Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-353

Stability of anchored slopes in macroporous volcanic rocks

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ABSTRACT: The analysis of slopes in low-density pyroclastic rocks differs fundamentally from conventional rock slopes because the volcanic material undergoes collapse under isotropic stress. This situation is aggravated in cases where slopes are supported by anchors, as these significantly increase the confinement of the rock mass. This research analyzes the stability of slopes in this type of rock using a numerical model with the innovative Discontinuity Layout Optimization (DLO) method, which is based on limit analysis. The model represents a simple slope in a uniform medium with an external compression at the slope face, representing the anchoring system. A nonlinear failure law is assigned, with collapse increasing in shape until, from a certain combination of stresses, it decreases to zero due to the material's de-structuring. This criterion is implemented in DLO through approximation with linear segments. The developed models show high solution stability and low computational cost, compared to conventional models that require specific programming for this criterion and generally exhibit numerical problems. The analysis considers the influence of the slope geometry, as well as the mechanical parameters of the material associated with a parabolic failure law, leading to general conclusions regarding the failure shape and behavior of slopes in this type of material.

KEYWORDS: Slope stability, collapse, Discontinuity Layout Optimization, pyroclastic rock.

1 INTRODUCTION

Pyroclasts are formed from fragments of magma expelled during volcanic eruptions. These may consist of (1) fine glass particles with extremely high specific surface area or (2) larger fragments that, upon solidification, form scoria and pumice, often containing trapped gas. Due to this composition, pyroclastic rocks exhibit low density and high porosity, which makes their geomechanical characterization and behavior particularly unique.

Infrastructure built on volcanic formations frequently encounters slope instability problems, leading to significant economic losses and social impacts. Landslides and rockfalls present considerable risks, especially on roads, where they can affect transportation networks and urban or recreational zones. Such hazards often demand urgent preventive measures (Michoud et al., 2012; Martino & Mazzanti, 2014).

Since the 1970s, studies have been conducted in various countries (including Italy, Japan, New Zealand, and Spain) on different types of volcanic rocks. Researchers such as Pellegrino (1970), Aversa and Evangelista (1998), and Cecconi and Viggiani (1998) presented results from tests on volcanic rocks and proposed strength criteria. Other global studies, including those by Adachi et al. (1981), Moon (1993), and Teymen (2020), have expanded our understanding of low-density volcanic rocks through experimental data and geomechanical property correlations.

In Spain, unique geomechanical characterization of pyroclasts has been observed in engineering studies conducted in volcanic regions, such as those involving dams like Campitos and Ariñez in Tenerife (Serrano, 1976), where triaxial and isotropic collapse tests were used to identify load conditions leading to mechanical collapse in foundation materials. Using pyroclasts with widely varying densities from different locations in the Canary Islands, Serrano and Olalla (1998) and Serrano et al. (2002) concluded that the geomechanical behavior of these materials depends on five key factors: compaction, alteration, welding, imbrication, and particle strength. Serrano et al. (2007) continued studying the strength and deformability of low-density pyroclasts through testing of new samples across the Canary Islands, providing new correlations among geomechanical parameters. Building on these studies, Conde (2013) and later Serrano et al. (2016) proposed a new classification for volcanic materials.

Volcanic materials behave differently from other geological formations due to their heterogeneity, anisotropy, and rapid strength degradation from alteration processes, especially under water influence. Specialized methodologies are therefore necessary to assess slope stability, estimate landslide probability, and analyze potential economic impacts.

In low-density volcanic materials, the mechanical response depends heavily on the applied load. At low stress levels, their resistance and deformation characteristics resemble conventional rocks. However, as load and internal stresses increase, particle bonds begin to break, initiating a process known as mechanical collapse. This sudden failure causes significant deformation and poses serious risks for structures built on these materials. After the collapse, particles reorganize into a more compact arrangement than the original.

Understanding and predicting the strength and deformability of pyroclastic materials is critical in civil engineering and construction, particularly in volcanic regions. For accurate slope design and stability evaluation, a suitable failure criterion is essential. Serrano et al. (2016) developed a model based on roughly 300 volcanic samples from the Canary Islands. This model is especially useful in slope analysis, enabling the determination of stress conditions that may trigger failure mechanisms in soil. Given the complexity of implementing this nonlinear criterion, the Discontinuity Layout Optimization (DLO) method offers a practical and rigorous approach to stability analysis.

2 METHODOLOGY

2.1. *Numerical Model of the Anchored Slope*

Figure 1 outlines the model used to represent the slope in volcanic rock. A homogeneous material is considered (acknowledging this simplification), focusing on the influence of collapse for the studied scenarios. The rock follows a parabolic failure criterion defined by the parameters *M, t* (isotropic tensile strength), and (P_c) (isotropic compressive strength) according to the rupture law proposed by Serrano (2016).

