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Estado del arte sobre métodos empíricos y numéricos de análisis de
estabilidad de cuevas: aplicación en tubo de lava de Al-Badia, en Harrat
Al-Shaam, Jordania

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Presentado por:

Ronald Eduardo Herrera Tamayo

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Ronald Eduardo Herrera Tamayo

Evaluadores



Firmado electrónicamente por:
SAMANTHA TAMARA
JIMENEZ OYOLA

Ph. D. Samantha Jiménez Oyola

Profesor de Materia



Firmado electrónicamente por:
DAVIDE BESENZON
VENEGAS

M. Sc. Davide Besenzon Venegas

Profesor de Materia

Ph. D. Luis Jordá Bordehore

Tutor de proyecto

Resumen

Las metodologías empíricas y numéricas para la evaluación geomecánica de excavaciones subterráneas han evolucionado en los últimos años para adaptarse a las condiciones geotécnicas y estructurales de las cuevas naturales, permitiendo evaluar su estabilidad y garantizar condiciones seguras para la exploración espeleológica. Este estudio analiza la evolución del estado del arte de estas técnicas en diversas regiones del mundo, evaluando su confiabilidad y contexto de aplicación, identificando las metodologías más adecuadas para determinar la estabilidad del tubo de lava de Al-Badia. La investigación se desarrolló a partir de un análisis bibliográfico y la caracterización del macizo rocoso mediante clasificaciones geomecánicas empíricas. Posteriormente, se aplicó el método numérico de elementos finitos para comparar los resultados obtenidos y modelar el comportamiento esfuerzo-deformación de la cavidad. Los resultados permitieron clasificar los sectores del tubo de lava de Al-Badia en zonas estables, de transición e inestables, utilizando gráficas empíricas de soporte y determinando factores de seguridad del macizo rocoso circundante.

Palabras Clave: Caracterización geomecánica; estabilidad estructural; colapso rocoso; tubo de lava.

Abstract

Empirical and numerical methodologies for the geomechanical assessment of underground excavations have evolved in recent years to adapt to the geotechnical and structural conditions of natural caves, enabling stability evaluation and ensuring safe conditions for speleological exploration. This study analyzes the evolution of the state of the art of these techniques worldwide, assessing their reliability and application context, and identifying the most suitable methodologies for determining the stability of the Al-Badia lava tube. The research was conducted through bibliographic analysis and rock mass characterization using empirical geomechanical classifications. Subsequently, the finite element numerical method was applied to compare the obtained results and model the stress-strain behavior of the cavity. The results allowed the classification of the Al-Badia lava tube into stable, transition, and unstable zones, using empirical support charts and determining the safety factors of the surrounding rock mass.

Keywords: Geomechanical characterization; structural stability; rock collapse, lava tuve.

Chapter 1. Introduction

1.1 Introduction

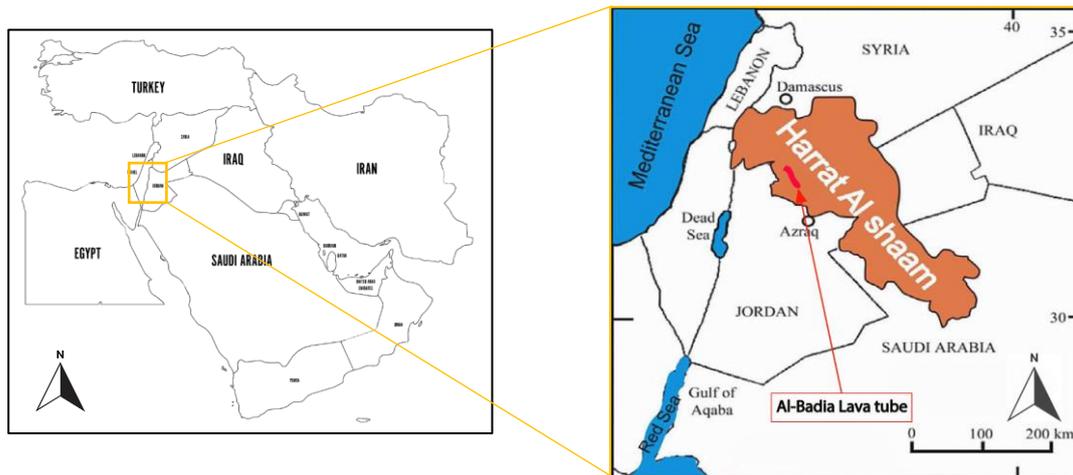
Caves are natural underground formations of great geological, historical and ecological significance. Unlike artificial excavations, these structures have generally remained open for extended periods, demonstrating their overall stability [1]. However, this inherent stability must be verified through internationally accepted criteria in terms of safety factors, failure mechanisms, support capacity charts, risk, and failure probability [2,3].

Stability analysis techniques for caves have been developed in various regions, with notable applications in Brazil, Spain, Turkey, Italy, and Ecuador (especially in the Galápagos Islands). The most significant advances have focused on karstic caves, although studies on ferruginous cavities and lava tubes have also been conducted.

To analyze cave stability, analytical, empirical, and numerical methods are employed, each with advantages and limitations. Analytical methods provide initial approximations but lack precision in complex scenarios [4]. Empirical methods, such as the RMR index, Barton's Q index, CGI index, and the scaled span mining method, allow for rock mass characterization and structural behavior prediction [5,6]. Meanwhile, numerical models, such as the finite element method, enable stress-strain behavior evaluation considering the specific geological characteristics of the rock mass [7,8].

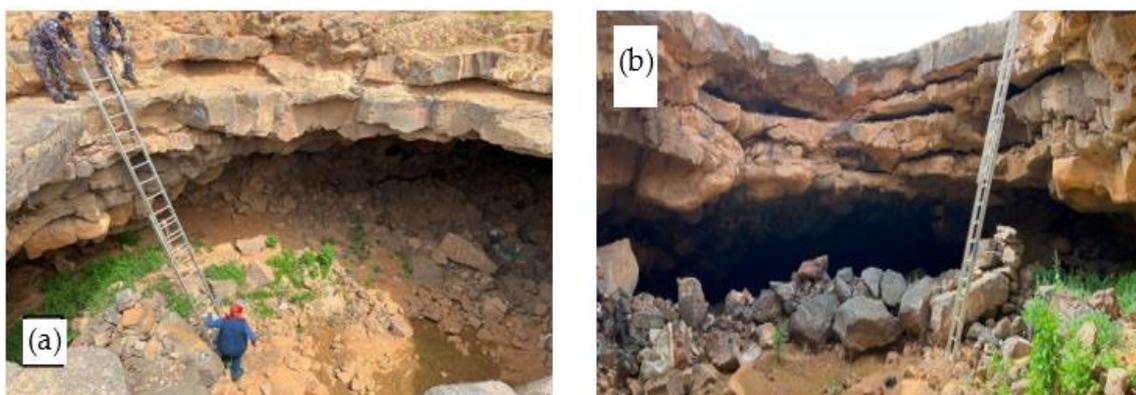
This study focuses on applying these stability analysis methodologies in the Al-Badia lava tube, located in the intercontinental lava plateau of Harrat Al-Shaam, in northeastern Jordan (Figure 1). This volcanic plateau, covering approximately 11,400 km², is one of the largest in the Middle East and is of significant geological and archaeological interest due to its interaction between volcanic, tectonic processes, and evidence of past human activity [9,10].

Figure 1. Geographical referencing of the study area, the Harrat Al-Shaam lava plateau, northeast Jordan. Adapted from [10].



