechnical compartmentalization

Abstract

Landslides constitute a recurrent natural hazard globally, severely impacting socio-economic and environmental systems. In Brazil, and particularly in the road infrastructure of Rio Grande do Sul, this vulnerability was dramatically evidenced by the extreme events of 2024. This study addresses the instability of 43 rock slopes along the BR-470 highway in the Serra das Antas region (between Bento Gonçalves and Veranópolis), a critical area with a history of rainfall-induced landslides structurally controlled by brittle discontinuities (columnar and sub-horizontal joints). The core objective was to perform a detailed geological-structural mapping of the Serra Geral Formation basaltic rock masses to diagnose instability patterns and define optimized intervention protocols. The methodology employed an integrated approach, combining detailed field geological-geotechnical mapping with kinematic and geomechanical analyses (limit equilibrium via Mohr-Coulomb and Hoek-Brown criteria). A geological-geotechnical compartmentalization of the rock masses was developed to reflect the complex structural heterogeneity, and the rock mass quality was assessed and classified using the *GSI* and *RMR* indices. Structural and kinematic analysis confirmed the prevalence of instabilities conditioned by these discontinuities, resulting in rockfall as the dominant failure mechanism (93% of cases), frequently associated with wedge failure (61%). The proposed stabilization solutions — including high-tensile steel mesh with anchored bolts and dynamic barriers — replace the traditional homogeneous treatment with a compartmentalized approach. It is concluded that compartmentalization constitutes an effective model, allowing technical and economic adjustments of the interventions to the specific geomechanical conditions of each segment, thereby increasing the reliability of the results and enhancing road safety.

1. Introduction

Landslides are a recurrent global natural hazard, causing severe socioeconomic and environmental impacts, and thousands of annual human fatalities (Kirschbaum & Stanley, 2018). These events are often associated with intense rainfall, occurring when the acting stresses exceed the rock mass shear strength. Instability arises from changes in slope geometry, external overloads, geotechnical degradation, or improper excavation (Smyth & Royle, 2000; Guzzetti et al., 2008; Kjekstad & Highland, 2009; Riselo et al., 2022).

Rainfall-induced landslides are a recurrent natural hazard in Brazil, severely impacting the road infrastructure in the South and Southeast regions (Dias et al., 2021; Bonini et al., 2025). The extreme event of 2024 in Rio Grande do Sul dramatically highlighted the magnitude of this risk (Andrades-Filho et al., 2025). In the state's mountainous areas, instability stems from the brittle structures within the Serra Geral Formation basalts, such as columnar, tabular, and relief joints (Pinheiro & Ceccato, 2025). Moreover, water saturation within these discontinuities and at the soil-rock interface in weathered basalt profiles acts as the main trigger for failures and rockfalls (Zhang et al., 2023).

#Corresponding author. E-mail address: geologagabrielamacedo@gmail.com
[1]Universidade Federal do Pampa, Departamento de Geologia, Caçapava do Sul, RS, Brasil.
[2]Universidade Estadual de Campinas, Departamento de Engenharia Civil, Campinas, SP, Brasil.
[3]Universidade de São Paulo, Instituto de Geociências, São Paulo, SP, Brasil.
[4]Universidade de São Paulo, Escola Politécnica, São Paulo, SP, Brasil.

Submitted on July 31, 2025; Final Acceptance on December 15, 2025; Discussion open until August 31, 2026.
Editor: Renato P. Cunha
https://doi.org/10.28927/SR.2026.012225

The prevalence of slope instabilities along highways can often be attributed to inadequate geological-geotechnical investigations during the project design phase. Detailed analyses of road cuts are essential for identifying potential failure surfaces and accurately determining safety factors. Given the increasing intensity of extreme climatic events in Brazil, a robust technical assessment is mandatory for delineating critical risk points along the highway network (Andrades-Filho et al., 2025). Although advanced technologies like remote sensing, geophysics, geotechnical instrumentation, digital terrain model analysis, and continuous monitoring are available, detailed field mapping remains indispensable. This direct approach enables the recognition of critical structures and incipient signs of instability often missed by indirect methods, thus providing the foundation for more effective engineering solutions.

The BR-470 highway section in Serra das Antas, situated between the municipalities of Veranópolis and Bento Gonçalves, serves as a strategic transportation corridor in Rio Grande do Sul. This particular segment faces significant geotechnical challenges, marked by a history of rockfalls, landslides, and shallow mass movements. These instability processes, characteristic of mountainous basaltic terrains, have been documented for decades (Pinheiro, 2000; Bressani et al., 1995; Bianchini et al., 1998; Bressani & Bica, 1998; Nadalin et al., 2020; Heidemann et al., 2021; Dias et al., 2021). Notably, in 2024, Veranópolis and Bento Gonçalvez were the municipalities most severely impacted by landslides triggered by extreme rainfall (Andrades-Filho et al., 2025). While these events exhibit a degree of cyclicity, their recent recurrence underscores the urgent necessity for improved technical actions aimed at geotechnical risk mitigation.

In this context, this study aimed to assess slope stability along BR-470 by conducting a geological-geotechnical characterization of the basaltic rock masses. This involved employing a structural compartmentalization approach to diagnose instability patterns and define optimized intervention protocols. Specifically, the research sought to perform detailed geological-structural mapping of the slopes, identify the predominant failure mechanisms, and classify the rock mass quality based on geological-geotechnical parameters. Ultimately, the goal was to propose tailored stabilization solutions for the defined compartments.

