



# Rock Slope Instability Risk Assessment in Open-Pit Quarries: A Comprehensive Approach

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## Abstract

This work aims to develop a simplified approach to assess slope stability in open-pit marble quarries. Each site is subject to field investigation to determine the relevant rock mass properties, using the scanline sampling technique to list the mechanic and geometric properties of the intact rock and rock mass discontinuities and collect samples for laboratory analysis of the relevant geotechnical properties. The stability conditions of each slope for planar, wedge and toppling mechanisms were then studied through kinematic analysis techniques, both qualitative and quantitatively. To determine the stability, both Limit Equilibrium Methods (LEM) and geomechanical classifications for rock masses are applied, namely the Slope Mass Rating. With the proposed approach, it is possible to determine a qualitative variable called the Risk Index, based on the *vulnerability* and the *hazard* of the slope, and address the most suitable control measures to eliminate the potential risks these sites represent.

## Keywords

Rock slope stability • Risk assessment • Open-pit quarries • Dimension stone

## 1 Introduction

Dimension stone extraction in Portugal dates back to the Roman Period, and this resource has been widely used as construction and ornamental raw material for the country's historical monuments. In recent years, economic and market constraints forced quarry owners to focus on the homogeneity of the extracted materials rather than the exploitations' sustainable longevity. Therefore, the main difficulty facing the adequate development of an open-pit quarry nowadays is to assure the slopes' geotechnical stability, which can be achieved using slope stability analysis. That is one of the most critical steps towards ensuring safer working environments because an inadequate slope design can eventually cause severe human and material damage. Given the high number of active and inactive quarries in the country, many with multiple and, occasionally, quite complex instability issues, any imminent risks can only be fully mitigated when a detailed slope stability analysis is combined with an adequate risk assessment.

The stability of rock slopes is crucial to public safety in transport infrastructures passing through rock cuts, as well as to personnel and equipment safety in open-pit quarries. Slope instability can be induced by many preparatory factors, namely adverse slope geometries and joint sets, soft or weathered slope materials, and the presence of groundwater. External loads caused by heavy or prolonged rain, seismic events or blasting can play a significant role in slope failures, typically acting as triggering mechanisms that can initiate failure. The slope stability of the open-pit marble quarries in the region of Estremoz-Borba-Vila Viçosa (Estremoz Anticline, Portugal) has attracted major concern after a large slope collapse on the EN255 on 19th November 2018. This event motivated the inception of the Intervention Plan for Quarries in Critical Situation approved by Cabinet Meeting n°50/2019, 5th March, which requires “*the definition of urgent and priority risk mitigation measures to avoid or, at least, reduces the critical situations in quarries*”.

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## 2 Methodology

Several techniques and methods for slope stability analysis have been developed over the years. These methods can be grouped into four categories, i.e., kinematic analysis, limit equilibrium, numerical modelling (based on deterministic or probabilistic methods) and empirical methods. Kinematic analysis is commonly used to predict the potential structural failure mechanism by projecting the slope and discontinuities' orientation on a two-dimensional stereograph net (Hoek and Bray 1981). Rock mass classification systems or empirical methods represent an essential tool that is often used for preliminary assessment of the rock mass's engineering behaviour, with proven usefulness due to the ease with which they can be implemented and their effectiveness in interpreting stability and recommending control measures. On the other hand, risk assessment is a versatile decision-making tool, as it involves considering the sources of risk, their consequences, and the likelihood of those consequences. Therefore, a methodology for assessing the stability of open-pit quarry cuts and the associated risk is suggested using a combination of kinematic analysis and empirical methods (Fig. 1).