This study area consists of six basaltic flow sequences, interspersed with tephra volcanoes, spanning from the Oligocene to the Holocene [9]. The most recent flows, located in the surface layers, are estimated to be around 400,000 years old. Since September 2003, a total of twelve caves, including lava tubes and cavities in pressure ridges, have been mapped and studied, underscoring the scientific and geological significance of the region [11]. The Al-Badia lava tube, located within this geological formation, extends for 445 meters and is accessible via a rock collapse zone, featuring an 8-meter vertical descent and a 16-meter horizontal span, as shown in Figure 2.

Figure 2. Al-Badia lava tube: (a) entrance collapse; (b) entrance collapse seen from below, with 16 m span. Taken from [12].



Natural cavities like Al-Badia form within lava flows when the surface cools and solidifies, creating a crust while lava continues to flow inside [13,14]. These caves are typically shallow, making them more susceptible to degradation processes that can compromise their structural stability and increase the risk of rockfalls.

This study aims to analyze the state of the art of empirical and numerical methods applied to cave stability assessment, with a specific focus on determining the structural stability conditions of the Al-Badia lava tube. The research was structured through the following activities: (I) development of the state of the art of empirical and numerical methodologies for cave stability analysis; (II) geomechanical characterization of the Al-Badia rock mass using empirical methods and stability analysis through support charts; (III) determination of geotechnical parameters and simulation of the rock mass stress-strain behavior using the finite element numerical method; and (IV) comparison of methodologies and discussion of results.

Chapter 2. State of the Art

2.1 Empirical Methodologies for Cave Stability Analysis.

The development of empirical methodologies has enabled underground excavation studies to be conducted in a structured manner, providing quantitative information for design and employing widely accepted terminology. These methodologies, based on observations and historical data, have been fundamental in assessing the stability of tunnels, mines, and, more recently, natural caves. The following sections present a chronological review of the main advancements in this field, highlighting their conceptual evolution and adaptation to specific conditions.

2.1.1. Early Classification Systems (1950s and 1960s).

Before the application of modern geomechanical classifications such as the RMR index and Barton's Q index, pioneering classification systems laid the foundation for rock mass analysis. Among them, the proposals of Terzaghi (1946), Lauffer (1958), and Deere (1967) stand out. These systems introduced key concepts such as rock mass deformability and support systems for excavations, although their approach was mainly qualitative [15,16].

2.1.2. Development of Modern Indices (1970s and 1980s).

During the 1970s, the most widely used geomechanical classification systems in rock engineering were developed: the Rock Mass Rating (RMR) index and Barton's Q index. The RMR system, initially proposed by Bieniawski (1973) at CSIR, evaluates parameters such as rock strength, discontinuity conditions, and groundwater. Over the years, this system has undergone several modifications, adjusting its parameters and scoring criteria while maintaining its fundamental principle [16,17].

On the other hand, Barton's Q system was developed at NGI between 1971 and 1974, based on the analysis of approximately 200 historical cases of tunnels and caverns. This index assesses factors such as rock quality, discontinuity conditions, and hydraulic stress, providing a preliminary empirical design for support systems [18]. Since its introduction, the Q system has undergone significant advancements, with updates in 1993 and 2002 incorporating data from new excavations in Norway, Switzerland, and India. With more than 1,260 documented records, it has been established as one of the most effective empirical methods for tunnel support design [19,20].

2.1.3. Adaptations for Mining Environments and Caves (1980s and 1990s).

The use of geomechanical classification systems in mining environments drove the development of methodologies adapted to specific conditions. A notable example is the MRMR system, introduced in 1974, which adjusts the RMR parameters for mining settings. This system incorporates factors such as weathering, mining-induced stresses, and discontinuity orientation, allowing for a more accurate assessment of the rock mass [17].

In the 1980s, the Mathews-Potvin empirical stability chart was developed, associated with Barton's Q index. This methodology considers additional factors such as stress concentration and discontinuity orientation, yielding more reliable results than the exclusive use of the Q index. However, its application in natural caves is limited due to the simplification of geological and geomechanical models [2].

2.1.4. Specific Methods for Natural Caves (2000s and 2010s).

Natural caves, being at shallow depths, can induce surface subsidence processes due to the collapse of pillars or roofs, affecting nearby structures [1]. To assess their stability, empirical techniques developed in mining have been applied, such as the scaled span method and discontinuity mapping following ISRM standards [21]. The scaled span

method, developed in the 1980s, has been adapted for cave analysis through the concept of overburden, allowing for the evaluation of failure probability and the safety factor of the rock mass above the cave. However, its applicability is limited by the simplification of overburden geometry and the assumption of a continuous and homogeneous rock mass.

In 2017, Jordá-Bordehore analyzed 137 caves and developed an adjusted version of the Q-index stability chart, specifically adapted for natural cavities. This modified model allows differentiation between stable, unstable, and collapsed caves, improving the accuracy of stability assessments [22].

2.1.5. Recent Advances (2020s).

Between 2015 and 2018, in the Carajás mining region of Brazil, the CGI geomechanical classification system was developed, applied, and calibrated in 63 spans of 27 caves near iron mines. This system, based on Bieniawski's methodology, represents the first empirical methodology specifically designed to assess the stability of natural caves in mining environments, providing a framework adapted to their particular geomechanical conditions [13,23,24].

2.1.6. Recent Advances (2020s).

Currently, empirical approaches have evolved into methodologies adapted to the characterization of rock masses affected by specific natural processes, such as in karst systems [25]. Furthermore, the complementarity of these methods with advanced stability analysis techniques has been promoted, such as block theory, along with more precise discontinuity mapping tools, like SfM photogrammetry and three-dimensional modeling. These techniques significantly improve the structural characterization of the rock mass and optimize stability models [26,27].

2.1.7. Recent Advances (2020s).

Table 1 presents, in chronological order and according to cave typology, representative studies on stability analysis, primarily developed through empirical methodologies. These studies have contributed to the understanding of the mechanical behavior of caves and, in some cases, have been complemented with numerical approaches for a more accurate evaluation.

Table 1. *Application studies of empirical methodologies in cave stability analysis.*

Cave type	Author and year	Place of study	Methodology applied	Main contributions
	Waltham, 2002 [28]	N/A	Geomorphological mapping	Classify karst caves into categories according to geotechnical interest for surface foundations.
	Sánchez, 2007 [29]	Cantabria, Spain	Geological and structural mapping	The level of risk of structural instability of the cave is evaluated using the NRI and SF indices.
	Parise, 2007 [21]	Apulia, Italy	Geological and structural mapping	They describe the mechanisms of rock block collapse inside caves.
	Geniş, 2015 [30]	Zonguldak, Turkey	RMR, Q index, R _{Mi} , GSI	They correlate empirical methodologies, analytical methods, and numerical methods.
Karst caves	Jordá-Bordehore, 2016 [2]	Castañar, Spain	Mathews-Potvin stability graph	Adapt a mining stability graphic method geometrically for caves.
	Riquelme, 2016 [26]	Mallorca, Spain	SfM	Use photogrammetric techniques and structural data collection to understand the kinematic behavior of the rock mass.
	Andriani, 2017 [25]	N/A	RES	Characterize the rock mass using a new empirical methodology with better applicability to carbonate rocks.
	Benrabah, 2024 [31]	Segovia, Spain	CGI, RMR, Q index	Complement the stability analysis of empirical indices with block theory
Benrabah, 2024 [24]	Maltravieso, Spain			

				(wedge kinematics) in the caves.
Lava caves	Jordá-Bordehore, 2016 [32]		Mining method of scaled width	They determine the safety factors of cave ceiling pillars.
	Bastidas, 2022 [33]	Galápagos, Ecuador	CGI, RMR, Q index	They identify stability, transition, and collapse zones using an empirical support graph for caves.
	Rodríguez, 2023 [13]			They use photogrammetric techniques to define the geometry of caves.
Iron caves	De Paula, 2018 [34]		MRMR and Q index	They use empirical support graphs in different safety factor scenarios.
	Brandi, 2019 [5]	Carajás, Brazil	MRMR	They determine the stability conditions of caves using Laubscher's empirical support graph.
	Brandi, 2020 [35]		CGI, RMR, and Q index	They describe the CGI methodology and establish a classification of susceptibility to structural instability in caves.
	Oliveira, 2020 [36]			They establish statistical correlations between RMR and Q with cave data.
Others	White, 2012 [1]	N/A	Geomorphological mapping	They describe the collapse mechanisms of cave ceilings.
	Jordá-Bordehore, 2017 [37]	Spain and Galápagos – Ecuador	Q index	They propose an adjusted empirical Q index graph specifically for its application in caves.