2. Study area: location and geoscientific setting

The study area is located in the northeastern portion of Rio Grande do Sul state, situated between the municipalities of Bento Gonçalves and Veranópolis, approximately 140 km north of Porto Alegre. The area is bounded by the geographic coordinates 28° 59’ 49.65” S, 51° 33’ 27.57” W, 29° 4’ 47.05” S, and 51° 33’ 56.42” W. This section of the BR-470 highway was selected due to its strategic economic and touristic significance and its high predisposition to instability processes, which is driven by the region’s structural and morphological characteristics, thus justifying the need for detailed investigation.

Geologically, the region is situated within the Paraná Basin and is dominated by volcanic rocks of the Serra Geral Formation, which date to the Cretaceous period. These rocks are predominantly tholeiitic basalts, formed by successive fissure eruptions that produced thick stacks of lava flows.

The basalts in the region exhibit massive or columnar structures, occasionally interbedded with amygdaloidal or vesicular layers containing secondary minerals such as zeolites. These rock masses are characterized by a complex network of discontinuities (e.g., cooling joints, tectonic fractures, and faults), which play a crucial role in their geomechanical behavior. These structures directly influence rock mass stability and its response to external actions, such as slope excavations or erosive processes (Silva et al., 2021). Figure 1 presents the location and geological map of the study area.

Morphologically, the area is situated on dissected terrain, featuring high elevations and incised valleys, characteristic of the Serra Geral Escarpment. This morphology favors the occurrence of erosive processes and mass movements. Figure 2 presents the hypsometric map of the area and photographic records of the slopes.

3. Methodology

Given the structural and lithological heterogeneity observed in the rock masses, an initial preliminary geological–geotechnical compartmentalization was carried out through visual inspection. This first stage enabled the recognition of sectors with distinct characteristics, supporting the initial subdivision of the mapped units. The consistency of this initial subdivision was subsequently refined using field-derived geological–geotechnical parameters, including material strength, Rock Quality Designation (*RQD*), spacing, persistence, and roughness of discontinuities, as well as groundwater conditions. As a result, the slopes were subdivided into smaller and more representative units, increasing the number of compartments from 18 to 43.

Geological materials were classified according to the British Standard BS 5930 (“Code of Practice for Ground Investigations”), published by the British Standards Institution (BSI) (BS, 2015), as summarized in Table 1.

Fundamental geometric data were collected to characterize the discontinuities present in the rock masses, including the strike and dip of these structures. All measurements are expressed using the Dip Direction/Dip notation. The characterization of discontinuities considered essential parameters such as spatial orientation, spacing, persistence, roughness, infilling, and aperture, following the guidelines established by Fiori & Carmignani (2009).

Geomechanical classification was conducted using the Rock Mass Rating (*RMR*) system (Bieniawski, 1989) and the

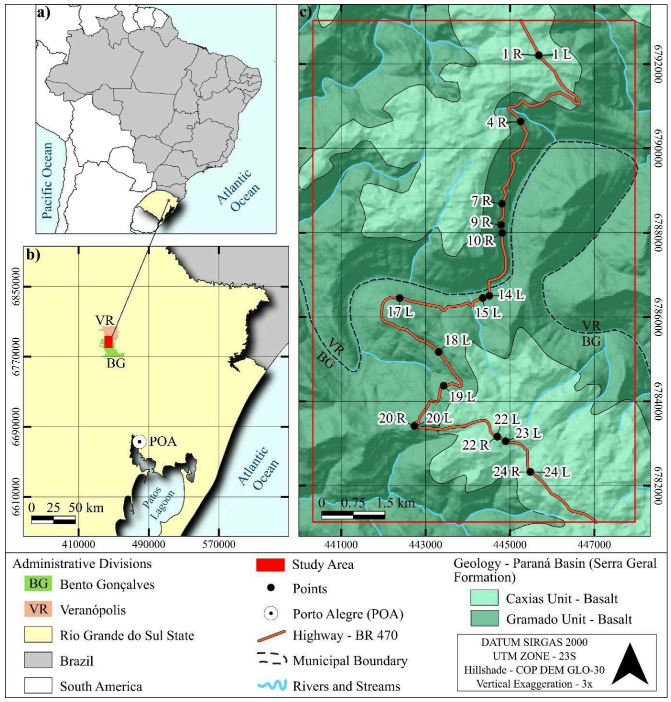

Figure 1. Location and geological map of the study area (BR-470 highway, Serra das Antas, Rio Grande do Sul). (a) Regional location of the study area in the Brazilian context. (b) Location in the state of Rio Grande do Sul, highlighting the municipalities of Bento Gonçalves and Veranópolis. (c) Geological map of the study area and the 43 rock slopes analyzed along the BR-470.

