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Article

Geomechanical characterization and stability analysis of the Baños del Inca cave (Ecuador) using empirical methods and photogrammetry.

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Abstract: The Baños del Inca is a cave of volcanic origin located in the Saraguro canton, Loja province, Ecuador. This area attracts a high number of tourists throughout the week. This research combines empirical methods based on geomechanical classifications, specifically the Q Index, Rock Mass Rating (RMR) and Geomechanical Cavity Index (CGI) with remote sensing techniques such as photogrammetry. The Structure from Motion (SfM) photogrammetric technique is used to reconstruct the cave environment in 3D. Preliminary analysis results indicate that the cave is generally stable, with no observable signs of instability or subsidence. However, the presence of cracks and loose wedged rocks and slabs on the ceiling indicate the potential for specific areas of instability and slab detachment in the long term. These areas require monitoring by more detailed analysis models. The integration of RMR, Barton's Q and CGI methods is beneficial in the engineering field as it allows for a more realistic and accurate examination of the area under investigation.

Key words: Cavity, geomechanical classifications, subsidence, stability, photogrammetry, rock mechanics.

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1. Introduction

The analysis of geological, hydrogeological, geometric and geotechnical factors is crucial in order to conduct a stability study [1]. Natural caves have a wide range of shapes and structures determined by the lithology and hydrogeological conditions of their location. The caves attract visits from both researchers and tourists, emphasizing the importance of conducting comprehensive risk assessments.

The first classification system in rock engineering is developed by Terzaghi about 40 years before 1946, specifically for steel reinforced tunnels. This classification methodology included analytical, observational and empirical approaches [2]. The stability of a cave is determined by key factors such as the properties of the rock mass, the section width, and the type of excavation. The general requirements for unsupported permanent underground tunnels are a joint coefficient or number of families ($Jn \leq 9$), a roughness coefficient of discontinuities or joints ($Jr \geq 1$), a joint modification coefficient (≤ 9), a coefficient reduction factor due to the presence of water ($Jw = 1$), and a factor related to the stress state ($SFR \leq 2.5$) [3].

As part of the stability analysis, it is crucial to establish geomechanical classifications and identify potential areas of subsidence and minor instability.

In the southern region of Ecuador, there is a prominent tourist attraction where various Inti Raymi rituals, ceremonies, and festivals are regularly performed. However, the absence of geotechnical data raises concerns about the safety of tourists visiting this location. Therefore, it is important to conduct a comprehensive geotechnical study of the cave in question to ensure the physical integrity of visitors.

This study, situated in the Saraguro canton, Loja province, focuses on a cave that is approximately 40 metres long and between 4 and 7 metres high from floor to ceiling. [5].

The main objective of this research is to carry out a thorough geomechanical characterisation and stability analysis, using both empirical methods and advanced photogrammetric techniques. For the aforementioned it is important to: (i) carry out a geotechnical characterisation of the study area based on empirical methods for geomechanical classification; and (ii) define the three-dimensional geometry of the cave using digital photogrammetry or SfM (Structure from Motion) from different geomechanical stations.

