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Rock Mechanics Aspects of Debar Crystal Cave – Macedonian Wonder of Nature

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Abstract

The article is dedicated to the Macedonian gypsum crystal cave, located near city of Debar. Another name that is used for this location is Alchija gypsum chamber. This is one of the few caves of this kind in the world that contain the unique selenite crystal. It is the most interesting gypsum cave in the world, beside the Giant Crystal Cave (Cueva de los cristales) in Mexico. The cave has a status of natural geological wonder, spaced in a unique geological environment with presence of active faults and hot thermal springs nearby. In addition, its entrance is only few meters above the water level of artificial Debar Lake. It is currently under concession of the company Knauf. Despite the fact that it was first discovered by the Romans more than 2200 years ago and it is a part of the largest gypsum quarry in the Balkans, the aspects of rock mechanics have not been presented to the wider scientific community. This is very important, having in mind that the underground openings are very large, without any kind of support, which is a challenge from stability and safety point of view, since sightseeing visits for groups of tourists are being occasionally arranged. From touristic and cultural heritage aspect, there are ideas to establish a cultural centre and concert hall in the cave. Therefore, security and rock stability are very important. The paper presents data about properties of the intact rock, rock mass, as well as acoustic properties of the main chamber. Results from some analyses are prepared to give an insight into the overall stability of the underground openings. Photogrammetry and LiDAR were used to produce initial 2D and 3D cave models, enabling detailed mapping and reliable stability assessments. Results from acoustic measurements and ambient temperature and humidity measurements are also presented. Results of the research open up a vista towards how to upgrade the cultural-technological dimension of the cave and its tourist promotion.

Keywords

Debar Crystal cave, Rock mass, Physical-Mechanical Properties, Stability.

1 Introduction

The Macedonian gypsum crystal cave presents one of the rarest underground formations worldwide, containing selenite crystals, comparable in significance to the well-known Cueva de los cristales in Naica Mexico. Recognized as a geological natural wonder, the cave is situated within a unique tectonic environment characterized by active faulting and proximal thermal springs. Alternative name for this unique location is Alchija gypsum chamber.

Gypsum from the underground has historically been used for medicinal purposes and occurs in three mineralogical forms: alabaster, anhydrite, and selenite. Currently, the site is under concession to Knauf-Radika company, which exploits gypsum primarily from surface quarries for industrial applications.Present-day exploitation is restricted to surface mining, with production focused on gypsum plasterboards, powder-based products, and mortars. Knauf-Radika operates as a major regional facility, with annual capacities of approximately 13 million m² of plasterboards and 200,000 tons of gypsum-based products.

Despite its discovery by the Romans more than 2200 years ago and its association with the largest gypsum quarry in the Balkans, the crystal cave's rock mechanics and stability aspects remain undocumented in the scientific literature.

The geological setting is complex, involving active faulting, seismicity, groundwater–surface water interactions, and the presence of thermal springs, all of which contribute to a distinctive engineering environment.

The cave comprises extensive underground openings that remain unsupported, posing significant challenges for stability and safety. This is particularly relevant given the occasional organization of tourist visits. The surrounding environment is further influenced by an artificial lake at the toe of cut slope leading to the entrance of the cave, tectonic disturbances, and weathered rock masses, which collectively increase susceptibility to instability.Beyond its geological significance, the cave has been proposed as a site for cultural development, including the establishment of a cultural center and concert hall. Such initiatives underscore the importance of ensuring structural stability and visitor safety.

The study presents data on intact rock and rock mass properties, as well as thermo-hygrometric and acoustic characteristics of the cave. Advanced surveying techniques, including combined photogrammetry and LiDAR, were employed to generate accurate 3D cave models, enabling detailed mapping and stability assessments. Complementary investigations included acoustic measurements, and monitoring of ambient temperature and humidity.

The idea of the paper is to use the analyses as initial insights into the overall stability of the underground openings and highlight the engineering challenges associated with unsupported spans in a faulted, hydrothermally active environment. It is considered that the integration of geotechnical, thermal, and acoustic data will contribute to a holistic understanding of the cave's engineering behavior. Findings should also inform strategies for enhancing the cultural-technological dimension of the site, supporting both its scientific documentation and its promotion as a tourist destination.