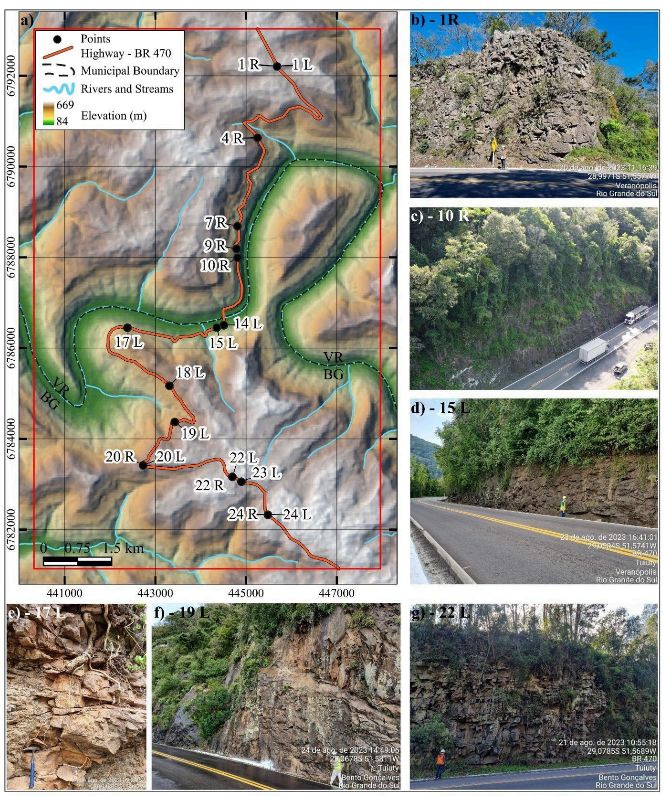

Figure 2. Geomorphological context and photographic records of the mapped slopes. (a) Hypsometric map of the study area (Source: Authors). (b) Highly fractured aspect of slope 1 (right side). (c) Tall and dense vegetation on the crest of slope 10 (right side). (d) Section in a curved segment of slope 15 (left side). (e) Sector of slope 17 composed of highly weathered rock with roots developed within rock fractures. (f) Frontal view of potential planar failure on slope 19 (left side). (g) Frontal view of slope 22 (left side).

Table 1. Engineering Classification of Rock Weathering Grades (Based on British Standard BS 5930:2015).

Grade	Description	Lithology	Excavation	Foundations
VI	Residual soil	Some organic content, no original structure	May need to save and re-use	Unsuitable
V	Completely weathered	Decomposed soil, some remnant structure	Scrape	Assess by soil testing
IV	Highly weathered	Partly changed to soil, soil volume exceeds rock volume	Scrape nb corestones	Variable and unreliable
III	Moderately weathered	Partly changed to soil, rock volume exceeds soil volume	Rip	Good for most small structures
II	Slightly weathered	Increased fractures, and mineral staining	Blast	Good for anything except large dams
I	Fresh rock	Clean rock	Blast	Sound

Geological Strength Index (*GSI*) (Hoek, 1983; Hoek & Brown, 1997; Hoek & Brown, 2018), supplemented by parameters from Barton's Q system (Barton et al., 1974; Barton & Choubey, 1977). This integrated approach aimed to: a) utilize the *RMR* in the field for rock mass compartmentalization and geotechnical solution guidance; b) employ the *GSI* for subsequent computational modeling; and c) use Barton's Q system parameters, such as *JRC* and *JCS*, to assist in determining fundamental parameters like the friction angle, essential for kinematic and numerical analyses.

Additionally, kinematic analyses were conducted to identify and evaluate potential failure mechanisms in the slopes, such as planar, wedge, and toppling failures.

The assessment of possible failure types at each point within the studied segments was based on field data, which were presented using stereonets. Specialized software from Rockscience (SWedge®, Rocplane®, and Slide®) was utilized for stability analyses.

Based on these assessments, containment measures were then defined considering the specific conditions and technical requirements associated with each instability scenario.

4. Results and discussions

Due to the substantial number of slopes mapped during fieldwork and the breadth of analyses performed, this section highlights only the examples deemed most representative of the overall investigation.

Based on the established geological–geotechnical compartmentalization, the key characteristics and associated risks were identified for each compartment. As an example, Table 2 presents Slope 18, subdivided into segments 18.1 to 18.8. Each compartment displays distinct attributes and varying degrees of susceptibility to instability. Segment 18.1 is characterized by predominantly soil materials and insufficient vegetation cover, whereas segments 18.2 to 18.7 and 18.8 comprise rock, ranging from highly weathered units to fresh rock.

GSI and *RMR* parameters were also evaluated and assigned to each segment. Figures 3 and 4 present general field records along Slope 7 and the corresponding plan view, including the proposed compartmentalization and the associated *RMR* and *GSI* values. Compartmentalization subdivided the slope into two segments: 7.1 and 7.2. Segment 7.1 is characterized by predominantly soil materials with isolated blocks of fresh rock and was assigned an *RMR* value corresponding to Class IV. Segment 7.2 consists mainly of fresh rock, with an *RMR* value classified as Class III.

As an additional example, Figure 5 shows that other mapped slopes also exhibited distinct *GSI* and *RMR* values for each of their defined segments. Slope 18 (Segments 18.1 to 18.8) and Slope 20 (Segments 20.1 and 20.2), also referenced in Table 2, similarly presented variations in these geomechanical parameters.

The segments predominantly composed of fresh rock, such as 1.2, 4.1 – 4.3, 9.2 – 9.4, 10.1, 14.1, 15.1–15.3, 19.1, 19.2, 23.1 and 23.2 have *RMR* between 61-80 (Class II), reflecting good rock mass quality. The mapped risks are concentrated in localized instabilities, mainly associated with large blocks and potential planar failures. The *GSI* values for these cases range from 40 to 75 – highly fractured to fractured rock masses. However, it should be noted that the fact that a rock mass has a high *GSI* value, characterizing it as a highly fractured rock, is not necessarily associated with a rock mass with a low *RMR* value.

Segments such as 1.3, 7.1, 18.8, 19.4, and 20.3 exhibit *RMR* values below 40 and are associated with the predominance of soil. In these cases, the mapped risks are related to the downslope movement of soil materials toward the highway. These sections exhibit significant instability, especially near the road, establishing critical conditions for highway operation. Recent studies show that basaltic slopes with similar characteristics collapsed during extreme precipitation in Rio Grande do Sul in 2024, reinforcing the need for preventive interventions (Andrades-Filho et al., 2025).

Table 2. Example of a geological-geotechnical description of compartments 18.1 - 18.8 mapped in the field.