2.2 Numerical Methodologies for Cave Stability Analysis.

Due to the limitations of empirical methods, numerical modeling has emerged as an advanced alternative for evaluating the stability of tunnels and underground cavities. Through the discretization of geotechnical parameters, these models allow for a more precise characterization of the ground behavior, classified into continuous and discontinuous models based on the structural conditions of the rock mass [38]. Below is a chronological and conceptual review of its evolution.

2.2.1. The Beginnings of Numerical Modeling (1960s).

In the 1960s, the finite difference method (FDM) was the first numerical approach used to solve partial differential equations in materials engineering. However, in the geotechnical field, the finite element method (FEM) gained prominence for its ability to discretize the domain into triangular elements, overcoming the limitations of FDM's regular node meshes [39,40]. FEM enabled the modeling of elasticity and plasticity problems in continuous media, though it was initially limited to simplified two-dimensional problems due to the computational constraints. Despite these limitations, its flexibility in handling material heterogeneity, modeling nonlinear deformations, and considering in situ stresses and gravitational effects marked a milestone in geotechnical engineering [7,41].

2.2.2. Advances in Computational Capacity and 3D Modeling (1970s).

With the increase in computational capacity in the 1970s, numerical methods experienced significant advancements. Algorithms were improved, allowing the simulation of three-dimensional problems and the incorporation of more complex boundary conditions [40]. These advances were crucial for applying these techniques to the analysis of underground excavation stability and, later, the modeling of natural caves. During this decade, traditional fracture models, such as the "Goodman joint element," were incorporated, although they had limitations in simulating large openings and displacements due to their focus on continuity. This drove the development of discontinuous shape functions and approaches like the "enriched FEM" and "generalized FEM," which allowed for more efficient simulation of fracture initiation and growth [39,42].

2.2.3. The Emergence of Discrete Methods (1980s).

In the 1980s, Discrete Element Methods (DEM) were developed to address problems in discontinuous media, such as rock masses with fractures and discontinuities. These methods are based on the formulation and solution of the equations of motion of rigid or deformable bodies, using implicit or explicit discretization schemes [39,43]. Explicit discretization, which calculates forces and movements in small time increments, proved ideal for modeling fractured materials with rapid dynamics, while implicit discretization was more suitable for problems involving small deformations [41,44]. The Discrete Element Method, with explicit discretization, became a key tool for the analysis of underground cavities with complex geomechanical conditions [45,46].

2.2.4. Integration of Complex Phenomena and Applications in Caves (1990s).

During the 1990s, numerical methods in rock mechanics experienced significant advancements due to increased computational capacity. FEM and DEM algorithms were optimized to include phenomena such as creep and progressive fracture. Additionally, the Boundary Element Method (BEM) became a key tool for studying the interaction between materials at the boundary of a domain or in complex geometries [39,41]. In this decade, the first numerical modeling studies of specific cave phenomena were conducted, such as ground subsidence due to roof collapse and the interaction between caves and surface structures, primarily applied to karst caves in Italy [3,47]. The UDEC software enabled the study of in situ stress in cavities influenced by faults, analyzing the interaction between stress relationships, fault inclination, and geotechnical parameters [8].

2.2.5. Modeling of Karst Environments and Consolidation of FEM (2000s).

In the 2000s, numerical methods evolved to study karst environments, incorporating models that analyzed the interaction between groundwater and rock, as well as the formation and evolution of caves over time [48]. FEM became the primary tool for

cave stability analysis, except in cases where the presence of discontinuities required the use of DEM. In Switzerland, FEM was applied in the study of caves formed in limestone, allowing the evaluation of different rock mass modeling scenarios and simulating the opening of fractures [49]. These advances enabled the determination of the variation in safety factors and the most critical failure mechanisms in karst caves.

2.2.6. Modeling of Karst Environments and Consolidation of FEM (2000s).

Starting in the 2010s, numerical methods have become a fundamental tool for cave stability analysis, incorporating improvements in algorithms and advanced measurement techniques, such as photogrammetry, laser scanning, and 3D image analysis [24,26]. Hybrid approaches combining FEM and DEM have allowed for more precise simulation of translational and rotational block movements, as well as large displacements [50]. Additionally, numerical models with probabilistic estimates have been developed to address the intrinsic variability of geotechnical parameters [51,52].

2.2.7. Present Day: Technological Revolution and Multifield Approaches.

Currently, the integration of new technologies such as artificial intelligence, multi-scale modeling, real-time simulations, and multifield approaches is revolutionizing geomechanical analysis [53–55]. These methodologies allow for the study of rock mass behavior from microfractures to global stability, generate predictive models from sensor data, and evaluate the interaction of thermal, hydrological, and geochemical processes. All of this contributes to improving the accuracy of underground structure stability analysis and optimizing their design and safety.

In conclusion, numerical methodologies have evolved significantly since their inception in the 1960s, adapting to the needs of geotechnical engineering and leveraging technological advancements to offer more precise and reliable solutions in the analysis of cave and underground cavity stability.

2.2.8. Representative Case Studies.

Table 2 compiles representative case studies that have contributed to the evolution of cave stability analysis through the application of numerical methodologies. Their main contributions are highlighted, offering valuable guidelines for future research.

Table 2. *Studies on the application of numerical methodologies in cave stability analysis.*

Cave type	Author and year	Place of study	Methodology applied	Main contributions
Karst caves	Parise, 2011 [3]	Apulia, Italy	FEM, DEM	Analyze the evolution of failure mechanisms in caves through numerical modeling.
	Perrotti, 2015 [56]		FEM	Use numerical simulations to understand how rock degradation and stress redistribution can lead to cave collapse.
	Geniş, 2015 [30]	Zonguldak, Turkey	FEM	Develop numerical models using geotechnical parameters of caves obtained from laboratory tests and empirical equations.
	Alemdag, 2019 [57]	Gümüşhane, Turkey		Use numerical models with deformation vectors to define boundaries where cave collapses are inevitable.
Lava caves	Bastidas, 2022 [33]	Galápagos, Ecuador	FDM, BEM	Analyze the stability of the cave using numerical models that incorporate geometry, induced stress, and the Hoek-Brown strength criterion.
Iron caves	Brandi, 2019 [5]	Carajás, Brazil	FEM	Compare deformation scenarios before and after the formation of the cave.
Others	Thote, 2016 [7]	N/A	FEM	Analyze the changes in the stress regime of caves with different shapes in an elastoplastic rock mass and their impact on stability.

Chapter 3. Materials and Methods

The stability study of the Al-Badia lava tube was carried out in two phases: fieldwork and desk analysis. Prior to its execution, a review of the state of the art was conducted to select the most appropriate methodologies based on the geological and structural characteristics of the cave. As a result, empirical techniques were employed, including the RMR, Barton Q, and CGI classifications, complemented by the mining method of scaled width to assess the stability of the overburden in critical sectors. Furthermore, the results were validated through numerical modeling using the finite element method (FEM), employing geotechnical parameters of the rock mass determined by the generalized Hoek-Brown strength criterion, providing a more detailed analysis of the stability conditions.

