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Multidisciplinary approach for the stability analysis of a historical hypogeum in the municipality of Cisternino in the UNESCO site of the Itria Valley (Puglia, Southern Italy), aimed at a refunctionalization and valorization of the site

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Abstract **– This contribution focuses on a multidisciplinary study approach in a cultural context of excellence, protected by UNESCO, in which there are many hypogea of anthropic origin, unexplored and sometimes unknown, which should be studied and valorized. Among these, the case of a historical hypogeum is reported, located under a trullo (a typical historical rural structure of the Itria Valley) that could be repurposed and valorized. The problem was addressed with a preliminary geophysical (seismic refraction, MASW and georadar), geotechnical, geological and geomorphological investigation on site, which allowed to define and size the hypogeum, the thickness of the vault that separates it from the overlying flooring of the trullo and the state of fracturing of the calcareous rock mass, in which it was excavated. This investigation was followed by the archaeological verification of the soil deposits, the levels of frequentation and the artefacts present inside the hypogeum, which allowed us to frame the historical period of its first use in the Late Middle Ages.**

The stability analysis was performed using a model, also defined thanks to geophysical investigations, along two transversal sections of the hypogeum, applying a calculation code that provides a synthetic representation of the set of deformation vectors found in the various sectors of the hypogeum section, analyzing the elastic stresses that affect the underground excavation, with the definition of the two-dimensional plane deformation.

The result of the stability verification showed that the areas affected by the vaults and areas close to the central septum are in conditions of potential collapse due to a greater structural weakness of the hypogeum both for the state of fracturing and for the alterations of the rock mass. This structural weakness could also be responsible for some crack patterns present in correspondence with the walls and vaults of the trullo above.

All this has made it possible to obtain the information that is absolutely essential for the correct planning of the consolidation interventions and subsequent enhancement of the site, without distorting it and preserving its historical-archaeological peculiarities, which constitute an added and indispensable value. Therefore, in order to use the hypogeum for tourist and cultural enhancement purposes, a structural consolidation intervention with low visual impact is advisable, which can favor the increase of the safety factor and at the same time preserve the nature and historical identity of the hypogeum.

I INTRODUCTION

This paper focuses on a multidisciplinary analysis conducted at a hypogeum located in the Barbagiulo district of the Municipality of Cisternino, beneath a historic trullo (a typical Apulian rural structure with a truncated cone roof). The aim of this analysis was to assess the stability of the cave's vaults.

The current "built" agricultural landscape of the Altamura Limestone appears to be organized into fields enclosed by characteristic dry-stone walls and is characterized by the presence of small, isolated rural structures. The area is crossed by the South/Est railway network and is characterized by a remarkable variety of tree crops, such as vineyards, olive groves, orchards, and cereal crops. To obtain detailed information about the structural configuration of the hypogeum, geological and structural surveys were conducted, which allowed us to identify the main elements characterizing the subsoil. These surveys revealed that the trullo construction area is founded on a calcareous substrate represented by the Cretaceous Altamura Limestone formation [1], composed of layers and banks of stratified limestone with marly intercalations, in a monoclinal arrangement with rather gentle slopes (7°-10°) clearly visible at the roof of the hypogeum. Overall, this formation presents a rather pronounced state of fracturing, in which main families determined by bedding planes and secondary families defined by articulated fracture systems with prevalent SW and SE dipping and consequent inclinations of 10°-80° can be distinguished.