2. Materials and Methods

2.1. Cave of los Incas, Saraguro

2.1.1. Regional geological context

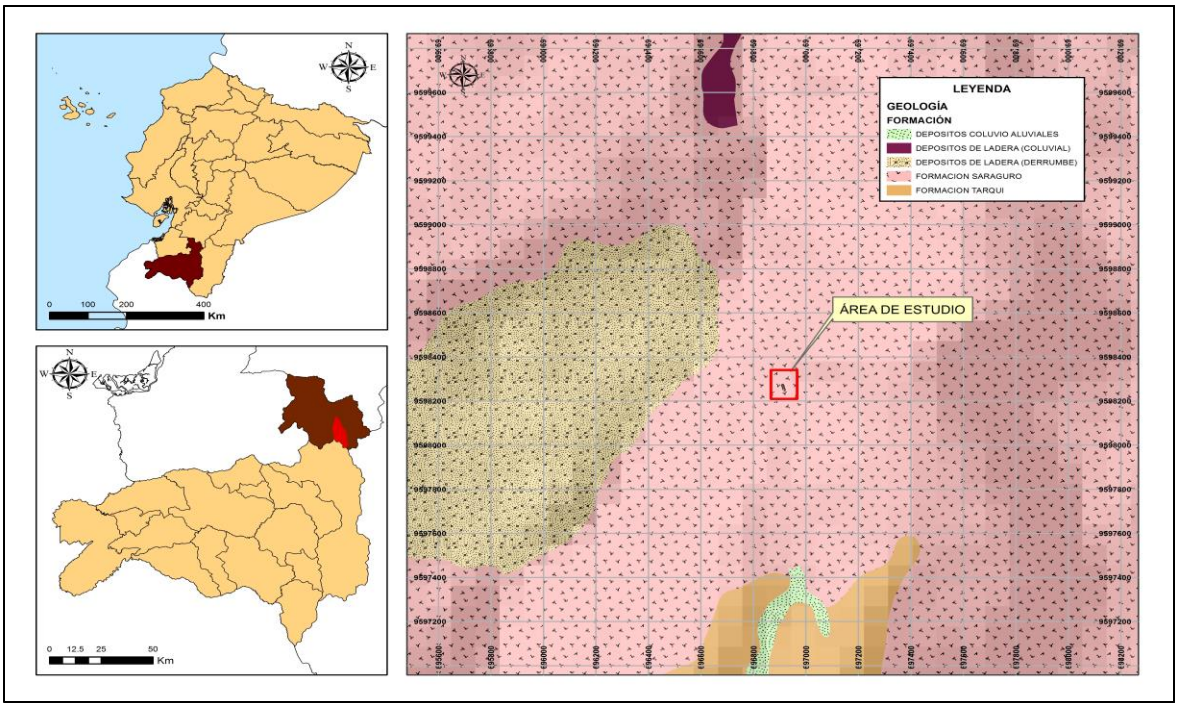
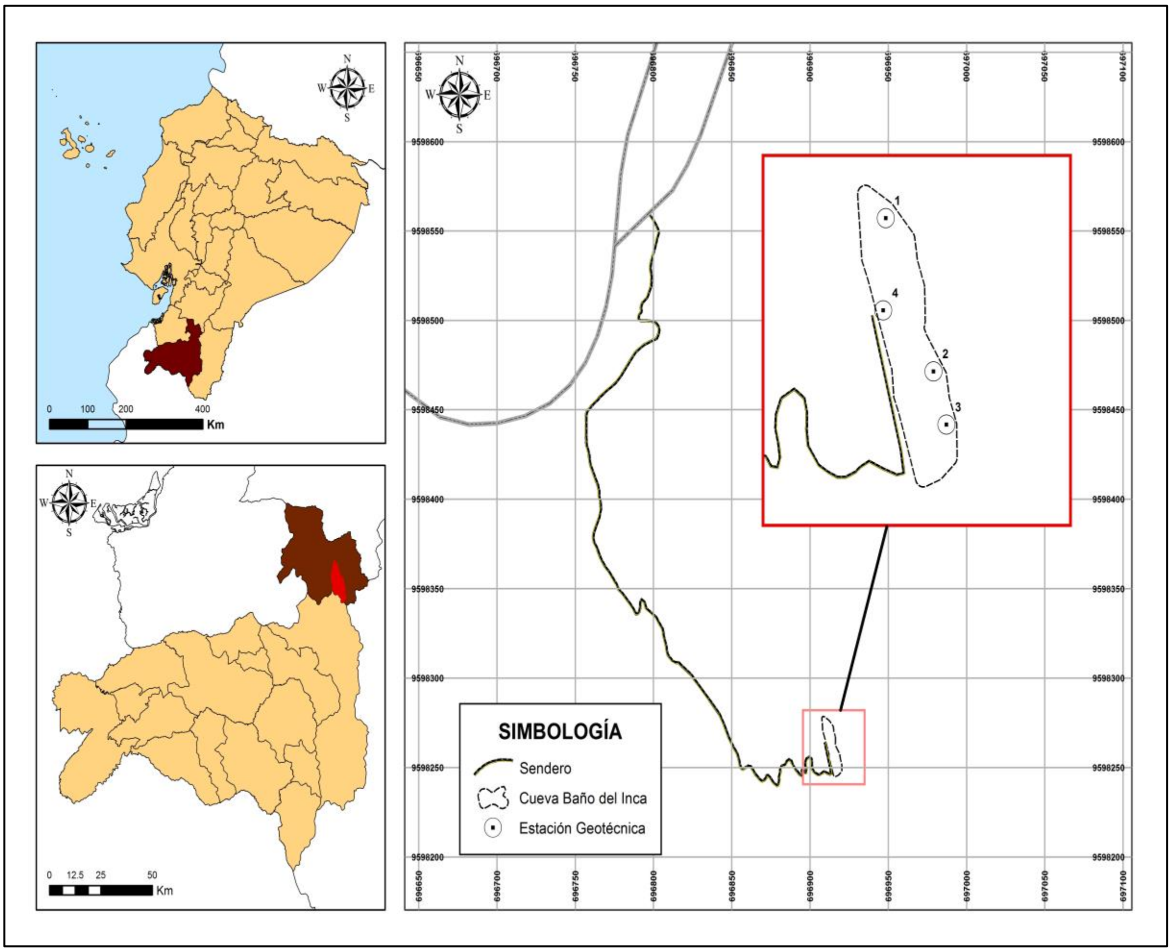


