Geotechnical Challenges and Stabilization Interventions in three Greek caves of Monumental Value

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ABSTRACT

Show caves are natural underground systems adapted for public access while often preserving archaeological, palaeontological, and geomorphological features of exceptional value. Their geotechnical management must reconcile visitor safety, monument-preservation constraints, and long-term performance under aggressive microclimatic conditions and high seismicity. This paper presents a mechanism-driven engineering framework for the investigation, analysis, design, and implementation of stabilization measures in such environments, illustrated through three Greek show caves of contrasting geotechnical character: Dikteon Cave (Crete), Theopetra Cave (Thessaly), and Petralona Cave (Chalkidiki). The regulatory framework used for the analyses are Eurocode 7 (CEN, 2004a) and Eurocode 8 (CEN, 2004b).

At Dikteon Cave, discontinuity mapping and kinematic analysis identified a limited number of structurally controlled roof wedges governing stability; these were stabilised by discrete, fully grouted stainless-steel anchors with minimal visual impact. At Theopetra Cave, the dominant hazard is external rockfall from steep slopes above the entrance and visitor route; the adopted solution combines selective reinforcement of unstable blocks with rockfall protection systems designed on the basis of stability analyses and rockfall trajectory and energy simulations. At Petralona Cave, the principal issue is the long-term stability of a near-vertical archaeological section excavated in heterogeneous infill deposits; stabilization was based on conservative characterisation, low-pressure grouting, highly limited reinforcement, and an observational approach supported by monitoring.

The three case histories demonstrate how a common engineering workflow can be adapted to fundamentally different instability mechanisms and material behaviours, and show that effective and heritage-compatible stabilization of show caves can be achieved through targeted, mechanism-driven interventions rather than through generalised or visually intrusive measures.

Keywords: Greek monumental caves; geotechnical engineering; Rock-mass stabilization; passive anchors; rockfall protection; cultural heritage

INTRODUCTION

Show caves differ fundamentally from engineered underground works. They are characterised by irregular geometry, discontinuity-controlled Rock-masses, long-term karst weathering, and strong spatial variability of material properties and boundary conditions. In many cases, they also preserve sensitive archaeological, palaeontological, and geomorphological features that impose severe constraints on investigation methods and admissible stabilization measures. In Greece, these difficulties are further amplified by the high level of seismicity, which requires explicit consideration of earthquake loading even for apparently localised instability mechanisms.

From a geotechnical point of view, the stabilization of show caves cannot be approached as a standard underground support problem. The governing hazards may range from structurally controlled wedge or block failures in competent Rock-masses, to slope-scale rockfall processes affecting cave entrances and access routes, to progressive degradation and ravelling of weak or heterogeneous infill deposits exposed by archaeological excavations. Treating such diverse situations using a single, uniform design philosophy is neither technically sound nor compatible with the strict constraints imposed by monument preservation.

- This paper addresses this problem through three representative Greek case studies that illustrate distinct “problem classes”:
- Dikteon Cave (Crete): internal instability governed by discontinuity-controlled wedges and blocks in limestone.
- Theopetra Cave (Thessaly): external rockfall hazard from steep slopes threatening the cave entrance and visitor routes.
- Petralona Cave (Chalkidiki): long-term stability of a near-vertical archaeological section excavated in heterogeneous infill deposits.

The purpose of the paper is not merely to document the stabilization measures implemented at these sites, but to demonstrate a mechanism-driven engineering workflow for the management of stability problems in monuments of this type. This workflow consists of: (i) targeted investigation under severe access and intervention constraints, (ii) identification of the governing instability mechanisms, (iii) selection of analysis tools and design approaches consistent with these mechanisms, (iv) definition of stabilization measures that are both technically effective and compatible with heritage requirements, and (v) implementation, documentation, and monitoring.

By comparing three sites with fundamentally different geological conditions, materials, and failure processes, the paper shows how the same general engineering logic can lead to very different intervention strategies, and illustrates why targeted, mechanism-based solutions are preferable to generalised or visually intrusive stabilization schemes in protected underground monuments.