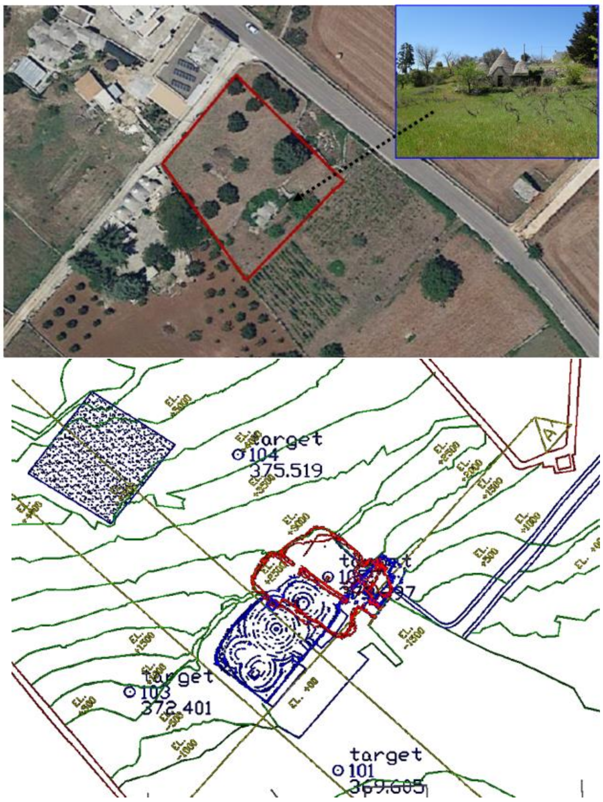


Figure 1- Top: Orthophoto showing the location of the study site (in red) and a photo of the front elevation. Bottom: Plan with aerial photogrammetry of the study site showing the location of the trullo (in blue) and the extent of the underlying hypogeum (red lines).

II MATERIALS AND METHODS

In order to geotechnically characterize the geological substrate in which the hypogeum was excavated, rock tests were carried out using the Schmidt Hammer (sclerometer). The survey, to support the verification of stability conditions, consisted of the detection of discontinuities on the stone terms with rigid/brittle behavior, carrying out the census on a scanning line of length adequate to describe the trend of the solutions of continuity that characterize the detected horizons by recording: geometric parameters of the discontinuities (orientation; spacing and frequency; RQD index), morphological parameters of the discontinuities (persistence, roughness/roughness, opening, filling) and mechanical parameters of the discontinuities and of the rock (strength measurements on discontinuities with a sclerometer, Bieniawki, Burton classification and shear strength with the Hoek and Brown failure criterion, using MIZ software) [2-3].

In order to obtain the plan of the hypogeum and the precise cross-sections on which to carry out the stability check, a laser scanner survey was carried out (Fig. 2).

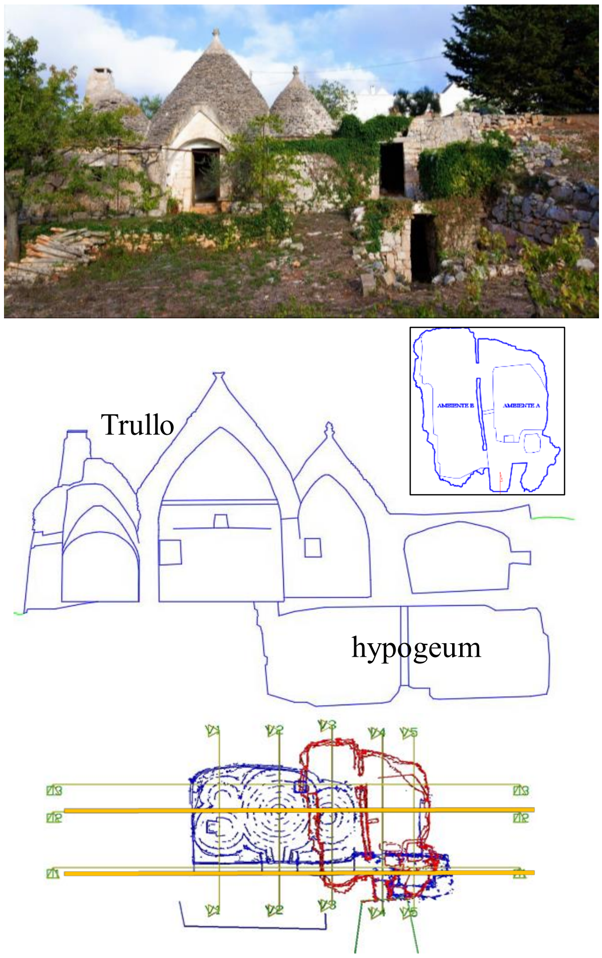


Figure 2 - Section of the trullo and the underlying hypogeum and, top right, plan of the two rooms A and B of the hypogeum. Below, the two topographic profiles for which the stability analysis was performed.

Stability assessment methods for rock vaults are currently based on simplified, almost static calculations based on limit analyses for elastic-plastic materials. The problem of calculating the forces at play along the entire perimeter of the cavity was addressed using the Examine 2D calculation code, which provides a summary representation of the set of deformation vectors found in the various sectors of the hypogeum section. Essentially, it is a program designed to analyze the elastic stresses affecting underground excavations, with the definition of two-dimensional plane deformation. Examine2D is a two-dimensional plane-strain indirect boundary element program for elastic stress analysis of underground excavations, primarily oriented toward rock excavations. It relies on parameters collected from the field and laboratory, as well as those derived from the RocLab Windows program.