Figure 1. Regional geology of the study area

The study area is located within the southern Ecuadorian segment of the Western Mountain Range, which is formed by the accretion of material from a tectonic plate through a subduction process (accretionary) [6]. Prominent geological formations in this region include the Tarqui, Sacapalca and Saraguro formations [7]. This mountainous terrain is accreted between the Cretaceous and Eocene periods, from about +/-114 to +/-44 million years ago. It is of volcanic sedimentary origin and its composition ranges from basaltic to andesitic [8].

These formations are predominantly composed of acidic volcanic rocks, distinguished by clear minerals (phenocrysts) and an alkaline composition. These formations are predominantly composed of acidic volcanic rocks, distinguished by clear minerals (phenocrysts) and an alkaline composition. Varieties within these formations include rhyolitic and dacitic tuffs, as well as andesites and rhyolites. [9]. The study area is located within the Tarqui Formation, which is characterised by the presence of dacitic and rhyolitic tuffs. [10].

2.1.2. Local geological context or study area



(a) **(b)**

Figure 2. Location of the study area. (a) Baños del Inca Cave – Saraguro. (b) Spatial location of the sampling.

The sector contains volcanic-clastic outcrops of rhyolitic tuffs (Mtr), which are observable in varying shades of white, light gray and brown. Predominant components include quartz, plagioclase, and feldspar, contributing to a distinct pyroclastic texture. Additionally, a micro-conglomerate (Pmc) is evident, exhibiting minor weathering and a clastic texture, characterized by subrounded clasts and a filling material consisting of sandy-clayey substances. Its formation is presumed to be a result of dynamic processes acting upon pre-existing rocks.

(a) **(b)**

Figure 3. Baños del Inca Cave. (a) Entrance to the caves. (b) Hand sample of the rock present in the study area (Rhyolitic Tuff).

2.2. Geomechanical Characterization

2.2.1. Geomechanical classifications

Geomechanical classifications assign numerical values to rock masses at an engineering level, primarily for the analysis of unsupported excavations, caves, caverns and slopes [11]. Since the 1970s, a combination of empirical methods, wedge analysis and, more recently, numerical methods have been used for the geotechnical analysis of underground spaces. The most commonly used geomechanical classifications in underground works are the Q Index and the Rock Mass Rating (RMR). It is important to note that both methods serve as initial benchmarks for assessing the stability and behaviour of rock masses, with a history of over 50 years of application. [12]. Following this analysis, additional precision is achieved through computational programs, which offer a more precise representation of rock behavior and deformation characteristics through numerical values.