3.1 Geomechanical Stations and Empirical Classifications of the Rock Mass

During the field phase, conducted in March 2024, geological, geotechnical, and structural information was collected through three geomechanical stations, located 90 meters from the entrance, at the entrance collapse, and at its base [12]. Parameters such as uniaxial compressive strength, orientation and condition of discontinuities, rock mass conditions, and groundwater presence were documented, following ISRM standards.

In the desk phase, the rock mass was classified according to its geotechnical quality using the RMR, Barton Q, and CGI systems. The RMR system, developed by Bieniawski in 1973, evaluates the stability of underground excavations based on the previously mentioned geological and structural characteristics. The results of this evaluation place the rock mass quality on a scale from 0 to 100, where the extremes correspond to "very poor" and "very good," as detailed in Table 3.

Table 3. Rock Mass Rating (RMR) Classification. Adapted from [16].

Score	100 - 81	80 - 61	60 - 41	40 - 21	< 20
Category	I	II	III	IV	V
Description	Very Good	Good	Fair	Poor	Very Poor

On the other hand, the Barton Q index was developed at NGI between 1971 and 1974 for the stability analysis of underground excavations [18, 22, 58]. This classification system is based on the estimation of rock mass quality parameters, which are integrated into three important factors: block size $\left(\frac{RQD}{J_n}\right)$, friction between discontinuities $\left(\frac{J_r}{J_a}\right)$, and active stress $\left(\frac{J_w}{SRF}\right)$. These factors determine the Q index according to Equation 1.

$$Q = \left(\frac{RQD}{J_n}\right) * \left(\frac{J_r}{J_a}\right) * \left(\frac{J_w}{SRF}\right) \quad (1)$$

Where:

- RQD = Rock Quality Designation
- J_n = Number of discontinuity families
- J_r = Roughness number of discontinuities
- J_a = Alteration number of discontinuities
- J_w = Water reduction factor in discontinuities
- SRF = Stress reduction factor

Unlike the RMR, whose index increases linearly, the Q index varies exponentially, ranging from $Q = 0.001$ for "exceptionally poor" quality with high deformability to $Q = 1000$ for "exceptionally good" quality, with virtually no discontinuities. This index provides support recommendations for underground excavations based on the rock mass quality, the geometry of the excavation, and the safety requirements defined by the ESR Factor through the empirical support chart associated with this methodology.

For the case of the Al-Badia lava tube, the Q index support chart was used to determine the support requirements for the cavity, considering tunneling criteria. Additionally, the empirical cave stability chart developed by Jordá-Bordehore [37] was employed to compare the results of the stability condition analysis, thus providing a more comprehensive evaluation.

Similarly to the previously mentioned geomechanical classifications, the quality of the rock mass of the Al-Badia lava tube and its susceptibility to structural instability were evaluated using the CGI index. This index, based on Bieniawski's methodology, uses a weighted sum of variables for its calculation, as presented in Equation 2.

$$CGI = \alpha RMR + \beta HR + \gamma CS + \delta CT \quad (2)$$

Where αRMR is the weighting of the RMR, βHR is the weighting of the hydraulic radius, γCS is the weighting of the roof shape, and δCT is the weighting of the roof thickness. The sum of these variables produces a value between 0 and 100, where high values indicate low susceptibility to structural instability and low values reflect a higher risk of collapse (Table 4).

Table 4. CGI Index Categories and Their Respective Levels of Susceptibility to Structural Instability of Cavities. Taken from [23].

Susceptibility to Structural Instability	Very Low	Low	Moderate	High	Very high
Category	$CGI > 80$	$60 < CGI < 80$	$40 < CGI < 60$	$20 < CGI < 40$	$CGI < 20$

In Equation 2, the variables consider different key aspects of rock mass stability. The RMR of Bieniawski classifies its quality, while the hydraulic radius, defined by the ratio between the area and perimeter of the cave, has been used in excavation stability studies since 1977 [59]. On the other hand, the roof thickness represents the vertical distance between the ground surface and the cave roof [13], and the roof shape, a

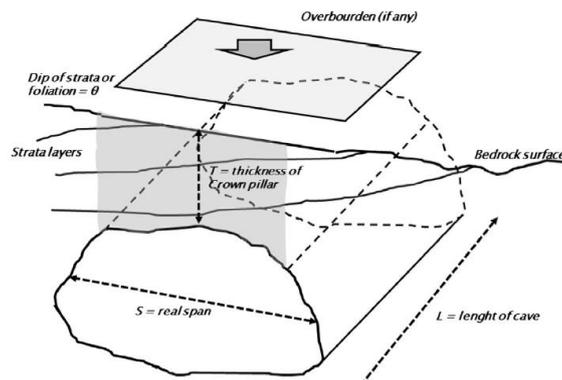
qualitative variable, influences the formation of blocks and wedge falls, classified into three main geometry types, as shown in Table 5.

Table 5. *Types of Roof Shape Geometries for Caves. Modified from [23,24]*

Roof Shape	Arch	Planar	Inverted Arch
Shape			
			
			
Description	Best class	Regular class	Worst class

To determine the values assigned to the weights of each variable in Equation 2, represented by the symbols α , β , γ , and δ , it is recommended to consult the references in this section, as these values will depend on the specific conditions and simulated scenarios for each cave. In addition to the empirical geomechanical classifications based on the parameters measured at the geomechanical stations, a stability analysis of the roof pillar or "overload" was carried out for each section of interest in the Al-Badia lava tube. For this, the scaling width method was applied, a mining technique that allows reducing the three-dimensional geometry of the overload to a measure proportional to the width of the cave (Figure 3). This method is based on the principle that, the larger the excavation, the higher the risk of failure and collapse of the overload [60].

Figure 3. *Roof pillar scheme in the context of natural caves. Taken from [32].*



Given a typical polyhedral geometry of a crown pillar (Figure 5) and the geomechanical conditions of the rock mass, the stability of this pillar would maintain the relationship of the variables in Equation 3.

$$Estabilidad\ del\ pilar = f\left(\frac{T\sigma_h\theta}{SL\gamma u}\right) \quad (3)$$

Where greater stability for any rock mass quality would be reflected in an increase of:

- T = The thickness of the rock mass
- σ_h = The in-situ horizontal stress
- θ = The dip of the foliation or underlying opening

While reduced stability would result from increases in:

- S = The pillar width
- L = The total length of the opening
- γ = The specific gravity of the rock mass
- u = The groundwater pressure

By integrating the terms of cavity geometry and rock mass characteristics in Equation 3, a deterministic approach was developed to evaluate the dimensions of the crown pillar over the geometry of the cavity opening, using the Crown Pillar Scaling (Scaled Crown Span – C_s) against a critical rock mass competency Q_{crit} . The concept of C_s was developed to geometrically characterize crown pillars in three-dimensional terms and their stability. This involved considering key components as indicated in Equation 4.

$$C_s = S\left(\frac{\gamma}{T(1 + S_R)(1 - 0.4\cos\theta)}\right)^{0.5} \quad (4)$$

Where:

- S = Crown pillar span (m)

- γ = Specific gravity of the rock mass (ton/m³)
- T = Thickness of the crown pillar (m)
- θ = Inclination of the rock mass
- S_R = Light ratio = S/L (crown pillar span / crown pillar strike length)

Regarding the critical rock mass competency Q_{crit} , the method establishes a limit span where failure could be expected, based on a regression fit of data represented by Equation 5.

$$S_c = 3.3 * Q^{0.43} * \sinh^{0.0016}(Q) \quad (5)$$

Where the term *sinh* aims to adjust for the marked trend of significant nonlinearity towards greater stability under high rock mass competency conditions. In this way, the safety factor for the crown pillar or "overload" is based on the relation in Equation 6, while the formula for the probability of failure depending on the safety factor is expressed in Equation 7.

$$FoS = \frac{S_c}{C_s} \quad (6)$$

$$Pf (\%) = \frac{100}{1 + 441 \exp(-1.7 C_s / Q^{0.44})} \quad (7)$$

Regarding the determination of an appropriate safety factor for natural caves, there is no universal criterion. However, relevant bibliographic references have been considered to establish recommended values. In excavations without support, a safety factor greater than 1.2 is suggested [32]. On the other hand, the Barton Q index uses the Excavation Support Ratio (ESR) to adjust the support design based on the rock mass quality and the type of excavation [34,58]. Additionally, the scaling method recommends a minimum safety factor of 2 for long-term excavations to minimize the probability of failure in crown pillars [60].

