

Geomechanical Characterization and Stability Assessment of a Basaltic Rock Mass in the Serra Geral Formation, Southern Brazil

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ABSTRACT: This paper presents a geomechanical characterization and stability assessment of a basaltic rock mass exposed during urban excavation works in Bento Gonçalves, southern Brazil. The study integrates structural mapping, scanline discontinuity measurements, Rock Quality Designation (RQD), Rock Mass Rating (RMR), Geological Strength Index (GSI) estimation, uniaxial compressive strength testing, Hoek-Brown failure criterion application, and stereographic kinematic analysis. Two geomechanical domains were identified: M1, representing fresh basalt with low fracture density (RMR = 82; RQD = 95.68%), and M2, consisting of fractured and weathered basalt with groundwater influence (RMR = 48; RQD = 73.6%). Laboratory testing yielded an average uniaxial compressive strength of 64.3 MPa. GSI values were estimated as 75 for M1 and 45 for M2. Equivalent Mohr-Coulomb parameters derived from Hoek-Brown analysis indicate a significant reduction in rock mass cohesion in the weathered domain. Kinematic assessment indicates no global planar, wedge, or toppling failures for the current slope geometry.

KEYWORDS: Rock mass characterization, Basalt, GSI, Hoek-Brown criterion, Slope stability.

1 INTRODUCTION

Excavations in volcanic rock masses require careful structural and mechanical assessment due to the intrinsic heterogeneity of discontinuity networks and weathering profiles. In the Serra Geral Formation basalts of southern Brazil, slope behavior is frequently governed by fracture density, joint persistence, and hydrogeological conditions rather than intact strength alone (Bieniawski, 1989; Hoek and Brown, 1997; ISRM, 1978).

This study presents a detailed geomechanical evaluation of a basaltic slope excavated during urban construction activities (Figure 1). The objective was to characterize rock mass quality, quantify mechanical parameters at both intact and rock mass scale, and assess slope stability using empirical and constitutive approaches.

2 GEOLOGICAL AND STRUCTURAL CONTEXT

The investigated slope exposes basalt flows of the Serra Geral Group within the Paraná Basin (Milani et al., 2007; CPRM, 2008). Field observations identified two distinct geomechanical domains (Figure 2).

Domain M1 consists of fresh to slightly weathered basalt with relatively low fracture density and well-defined blocky structure. Discontinuities are predominantly subvertical and form an orthogonal joint system typical of basaltic flows (Figure 3).

Domain M2 corresponds to an intensely fractured and weathered sector. Fracture spacing is reduced, joint apertures increase, and local saprolitic transitions are present (Figure 3). Groundwater seepage was observed in localized zones, particularly near intrusive features.

The excavation reaches approximately 15 m in height and 80 m in length, with local slope inclinations approaching 70 degrees.