The empirical Q-index rock classification method, which is an integral part of tunnel stability analysis, has six parameters. These parameters can be estimated by a combination of in-situ mapping and geological engineering knowledge as defined in the following equation [13]:

$$Q = \frac{\mathrm{RQD}}{\mathrm{Jn}} \cdot \frac{\mathrm{Jr}}{\mathrm{Ja}} \cdot \frac{\mathrm{Jw}}{\mathrm{SRF}}$$

The Cavity Geomechanical Index (CGI) is formulated based on the geomechanical analysis, developed by Bieniawski (1989), using variables (RMR, Hydraulic Ratio, Ceiling Shape and Ceiling Thickness) derived from literature, knowledge and the authors' expertise in geostructural mapping. This method is used to assess the structural stability of the cave [2], [14].

i. Rock Mass Rating by Bieniawski (1989) – RMR. - a quantitative measure of the quality of the rock mass in the cave environment.

ii. Hydraulic Ratio – HR. - a quantitative measure of the relationship between the area and perimeter of the cave under investigation.

iii. Ceiling Shape – CS. - a qualitative assessment of whether the geometry of the cave ceiling facilitates or hinders block formation.

iv. Ceiling Thickness – CT. - a quantitative parameter indicating the depth of the cave ceiling relative to the ground surface.

The above components are illustrated in the following equation.

$$CGI = \alpha\ RMR + \beta\ HR + \gamma\ CS + \delta\ CT$$

Chart 1. Levels of susceptibility to structural instability according to the CGI index [15]

Susceptibility to structural instability	CGI	Symbology
Very high	0 – 20	
High	21 – 40	
Moderate	41 – 60	
Low	61 – 80	
Very low	81 – 100	

2.2.2. Geomechanical stations

Four geomechanical stations are established, where GSI, RMR, Q-Index, and simple resistance calculations are conducted in situ using the Sclerometer or Schmidt hammer type L, employing an impact energy of 0.735 Nm. The objective is to estimate the compressive strength of the rock based on various measurements obtained from the rebound of the hammer [16].

The number of stations is determined by the geomechanical characteristics observed in the field, which served as a representation of the geostructural conditions in the study area. Data collected included DipDir/Dip and discontinuity details such as spacing, persistence, opening, roughness, weathering, presence of water and type of filling [17].

3. Results

3.1 Photogrammetry

3.1.1. Cave geometry using photogrammetry

The technique used to reconstruct the study area is Structure from Motion (SfM), which generates point clouds by superimposing digital photographs (stereo-photogrammetry). This process facilitated the creation of a network of control points that allowed the reconstruction of the study area in 3D, allowing the observation of texture, rock composition and geological structures [18].

Initial reference points are designated to facilitate comprehensive documentation of the entire study area through photography. In this case, four base points are established. A critical aspect of this technique is the precise overlap of images. For this case study, approximately 2,600 photographs were taken, ensuring an overlap of more than 70% to achieve a high-quality 3D reconstruction.

The software used for this process is Agisoft Metashape, which provides a workspace for conducting various procedures aimed at reconstructing the Baños del Inca cave in Ecuador in 3D.

Key processes include initial alignment of field photographs, followed by point cloud and depth filtering within the photographs (build dense cloud). A mesh is then generated to facilitate the observation of geological structures.