Each site is subject to field investigations to determine the rock mass's relevant properties (including intact rock and discontinuities). These include rock type, rock weathering, condition of discontinuities (orientation, spacing, aperture and filling, persistence, wall weathering), groundwater presence, and the geometrical description of the slope, such as slope height, face dip and dip direction. The following step involves laboratory testing to determine the relevant geotechnical properties of rock samples. In this methodology, it is suggested to perform uniaxial compressive strength tests

and tilt tests to determine the unconfined compressive strength (UCS) of the rock and the basic friction angle for discontinuities ( $\phi_b$ ), respectively (Bruce et al. 1989). For marble open-pit quarry slopes failure is, in general, structurally controlled, except in localized areas where groundwater flows through the more persistent joint sets typically form highly weathered areas filled with silty clay soil from the dissolution of  $\text{CaCO}_3$  (karst cavities). Two types of approaches are used: kinematic analysis and the RMR (Rock Mass Rating) system (Bieniawski 1989).

Kinematic analysis is used to determine the likelihood of planar, wedge and toppling failures and assess the most critical failure surface on the rock slope. The RMR is a system that rates the rock mass quality based on five parameters that represent different conditions of the rock material and the discontinuities. These parameters are UCS of intact rock, RQD (Rock Quality Designation), the spacing between discontinuities, condition of discontinuities and groundwater. This RMR system is known as "the basic RMR", and it gives a value that ranges between 0 and 100 (Bieniawski 1989).

Based on the results of the RMR and the identification of the most critical failure from the kinematic analysis, the SMR (Slope Mass Rating) system is applied to the slope. The SMR system is derived from the RMR, where adjustment factors representing the discontinuity orientations towards the slope are subtracted from the basic RMR ( $\text{RMR}_b$ ) and the effect of the excavation method (e.g., Romana 1985; Anbalagan et al. 1992). The continuous SMR system (Tomás et al. 2007) replaces the rating system adopted in the original SMR with continuous functions (Riquelme et al. 2014). Both approaches can be used.