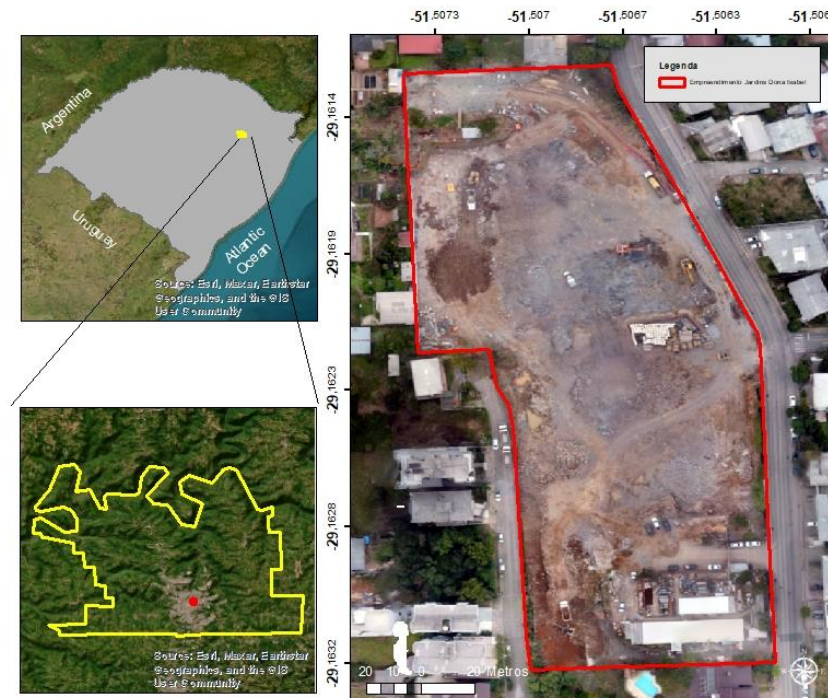


Figure 1. Site Location.

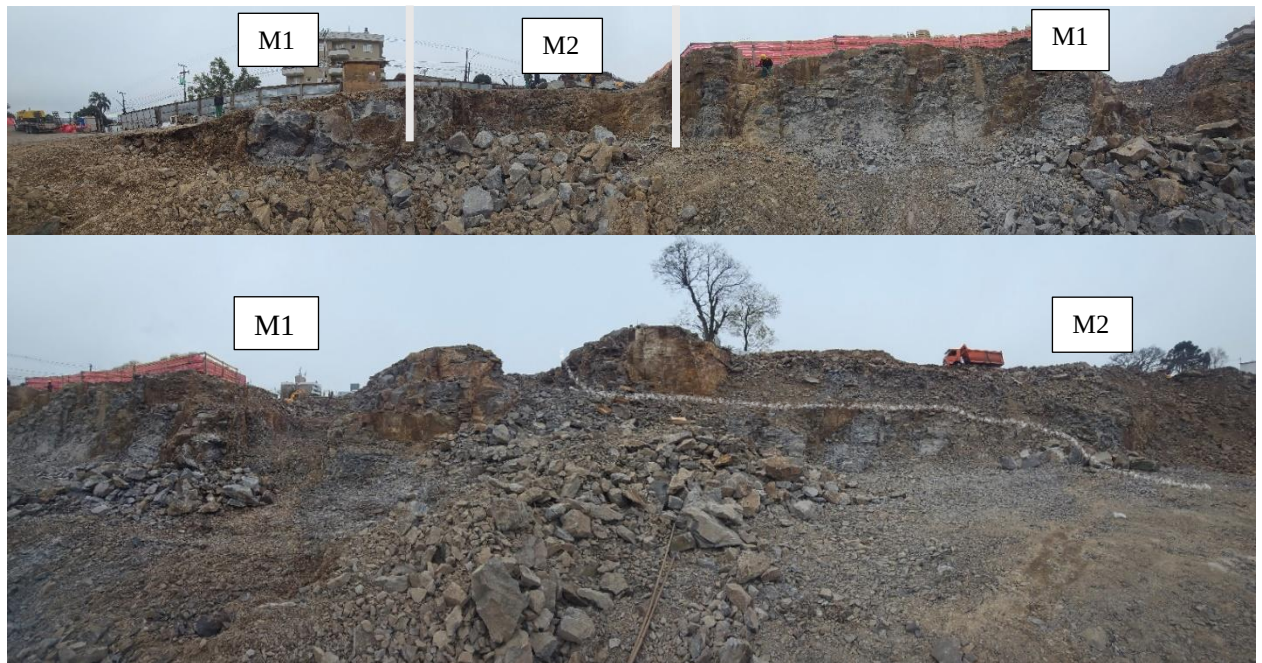


Figure 2. Structural Domain Mapping (M1 vs M2).