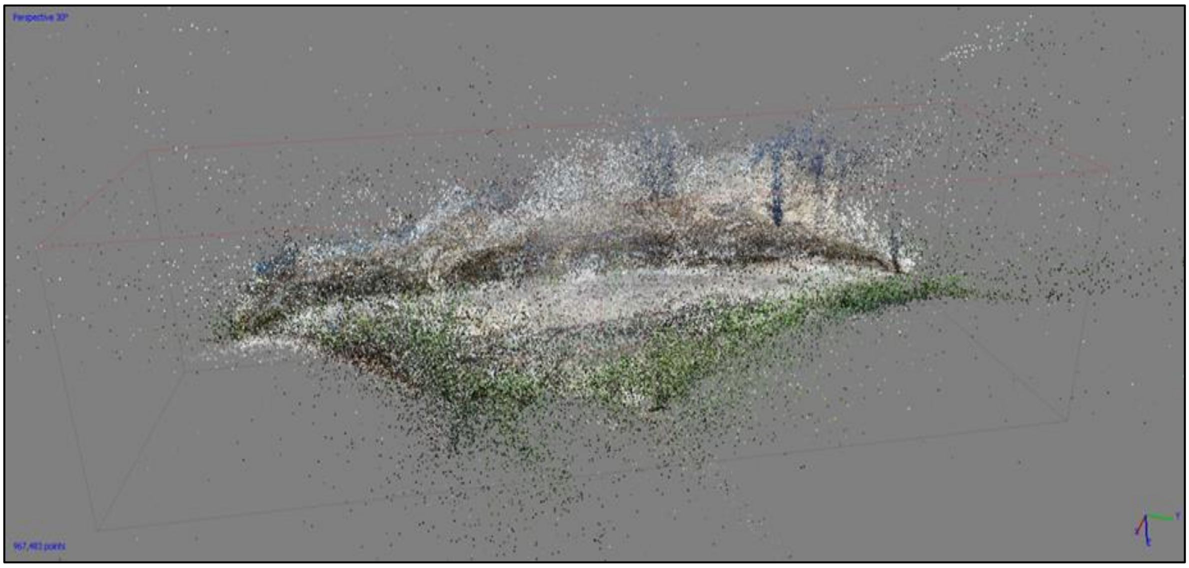


Figure 4. Baños del Inca Cave Cloud Points

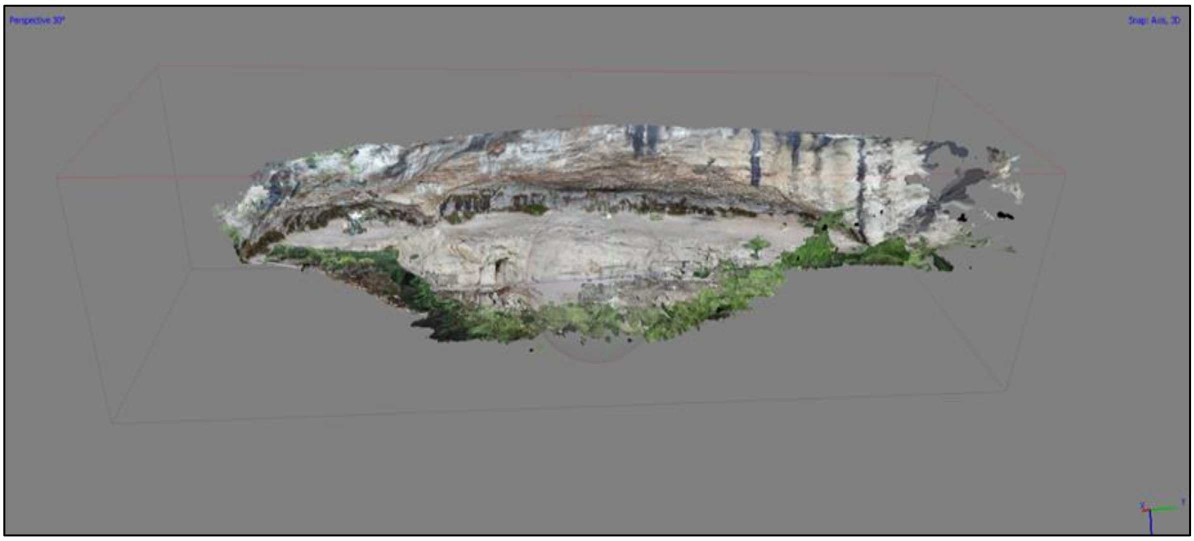


Figure 5. Shading of the Baños del Inca Cave.