2 Geographic position and geological setting of the area

The site is situated in the western part of the country, close to the border with Albania near Macedonian city – Debar. The entrance to the underground chamber is only few meters above the level of the artificial Debar Lake. In geological and tectonic term, the analyzed area, belongs to one of the main Macedonian geotectonic unitsknown as Tzukali–Krasta zone. An abstract from geological map of the area is presented in Figure 1. It is visible, that the gypsum– anhydritedeposits are the most widespread rocks in the area with estimated thickness around 500 m. Within the gypsum mass, organic matter, fragments of limestone, cherts, and native sulfur appears. Anhydrite occurs in the inner part of the gypsum mass, where it gradually transitions into a variety of gypsum—alabaster. Since the transition from anhydrite ($CaSO_4$) to gypsum ($CaSO_4 \cdot 2H_2O$) involves a physical increase in volume, the gypsum is forcibly folded, creating a characteristic structure of folding due to swelling caused by hydration (diapiric folding).Beside gypsum-anhydrite deposits, the Upper Cretaceous flysch-like sediments represented by sandstones, clay shales, siltstones, marls, marl limestones, and more rarely conglomerates and cherts are dominant in the wider area.

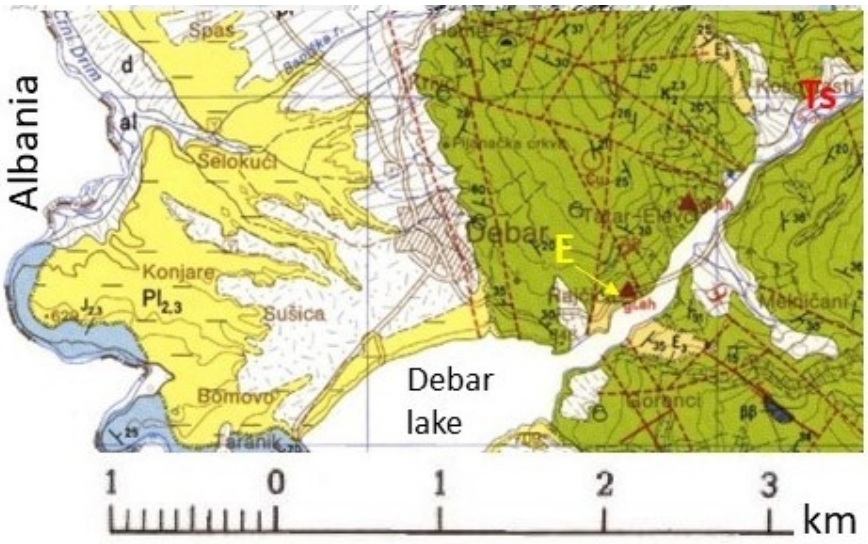


Fig. 1 An abstract fromBasic Geological Map of Macedonia near town Debar (lower section): E-entrance in the gypsum chamber, gi, ah-gypsum and anhydrite rock mass complex; $K_2^{2,3}$-Cretaceous flysch complex; E_3-Eocene flysch, $Pl_{2,3}$ - Pliocene Lake sediments; d-al-sediments with quaternary geological age; Ts-zone of thermal springs – Spa centre Kosovrasti.

The origin and geological age of the gypsum deposits are still problematic. The prevailing opinion is that they most likely formed through metasomatism, by transformation of limestones under the influence of thermal and other waters. Some authors consider that the present position of the gypsum-anhydrite formations is the result of diapiric intrusion into the zone of a major regional rupture structure during these intense tectonic movements, which also explains their current condition (Dumurdzanov et al., 2005).The area is also characterized with dominant extensive tectonic regime in SE Europe in Neogene. The valley of the Radika River intersects gypsum and alabaster masses, and represents a significant part of Elbasan – Debar – Skopje – Kjustendil fault. In the immediate vicinity of Debar, the so-called Zhupski Fault is also present (Burchfiel et al. 2016).

In the chamber, the rock mass is completely represented by the crystal gypsum mineral selenite. Some of the largest crystals found in the chamber has metric dimensions, forming beautiful forms. Their hardness is 2 in the well-known Mohs scale, they exhibit perfect cleavage along one dominant plane,and two other planes. This structural arrangement produces smooth separation surfaces, giving selenite its characteristic fragility, silky lustre, and tendency to form blade-like or tabular crystals(Figure 2).



Fig. 2 A view on large crystal form of gypsum-selenite in the cave (left) and at the level of rock sample (right) with visible dominant and secondary cleavage planes.