As a reference for the analysis of the Al-Badia lava tube, the study of the Altamira Cave (Spain) was considered, where two indices were applied to assess structural stability: the Natural Risk Index (IRN) and the Safety Factor (FS). The calculations for these indices considered geographic, geomorphological, and geotechnical parameters, using non-destructive techniques such as seismic profiles and electrical resistivity tomography [29]. The results obtained from this study highlight the relationship between these indices (Table 6), providing a reference framework for the protection and conservation of natural cavities.

Table 6. Relationship between IRN and FS for defining protection areas in the Altamira Cave, Spain. Adapted from [29].

Natural Risk Index	Very High	High	Medium	Low
Safety Fator	SF < 0.50	0.50 < SF < 0.80	0.80 < SF < 1.20	SF > 1.20

3.2 Analysis through Numerical Modeling.

The stability analysis of the Al-Badia lava tube was complemented by numerical modeling of the cave's sections of interest. During the field phase, the cross-sectional geometry of these sections was determined through photogrammetric surveys using the *Structure from Motion* (SfM) technique. This methodology enabled the generation of a three-dimensional model of the cave, from which the necessary characteristic sections for numerical modeling were obtained.

In the office phase, the *Examine 2D* software was used, configured under an elastic-plastic behavior and applying the generalized Hoek-Brown criterion. This procedure is particularly relevant since many caves develop in rock masses with good to excellent quality, located at shallow depths and with limited overburden. This approach allowed

the stability of the rock mass to be assessed through key indicators, such as safety factors and displacements within the cave span.

The numerical model was implemented using the finite element method (FEM), simulating the rock mass as a homogeneous and degraded medium, with properties adjusted based on geomechanical classifications. The geotechnical parameters used were determined from field observations, such as the Geological Strength Index (GSI) and the uniaxial compressive strength (UCS), measured using a Schmidt hammer. Additionally, bibliographic data were incorporated to obtain values for density and other parameters depending on the rock type and its degree of fracturing, which are necessary for applying the Hoek-Brown failure criterion. The elastic parameters of the rock mass were estimated using the *RocData* software from Rocscience, based on the collected data.

Chapter 4. Results

4.1. Stability Assessment Using Empirical Methods.

The geomechanical characterization of the rock mass in the Al-Badia cave was carried out through geomechanical stations located in three sections of interest: 90 meters from the entrance, near the rocky collapse at the access, and at the lower part of this. Based on the parameters obtained, the quality of the rock mass was assessed using the geomechanical classifications RMR and Barton's Q. The results of this assessment are presented in Tables 7 and 8, respectively.

Table 7. RMR Classification Obtained at Each Geomechanical Station of the Al-Badia Lava Tube. Adapted from [12].

Parameters*		Geomechanical Station 1		Geomechanical Station 2		Geomechanical Station 3	
		Value	Score	Value	Score	Value	Score
RMR 1	UCS	42 MPa	4	42 MPa	4	42 MPa	4
RMR 2	RQD	80 %	15	95 %	20	80 %	15
RMR 3	Spacing	0.2 m	9	0.4 m	10	0.2 m	9
RMR 4	Continuity	10 – 20 m	1	10 – 20 m	1	> 20 m	0
	Opening	> 5 mm	0	> 5 mm	0	> 5 mm	0
	Roughness	Very rough	6	Very rough	6	Very rough	6
	Alteration	Grade II - III	4	Grade II	5	Grade I - II	5
	Filling	Silt	0	Hard fill	2	No fill	6
RMR 5	Water	Slightly wet	10	Slightly wet	10	Dry	15
RMRb (1989)		49		58		60	
Class		III - Regular		III - Regular		III - Regular	

Note. RMR 1 = Uniaxial compressive strength; RMR 2 = RQD; RMR 3 = Joint spacing; RMR 4 = Discontinuity condition; RMR 5 = Groundwater conditions; RMRb (1989) = Bieniawski's basic RMR index (1989).

Table 8. *Q* index obtained at each of the geomechanical stations of the Al-Badia lava tube. Taken from [12].

Parameters	Geomechanical Station 1		Geomechanical Station 2		Geomechanical Station 3	
	Value	Score	Value	Score	Value	Score
RQD	80 %	80	95 %	95	80 %	80
J_n	3 families	9	4 families	15	3 families	9
J_r	Wavy rough	3	Wavy rough	3	Wavy rough	3
J_a	Clayey fill	4	Slightly altered	2	Slightly altered	2
J_w	Slightly wet	1	Slightly wet	1	Dry	1
*SRF	Low stresses	2.5	Span > overburden	5	Span > overburden	5
Q index	2.7		1.9		2.7	
Actual Span	12 m		16 m		16 m	
ESR	0.8		0.8		0.8	
Span/ESR	15 m		20 m		20 m	

Note. Adjusted SFR score of 5 when the overburden thickness is less than the span

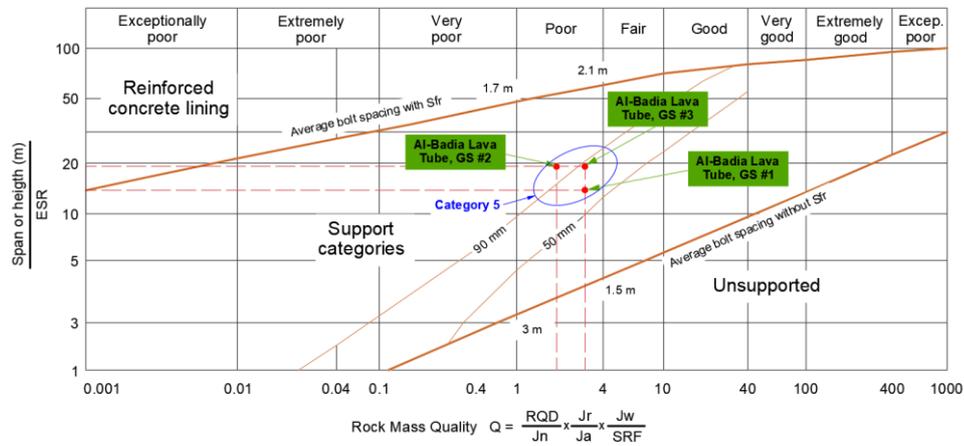
In Table 7, it is observed that the rock mass of the Al-Badia lava tube is classified as Class III – Regular, according to the RMR geomechanical classification system. This evaluation corresponds to the basic RMR index, meaning it does not include corrections for the orientation of discontinuities with respect to the excavation direction, a factor particularly relevant in tunneling studies.

If this classification were applied to a tunnel, it would imply that the cave requires support based on bolting and shotcrete, without the need for metal arches [16]. For its specific application in caves, the RMR values obtained at each geomechanical station will be used in the analysis based on the geomechanical classification of the CGI index.