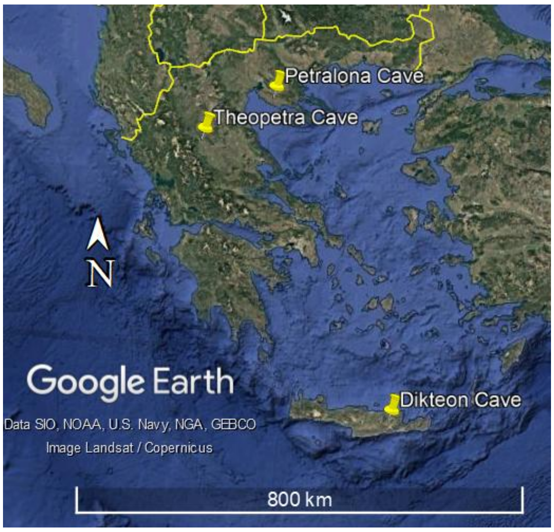

Figure 1. *Location map of Dikteon Cave (Crete), Theopetra Cave (Thessaly), and Petralona Cave (Chalkidiki).Source: Google Earth (Google, n.d.)*

METHODOLOGICAL FRAMEWORK

Multidisciplinary constraints in monument preservation

All three sites are protected monuments subject to strict archaeological and environmental supervision, which imposes significant constraints on both investigation and intervention. Any stabilization measure must therefore combine long-term effectiveness and durability with a high degree of visual discretion and minimal physical intrusion. In practice, this means that working space and access are often severely limited, intrusive investigations may be restricted or even prohibited, and material selection must account for the permanently humid cave environment, particularly with regard to corrosion resistance and grout compatibility. In addition, sensitive areas such as speleothems and archaeological deposits must remain untouched and, where possible, interventions should be reversible or at least fully traceable. Within this framework, the adopted strategy favours targeted stabilization of clearly identified failure mechanisms, while avoiding generalised linings or extensive surface treatments except in cases where the severity of the hazard makes such measures unavoidable.

Investigation strategy

The investigation programmes were designed to obtain the maximum possible amount of information while causing minimal disturbance to the sites. To this end, they combined detailed engineering geological mapping and geomorphological survey with systematic discontinuity surveys carried out at cave entrances, along accessible underground surfaces, and on external slopes. Where permitted, selective laboratory testing was performed to support material characterisation, while in situ index testing, such as Schmidt hammer measurements, was used to assist in the estimation of intact rock strength. In addition, geometric surveys were conducted with sufficient resolution to allow reliable definition of potential wedges and the layout of stabilization measures. In areas where direct observation was limited, for example due to speleothem cover, conservative ranges of geotechnical parameters were adopted and subsequently cross-checked against evidence of past instability and the observed behaviour of the Rock-mass.

Stability analysis approaches

Stability assessment followed a hierarchical approach. Initial kinematic screening using stereographic projection identified potential failure mechanisms. In the case studies of Diktaion and Theopetra Caves, these were followed by limit equilibrium analyses of critical blocks and wedges under static and seismic loading conditions. For slope-scale problems, two-dimensional analyses were applied where appropriate.

In addition to the aforementioned, at Theopetra Cave, kinematic rockfall analyses were used to evaluate runout and energy along visitor routes, informing the design of protection systems such as rockfall protection barriers and stainless steel protective meshes. In Petralona Cave, the focus was on long-term degradation and progressive instability rather than instantaneous failure.

Based on the conducted investigations and analyses, the expected instability mechanisms differ among the examined caves but are consistently controlled by geological structure, material properties, and external actions. In the Diktaion and Theopetra caves, instability is predominantly governed by discontinuity-controlled mechanisms within limestone Rock-masses, including wedge sliding, planar sliding, and local block detachment formed by the intersection of persistent joint sets. These mechanisms are particularly critical near cave entrances and along exposed slopes, where stress relief, weathering, and seismic excitation may significantly reduce stability margins and trigger block detachments.