The stress variations calculated by Examine2D are somewhat exaggerated because the actual stress flow around the edges of the excavation/underground cavity is not taken into account. All stress is forced to flow around the underground cavity parallel to the analysis section. Taking this effect into account, the analysis can still provide useful information on the behavioural tendencies of the rock mass in these cases.

To define the stress induced by the rock mass in the void, determined by the underground cavity, we assume, in a simplified form compared to reality, that the surrounding material is homogeneous, isotropic, and linearly elastic factors that largely characterize the limestone mass within which the cavity develops.

For the calculation, performed along the two topographic profiles (Fig. 2), the main parameters related to the structural analysis were entered, taking into account that the stress criterion is the generalized Hoek-Brown criterion and the analysis is that of plane strain. This results in a stress field around the cavity, which indicates the variations in the boundary forces. By entering the elastic and strength properties of the rock mass (Young, Poisson, G, etc.), it is possible to obtain a fairly accurate estimate of the stress field at the boundary of the void.

The resulting model provides a visualization of the so-called strength factors, which represent the ratio between the rock strength and the stress existing at the cavity boundary. If the ratio is less than 1, it means that the soil could collapse under the stress conditions; conversely, if the ratio is greater than 1, it would hold.

The stress, displacement, and strength factor are calculated at each point of the stress grid, and the resulting contours are generated by interpolation from the data at the grid points.

The program output was set to the strength factor. This represents the ratio of the material strength to the induced stress at a given point. The material strength is based on the strength properties of the rock material, and the induced stresses are determined by the elastic stress distribution calculated from the boundary element analysis.

All three principal stresses ($\sigma 1$, $\sigma 3$, and σZ) are used in the resistance factor calculation; therefore, the resistance factor in Examine2D can be considered three-dimensional.

The geological study was also accompanied and integrated with a geophysical campaign conducted using seismic refraction and ground penetrating radar.

III ARCHAEOLOGICAL CONTEXT

The Cisternino area, an exemplary example of the varied landscape of the Brindisi Murgia, represents an area of extreme interest from the point of view of archaeological research, not only for the wealth of known evidence, but also for the extensive documentation collected. It is rich in archaeological evidence ranging from the Bronze Age to the Hellenistic-Roman period, that is, between the end of the 4th century BC and the end of the Roman Empire [4-5]. The evidence reported by the collections by Punzi [6-7] has yielded flint and obsidian artefacts, together with research conducted by the "Valle d'Itria" Archaeological Group, which has allowed the recovery of impasto earthenware fragments generally attributable to the Bronze Age and lithic industry attributable to a prehistoric facies.

The investigated area is located approximately 1 km W of the Potere-Sant'Anna site, and approximately 1.7 km NE of Monte Castel Pagano and approximately 500 m from the Calabrese locality where, in the 70s of the last century, scholars found some tombs of an unspecified period.

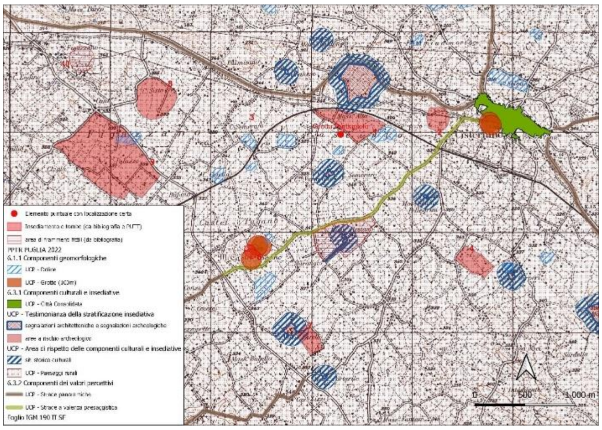


Figure 3 - Map of the sites listed in the specific information sheets and location of the Grotta Barbagiulo district.

The hypogeum's vault extends along a strata surface, and for this reason, it has a pseudo-flat section and a slight slope toward the entrance. The entire cavity was then divided into two rooms separated by a masonry partition, with various openings and structural discontinuities. This partition is somewhat degraded and therefore not currently capable of providing a load-bearing function. The cavity in question has an entrance characterized by a false limestone wall that leads into the first room, "Room A," which is separated from the second room by a false wall of uncertain function. Room A measures 6.40 x 3.60 meters, while Room B measures approximately 9 x 3.30 meters.