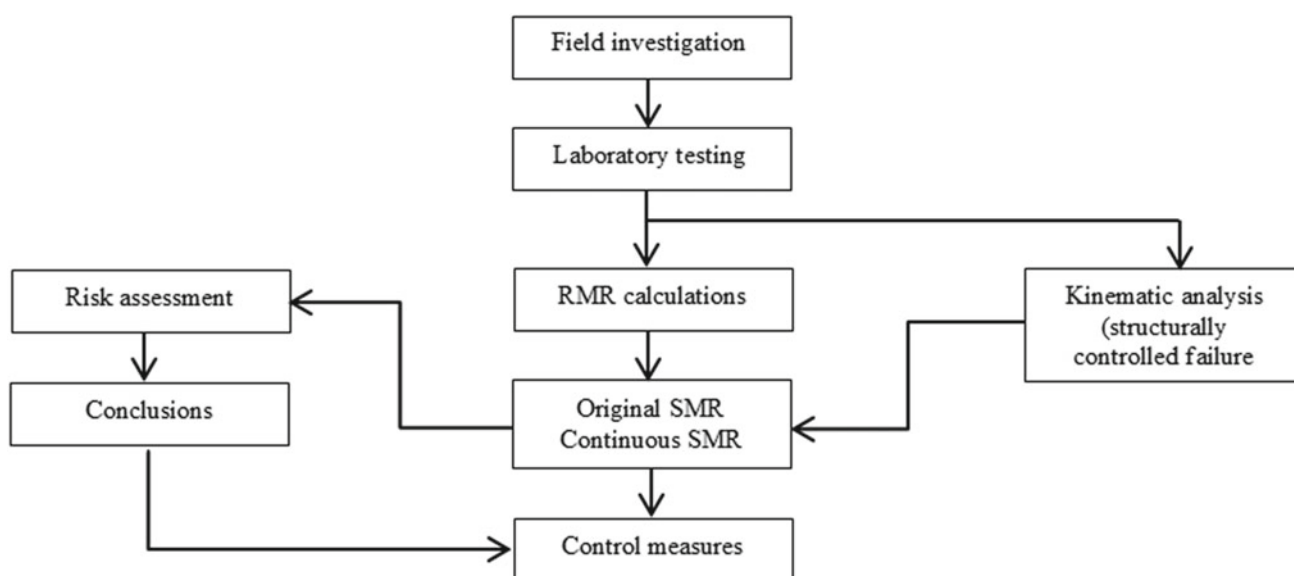


Fig. 1 Proposed methodology flowchart

**Table 1** Planned control measures based on the proposed risk index

| Risk Index | Classification | Planned mitigation measures  |
|------------|----------------|--|
| 25         | Critical       | <ul style="list-style-type: none"> <li>• Total or partial suspension of labour</li> <li>• Structural measures (slope stability) and surface drainage</li> <li>• Security perimeters/access restriction</li> <li>• Removal of unstable wedges</li> <li>• Monitoring measures</li> </ul> |
| 20-24      | Very high      | <ul style="list-style-type: none"> <li>• Re-profiling/induced blasts</li> <li>• Structural measures (slope stability) and surface drainage</li> <li>• Security perimeters/access restriction</li> <li>• Removal of unstable wedges</li> <li>• Monitoring measures</li> </ul>           |
| 15-20      | High           | <ul style="list-style-type: none"> <li>• Structural measures (slope stability) and surface drainage</li> <li>• Security perimeters/access restriction</li> <li>• Periodic removal of unstable wedges</li> <li>• Monitoring measures</li> </ul>   |
| 10-15      | Moderate       | <ul style="list-style-type: none"> <li>• Security perimeters/access restriction</li> <li>• Periodic removal of unstable wedges</li> <li>• Monitoring measures</li> </ul>   |
| 5-10       | Low            | <ul style="list-style-type: none"> <li>• Periodic removal of unstable wedges</li> <li>• Monitoring measures</li> </ul>   |
| 0-5        | Insignificant  | <ul style="list-style-type: none"> <li>• Monitoring measures</li> </ul>  |

The next stage consists of a qualitative risk assessment where the terms hazard (H) and vulnerability (V) are categorized on a scale of 1–5, providing a risk index adapted from the work produced by Costa et al. (2009), revised by Brissos (2013), Brissos et al. (2014) and Caetano et al. (2015), applied to instability risk assessment in natural slopes. It should be noted that H is to be understood as an apparent hazard, differing from the concept commonly used since it is not derived from a probabilistic assessment of the damaging phenomenon but rather from the obtained SMR class.

This risk classification encompasses a fair degree of subjectivity, yet it allows for the concentration of resources on sites that demand immediate intervention and implementation of control measures (Table 1). Subsequently, limit equilibrium techniques or other methods can refine the stability analysis of the sites' that shows very high or critical risk.

### 3 Results

The described methodology was implemented on the NE slope of an open-pit marble quarry (Site A) located in the Estremoz Anticline, Portugal (Fig. 2).

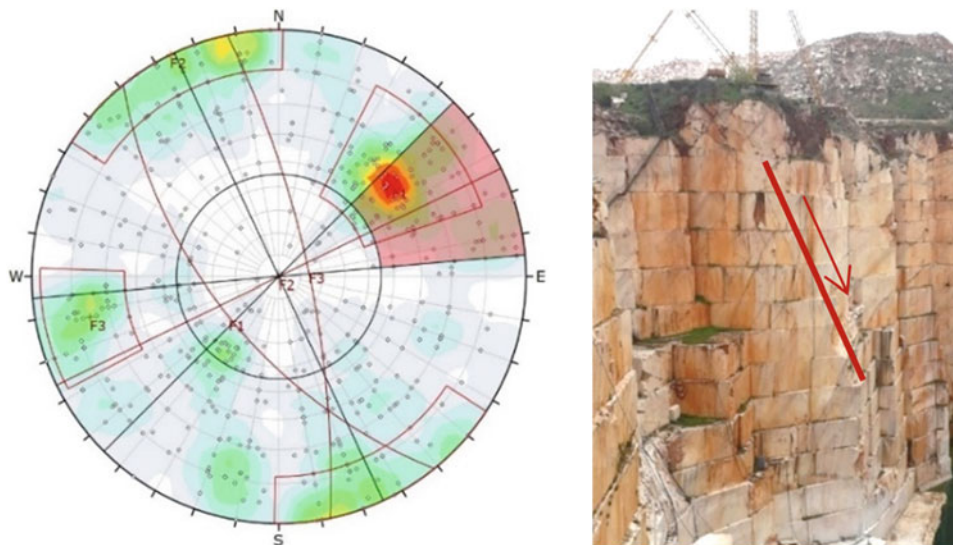
For site A, kinematic analysis, using *Rocscience* software *Dips*, indicated that the most unfavourable structural movement is planar sliding along a joint set sub-parallel to