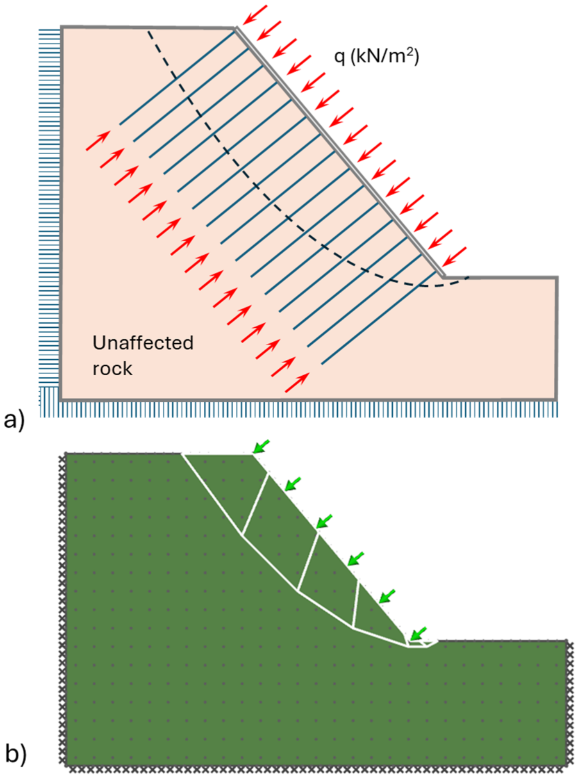

Figure 1. (a) Slope with anchorage diagram; (b) Simplified numerical model using DLO.

The slope geometry is defined by its height *H* and inclination *β*, with horizontal surfaces at the crest and toe. Internal terrain boundaries are fixed and placed far enough to avoid influencing results.

The anchoring system is modeled as a uniform stress applied to the slope face, assuming the anchorage force is distributed via a surface containment element. Anchors are considered long enough to exceed the sliding wedge, so their detailed behavior is omitted. The anchor stress is constant from the toe up to 4/5 *H*, then reduced to one-tenth in the top 1/5 *H* to prevent local instability. This simplified model aims to replicate the stress state induced by anchoring in pyroclastic slope stability.

The macroporous material has low density, approximately 10 to 15 kN/m³ (Serrano et al., 2016). A porosity of 50% and potential saturation from concentrated rainfall are considered, which increases the unit weight to 20–25 kN/m³. The study includes scenarios for unit weights of 10, 15, 20, and 25 kN/m³, representing dry to saturated conditions.

2.2. *Discontinuity Layout Optimization (DLO) Method*

The DLO method, developed by Smith and Gilbert (2007), is based on classical limit analysis, but unlike traditional approaches, it does not assume a predefined failure mode. Instead, all possible failure mechanisms are identified through a network of nodes, with the critical one being the lowest-energy configuration. The failure lines connecting these nodes are determined via optimization.

Solution accuracy increases with node density, and the result is considered an upper-bound solution. The method maintains the simplicity of classical analysis while allowing efficient failure mechanism identification. Its advantages and low computational cost make DLO highly recommended for geotechnical problems (Smith, 2007). Figure 1 (right) shows a slope model with anchors using DLO, including the resulting failure mode (white lines).

2.3. *Failure Criterion*

Based on the empirical study by Serrano et al. (2016), a parabolic failure criterion is proposed for low-density pyroclastic materials. Previous authors suggested various yield surfaces, prompting further study, and the parabolic model adopted here.

The geomechanical behavior of these materials is highly influenced by their structure. At low confinement levels, their stress-strain response is elastic and linear. However, after reaching peak stress, marked brittleness is observed, especially under low confinement. This necessitates a highly nonlinear failure law, complicating numerical analysis.

In the DLO method, this criterion is implemented via piecewise linear approximation, using secant lines—a technique previously employed by the authors (Galindo et al., 2021).

Two failure criteria are applied in this study:

1. Parabolic collapse criterion for the pyroclastic layer: (*Pc*=1 MPa; *t*=10 kPa; *M*=1.5)
2. Envelope criterion without collapse: includes a parabolic segment up to maximum shear stress and a horizontal tangent afterward

Both criteria are illustrated in Figure 2.