3 Methods for laboratory testing and field measurements

3.1. Rock mechanics tests

Key stone in the working methodology is based on combination of the results from field and laboratory tests. They were used in the integral analyses for extrapolation of data from laboratory to the rock mass scale. In this case, a Schmidt Hammer Rebound Values (SHRV) are conducted in the field(Figure 3).In addition, geodetic and acoustic measurements were prepared. Typical

characterisation tests as Uniaxial Compressive Strength (UCS), Point Load Tests (PLT), tilt tests, density(ρ),water absorption(A) and Slake Durabilitywere performed in laboratory conditions.



Fig. 3 Upper left -field measurements of Schmidt Hammer Rebound; Upper right -geodetic measurements for 3D Mapping, lower left– tilt test; lower right – Slake durability apparatus used for the testing.

3.2. Geodetic measurements

Spatial data acquisition was performed using the Leica BLK360 G1, a platform selected for its ability to deliver high-accuracy measurements within complex, subterranean environments. The scanner captured dense point clouds alongside HDR panoramic imagery, ensuring both geometric precision and realistic visualization of the cave chambers. To maintain structural integrity during reconstruction, scan positions were strategically distributed to ensure significant overlap. This overlap was critical for minimizing registration errors and ensuring a seamless transition between the cave's intricate internal geometries (Kasapovski et al 2025).

To complement the engineering-grade LiDAR data, high-resolution imagery from an iPhone 14 Pro were captured using a DJI Osmo Mobile gimbal and integrated via mobile photogrammetry. This hybrid approach enhances image stability and visual consistency during data acquisition, adding a layer of visual accessibility to the technical model while enabling immersive virtual walkthroughs without compromising spatial rigor.

3.3. Thermo-Hygrometric and Acoustic Measurements

Complementing the rock mechanic tests and geodetic measurements, the research integrates in situ measurements of environmental parameters, namely air temperature and relative humidity, as well as background noise levels and reverberation time.

The environmental conditions inside the chamber were monitored by measuring air temperature and relative humidity using a TESTO 606-2 (0560 6062) handheld thermo-hygrometer. Monitoring was carried out over several hours during the field investigation conducted in December 2025, during which five measurements were recorded.

Reverberation time (RT) and background noise (BN) were measured in one-third-octave frequency bands from 100 Hz to 5000 Hz. Measurements were performed using a Class 1 Cirrus CR:171B sound level meter, calibrated with a Cirrus CR:515 acoustic calibrator before and after the session. To minimize disturbance, only two individuals were present during measurements. RT was determined using an impulsive excitation method with balloon bursts as the sound source. Five measurements were conducted for source–receiver distances ranging from 10 m to 15 m. Reverberation time was estimated from decay curves using the T30 method (−5 dB to −35 dB), and mean values with standard deviations were calculated following Nowoświat (2023) and Kuttruff (2016).

Background-noise measurements were performed to characterize the ambient acoustic conditions and to confirm that the noise floor was sufficiently low for reliable reverberation-time estimation. Three measurements were obtained at selected receiver positions under quiet conditions using the sound level meter.

4 Results

4.1. Rock Mechanics Results

The detailed presentations of the results overcome the frame of this article, but in order to have a view on the main parameters of the intact rock samples, in Table 1, Figure 4 and Figure 5, only the main data about basic physical and mechanical properties of the rocks are presented.

Table 1. Results from testing of main physical and mechanical properties of intact parts

Sample No	**Density ρ(Mg/m^3)**	**Uniaxial compressive strength UCS (MPa)**	**Sample No**	**Density ρ(Mg/m^3)**	**Uniaxial compressive strength UCS (MPa)**
1	2,288	27.90	9	2,230	14.01(*)
2	2,236	29.71	10	2,243	21.79(*)
3	2,273	30.14	11	2,250	17.4(*)
4	2,276	28.92	12	2,237	27.61(*)
5	2,216	33.39	13	2,250	16.52(*)
6	2,244	40.08			
7	2,254	42.07			
8	2,215	32.42			
Note (*)	This samples are tested in saturated conditions				

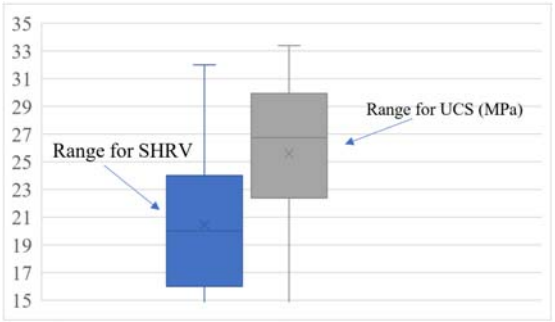


Fig. 4 Box and whisker chart for SHRV and UCS.