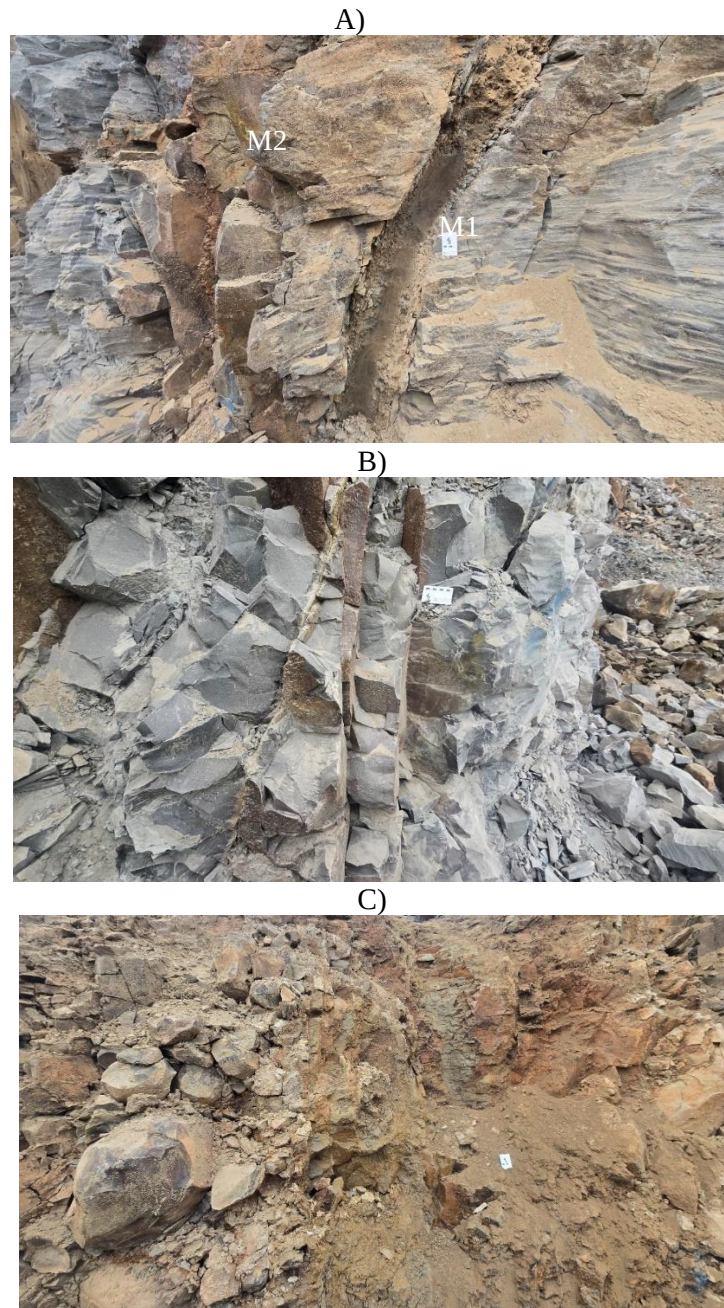


Figure 3. A) Contact zone between domains M1 and M2, where we observe an intrusive dike with the presence of a saprolite with a high moisture content; B) Fracturing observed in M1 shows a spacing of 30 to 50 cm with little or no opening of discontinuities, demonstrating that it is a rock mass of good quality; C) Material from M2 shows an intrusive dike with saprolitic material in contact with the rock mass, which is intensely fractured into small, easily detachable pieces with large spacing, indicating poor rock mass quality.

3 ROCK QUALITY DESIGNATION (RQD)

RQD was estimated from discontinuity frequency measured along scanlines performed on exposed slope faces. A total of 34 structural measurements were collected and analyzed separately for each geomechanical domain.

RQD was calculated using the empirical relationship proposed by Bieniawski (1989):

$$RQD = 110.4 - 3.68 \lambda \quad (1)$$

- where λ represents the number of discontinuities per meter.

In domain M1, the average fracture frequency was approximately 4 discontinuities per meter. Substituting into Equation (1):

$$RQD = 110.4 - 3.68 \times 4$$

$$RQD = 95.68 \%$$

In domain M2, the fracture frequency increased to approximately 10 discontinuities per meter:

$$RQD = 110.4 - 3.68 \times 10$$

$$RQD = 73.6 \%$$

These values indicate excellent rock quality in M1 and moderate rock quality in M2, confirming the structural contrast observed in the field.