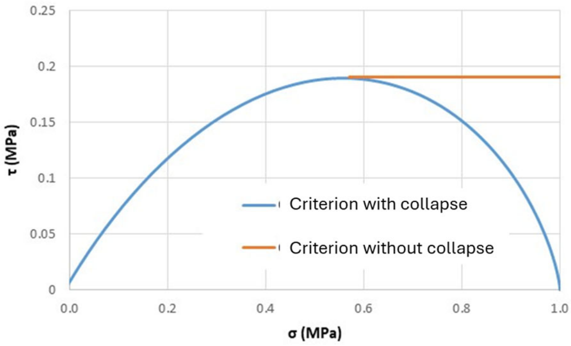

Figure 2. Complete parabolic failure criterion considered for rock with collapse, and parabolic criterion with horizontal tangent for non-collapse rock (the descending branch of the curve is omitted).

The failure law proposed by Serrano et al. (2016), using Cambridge variables (p, q), is expressed as:

$$q = M(p+t)\left(1-\frac{p+t}{P_c+t}\right) \qquad (1)$$

Here, *t* is the isotropic tensile strength, *Pc* is the isotropic compressive strength (collapse load), and *M* is a friction parameter derived from low stress triaxial tests, depending on the instantaneous friction angle.

Triaxial tests on various pyroclasts revealed that welded lapilli show lower average \(t\) values (9% of collapse load) compared to pumice (18% on average), with most pyroclasts exhibiting much lower values (around 1%). Most materials had *M* values between 1.5 and 3.

These findings help understand the mechanical behavior of volcanic rock masses and support the development of more accurate slope stability models for volcanic environments.

3. RESULTS AND DISCUSSION

Three different models were calculated to assess the effect of anchoring on volcanic slopes:

- Unanchored slope, for which the safety factor was computed.
- Slope using a no-collapse material, with the anchor force adjusted to achieve a safety factor of 1.
- Same case as above, but with a collapse-prone material; the safety factor was recalculated accordingly.

A reference slope with an inclination of β = 50º was selected, varying the height between 10 m and 50 m in 5 m increments. For each configuration, results from the three models were compared, analyzing changes in the safety factor due to anchoring.

Figures 3 and 4 show the slope's safety factor for the three terrain models under different unit weight hypotheses, evaluating the influence of saturation concurrent with anchorage application.

For a dry pyroclastic terrain (unit weight between 10 and 15 kN/m³, Figures 3a and 3b), anchoring is necessary to stabilize slopes taller than 20 and 15 meters, respectively. As expected, taller slopes have lower safety factors, and the anchor stress must increase significantly. When collapse is considered, the results for these cases remain identical, indicating failure points occur within the rising branch of the failure curve.

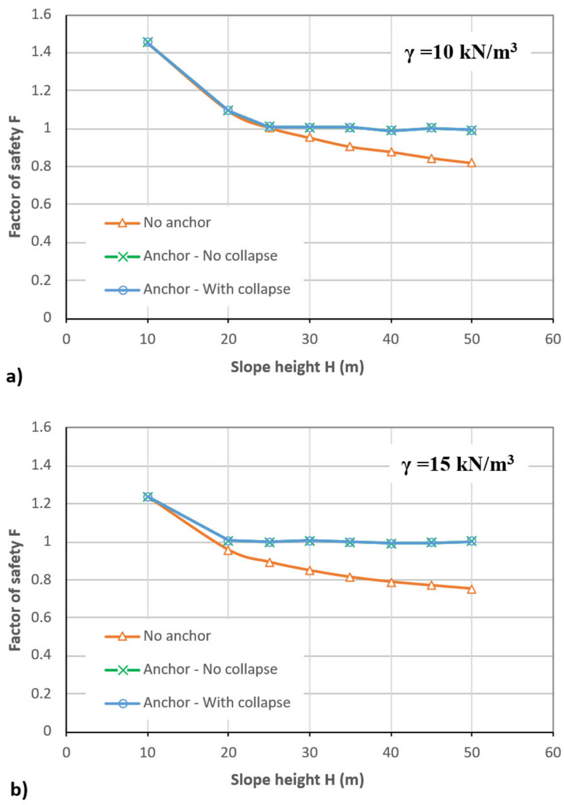

Figure 3. Comparison of safety factors for a slope with β = 50º across three terrain models and varying unit weight hypotheses. (a) Rock weight 10 kN/m³, (b) Rock weight.15 kN/m³,

For unit weights of 20 and 25 kN/m³ (Figures 4a and 4b), no-collapse behavior is similar, though higher anchor forces are needed. However, collapse-prone behavior diverges for respective slope heights of 40 m and 30 m, where applying the same anchor stress no longer yields a safety factor of 1. This is due to reduced terrain resistance (descending branch of the failure curve). At greater heights, a striking phenomenon occurs: the collapse-prone model curve intersects the unanchored model curve. This suggests that anchoring—contrary to expectations—can destabilize the slope by inducing collapse. This is a key finding of this research.