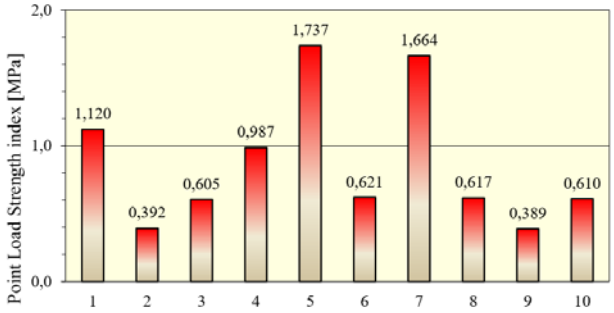


Fig. 5 Results from Point Load Tests.

From the Table 1 and Figure 4, it is visible that values of UCS varies a lot both fordry and saturated samples. From 5, it is visible that values of Point Load Testalso vary a lot. During the testing, it was evident that when the samples are tested parallel with dominant cleavage plane, the values are low comparing them for a direction normal to dominant cleavage plane. These lower values parallel to main cleavage are usually below the line that represents PLT=1 in Figure 2. During testing, because of low hardness, during the testing, some penetration of the point testing device into sample is evident, so the results are of questionable nature. Further tests are suggested with Needle penetrometer test (NPT).

Water absorption during saturation had a value from 1,4-1,6%. This finding indicates that all other mechanical properties of gypsum rock are strongly dependent on the water content. One simple but very indicative indicator is the density, with aaverage value aroundρ=2,24 Mg/m^3. This range indicates that anhydrite in these zones has transformed into gypsum rock, because anhydrite usually has significantly higher density (approximately 3 Mg/m³). Average value for UCS is around UCS=25 MPa (minimal values from 14-18MPa), while for SHRV=23.According to the ISRM Suggested Methods (Ulusay, 2007) for classification of intact rock strength, gypsum samples with a uniaxial compressive strength (UCS) in the range of 20–30 MPa fall into the in Class R3 (Medium-strong) to Class R2 (Weak rock) under the ISRM system. It is interesting that the material has sufficient strength for engineering applications but requires careful consideration of water sensitivity in design. Some

samples were subjected to Slake Durability Tests, starting with an initial weight of 526.48 g, then 511.82 g after the first cycle and 499.32 g after the second cycle. The calculated indices are 97.2% (first cycle) and 94.8% (second cycle), which classify the mineral gypsum as high durability medium according to ISRM method(ISRM Suggested Method, Franklin & Chandra, 1972).

When we come to the rock mass scale, the structure of the gypsum rock mass is very interesting. Gypsum rock masses with RQD values of 90–100% typically exhibit a highly interlocked blocky structure, in general free of alteration and with minimal water inflowonly on some places (Figure 6).



Fig. 6 Left – Core from the drilling of borehole D-7 at the close structure to the chamber – Melnicki bridge; Right- A look of gypsum rock mass at the largest chamber with span up to 20 meters.

In such conditions, the rock mass maintains high integrity, and discontinuities are tight and well-interlocked, reducing block detachment andlimited shear mobilization.

Without entering into detailed descriptions, the principal rock mass parameters and their ranges across established classification systems are summarized in Table 2. The Q-system (Barton et al., 1974), RMR system (Bieniawski, 1973–1989), RMQR system (Aydan et al., 2014), and the authors' ERMR system (Jovanovski and Peshevski, 2013)are applied to illustrate the variability of values from different perspectives. The relatively high Q, RMR, and RMQR ratings provide empirical confirmation of the stability of unsupported openings. In practice, measured spans are typically around 10 m, reaching up to 20 m in chamber excavations.