In contrast, the Petralona Cave exhibits a fundamentally different failure mechanism, associated with the progressive degradation and potential localised shear failure of unconsolidated to weakly cemented cave infill deposits forming a near-vertical archaeological section. In this case, instability is driven by loss of apparent cohesion, moisture effects, and long-term material deterioration, rather than by abrupt Rock-mass failure.

Design framework and documentation

The design framework is based on a structured synthesis of architectural documentation, historical evidence, geotechnical investigation and structural analysis. Emphasis is placed on identifying the governing failure mechanisms associated with the interaction between the weak internal infill and the surrounding rock-mass. The available documentation is not treated as an end in itself, but as input to a targeted analytical process supporting diagnosis and intervention design. The adopted framework integrates qualitative observations with quantitative analyses, allowing consistent interpretation across different investigation scales.

Table 1 provides an overview of site conditions, dominant instability mechanisms, analytical approaches, and stabilization strategies for the three caves.

Table 1. Overview of site conditions, dominant instability mechanisms, analytical approach, and stabilization strategy for the three caves.

Cave (Location)	Geological/ Material context	Dominant Hazard	Main analysis tools	Key Stabilization Measures	Verification/ Outcome
Dikteon (Psychro, Crete)	Limestone; discontinuity-controlled roof/entrance	Wedge sliding; block detachment; local rockfalls	Kinematic and wedge stability (static & seismic)	Passive anchors AISI316 Ø27, fully grouted; local scaling where permitted	Wedge FoS[1]: before 0 up to 1.2; after 1.12 up to 2.36
Theopetra (Trikala, Thessaly)	Limestone slopes up to ~90 m above route	External rockfall; wedge/planar failures near entrance	Kinematic and wedge stability; rockfall simulation	Selective anchoring; barriers (energy class 5000kJ, 6m), mesh	Barrier energy absorption 100% Wedge[2] FoS: before 0 up to 0.63; after 2 up to 5
Petralona (Chalkidiki)	Heterogeneous infill deposits; archaeological section	Progressive ravelling; local shear; moisture-driven degradation	Observational and conservative stability checks; staged improvement	Low-pressure grouting; discreet reinforcement only where permitted; monitoring	FoS PS[3]: before 0.68 up to 2.53 after 1.01 up to 3.77

[1]FoS: Factor of Safety; [2]2-d Analyses of the roof wedges; [3]PS: 2-D Pseudostatic Plain Strain Analysis of the sediments

The geotechnical and Rock-mass parameters adopted for the numerical analyses were derived from detailed rock mechanics and laboratory testing programmes carried out independently for each cave. Table 2 summarises the representative values finally selected for design and verification analyses. These values reflect both the intact rock properties and the degradation induced by jointing, tectonisation, and weathering, as expressed through GSI-based Rock-mass classifications and equivalent deformability and strength parameters (Hoek 1980a,b; Marinos & Hoek 2000; Hoek 2002). For the Petralona Cave, particular emphasis was placed on the mechanical characterisation of the archaeological infill and debris deposits, which control the stability of the excavated vertical faces. In all cases, conservative parameter selections were adopted in order to ensure that the proposed stabilization measures remain robust under adverse geological and mechanical conditions.

Table 2. Representative geotechnical parameters adopted in the three case studies

Site	Material	γ kN/m³	GSI	Ei GPa	Erm GPa	UCS_{intact} MPa	$\sigma_{ci,RM}$ MPa	φ °	c kPa
Dikteon	Intact Limestone rock-mass	25.2	90	17.5	16.5	30	20.5-35.0	-	-
	Cracked Limestone rock-mass	25.2	45-50	17.5	5.4	30	6.6	-	-
	Joints	-	-	-	-	-	-	30	0
Theopetra	Limestone Rock-mass	26.3	-	28.0	-	50	-	-	-
Petralona	Limestone Roof	25.0	75	25.0	20.4	50	12.4	60	1250
	Limestone wall	26.0	60	20.0	10.4	40	4.2	60	530
	Debris infill	24.0	10~40	4.5	0.1~ 0.7	15	0.04~ 0.5	45~ 55	1~75
	Cemented Deposits	19.0	-	-	5.0	16	-	60	400
	Clayey Gravel	19.0	-	15~20	-	-	-	36~ 40	10~15