In Table 8, in addition to the rock quality *Q* index for each geomechanical station, the ESR (Excavation Support Ratio) factor, used in Barton’s classification to define the type of support based on the rock mass conditions and safety requirements, is included. In this case, an ESR of 0.8 was assigned, suitable for a public access excavation. With

this value and the actual span of the cave, the Equivalent Dimension (D_e) was calculated, which allowed determining the required support type from Barton's support chart (Figure 4).

Figure 4. Support requirements for each section of the Al-Badiah lava tube according to the Barton support chart. Adapted from [12,58]



According to Figure 4, and based on the Barton support chart for tunneling conditions, the sections of interest are outside the self-supporting zone, falling within support category 5, where the installation of bolts and fiber-reinforced shotcrete is recommended as support elements [18].

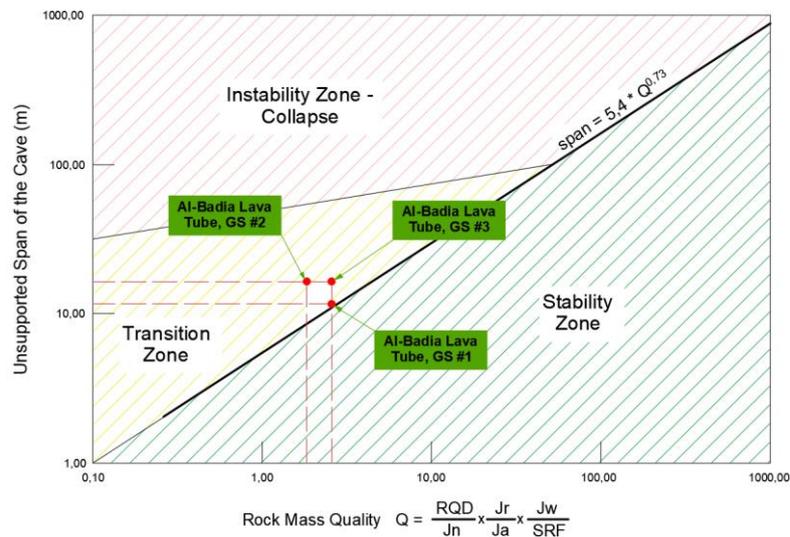
To contrast the obtained results, the Q index data were projected against the actual width of the sections of interest on the empirical cave chart [12]. As shown in Figure 5, none of these sections are in the collapse zone. The section corresponding to geomechanical station 1 (the narrowest) is located at the boundary between the stable and transition zones, while the other two sections, including the rock collapse at the entrance, fall within the transition zone.

These results, however, do not accurately reflect the reality observed inside the cavity. Section 3, which represents a rock collapse, should be positioned in the collapse zone. However, there remains uncertainty about whether this collapse corresponds to a complete roof failure or a *skylight-type opening*, which is characteristic of lava tubes

where the roof crust does not fully close. On the other hand, Section 2 should also be closer to the collapse zone, as it corresponds to an area with block shedding that has evolved into a natural arch of release.

These findings suggest the need to adjust the boundaries between the different zones represented on the empirical chart. Alternatively, the results could be influenced by an overestimation of the geotechnical parameter J_n .

Figure 5. Stability conditions of the sections of interest in the Al-Badia lava tube according to the empirical cave stability chart. Adapted from [12,22]



As part of the stability assessment of the Al-Badia lava tube, the susceptibility to structural instability of each section of interest was evaluated by calculating the CGI index. The results obtained are presented in Table 9. To determine the geometric parameters of the CGI index, a photogrammetric survey of the sections of interest was carried out using the SfM (Structure from Motion) methodology. This technique allowed for the generation of three-dimensional models with control points for orientation and metric measurements, enabling precise scaling of the actual geometry of the cave. The 3D models obtained are shown in Figure 6 and can be explored in detail through the links provided in the figure description.

Table 9. CGI index obtained at each of the geomechanical stations of the Al-Badia lava tube. Based on [12, 35].

Parameters		Geomechanical Station 1	Geomechanical Station 2	Geomechanical Station 3
RMR	RMR			
	Bieniawski	49	58	60
	Description	Class III – Regular	Class III – Regular	Class III – Regular
Weighting	CGI	39	39	39
	Hydraulic			
	Radius	1.60	1.84	2.04
HR	Description	Regular	Large	Large
	CGI	15	0	0
	Weighting			
CS	Roof Shape			
	Description	Arch	Arch	Arch
	CGI	10	10	10
CT	Roof			
	Thickness	8 m	5 m	4 m
	Description	Regular	Regular	Regular
Weighting	CGI	5	3	3
	CGI Index	69	53	53
	Structural Instability Susceptibility	Low	Moderate	Moderate

Figure 6. Three-dimensional model of the sections of interest in the Al-Badia lava tube:

(a) Geomechanical Station 1: <https://sketchfab.com/3d-models/bodia-cave-1-0a7f13155a0842d49daafe1cf683da9e>;

(b) Geomechanical Station 2: <https://sketchfab.com/3d-models/bodia-cave-2-f346b60a3c98419bb1cf432c9839365a>;

(c) Geomechanical Station 3: <https://sketchfab.com/3d-models/bodia-cave-3-55bee8dc653e4c5e843d798c807db4f2>.

Adapted from [12].



The results obtained in Table 9 show a correlation between the degree of susceptibility to structural instability determined by the CGI index and the observed rock mass conditions within the cave. This is particularly evident in geomechanical stations 2 and 3, where rock block detachment conditions were identified, as previously indicated.

To complement the stability assessment of the Al-Badia lava tube using geomechanical classifications, an analysis of the safety factor and failure probability for the roof pillars in each of the sections of interest was conducted using the mining scaled span method. The results of this analysis are presented in Table 10.

Table 10. *Structural Stability Conditions of the Al-Badia Lava Tube Obtained Through the Application of the Mining Scaled Span Method [12,35].*

Geomechanical Station	* Parameters of the Mining Scaled Span Method										
	S (m)	γ (tn/m ³)	L (m)	T (m)	$\frac{S_R}{= S/L}$	θ°	C_s	Q	S_c	FoS	PoF (%)
GS - 1	12	2.75	1	8	12	0	2.91	2.7	5.07	2.01	3.48
GS - 2	16	2.75	1	5	16	0	5.01	1.9	4.36	0.87	58.23
GS - 3	16	2.75	1	4	16	0	5.01	2.7	5.07	1.01	35.72

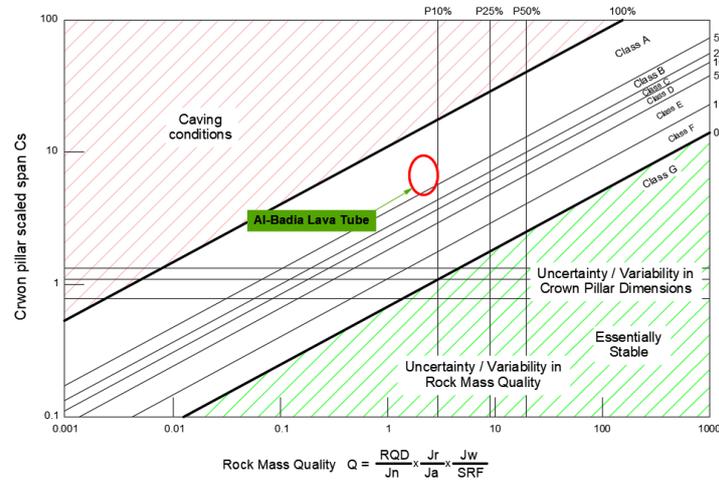
Note. S = Crown pillar span; γ = Unit weight; L = Opening length; T = Overburden thickness; S_R = Span ratio; θ = Rock mass inclination; C_s = Scaled span; Q = Q index; S_c = Maximum span; FoS = Factor of Safety; PoF = Probability of Failure

Regarding the results in Table 10, an opening length of 1 m was used in each section to ensure comparability with safety factors from numerical modeling, which considers a 1 m third-dimension projection. It is important to note that as the opening length increases, the safety factor decreases and the probability of failure rises.