Table 2. Data about rock mass properties and range of rock mass classes using Q, RMR, RMQR and ERMR systems

RQD/Jn (max/min)	**Jr/Ja**	**Jw/SRF**	**UCS (MPa)**	**Unit weight (kN/m^3)**	**Water absorption A(%)**	**RMR**	**Q**	**RMQR**	**ERMR**
95/1	1,5/1	1/2,5	18-25	22,5	1,3-1,7	62	57	82	59
90/2	1,5/1	1/2,5	18-25	22,5	1,3-1,7	57	27	80	54

Note:**RQD** – Rock Quality Designation (%), measure of core recovery quality, $\mathbf{J_n}$ – Joint set number, representing the number of joint sets, $\mathbf{J_r}$ – Joint roughness number, describing surface roughness of joints, J_a – Joint alteration number, describing degree of weathering or alteration,**Jw** – Joint water reduction factor, accounting for groundwater conditions, SRF – Stress Reduction Factor, representing the effect of stress conditions.

Range of values for rock mass scale estimated using Hoek-Brown criteria are presented in Figure 7.

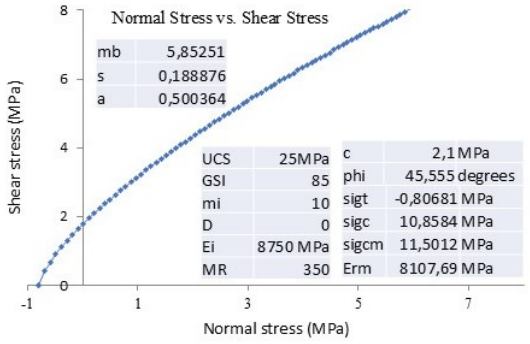


Fig.7 Estimation of rock mass shear strength and deformability using Hoek-Brown criteria, where a constant *mi* is defined empirically.

The analyses of the results suggests that, for weak and soluble rocks as gypsum, the RMQR system offers a more suitable framework for assessing large unsupported spans in sensitive rock masses. Furthermore, when ERMR = 59, the rock mass falls within the transition zone between ripping and blasting excavation classes, thereby corroborating the excavation methods previously employed.

4.2. Spatial Reconstruction Results from geodetic measurements and Model Validation

The final results demonstrate that the BLK360 is a reliable tool for cave documentation, yielding low bundle errors and high-quality alignment. This precision allows for the detailed identification of fracture zones, structural deformations, and stability risks. By merging the technical accuracy of laser scanning with the visual clarity of mobile photogrammetry, this workflow provides a robust foundation for long-term digital monitoring, precise spatial analysis, and immersive visualization for presentationpurposes. The results are presented in Figure 8.

4.3. Results Thermo-Hygrometric and Acoustic Measurements

Thermo-hygrometric measurements indicate stable environmental conditions within the chamber, with an average air temperature of 17.7 °C and a mean relative humidity of 58%. These values are consistent with previously recorded environmental data, suggesting that the chamber conditions remain relatively stable throughout the year, despite the variation in the outside temperature and humidity. Higher relative humidity levels, reaching approximately 78%, were observed in zones near the chamber walls. Measurements at the wall surface indicated a moisture content of approximately 10% in the near-surface wall material.