Segments	Height (m)	Field description	Mapped risks
18.1	2-8	Predominant soil, absence of vegetation cover on the slope face.	Soil mass movement
18.2 - 18.7	12-15	Predominantly sound rock, with few fractures forming blocks. Blocks occur at the top of the slope.	Rockfall
18.8	12-15	Predominantly weathered rock, with fractures creating boulders and boulders at the top of the slope.	Rockfall

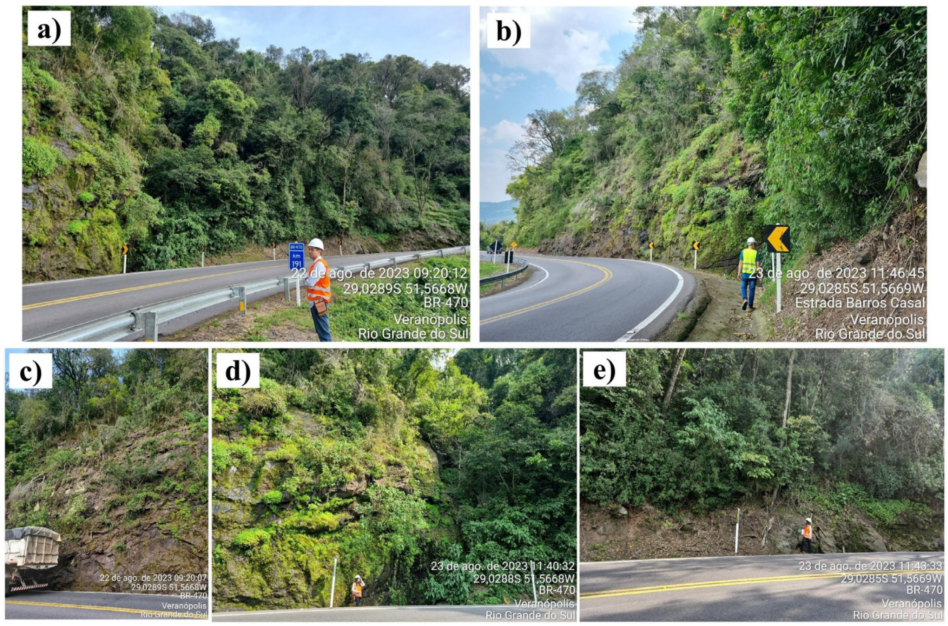

Figure 3. Photographic records along slope 7: (a) Side view of sector 7.1 (b) Side view of sector 7.2 (c) Front view of sector 7.2 predominantly composed of fresh rock (d) Front view of the thalweg (e) Front view of sector 7.1 with intercalation of soil and fresh rock.

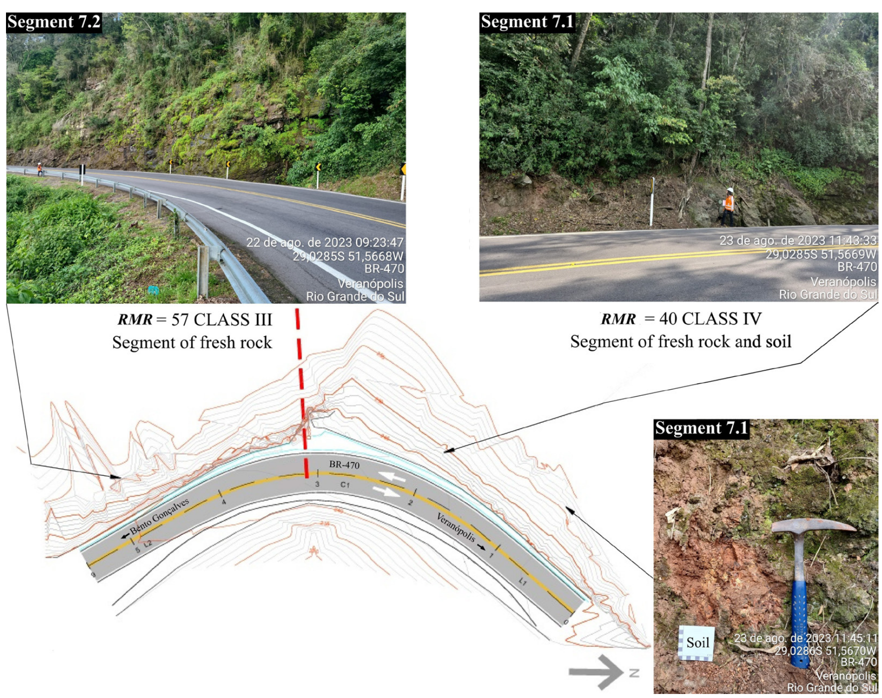

Figure 4. Plan view example of the geological-geotechnical compartmentalization for slope 7. The compartment 7.1 = *RMR* 40 – Class IV and 7.2 = *RMR* 57 – Class III.