The mining scaled span method analysis reveals that some sections of the Al-Badia lava tube have safety factors below 1, indicating high failure probability. Using the scaled span stability chart in Figure 7, which evaluates stability in different rock geometries and qualities, it is concluded that public access to the Al-Badia lava tube should be restricted and it should undergo advanced monitoring, as its stability is only short-term [12,60].

However, it is notable that the cavity has existed for thousands of years, with the only recorded collapse at the entrance, suggesting the methodology may be overly conservative.

Figure 7. Stability conditions of the sections of interest in the Al-Badia lava tube according to the scaled span chart. Adapted from [60].



4.2. Stability Assessment Using Numerical Methods.

To compare the results from the rock mass evaluation with empirical methods, three numerical models were developed using the finite element method, applied to the sections of the Al-Badia lava tube. These sections were defined through scaled 3D models generated using the SfM (Structure from Motion) photogrammetry technique, ensuring accurate representation of the rock mass geometry.

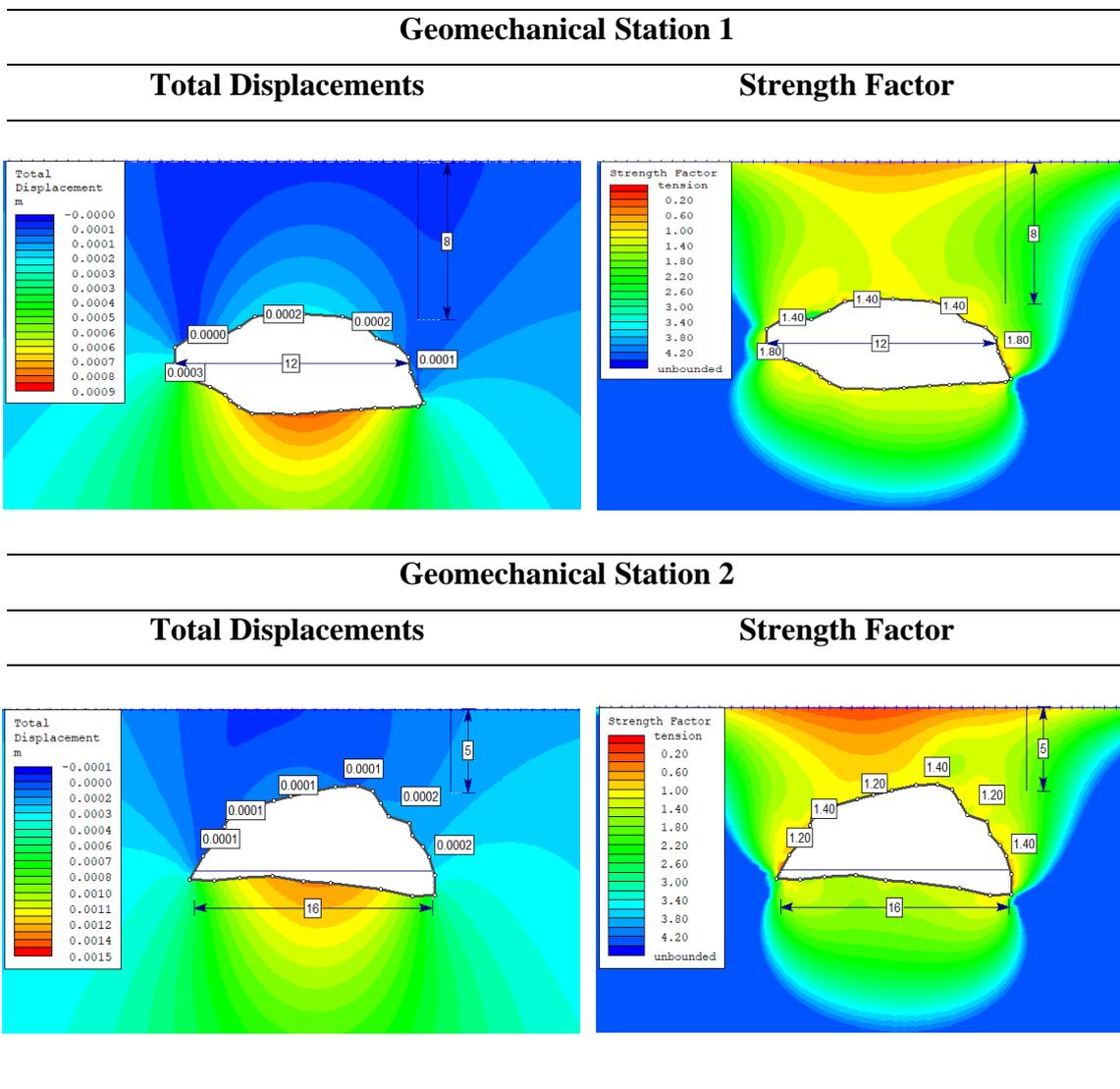
Stress-strain numerical modeling was performed using Examine 2D software, considering an elasto-plastic geomechanical behavior based on the generalized Hoek-Brown strength criterion. This criterion includes parameters like the rock mass quality index (GSI), uniaxial compressive strength (σ_c) of the intact rock, and structural conditions, enabling the identification of deformation zones and potential failures. The geotechnical parameters used are listed in Table 11, and the visual model representations for each section are shown in Table 12.

Table 11. Geotechnical Input Parameters in the Examine 2D Program.

Geomechanical Station	* Parameters									
	<i>S</i> (m)	γ (MN/m ³)	<i>T</i> (m)	<i>UCS</i> (MPa)	GSI	<i>m_i</i>	<i>D</i>	MR	EM (MPa)	ν
GS - 1	12	0.027	8	42	55	25	0	350	6001	0.2
GS - 2	16	0.027	5	42	50	25	0	350	4516	0.2
GS - 3	16	0.027	4	42	60	25	0	350	7644	0.2

Note. *S* = Span; γ = Unit weight; *T* = Overburden thickness; *UCS* = Uniaxial compressive strength; GSI = Geological strength index; *m_i* = Intact material parameter; *D* = Disturbance factor; MR = Rock mass parameter; EM = Rock mass modulus of deformation, ν = Poisson's ratio of the rock mass

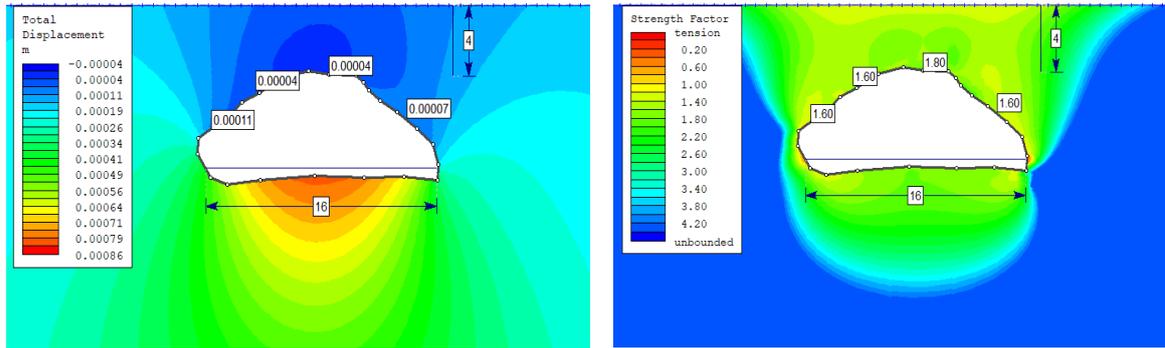
Table 12. Numerical Models for Stability Assessment of the Al-Badia Lava Tube.