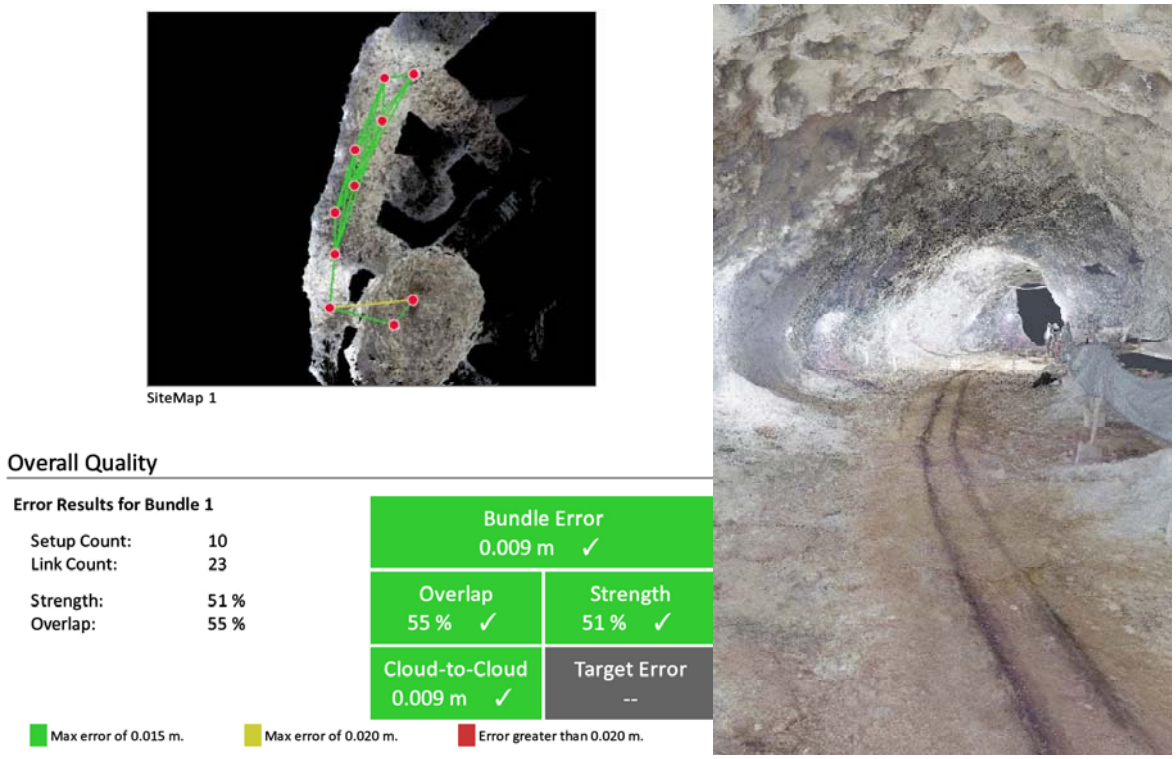


Fig. 8 Scan alignment quality and geometric accuracy report (left); 3D photorealistic model (right).

The measured background noise levels inside the chamber were low across the analysed frequency bands, ranging from approximately 9 dB to 20 dB (Figure 9). The lowest levels were observed in the mid-frequency range (250–500 Hz), while slightly higher values occurred at low frequencies (100–160 Hz) and around 800 Hz. The increase near 800 Hz may be attributed to airflow within the chamber galleries. Overall, the ambient noise levels remained sufficiently low and did not affect the accuracy of the reverberation time measurements, indicating favourable conditions for potential musical or theatrical use.

Reverberation time (RT) was evaluated as T30 for five source–receiver configurations in one-third-octave frequency bands ranging from 100 Hz to 5 kHz. The maximum sound pressure levels generated by the excitation source during the measurements ranged between 70 and 90 dB. For each frequency

band, the mean value and standard deviation were calculated based on the five measurements, and the results are presented in Figure 10. The results indicate a gradual decrease in RT with increasing frequency. The highest value was observed at 100 Hz (T = 1.616 s), while the lowest value occurred at 5 kHz (T = 0.884 s). In the mid-frequency range, the RT remained approximately constant at around 1.0 s.

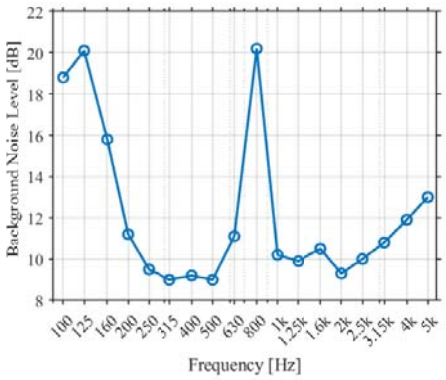


Fig. 9 Background noise level.

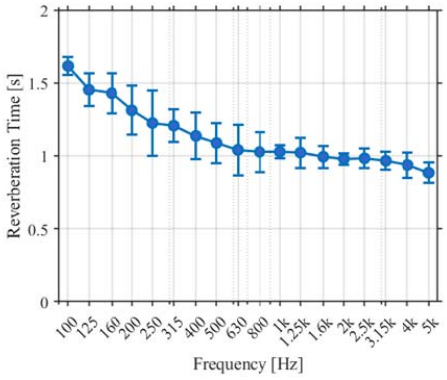


Fig. 10 Reverberation time (Mean±Standard Deviation).

4.4. Some stability considerations

For a soluble and moderately weak rock such as gypsum, the observed long-term stability is particularly noteworthy: openings have remained stable for more than 20 years following the cessation of active exploitation. It shall be noted, that till now, there are no any stress measurements in the chamber. The reasons of stable opening, most probably is in the effect of the geometry and stress redistribution that induce arching effects, where load transfer occurs through the interlocked blocks, stabilizing the excavation roof and walls. This facts explain why certain unsupported openings have remained stable for more than two decades, despite the surrounding tectonic setting. The combination of high rock mass quality,minor localwater inflow, interlocked structure and stable humidity provides long-term stability under modest extensional stresses, with arching acting as a natural reinforcement of the excavation span. Just to see the range of stable openings from some known sources in relation with the Crystal cave openings, the range of values is presented in Figure 11, presenting occupied area in known Barton's diagram and diagram presented by Aydan (Barton, 1976, and Aydan, 2026-in print).