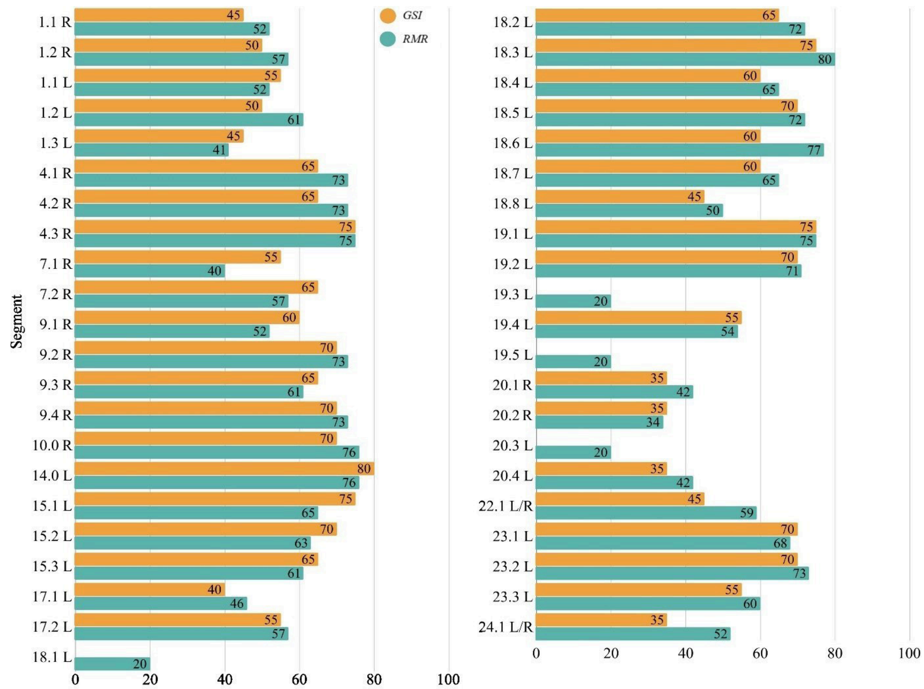

Figure 5. *GSI* and *RMR* values obtained for each mapped segment.

Structural measurements were collected across all segments, except in locations where access was restricted due to dense vegetation or instability hazards. In total, 526 measurements of fractures and unloading joints were obtained. Stereographic analysis of these data revealed two dominant discontinuity sets: subvertical joints associated with columnar disjunction (consistent with observations by Fan et al., 2017; Pacheco et al., 2018; Nadalin et al., 2020), and subhorizontal joints representing the prevailing structural systems. Figure 6 presents the stereographic projection derived from these measurements.

The structural configuration of the mapped basalts favors the formation of unstable blocks and the activation of multiple instability mechanisms, with rockfalls observed in 94% of the slopes, followed by wedge failures (61%), block rolling (44%), planar failures (39%), and toppling (22%), often occurring simultaneously. These results are consistent with those mapped by Nadalin et al. (2020), who indicated that approximately 75% of the potential movements in the slopes analyzed in their study correspond to wedge slides, corroborating the predominance of this mechanism in the region.

The potential instability types identified in the slopes are summarized in Table 3, highlighting the occurrence of multiple failure mechanisms in each slope.

Figure 7 illustrates examples of stereonets developed for slopes at points 19 (a) and 24 (b). For these locations, based on the mapped fracture sets, potential planar and wedge failures were identified at slope 19, as well as toppling failures at slope 24.

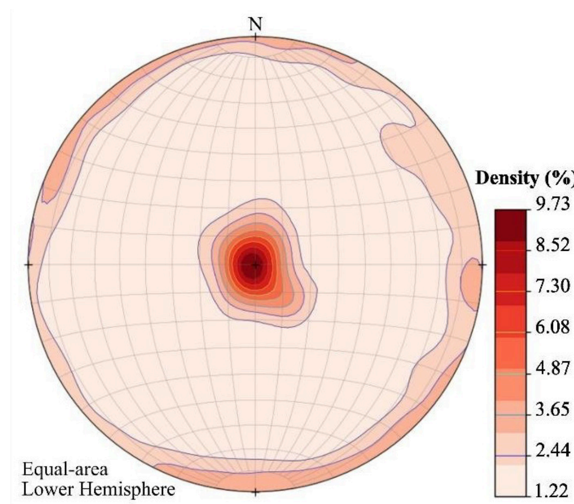

Figure 6. Stereonet generated from field measurements. It is possible to visualize the two main families of discontinuities mapped in the field: one with a subvertical orientation and the other with a subhorizontal orientation.

Table 3. Potential failure types for the mapped slopes.

Types of failure	Number of slopes	Percentage of slopes with this problem (%)
Planar Failure	7	39
Wedge Failure	11	61
Toppling	4	22
Upstream Slope	8	44
Rockfall	15	94
No Failure	4	22