4 ROCK MASS RATING (RMR)

The RMR classification incorporated intact compressive strength, RQD, discontinuity spacing, joint condition, groundwater condition, and joint orientation, following the classification procedure proposed by Bieniawski (1989).

Laboratory testing yielded an average uniaxial compressive strength of 64.3 MPa.

The calculated RMR values were:

$$RMR (M1) = 82$$

$$RMR (M2) = 48$$

M1 is classified as very good rock (Class I), whereas M2 corresponds to fair rock (Class III). The reduction in RMR in M2 is primarily associated with higher fracture frequency, joint weathering, and groundwater influence.

Table 1. Rock mass classification parameters for domains M1 and M2.

Parameter	M1	M2
Intact Strength / Degree of Weathering	100–250 MPa (Very Strong Rock)	5–25 MPa (Weak Rock)
Discontinuity Orientation	SE–SW–NW	SE–SW–NW
Discontinuity Spacing	30–50 cm	10–30 cm
RQD (%)	95.68	73.6
Discontinuity Persistence	1–3 m	1–3 m
Discontinuity Aperture	0.1 cm	1–20 cm
Discontinuity Infilling	Medium strength material	Medium strength material
Discontinuity Roughness	Rough planar	Smooth to rough planar
Wall Weathering Condition	Fresh	Decomposed
RMR Rating – Intact Strength	12	2

Parameter	M1	M2
RMR Rating – RQD	20	13
RMR Rating – Spacing	10	8
RMR Rating – Discontinuity Condition	25	15
RMR Rating – Groundwater	15	10
RMR Rating – Orientation	0	0
TOTAL RMR	82	48

5 GEOLOGICAL STRENGTH INDEX (GSI)

The Geological Strength Index (GSI) was estimated from field observations of rock structure, discontinuity surface condition, weathering degree, and block interlocking (Hoek and Marinos, 2000). Domain M1 was characterized by a blocky, fresh to slightly weathered basaltic rock mass, whereas domain M2 showed a more disturbed, weathered, and fractured condition.

The estimated GSI values were 75 for domain M1 and 45 for domain M2. These values were subsequently used as input parameters for the Hoek-Brown failure criterion and for the derivation of equivalent Mohr-Coulomb parameters.

6 HOEK-BROWN FAILURE CRITERION

To estimate rock mass strength parameters, the generalized Hoek-Brown criterion was applied (Hoek and Brown, 1980, 1997; Hoek et al., 2002). The criterion is expressed as:

$$\sigma_1 = \sigma_3 + \sigma_{ci} (m_b \sigma_3 / \sigma_{ci} + s)^a \quad (2)$$

- where:
 σ_{ci} = intact compressive strength
 m_b , s , and a = rock mass constants dependent on GSI
 m_i = intact rock constant (assumed as 25 for basalt)

Using $\sigma_{ci} = 64.3$ MPa and standard Hoek-Brown correlations:

For M1 (GSI = 75):

m_b approximately 7.5
 s approximately 0.11
 a approximately 0.5

For M2 (GSI = 45):

m_b approximately 1.7
 s approximately 0.003
 a approximately 0.5

The reduction of parameter s from 0.11 to 0.003 demonstrates the strong degradation of rock mass strength in the fractured domain.

7 EQUIVALENT MOHR-COULOMB PARAMETERS

For practical slope stability interpretation, equivalent Mohr-Coulomb parameters were derived from the Hoek-Brown envelope within the low confinement stress range typical of shallow slopes (Hoek et al., 2002).

The estimated equivalent parameters are:

For M1:

Equivalent cohesion approximately 2.0 MPa

Equivalent friction angle approximately 45 degrees

For M2:

Equivalent cohesion approximately 0.25 MPa

Equivalent friction angle approximately 35 degrees

These results indicate a substantial reduction in effective cohesion in the weathered domain, explaining localized block detachment observed during excavation.