The first room features a series of elements that confirm the cave's human use. Near the entrance is a well and,

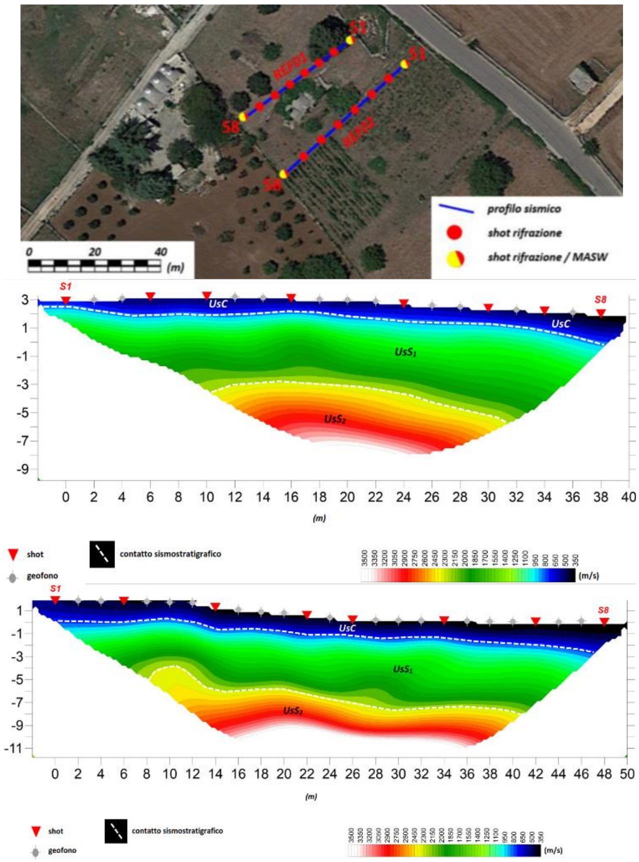
along its right side, a roughly quadrangular basin measuring 114 m x 90 cm, with a layer of plaster on the inside. Inside the well, the water level is -1 m. The floor of this first room features different elevations: along the south side, corresponding to Room B and the wall, there is a sort of seat 20 to 40 cm high, while the floor features a series of small artificial basins covered with friable earth.
Room B does not feature any architectural elements that indicate human activity; Nevertheless, the floor of this room seems to have been significantly removed and reworked: from the traces visible on the limestone rock, it is possible to observe how the current level of the ground is lower by about 60 cm.

Figure 4 - Room A of the hypogeum. On the floor level are a series of small basins filled with red earth and a basin and well/cistern; at the top right is the storage niche containing a large quantity of semi-buried ceramic materials, with a detail of the late medieval archaeological finds (bottom); at the center right is evidence of late medieval earthenware fragments, found outside the site.

In the storage niche of Room A, near the largest basin, semi-buried ceramic materials from the late medieval period are present (Fig. 4). In Room B, two large light-coloured amphora stoppers are present, clear evidence of the rural nature of the site. Numerous late medieval ceramic fragments were found outside the structure, including kitchen ware and monochrome green glazed ware (Fig. 4).

IV GEOPHYSICAL PROSPECTIONS

The geological study was accompanied and integrated with a geophysical campaign using seismic refraction and ground penetrating radar. Specifically, the geophysical survey, conducted along two profiles (Fig. 5), yielded the Vp values for three seismic stratigraphic units, defined as follows:
$Vp1 = 0 – 2{,}1 = 712$ m/sec
$Vp2 = 2{,}1 – 5 = 1850$ m/sec
$Vp3 = >5m = 2700$ m/sec



Layers	Vs (m/s)	Top depth	Thickness
1	290	0.0	1.3
2	670	1.3	1.4
3	820	2.7	1.9

Figure 5 – Location of the two seismic tomography profiles, P-wave profiles and thickness and Vs parameters.