Figure 6. Detail of the Shading of the Baños del Inca Cave

3.1.2. Data collection with geomechanical station

A geomechanical station is defined as an organized set of observations aimed at determining the geomechanical conditions of the rock mass. This involves establishing a comprehensive sketch of the structures and outcrop, evaluating the Rock Compressive Strength (RCS) using the Schmidt hammer, Rock Quality Designation (RQD), and assessing all conditions related to joints (such as spacing, persistence, opening, roughness, weathering, presence of water, and type of filling) [18].

3.1.3. Stability evaluation using geomechanical classifications: Q index and CGI

Four geomechanical stations are installed throughout Baños del Inca to analyze the rock mass. This resulted in stations 1, 2, and 4 being classified as medium rock type (III), while station 3 is classified as good rock class (II) according to the Rock Mass Rating (RMR) (see Table 2). Similarly, Barton's Q classification indicated an average rock quality, as shown in Chart 3.

Chart 2. Determination of the RMR of the geomechanical stations

		Stations			
Parameters		**1**	**2**	**3**	**4**
RMR1		2	2	4	2
RMR2		10	12	12	10
RMR3		17	20	18	18
	Persistence	2	4	4	2
	Opening	5	5	5	5
RMR4	Rugosity	3	3	5	3
	Stuffed	6	6	6	6
	Disturbance	6	6	6	6
RMR5		10	10	15	15
Basic RMR		61	68	75	67

RMR corrected	51	58	65	57

Note: RMR1, Simple Compressive Strength (UCS); RMR2, Rock Quality Index (RQD); RMR3, Spacing of discontinuities; RMR4, Condition of discontinuities; RMR5, Presence of Water.

Chart 3. Determination of Barton's Q of geomechanical stations

	Stations			
Parameters	**1**	**2**	**3**	**4**
RQD % Rock Quality Designation	50	60	70	60
Jn number of joints	12	9	12	12
Jr joint roughness number	4	4	4	4
Ja joint alteration number	2	2	1	1
Jw reduction due to the presence of water	1	1	1	1
SRF Stress reduction factor.	1	2.5	2.5	2.5
Q	8.33	5.33	9.33	8.0
Quality	Average	Average	Average	Average

Chart 4. Determination of the CGI of the geomechanical stations

		Stations			
Parameters		**1**	**2**	**3**	**4**
RMR	Value	51	58	65	57
	Description	III Regular	III Regular	II Good	III Regular
	CGI Scoring	30	30	45	30
HR	Value	3.5	7.22	7.16	4.9
	Description	Long	Long	Long	Long
	CGI Scoring	0	0	0	0
CS	Value				
	Description	Planar	Planar	Planar	Planar
	CGI Puntaje	4	4	4	4
CT	Value	3.90	3.97	3.97	6.47
	Description	Regular	Regular	Regular	Regular
	CGI Scoring	2	2	2	2
CGI		36	36	51	36
TYPE CGI		High	High	Moderate	High

Note: RMR, Rock mass classification; HR, Hydraulic Ratio; CS, Ceiling Shape; CT, Ceiling thickness.

3.1.4. Stability evaluation using empirical methods

Figure 7 shows that all the sections analyzed are within the stable zone. This trend is attributed to the significant width of the cave and the moderate values suggested by the Q index.