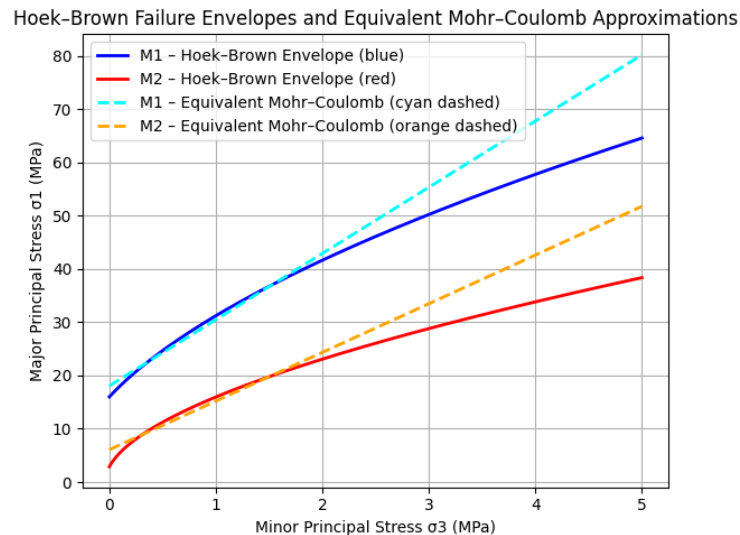


Figure 4. Hoek-Brown failure envelopes for domains M1 and M2 and equivalent Mohr-Coulomb linear approximations under low confinement conditions. Blue line: M1 Hoek-Brown envelope; Red line: M2 Hoek-Brown envelope; Cyan dashed line: M1 equivalent Mohr-Coulomb approximation; Orange dashed line: M2 equivalent Mohr-Coulomb approximation.

8 KINEMATIC ANALYSIS

Kinematic stability was assessed through lower-hemisphere stereographic projection of the measured discontinuity sets and slope orientation (Priest, 1993; ISRM, 1978). The objective was to verify the geometric feasibility of planar sliding, wedge failure, and toppling mechanisms under the current excavation geometry.

The slope face presents an orientation of approximately 350° dip direction with 70° dip. Three dominant joint sets were identified from scanline mapping:

J1: 291°/85°

J2: 141°/86°

J3: 238°/84°

All joint sets exhibit steep dips, predominantly subvertical, which significantly reduces the likelihood of planar sliding under the present slope inclination.

Planar failure requires that discontinuity dip direction is within $\pm 20^\circ$ of the slope dip direction and that discontinuity dip is less than the slope dip but greater than the friction angle. In the present case, none of the identified joint sets satisfy both directional and dip magnitude conditions simultaneously.

Wedge failure potential was evaluated by analyzing the intersection lines between joint sets. Although orthogonal joint systems exist, their intersection lines do not daylight in the slope direction within the kinematically admissible zone defined by the friction cone ($\phi \approx 40^\circ$). Therefore, wedge sliding is not geometrically feasible.

Toppling failure typically requires steeply dipping discontinuities oriented roughly parallel to the slope face but dipping into the excavation. The measured joint sets do not exhibit inward-dipping geometry, thus eliminating toppling susceptibility.

The stereographic projection confirms that no global kinematically admissible failure mechanism is present under current slope conditions.

Lower-Hemisphere Stereonet – Great Circles, Wedge Intersections, and Planar Kinematic Envelope