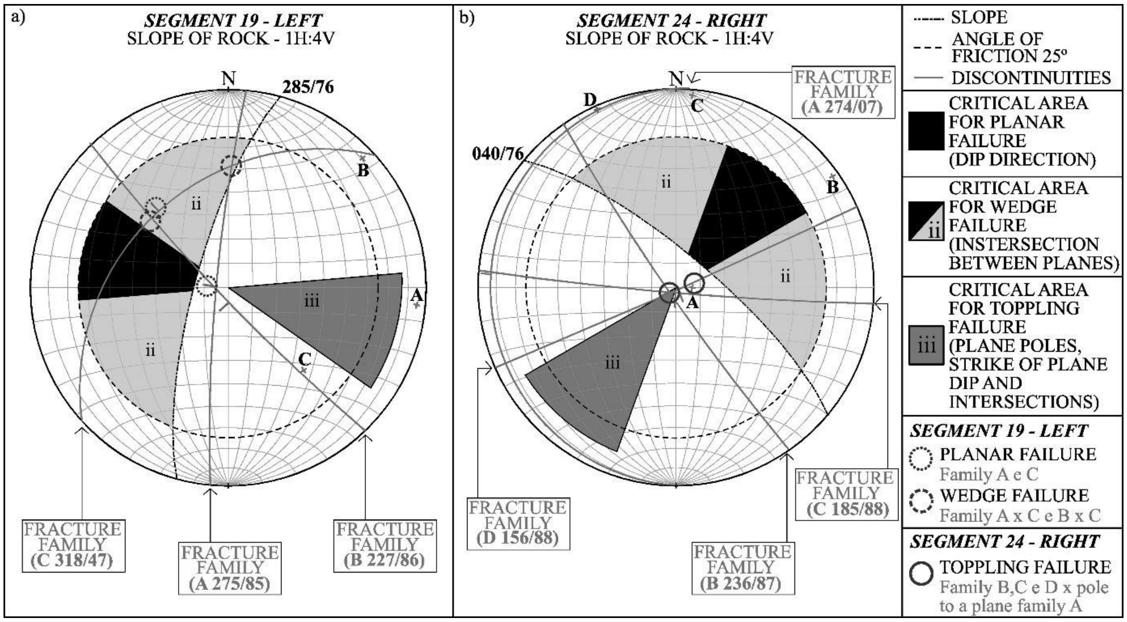

Figure 7. Stereonets of slopes (a) 19.1 – 19.5 left side and (b) 24.1 right side.

The integrated analysis of the structural mappings, field descriptions, and geomechanical parameters (*GSI* and *RMR*) enabled the characterization of the geological–geotechnical variability of the slopes along the studied sectors.

Based on this analysis, engineering solutions were proposed for each segment, involving a strategic combination of geotechnical techniques such as drainage systems, geometric reconfiguration, and the application of active support measures, such as soil nailing, as well as passive measures, including dynamic barriers and block stabilization. Table 4 presents examples of the stabilization solutions proposed for Compartments 7.1 and 7.2, as well as for Compartments 9.1, 9.2, 9.3, and 9.4.

As illustrated in Figure 4, Slope 7 was subdivided into Compartments 7.1 and 7.2 due to marked structural and geomechanical variations along its extent. Compartment 7.1 consists of a heterogeneous mass composed of both intact rock and soil, with localized concentrations of rock blocks near the toe. For this sector, an integrated stabilization scheme was recommended, comprising vegetation removal on the slope and crest (mainly trees), resloping procedures— including surface cleaning, removal of loose blocks, and elimination of negative faces— and mechanical reinforcement by soil nailing with a shotcrete facing, supplemented by a deep drainage system of the Horizontal Drainage (HD) type. Compartment 7.2, an analogous stabilization approach was proposed, excluding only the deep drainage system, which was deemed unnecessary given the local geotechnical conditions.

In Slope 9, the proposed interventions aim to mitigate instabilities resulting from the presence of disaggregated rock blocks, open cavities, and unfavorable geometric conditions along the slope face. The initial strategy focuses on the immediate stabilization of the lower segments: in Segments 9.1 and 9.2, regrading is recommended, accompanied by surface cleaning and vegetation removal to eliminate loose blocks and correct negative surfaces that are potentially susceptible to failure. In highway slopes located in mountainous regions, it is common for part of the instabilities to be associated with the extensive upslope hillside, where limited accessibility

Table 4. Examples of suggested geological-geotechnical solutions.

Section	Segment	Proposed solution
7 right side of the highway	7.1*	*Removal of slope and crest vegetation (mainly trees) + Resloping (scaling, removal of loose blocks and negative faces) + Soil nailing with shotcrete facing.
	7.2**	**The same solution proposed for segment 7.1 should be applied, adding the deep drainage solution (HD - Horizontal Drainage).
9 right side of the highway	9.1 e 9.2***	***Removal of vegetation along the slope face + Resloping (scaling, removal of loose blocks and negative faces)
	9.3 e 9.4****	****Dynamic barrier at the slope crest line and filling of cavities with concrete and steel bars grouted into the rock, associated with simple drainage. Fixing prominent high-risk rocks with the execution of rock anchors

restricts the application of conventional stabilization measures. Therefore, for Segments 9.3 and 9.4, the installation of dynamic barriers at the slope crest is proposed—na internationally consolidated technique, particularly in countries such as Switzerland and Japan, for containing high-energy rockfalls originating from upper portions of the hillside.

The geotechnical pathologies observed in Sectors 7 and 9 result from the combined effects of the structural configuration of the basaltic rock mass, the steep morphology typical of mountainous environments, and the influence of dense vegetation cover characteristics of tropical regions. The presence of prominent structural discontinuities, coupled with high topographic gradients and accelerated weathering processes, promotes the mobilization of rock blocks, the formation of cavities, and the progressive degradation of slope surfaces. The solutions proposed for these sectors—including controlled vegetation removal, regrading, mechanical reinforcement, and drainage— are technically applicable to other highway slopes developed in basalts under analogous geomorphological conditions. However, despite the apparent lithological uniformity, each slope presents its own geological history, reflected in distinct structural and geomechanical conditions. Therefore, the replication of these measures must be preceded by a site-specific technical assessment to ensure their suitability to the local instability mechanisms.

In summary, large-magnitude instabilities require more robust interventions, which can significantly increase costs and, in some cases, render certain geotechnical solutions unfeasible. In this context, beyond technical and economic evaluations, there is a clear need for greater agility in the processes involving the investigation, selection, and implementation of stabilization measures. Considering increasingly atypical weather patterns—characterized by episodes of intense rainfall—combined with the inherent geomorphological and geotechnical characteristics of the slopes, delays in implementing such measures may lead to the worsening of existing pathologies, substantial material damage, and, most critically, risks to human life. This scenario reinforces the importance of faster decision-making procedures supported by monitoring systems, systematic mapping, and rapid-response protocols, ensuring that preventive interventions are prioritized before the geotechnical condition becomes critical.