Geomechanical Station 3

Total Displacements

Strength Factor



As shown in the models presented in Table 12, the displacements at the cave's perimeter are on a millimeter scale. The safety factors calculated for the three sections of interest are all greater than 1, ranging from 1.20 to 1.80. The most critical case is Section 2, where a zone on the cave's ceiling was identified with a safety factor of approximately 1.20. This situation is likely due to the specific geomechanical properties of the rock mass in this area, combined with the planar geometry of the ceiling, which favors the generation of beam-like stress.

According to the observations made inside the cave, the results from the numerical modeling align with the observed stability conditions. Specifically, in Section 2, which has the lowest safety factor, rock block detachments have been recorded. In Section 3, old detachments have also been identified, but the safety factor obtained could reflect the formation of a natural equilibrium arch following these events.

Chapter 5. Discussion of Results

The analysis of the stability conditions of the Al-Badia lava tube was conducted using both empirical and numerical methods, originally developed for tunnel and mining applications. These methodologies were adjusted to the specific characteristics of the cavity, taking into account geological and structural criteria. The results obtained are summarized in Table 13, which highlights key trends regarding the stability of the rock mass.

Table 13. *Comparison of Stability Analysis Methods for the Al-Badia Lava Tube.*

Geomechanical Station	Empirical Methods			Numerical Method		Field Inspection
	RMR	Q Index	CGI	Scaled Span	FEM	
Geomechanical Station 1	Transition	Transition	Stable	Stable	Stable	Stable
Geomechanical Station 2	Transition	Transition	Transition	Unstable	Stable	Stable
Geomechanical Station 3	Transition	Transition	Transition	Transition	Stable	Stable

According to Table 13, the RMR index suggests that the cave is in a transitional stage toward instability. This is reflected in the quality of the rock mass, which requires support elements such as bolting and shotcrete. A similar interpretation is obtained from the Q index, where both the Barton support graph and the empirical graph specific to caves indicate that the rock mass requires structural reinforcements. These observations suggest that while the cave is not in immediate collapse, it could evolve toward instability over time due to the progressive degradation of the rock mass.

Regarding the CGI index, the results show low susceptibility to structural instability in the sections classified as stable. However, areas with moderate susceptibility were

considered to be transitioning toward instability, confirming the need for continuous monitoring and targeted reinforcements.

For the overload pillars, the mining scaled span method was used. In this case, sections with a safety factor greater than 1.20 were classified as stable, while those with values between 1.00 and 1.20 were considered transitional, and those below 1.00, as unstable. This conservative classification incorporates the variability of the data obtained from geomechanical mapping and the inherent limitations of the method, as well as the susceptibility of the mass to degradation, especially in thin pillars.

The finite element numerical analysis yielded results consistent with the field observations, establishing as stable any section with a safety factor above 1.20. Overall, the numerical model confirmed that the cave does not present an immediate collapse threat, and the observed rockfalls were interpreted as part of the natural process of vault stabilization over thousands of years of formation.

Based on the results obtained, it is concluded that the empirical methodologies used tend to be conservative, providing support solutions that, in some cases, overestimate the actual needs of the lava tube. However, this conservative approach is beneficial in specific sectors where spot reinforcements are required. These techniques should be progressively adjusted as more specific stability data on natural cavities are accumulated, given that they were originally designed for short-term artificial works.

Finally, the importance of a comprehensive assessment that combines empirical and numerical methodologies, supported by geotechnical criteria, is emphasized. The stability conditions of caves depend not only on the geomechanical classifications used but also on the intrinsic variability of the rock mass and its susceptibility to weathering processes that degrade its strength properties over time. Therefore, the selection of analysis

techniques must adapt to the particularities of each case, as described in the state of the art of this research.

Chapter 6. Conclusions

The analysis and description of various techniques used internationally to assess the stability of caves allowed for the identification of their applicability in different geological and structural contexts. In the specific case of the Al-Badia lava tube, both empirical and numerical methods were applied, which, although initially designed for tunneling and mining works, have been progressively adjusted to study natural caves.

The geomechanical classification system RMR characterized the rock mass of the Al-Badia lava tube as of regular quality (Class III), with an RMRb score ranging between 49 and 60. On the other hand, the Q-index determined that the rock mass quality is "poor," with values ranging from 1.9 to 2.7.

These results tend to be conservative, as they suggest the need for structural support techniques for the cave. The same applies to the CGI index, which evaluates the susceptibility to structural instability of the rock mass as "low" to "moderate," with values ranging from 53 to 69. Additionally, the mining scaled span method identifies critical sectors in the cave, where the safety factors are less than 1.0 and the probabilities of failure exceed 50%.

This is because these methodologies were originally designed for artificial underground infrastructures, which do not always accurately represent the geological, structural, and excavation conditions of natural caves. However, recent adjustments, such as the empirical chart based on Barton's Q-index, have improved their applicability to such formations. These tools represent an opportunity for the development of new methodologies that correlate stability/instability based on the geometric conditions and geomechanical quality of the rock mass.

The use of numerical methods, such as finite element analysis, allowed for a more accurate modeling of the stress-strain behavior of the Al-Badia lava tube's rock mass.

This analysis was made possible by the implementation of photogrammetric techniques, which captured the cave's geometry at scale. However, it is important to emphasize the correct characterization of geotechnical parameters and the proper selection of the strength criterion used as a constitutive model to ensure the validity of the results.

The stability analysis results indicate that, in general, the Al-Badia lava tube does not present an imminent risk of collapse, as the safety factors obtained through numerical analysis exceed 1.2. However, the need for a normative value for this parameter in cave stability analysis is highlighted. The observed rockfalls are attributed to natural stabilization processes that have occurred over thousands of years. However, specific areas with signs of instability were identified, requiring attention and continuous monitoring to ensure safety.

It is suggested that future research focus on the detailed characterization of the geotechnical properties of the rock mass using probabilistic analysis techniques. This would allow for a better representation of the mass's intrinsic variability and yield more accurate and reliable results.

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CERTIFICACIÓN DE APROBACIÓN DE PROYECTO DE TITULACIÓN

Madrid, 19 de marzo de 2025

M. Sc.

Davide Besenzon Venegas

Coordinador del Programa

Maestría en Geotecnia

En su Despacho

De mi consideración:

Yo, **Luis Jordá Bordehore**, de nacionalidad **española**, portador del pasaporte No. **PAT561314**, en mi calidad de Tutor del Proyecto de Titulación correspondiente a la **Maestría en Geotecnia, VI Cohorte**, de la Escuela Superior Politécnica del Litoral (ESPOL), certifico lo siguiente:

Con fecha **28/01/2025**, acepté la tutoría del estudiante **Ronald Eduardo Herrera Tamayo**, con **cédula de identidad No. 1600527301**, para el desarrollo del proyecto de titulación denominado: *“Estado del arte sobre métodos empíricos y numéricos de análisis de estabilidad de cuevas: aplicación en tubo de lava de Al-Badia, en Harrat Al-Shaam, Jordania”*.

Certifico que este trabajo de titulación fue supervisado de manera continua durante todo su desarrollo, revisado en cada una de sus etapas y, finalmente, aprobado por mi persona en su versión final, entregada el día 24/02/2025.

Particular que pongo en su conocimiento para los fines pertinentes.

Firmado por JORDA BORDEHORE LUIS - ***2787** el día
19/03/2025 con un certificado emitido por AC FNMT
Usuarios

Atentamente,

Ph. D. Luis Jordá Bordehore

Tutor del Proyecto

Correo electrónico: ljorda@espol.edu.ec; ljbordehore@gmail.com