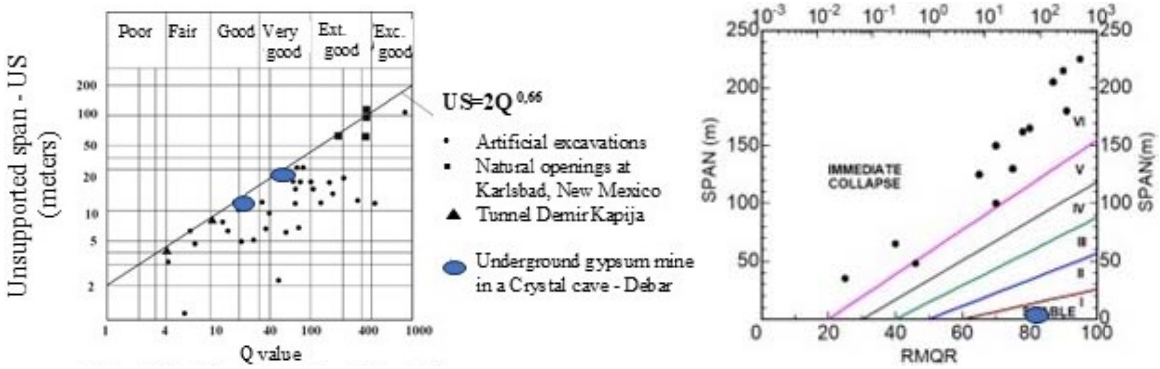


Fig.11 Left – Presentation of largest underground openings and position of Crystal cave near Debar using Barton diagram; Right - Position of openings for Crystal cave in a diagram representing RMQR value and span (Aydan, 2026).

Initial analyses are prepared with limited data available about stress conditions using EXAMINE2D software. With a density of 2,25Mg/m³ and an overburden depth of 270 m, the resulting vertical stress (σv) can be estimated with high confidence at approximately 6.1 MPa. When compared with the intact rock strength (UCS = 25 MPa),the ratio of intact compressive strength to vertical stress is approximately 4.1. In brittle lithologies such as limestone or granite, such a low stress–strength ratio would typically promote spalling or stress-induced tensile cracking. In gypsum, however, the same stress level favours plastic redistribution rather than brittle failure. The rock mass is sufficiently strong to prevent immediate collapse, yet deformable enough to accommodate minor strain, progressively closing micro-discontinuities and transforming the arched roof into a single, pre-stressed structural unit.Results are presented in Figure 12.