5. Conclusion

This study demonstrated the effectiveness of the geological-geotechnical mapping of road slopes in basaltic rock masses in Southern Brazil. The integrated methodological approach, which combined detailed field geological-geotechnical characterization with kinematic and geomechanical analyses, allowed for a technical characterization of the variability of the rock masses and their instability patterns. The integration of the techniques employed is key to guiding the adoption of engineering solutions.

The developed compartmentalization reflects the complex structural and lithological heterogeneity of the basaltic slopes. The subdivision of the slopes into smaller compartments proved to be an essential tool for refining the understanding of the rock mass behavior and increasing the reliability of the stability results.

Structural analysis confirmed the prevalence of instabilities conditioned by columnar jointing and the predominant sub-horizontal systems in the Serra Geral Formation basalts of the region. Rockfall is the dominant failure mechanism, frequently associated with wedge failures and block rolling.

The integrated analysis of the *GSI* and *RMR* indices made it possible to differentiate the rock mass quality and correlate it directly with the type of intervention required. It is observed that the degree of slope degradation dictates the complexity of the engineering solution. Therefore, the proposed solutions must be adapted to the specific geotechnical condition of each compartment.

The geological-geotechnical solutions proposed herein substitute the homogeneous treatment of rock masses, often adopted in engineering solutions, with a compartmentalized approach, which enables a more precise evaluation of the structural and geomechanical variations along the slope. Geological-geotechnical compartmentalization as a basis for the stabilization project offers an efficient model for works on basaltic rock slopes. This strategy allows for the proper adjustment of the type, extent, and cost of mitigation to the specific geomechanical reality of each segment.

Acknowledgements

The authors would like to thank the National Department of Transport Infrastructure (DNIT) for its initiative in promoting studies in the investigated area and for granting access to the region, which enabled the development of this research.

Declaration of interest

The authors have no conflicts of interest to declare.

Authors' contributions

Gabriela Macedo Miranda: conceptualization, data curation, visualization, writing – original draft, validation, writing – review & editing. Marcos Saito de Paula: conceptualization, supervision, funding acquisition. Ricardo José Mirisola Rodrigues: conceptualization, funding acquisition. Fernanda Castells Vidaller Laurino: conceptualization, funding acquisition.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of the generative artificial intelligence (GenAI) tool Gemini, developed by Google, with the purpose of correcting the grammar of selected sentences in the manuscript. The entire process of using this tool was supervised, reviewed, and, when necessary, edited by the authors. The authors assume full responsibility for the content of this publication, which involved the use of GenAI.

List of symbols and abbreviations

BR	Federal Highway
BS	British Standards
BSI	British Standards Institution
DNIT	National Department of Transport Infrastructure
GSI	Geological Strength Index
JRC	Joint Roughness Coefficient
JCS	Joint Wall Compressive Strength
HD	Horizontal Drainage
RQD	Rock Quality Designation
RMR	Rock Mass Rating

References

Andrades-Filho, C.O., Mexias, L.F.S., Quevedo, R.P., Herrmann, P.B., Oliveira, G.G., Cremon, É.H., Cargnin, B.R., Reis, M.S., Novakoski, K.R., Santos, D.C., Sluter, C.R., Iescheck, A.L., Guasselli, L.A., Junior, M.R., Gruber, N.L.S., Philipp, R.P., Michelin, C.R.L., Viero, A.P., Gonzatti, C., Rosa, M.L.C.C., Barboza-Pinzon, E., Schumacher, R.G., Cárdenas, S.M.M., Soares, V.M., Núñez, W.P., Mendonça, R.R., Silva, M.O.R., Silva, M.C., Bressani, L.A., Peres, L.D.S., Mevel, L.B., Dorneles, J.I., Cacciatore, J.A., Jacques, F.M., Duarte, L.C., Diniz, F.C., Petry, L., Schwarzer, G., Carneiro, M., & Giaccom, B. (2025). The biggest landslide event in Brazil: preliminary analysis of the Rio Grande do Sul mega disaster in May 2024. *Landslides*, 22(11), 3615-3624. https://doi.org/10.1007/s10346-025-02587-8.

Barton, N., Lien, R., & Lunde, J. (1974). Engineering classification of rock masses for the design of tunnel support. *Rock Mechanics*, 6(4), 189-236. https://doi.org/10.1007/BF01239496.

Barton, N., & Choubey, V. (1977). The shear strength of rock joints in theory and practice. *Rock Mechanics*, 10(1), 1-54. https://doi.org/10.1007/BF01261801.

Bianchini, M.R., Bressani, L.A., Bica, A.V.D., & Pinheiro, R.J.B. (1998). Study of the instability of a road cut slope in São Jerônimo, RS. In *Proc. XI COBRAMSEG* (pp. 1273-1280). Brasília: ABMS.

Bieniawski, Z.T. (1989). *Engineering Rock Mass Classifications: a complete manual for engineers and geologists in mining, civil, and petroleum engineering*. Hoboken: John Wiley & Sons.

BS 5930. (2015). *Code of practice for ground investigations.* British Standards Institution, London, UK.

Bressani, L.A., Bica, A.V.D., & Tonon, J. (1995). Principais tipos de instabilidade de taludes junto a rodovias do estado do Rio Grande do Sul. In *Proc. 29ª Reunião Anual de Pavimentação* (Vol. 2, pp. 516-527). Cuiabá: ABPv.

Bressani, L.A., & Bica, A.V.D. (1998). Condicionantes hidráulicos e mecânicos de algumas rupturas de taludes do Rio Grande do Sul. In *Proc. Simpósio de Prática de Engenharia Geotécnica da Região Sul (GEOSUL'98)* (Vol. 1, pp. 109-122). Porto Alegre: ABMS.