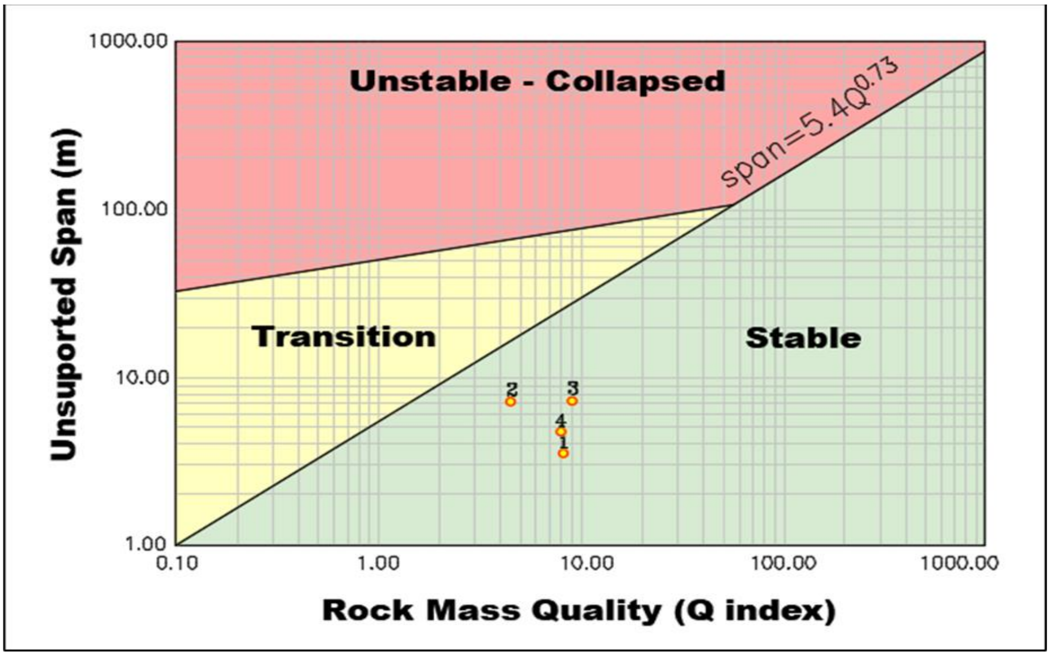
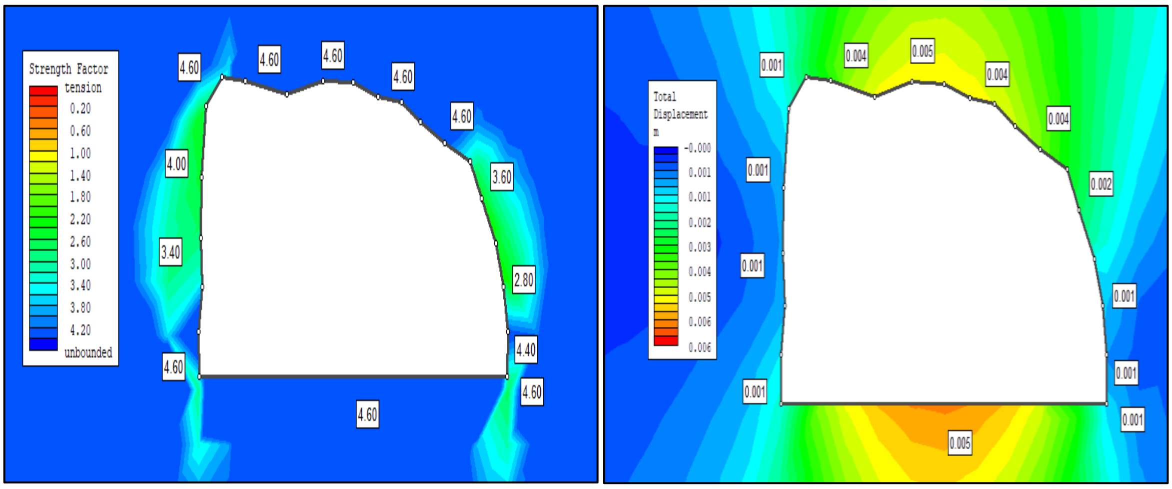


Figure 7. Tunnel stability, represented with the Q index, adapted and modified from Jordá (2017) [11]

A numerical simulation is conducted using the Boundary Element Method with Examine 2D. As shown in Figure 8, in scenario (a), the resistance factor suggests no stress effects within the cave. Conversely, in scenario (b), the model indicates that the total displacements are negligible, suggesting that the cave is stable. However, the presence of cracks in the ceiling could pose a long-term risk, potentially leading to specific areas of instability.

Chart 5. Input calculation parameters used in the Examine 2D program.