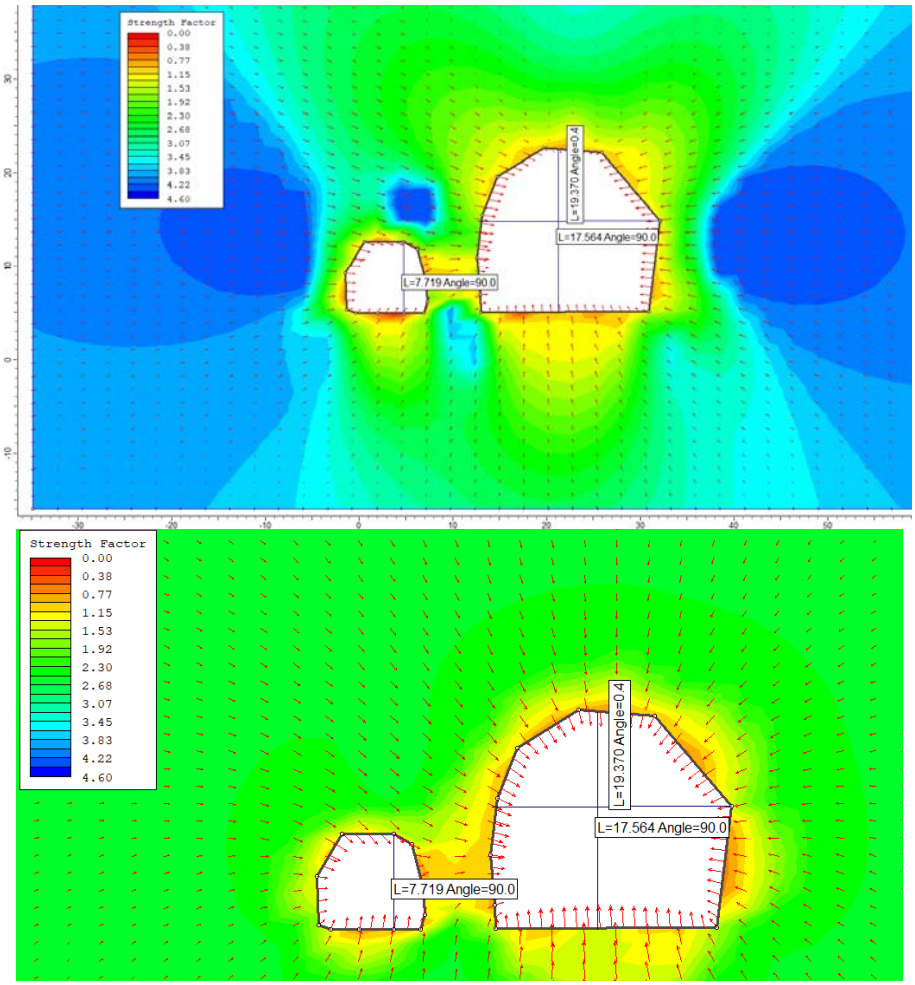


Fig. 12 Range of strength factor calculated in EXAMINE2D software for a case of horizontal stress equal to 3 MPa (upper section) and 6 MPa (down section) using Hoek-Brown parameters from Figure 7.

Although the calculated strength factor(SF) presented in Figure 12indicates borderline conditions in certain local zones around the excavation, the long-term stability of the opening can be attributed to several reinforcing mechanisms. In tectonically active regions such as Debar, assuming a K-ratio close to unity, the horizontal stress (σ_h) is likely of similar magnitude to the vertical stress, on the order of 6 MPa. This most probably produces a biaxial confining stress state at the crown of the excavation.In this setting, the vertical stress activates the primary arching mechanism, while the horizontal stress provides lateral confinement, effectively clamping discontinuities and preventing block detachment. The relatively low density of gypsum (≈2,25 Mg/m³), compared to typical hard rock (~2.7 Mg/m³), reduces gravitational driving forces by about 15%, while the rock mass still preserves high frictional resistance.Together, these factors can be a reasonable explanation about the documented long-term stability of the unsupported excavation, without progression toward failure. The interplay of arching, lateral confinement, and reduced driving stresses has maintained equilibrium despite the seemingly marginal strength ratio.Of course, these statements should be confirmed with in-situ stress monitoring by known methods, while deformation can be tracked using extensometers, convergence measurements, laser scanning, and microseismic monitoring. Together, these complementary methods can provide a reliable framework, ensuring long-term stability assessment.

5 Possibility fortourism, cultural scientific events in the cave

The measured environmental and acoustic conditions indicate that the chamber provides a stable and suitable environment for potential touristic and cultural use. The moderate temperature and relative humidity, together with low background noise levels and favourable reverberation time characteristics, support conditions appropriate for activities such as guided visits, musical performances, and small-scale cultural events.Experiences from several former salt mines in Europe that have been successfully transformed into tourist attractions, combining geological and rock mechanic aspects, history, and cultural heritage as Turda Salt Mine in Romania, Wieliczka Salt Mine in Poland, and Berchtesgaden Salt Mine in Germany(Cieślik, 2019). Such experiences can be useful in further plans for the tourism

and cultural events in the cave. This is interesting also, knowing that in the closest area, the National Park "Mavrovo" and river Radika area together with Spa-centreKosovrasti creates perfect preconditions for such development. From scientific point of view, the Debar Crystal cave can also be credibly presented as a natural laboratory for rock mechanics, which can have a positive input on thewider scientific society.

6 Conclusion

The Macedonian gypsum crystal cave near Debar represents a rare geological wonder of global significance, combining unique selenite formations with large unsupported underground openings in a tectonically active environment. Despite these facts, in the literature, till now there are no detailed description of this unique phenomenon.The integration of rock mechanics data, acoustic properties, and advanced mapping techniques such as photogrammetry and LiDAR provides a reliable basis for assessing stability and safety, while simultaneously opening opportunities to enhance its cultural and touristic value through sustainable promotion and heritage development.

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