Bonini, J.E., Parenti, C., Grassi, F., Mancini, F., Vieira, B.C., & Soldati, M. (2025). Assessing landslide susceptibility and dynamics at cultural heritage sites by integrating machine learning techniques and persistent scatterer interferometry. *Geomorphology*, 469, 109522. https://doi.org/10.1016/j.geomorph.2024.109522.

Dias, H.C., Hölbling, D., & Grohmann, C.H. (2021). Landslide susceptibility mapping in Brazil: a review. *Geosciences*, 11(10), 425. https://doi.org/10.3390/geosciences11100425.

Fan, Q., Feng, X., Weng, W., Fan, Y., & Jiang, Q. (2017). Unloading performances and stabilizing practices for columnar jointed basalt: a case study of Baihetan hydropower station. *Journal of Rock Mechanics and Geotechnical Engineering*, 9(6), 1041-1053. https://doi.org/10.1016/j.jrmge.2017.07.003.

Fiori, A.P., & Carmignani, L. (2009). *Fundamentos de mecânica dos solos e das rochas: aplicações na estabilidade de taludes* (2. ed.). São Paulo: Oficina de Textos.

Guzzetti, F., Peruccacci, S., Rossi, M., & Stark, C.P. (2008). The rainfall intensity–duration control of shallow landslides and debris flows: an update. *Landslides*, 5(1), 3-17. https://doi.org/10.1007/s10346-007-0112-1.

Heidemann, M., Bressani, L.A., Pinheiro, R.J.B., Silveira, R.M., Nichel, A., & Maximiliano, J.V.E. (2021). Lessons learned from some landslides in Rio Grande do Sul, Brazil. In *Proceedings of the 13th International Symposium on Landslides*, Cartagena, Colombia. London: International Society for Soil Mechanics and Geotechnical Engineering.

Hoek, E. (1983). Strength of jointed rock masses. *Geotechnique*, 33(3), 187-223. https://doi.org/10.1680/geot.1983.33.3.187.

Hoek, E., & Brown, E.T. (1997). Practical estimates of rock mass strength. *International Journal of Rock Mechanics and Mining Sciences*, 34(8), 1165-1186. https://doi.org/10.1016/S1365-1609(97)80069-X.

Hoek, E., & Brown, E.T. (2018). The Hoek–Brown failure criterion and *GSI*–2018 edition. *Journal of Rock Mechanics and Geotechnical Engineering*, 11(3), 445-463. https://doi.org/10.1016/j.jrmge.2018.08.001.

Kjekstad, O., & Highland, L. (2009). Economic and social impacts of landslides. In K. Sassa & P. Canuti (Eds.), *Landslides – disaster risk reduction* (pp. 573-587). Berlin: Springer. https://doi.org/10.1007/978-3-540-69970-5_30.

Kirschbaum, D., & Stanley, T. (2018). Satellite-based assessment of rainfall-triggered landslide hazard for situational awareness. *Earth's Future*, 6(3), 505-523. https://doi.org/10.1002/2017EF000715.

Nadalin, L.F., Fiori, A.P., Giusti, D.A., & Salamuni, E. (2020). Investigação geotécnica de taludes rochosos por meio da análise estrutural: estudo de caso da BR-116, Rio Grande do Sul. *Geologia USP*, 20(4), 235-255. https://doi.org/10.11606/issn.2316-9095.v20-150990.

Pacheco, F.E.R.C., Caxito, F.A., Moraes, L.C., Marangoni, Y.R., Santos, R.P.Z., & Pedrosa-Soares, A.C. (2018). Basaltic ring structures of the Serra Geral Formation at the southern Triângulo Mineiro, Água Vermelha region, Brazil. *Journal of Volcanology and Geothermal Research*, 355, 136-148. https://doi.org/10.1016/j.jvolgeores.2017.06.019.

Pinheiro, R.J.B. (2000). *Estudo de alguns casos de instabilidade da encosta da Serra Geral no Estado do Rio Grande do Sul* [Doctoral thesis, Federal University of Rio Grande do Sul]. Federal University of Rio Grande do Sul's repository (in Portuguese). http://hdl.handle.net/10183/118558.

Pinheiro, R.J.B., & Ceccato, H.D. (2025). The study of a large slide of natural slopes in mountainous areas of South Brazil. *Caderno Pedagógico*, 22(4), e14399. https://doi.org/10.54033/cadpedv22n4-243.

Riselo, B.C.T., Passini, L.B., & Kormann, A.C.M. (2022). Stability analysis of a slope and runout analysis movement of the mobilized-mass volume. *Soils and Rocks*, 45(4), e2022003822. https://doi.org/10.28927/SR.2022.003822.

Silva, B.A., Calegari, M.R., Pinheiro, M.R., & Fujita, R.H. (2021). Lithostructural and tectonic determinants in the geomorphic evolution of the Basalt Plateau–Southern Brazil. *Journal of South American Earth Sciences*, 110, 103351. https://doi.org/10.1016/j.jsames.2021.103351.

Smyth, C.G., & Royle, S.A. (2000). Urban landslide hazards: incidence and causative factors in Niterói, Rio de Janeiro State, Brazil. *Applied Geography (Sevenoaks, England)*, 20(2), 95-118. https://doi.org/10.1016/S0143-6228(00)00004-7.

Zhang, Q., Luo, Z., Chen, Y., & Wang, Z. (2023). Physical model experiments on failure mechanism on slopes of weathered basalt soils during heavy rainfall events. *Materials*, 16(2), 832. https://doi.org/10.3390/ma16020832.