These values represent a reasonably reliable estimate of the average velocities at various subsurface levels, including the limestone mass surrounding the cavity under examination. Essentially, a first level with medium-low velocities due to intense fissures combined with the presence of *terra rossa* inclusions in the discontinuities is followed by a second level with medium velocities, also characterized by widespread fissures but structurally more compact. The velocity of the substrate, located at a depth greater than 5 m, indicates a medium-high level of compactness.
These observations, when applied to the hypogeum examined, indicate a structural fragility of the dome, a relative compactness of the sides, and a good consistency of the substrate. These factors influence not only the hypogeum's geomechanical behavior hypotheses, but also the parameters of subsequent calculations and the construction interventions to be carried out.
The GPR survey was carried out along 10 profiles (Fig. 6), using a Hi-Mod GEORADAR, developed by IDS Italia, using a dual-frequency antenna (200 MHz-600 MHz),

which allows for a good compromise between resolution (medium-high) and penetration (medium). This choice was dictated by the need to identify the presence of anomalous bodies, up to a maximum depth of 3-4 m. The GPR scan datasets were processed using the REFLEXW software (Reflexw - Sandmeier Geophysical Research).

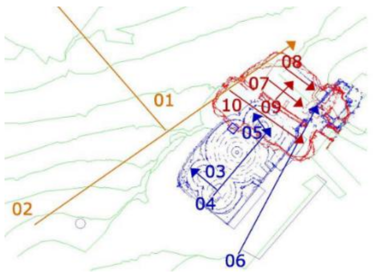


Figure 6 – Plan of the 10 GPR profiles. The floor level of the trullo is indicated in blue, and the underground chamber below is indicated in red.

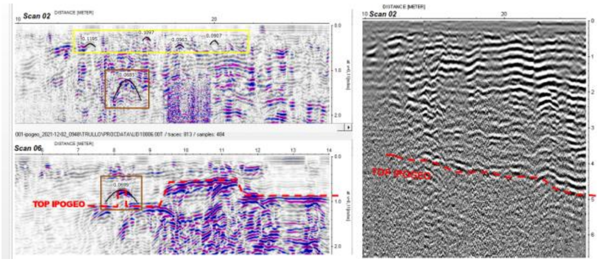


Figure 7 – Interpreted radargrams of profiles 2 and 6.

V GEOMECHANICAL CHARACTERS

Geomechanical analyses performed with the Schmidt hammer (sclerometer) provided average R values equal to 27.33 and 30.16, correlated to the uniaxial compressive strength equal to 46.54 3 48.09. Meanwhile, the RQD value was deduced from measurements on the fracture families affecting the rock mass, with values ranging between 59% (upper wall) and 87% (lower wall), with an average of 69.9%. The spacing between the various joints enclosed in the layers were found to be close to moderately distant. Regarding the geotechnical parameters, a volumetric weight γ of 2.2 g/cm^3 was reported, while the cohesion C and internal friction ϕ, derived from the corrected Benianski method, were found to be: C = 219 kPa $\phi = 27°$.

According to Hoek Brown's calculation, the shear strength values predict a cohesion C of 147 kPa and $\phi = 35°$ $\tau = 360$ kPa, while for Barton the values are equal to $\phi = 56.7$ and $\tau = 456$ kPa. Finally, rock masses, presenting greater diffusion and subvertical discontinuities, where these are more widespread, present a higher hazard index due to the possible detachment of disaggregated elements. In order to summarise and evaluate the shear resistance parameters (ϕ and C) indicated above, for the purposes of subsequent calculations, the possible average values are indicated:

Uniaxial compressive strength: 50 MPa
Roughness coefficient: 8
RQD index: 73
Volume weight: 2.2 g/cm^3
Friction angle: $\phi = 30°$
Cohesion (c) = 219 kPa (0.22 MPa)

In reality, in the specific case of calcareous rock materials, we cannot speak of true aggregation, but rather of aggregation conditions between the various rock elements that make up the vault and sides of the hypogeum, which present quite variable configurations. The vault has an irregular cross-section, with an average thickness of about 50 cm, thus visibly insufficient to support any loads and sustain itself over time. Possible settlement of the vaults of the hypogeum may also have contributed to the development of some crack patterns present in the trullo.

VI STABILITY ANALYSIS

The potential mechanism of instability in the hypogeum can essentially be traced back to the collapse of the vault, through successive phases of detachment of particularly fractured blocks. Secondary and very localized, destabilizing stresses along the lateral walls of the hypogeum can be considered, given the subhorizontal limestone layers. However, the partition dividing the two spaces does not exhibit obvious crushing phenomena, which could suggest deformation mechanisms of collapse of the vault. This model, in its evolution, would be similar to that of a beam subjected to bending stresses perpendicular to the plane axis of the subhorizontal layers. It follows that the static behaviour of this beam would depend not only on the dimensions of the vault, but also on the level of fracturing of the layers and the resulting tension between the individual ashlars. It follows that a reliable approach to the problem of the stability of the hypogeum vault can be based on that of an elastic beam supported at its ends [8]. The same authors have provided a corrected abacus, useful for evaluating the stability of the vault of a cavity, represented as a function of its length (span) and the thickness of the layer above it. In order to calculate the stability of the vaults and pillars of the hypogeum, an Examine 2D calculation algorithm [9] was applied, the results and parameters used are reported below (Figs. 6-9).