the slope and dipping approximately 50–70°SW with a basic friction angle of 45°, as determined by tilt testing. The most critical element of this joint set (highlighted in red in Fig. 2) intersects the slope from the surface and shows itself along the slope's face until approximately 38 m from its base. The persistence of this element was estimated at approximately 50 m. Therefore, the SMR classification deemed the site prone to sliding along some of the more persistent joints and joint intersects (for wedge failure). Results are shown in Table 2.

The Risk Index for site A (Fig. 2) was found to be very high, resulting from a high H rating based on the SMR results (favouring the risk of sliding of the rock mass along the identified joint), and a high V rating, as there is an operating derrick crane on top of the slope (static and dynamic loads), while work is underway at the toe of the bench leading to the presence of operators and equipment. Furthermore, there is a substantial thickness of residual soil at the top of the slope, which can be mobilized by runoff and other erosion agents.

To refine the geotechnical model regarding the very high risk of this site, a limit equilibrium analysis (Wyllie and Mah 2004) was conducted to estimate the dimension of the unstable mass as well as the corresponding factor of safety (FS) (Fig. 3). Calculations considered a unit weight of the rock ( $\gamma$ ) of 27 kN/m<sup>3</sup>, a mass height (h) of 46 m and a horizontal distance between the face of the slope and the outcrop (X) of 25,5 m with a dip angle ( $\psi$ ) of 61°, leading to

**Fig. 2** Characterization of site A. Stereographic projection and identification of the most critical fracture (in red) affecting the slope



**Table 2** Results obtained for site A

| Site | Critical structural failure | RMRb    | Original SMR | Continuous SMR | Rating SMR | Failures SMR         | Stability SMR | Risk Index     |
|------|-----------------------------|---------|--------------|----------------|------------|----------------------|---------------|----------------|
| A    | Planar slide                | 69 (II) | 27           | 26             | IV         | Planar or big wedges | Unstable      | Very high (20) |

a mass weight (triangular wedge) of 16.334 kN/m. No tension cracks were identified in the upper surface or the face of the slope. It was also considered that the area of the sliding surface was 52,59 m<sup>2</sup>/m with the cohesion of 160 kPa (the value was estimated on-field shear strength assessment and literature results by Costa 1992), which resulted in a factor of safety of 1,14, lower than that required for temporary open-pit slopes (Wyllie and Mah 2004).