Parameters	Value
Overload Unit Weight (MN/m3)	0.024
Em (MPa)	2547.14
Poisson Coefficient	0.265
Compact Intact Strength (MPa)	175
GSI	80
mi	13
D	0



(a) **(b)**

Figure 8. Modeling of cave station 2. (a) Strength factor tension. (b) Total displacements.

5. Conclusions

A preliminary analysis of the cave has been carried out using empirical methods and stress-strain evaluation, and does not indicate any current instability problems. While the Q index suggests stability, the CGI raises some concerns, although it is considered to be conservative. Although the CGI indicates overall instability, the cave remains intact. In this context, the Q index is a more accurate reflection of reality than the CGI, which is poorly validated for caves in calcareous terrain, unlike the ferrous lithotypes of Brazil for which it is designed. The stress-strain analysis shows a safety factor of more than 2.8, which is visually confirmed by the absence of significant cracks. It appears that the cave is stabilized under tension, with minimal overall displacement. However, in the long term, these ceiling cracks may become critical factors for specific areas of instability.

The stability of a cave depends on several critical factors: the characteristics of the rock mass, the dimensions of the section, and the method of excavation. Specific methodology, designed for caves rather than tunnels, has been used to assess support structures. The implementation of passive fortifications in caves could have a visually disruptive effect; thus it is advisable to provide a safe pathway instead. In addition, given the large number of visitors to these caves, a thorough survey is recommended to identify and categorize the most significant unstable areas.

Fieldwork plays a vital role in providing essential data for the study, such as Rock Compressive Strength (RCS) and discontinuity-related data. This highlights its complementary nature to remote Structure from Motion (SfM) photogrammetry techniques.

6. Recommendations and future work

It is recommended to conduct regular monitoring of the study area every six months, particularly after rainfall, to verify the absence of movements. The application of photogrammetry has facilitated the creation of a geometric model of the cave, which is essential for conducting complementary geomechanical analyses. However, it is essential to consider important parameters for this process, such as ensuring a 70% overlap between photographs.

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CERTIFICACIÓN DE REVISIÓN DE PROYECTO DE TITULACIÓN

Por medio de la presente, Yo Davide Besenzon Venegas, Coordinador del Programa de Maestría en Geotecnia de la Escuela Superior Politécnica del Litoral (ESPOL), certifico que:

Con fecha 25 de enero de 2024, el estudiante Rolando Alejandro Silva Yaguachi con número de identificación 1105183782, de la Cohorte 5, presentó la propuesta de su tema de titulación al Comité Académico del programa. Posteriormente, con fecha 31 de mayo de 2024, el Comité revisó y aprobó la propuesta mediante la FICT-CA-GEOTEC-011-2024, cumpliendo con los requisitos establecidos para la aprobación del tema.

A partir de dicha aprobación, el estudiante mantuvo reuniones periódicas con el tutor designado, Luis Jordá Bordehore, para la elaboración y desarrollo de su proyecto de titulación, siguiendo los lineamientos establecidos por el programa. Con fecha 12 de junio de 2024, el estudiante presentó y sustentó su proyecto de titulación ante el tribunal evaluador asignado, cumpliendo con el proceso formal de evaluación académica.

Por lo tanto, en calidad de Coordinador del Programa de Maestría en Geotecnia, certifico que el trabajo de titulación denominado **"Caracterización geomecánica y análisis de estabilidad en la Cueva de Baños del Inca (Ecuador) mediante métodos empíricos y fotogrametría"**, realizado el estudiante Rolando Alejandro Silva Yaguachi con número de identificación 1105183782, ha sido revisado y evaluado conforme a los lineamientos y estándares establecidos por el programa.

Debido a circunstancias externas, no ha sido posible obtener las firmas de los involucrados (estudiante, tutor(es) y/o evaluadores). No obstante, en calidad de Coordinador del Programa, certifico que el proyecto cumple con los requisitos académicos y ha sido revisado para su presentación y archivo institucional.

Atentamente,

Firmado electrónicamente por:
DAVIDE BESENZON VENEGAS

M. Sc. Davide Besenzon Venegas
Coordinador de la Maestría en Geotecnia