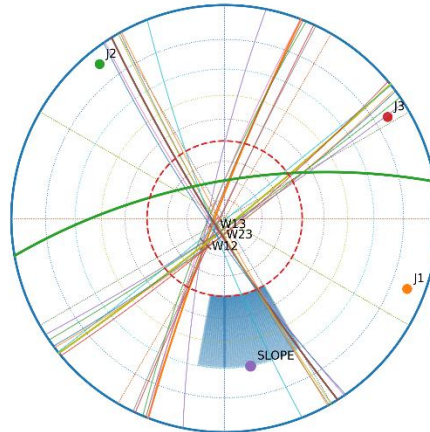


Figure 5. Lower-hemisphere stereonet (equal-angle projection) showing the great circles of the representative joint sets (J1, J2, J3) and the slope face, with poles plotted for each set. The shaded region represents the planar sliding kinematic window (dip direction within $\pm 20^\circ$ of the slope dip direction, dip between the friction angle $\phi = 40^\circ$ and the slope dip). The dashed circle indicates the friction cone boundary for poles ($\phi = 40^\circ$). Wedge intersection lines (W12, W13, W23) are plotted as “x” symbols, demonstrating that wedge intersections do not daylight within the kinematically admissible region for the current slope geometry.

9 DISCUSSION

The integrated geomechanical assessment demonstrates that slope stability is governed by the interaction between structural geometry and rock mass degradation rather than intact rock strength alone. Although laboratory testing indicates moderately high intact compressive strength (64.3 MPa average), the mechanical behavior at slope scale is strongly influenced by fracture density, weathering, and discontinuity condition.

The RQD and RMR classifications clearly differentiate the two domains, with M1 exhibiting excellent structural quality and M2 showing significant degradation. However, empirical classifications alone do not fully capture the mechanical implications of this contrast. The incorporation of GSI and the Hoek–Brown failure criterion allowed quantification of rock mass strength reduction, particularly the substantial decrease in equivalent cohesion in domain M2.

The derived Hoek–Brown parameters reveal that while intact strength remains relatively high, the rock mass parameter s decreases exponentially with GSI reduction. This behavior explains why localized instability occurs even in a rock mass composed of strong basalt: mechanical degradation at the discontinuity scale controls failure mechanisms.

The stereographic projection further confirms that global structural instability is not kinematically admissible. None of the discontinuity sets satisfy planar sliding conditions within the $\pm 20^\circ$ directional tolerance relative to the slope face while simultaneously meeting dip magnitude constraints. Similarly, wedge intersections do not daylight within the admissible sliding window defined by the friction angle. Toppling mechanisms are also geometrically excluded due to the absence of inward-dipping discontinuities.

The shaded kinematic envelope demonstrates that observed joint poles fall outside the planar failure window. Intersection lines between joint sets, although present, do not satisfy plunge and daylighting conditions required for wedge sliding.

This case reinforces that basaltic slopes within the Serra Geral Formation must be evaluated through domain-based characterization, integrating empirical classification, constitutive modeling, and geometric analysis. Homogeneous treatment of the rock mass would lead to either overconservative design in competent zones or underestimation of localized instability in degraded sectors.

10 CONCLUSIONS

The geomechanical characterization of the investigated basaltic slope demonstrates that stability behavior is controlled by structural heterogeneity and mechanical degradation rather than intact rock strength alone.

Two distinct domains were identified. Domain M1 exhibits excellent structural quality (RQD 95.68%, RMR 82, GSI 75) and high equivalent rock mass strength. Domain M2 presents moderate to fair quality (RQD 73.6%, RMR 48, GSI 45), characterized by increased fracture density, weathering, and groundwater influence.

Application of the Hoek–Brown criterion quantified the reduction in rock mass strength associated with GSI decrease. The derived equivalent Mohr–Coulomb parameters indicate a substantial reduction in effective cohesion in the fractured domain.

Kinematic analysis using lower-hemisphere stereographic projection demonstrated that planar sliding, wedge failure, and toppling are not geometrically admissible under the present slope orientation. The absence of joint poles within the planar failure window and the non-daylighting nature of wedge intersections confirm that no global structural instability mechanism is active.

The study highlights the importance of combining empirical rock mass classification systems (RQD, RMR), geological strength indexing (GSI), constitutive failure modeling (Hoek–Brown), and explicit kinematic assessment when evaluating basaltic slopes in heterogeneous volcanic terrains.

Such integrated methodology reduces uncertainty, improves interpretation reliability, and supports technically consistent decision-making in excavation projects involving fractured volcanic rock masses.

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