#### 4 Control and Risk Mitigation Measures

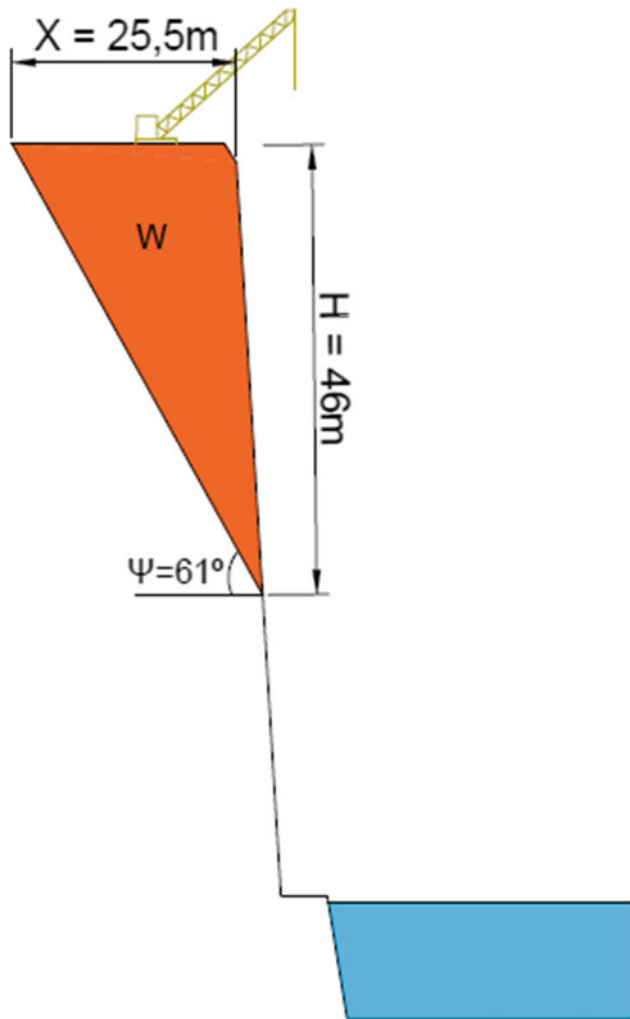
Several risk mitigation measures were discussed with the quarry owner and site engineers. Regarding the very high-risk index obtained for this specific site, risk mitigation measures proposed include:

- Slope re-profiling—controlled removal of the identified unstable rock mass.
- Periodic removal of any other potentially unstable rock masses.
- Periodic slope monitoring using high-precision topography devices (UAV).
- Instrumentation plan—Implementing fissurometers in the critical fractures of the most unfavourable joint sets considered in the SMR calculations and surface surveying techniques to detect any vertical movements.

- Access restriction/alteration (until slope re-profiling is complete). Restrict the derrick crane's use only to maintenance operations and extraordinary activities in which its use is mandatory and create a security perimeter of 30 m along the base of the slope.

If the unstable rock mass remains, other measures will need to be implemented, namely rock support bolts to increase the slope's FS. Based on the conducted calculations, to obtain a factor of safety of 2,0, the bolting force must be 1461 kN/m. The rock bolts must be placed in vertical rows of 5 bolts, horizontally spaced by 2,05 m, with as many vertical rows as required to obtain the mass's total coverage (Wyllie and Mah 2004).

Depending on the type of slope, its current status (if it is under active exploitation or if its geometry has been finalized) and the size of the unstable wedge(s), other solutions can be implemented, for example, rolled cable nets that can offer protection against small-sized but, nonetheless, hazardous rockfalls over wide areas of the slope. In the studied region, most marble quarries are exploited by different companies over small areas, which result in adjacent and very deep sub-vertical open-pit quarries whose boundaries are often subject to slope instability issues. Other alternatives can be sought in these cases, such as integrated exploitation with adjacent quarries, which can effectively eliminate the risk.



**Fig. 3** Limit equilibrium model for site A

It should be noted that a given slope that, at any moment, is considered as stable, during continuing exploitation can rapidly evolve into an unstable one. Therefore, the geotechnical model of the slope must be adapted accordingly, and some adjustments must be made to update the current model if necessary, namely if tension cracks are identified.

## 5 Concluding Remarks

In summary, the proposed approach, combining kinematic analysis and empirical methods, allows to study of quarry slope stability and subsequently prioritize several high-risk sites over a short timeframe in order to determine the need for further studies and/or risk mitigation measures, as enforced by the Portuguese Intervention Plan for Quarries in Critical Situation.

This approach was applied to the study of several sites in the region of Estremoz-Borba-Vila Viçosa and produced

satisfactory results for both quarry owners and regulators. The conducted analysis allowed identifying many different slope stability issues that represent a risk for the existing receptors. Therefore, several control and mitigation measures were proposed for these sites, ranging from site monitoring to the temporary, total or partial, suspension of labour.

Further work is required to improve the proposed methodology. To this end, incorporating laser scanning techniques via UAV in order to improve the geological data acquisition process can be a step forward, as the traditional scanline sampling technique is highly dependent on accessibility to the study areas, which can be a severe limitation in open-pit quarries bordered by sub-vertical slopes.

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