Such behavior is more pronounced on steeper slopes and less so on gentler ones, particularly when a design safety factor greater than 1 is desired (1.5 is common practice).

Figure 4 explains this behavior through stress changes at the slope's base. Using Mohr's circle representation for a 40 m slope with γ = 25 kN/m³, both collapse-prone and no-collapse cases show that, in the collapse model, the stress circle shifts toward the descending branch of the parabolic criterion, revealing a significant reduction in material strength.

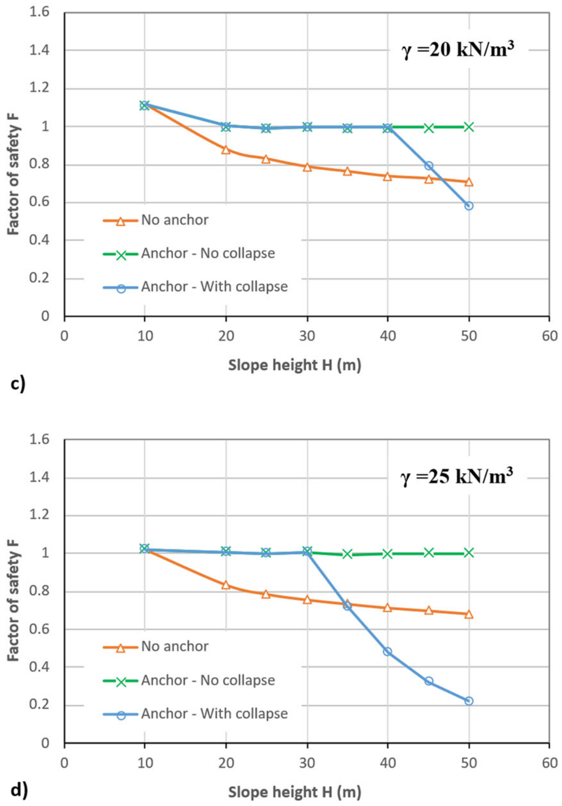

Figure 4. Comparison of safety factors for a slope with β = 50º across three terrain models and varying unit weight hypotheses. (a) Rock weight 20 kN/m³, (b) Rock weight 25 kN/m³.

Finally, Figure 5 displays the failure modes of the same two cases. In the collapse-prone scenario (Fig. 5b), general failure occurs at the slope base due to a major strength reduction caused by stress levels exceeding 0.5 MPa (descending zone of the failure envelope).

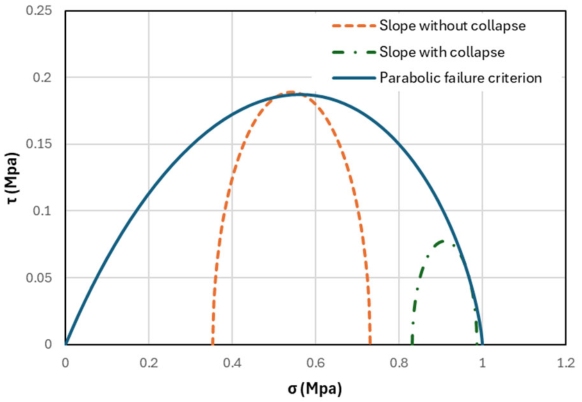

Figure 5. Mohr circle comparison for the most stressed points at the base of the slope with H = 40 m and γ = 25 kN/m³, using the non-collapse and collapse models, respectively.

3 CONCLUSIONS

A numerical model has been developed to study the behavior of slopes in macroporous pyroclastic rock and the influence of anchor support systems on their stability.

Results indicate that beyond a certain slope height—especially under conditions of saturation due to intense rainfall episodes—the failure risk increases significantly. This is directly related to the collapse behavior of macroporous volcanic rocks.

Such a collapse risk arises when the anchor stress, combined with the increased weight due to saturation, leads to stress levels at the slope's toe approaching the descending branch of the failure criterion.

It is observed that, in some cases, anchoring the slope may be counterproductive for its stability, accelerating failure by increasing proximity to collapse conditions according to the failure criterion.

A reference slope of 50º inclination was studied with a theoretical design criterion aiming for a safety factor F=1. In real scenarios, where the design safety factor is typically F=1.5, the previously described effects and collapse influence would be even greater than those presented in this study.

4 ACKNOWLEDGEMENTS

This publication is part of project PID2022-139202OB-I00, "Neural Networks and Optimization Techniques for the Safe Design and Maintenance of Transportation Infrastructure: Geotechnics of Volcanic Rocks and Slope Stability (IA-Pyroslope)," funded by the State Research Agency of the Ministry of Science, Innovation and Universities and the European Regional Development Fund, MCIN/AEI/10.13039/501100011033/FEDER, EU.

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