Figure 6 - Calculation of the Strength Factor in the hypogeum along section 1 (Fig. 2). The parameters used are visible on the right. The color scale shows strength or resistance factor values less than 1 (colors from yellow to red) along almost the entire surface of the flat vault.

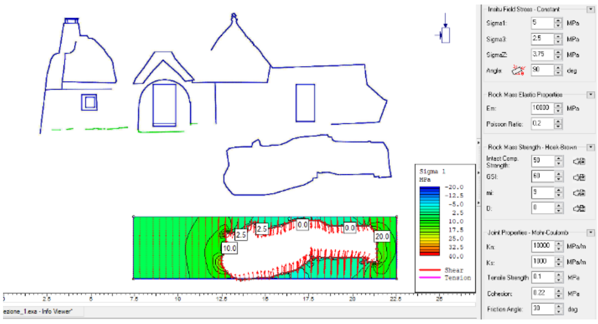


Figure 7 - Section 1 analyzed with the same parameters in which the trend and values of σ1 are shown.

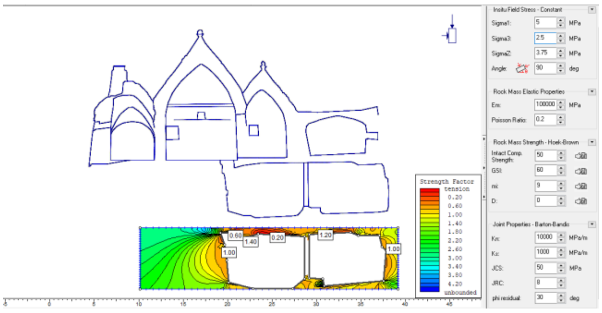


Figure 8 – Section 1 analyzed with the same parameters in which the trend and values of σ1 are shown.

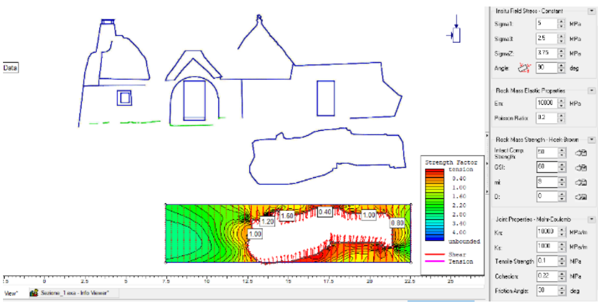


Figure 9 - Calculation of the Strength Factor in the hypogeum along section 2 (Fig. 4). The parameters are visible on the right. The color scale shows the values of the strength or resistance factor less than 1 (colors from yellow to red) along almost the entire surface of the flat vault.

VII DISCUSSION AND FINAL REMARKS

To determine structural weaknesses in the historic hypogeum beneath the trullo and verify the resistance factor values of the vaults and pillars along the transverse profiles, on-site visual analyses, in-situ geomechanical tests, and checks on the state of fracture of the rock mass characterizing the geological substrate of the trullo and the underlying hypogeum were conducted.

Following this on-site assessment, the safety factor of the hypogeum was calculated along the two sections using the Examine 2D calculation algorithm. This calculation revealed substantial structural weakness in the rock mass, especially in correspondence with the flat and slightly inclined vaults, with values less than 1.

The results show that the areas affected by the vaults and areas close to the central partition are in a state of potential collapse. Applications of the program on the two sections of the hypogeum revealed a resistance factor of less than 1, therefore the cavity may require consolidation interventions along both sections. All weak areas must be supported to increase the safety factor.

This structural weakness could also be responsible for some crack patterns present in the walls and vaults of the trullo above.

The rock mass in both areas A and B is strongly affected by the presence of a dominant family of discontinuities (stratification) arranged in a landslide-like manner, as well as individual discontinuities with a predominantly sub-vertical development, particularly visible in the upper portion of the wall.

Therefore, for the potential use of the hypogeum for tourism and cultural purposes, a low-impact structural consolidation intervention is recommended, which can help increase the safety factor while simultaneously preserving the nature and historical identity of the hypogeum.

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