CASE STUDY: DIKTEON CAVE (PSYCHRO, CRETE)

Geological Conditions and Stability Challenges

Dikteon Cave is located above the village of Psychro on the Lasithi Plateau, at an elevation of approximately 1,025 m. The cave is developed within limestone formations and consists of an upper, non-accessible part and a lower section open to visitors. The accessible part extends over approximately 60 m, while the total cave area is about 2,200 m² (Figure 2). Extensive speleothem development locally limits direct observation of the Rock-mass and constrains both investigation and intervention.

Instability phenomena have been documented both inside the cave and in the entrance area. Near the entrance, stress relief and weathering promote loosening and detachment of blocks from the exposed Rock-mass. Inside the cave, the Rock-mass is intersected by several persistent discontinuity sets whose intersections define discrete roof wedges above the visitor routes, creating a clear potential for structurally controlled instability. The investigation and design basis follow the geotechnical–rock mechanics study and the implementation study (Egglezos, 2016, 2023).

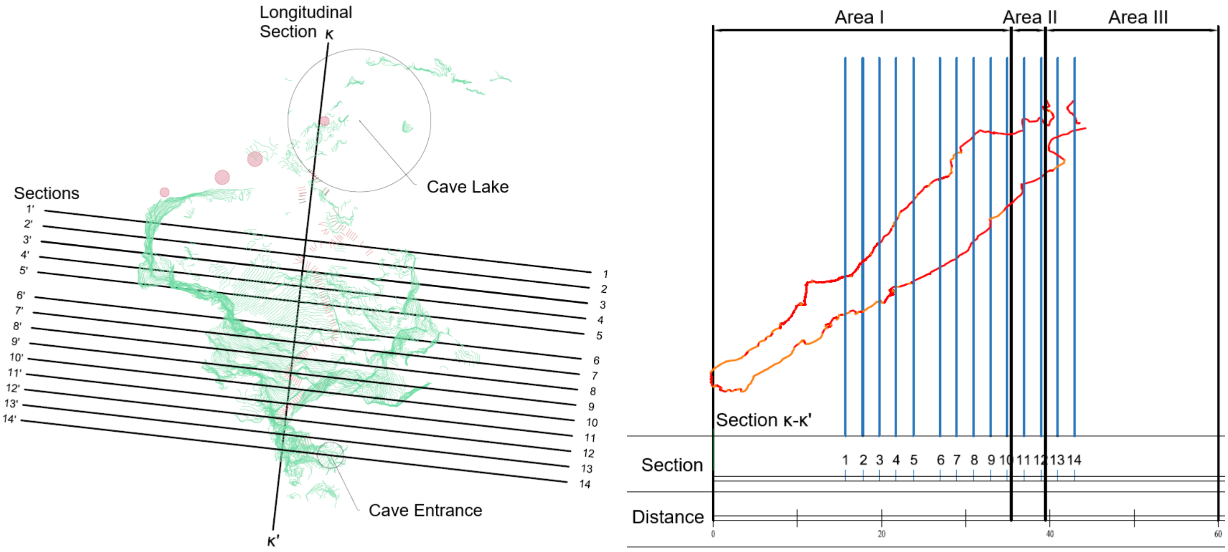

Figure 2. Plan view (Left) and longitudinal (Right) section of Dikteon Cave showing investigated zones and stabilized locations.

Kinematic Assessment and Limit Equilibrium Evaluation of Roof Wedges

Engineering geological mapping was concentrated in the entrance zone and in the first part of the accessible cave, where direct observation of the Rock-mass was possible. Three main discontinuity sets were identified, whose intersections form a limited number of kinematically feasible roof wedges (Figure 3). Kinematic analysis showed that wedge sliding is the dominant potential failure mechanism, while planar sliding and toppling are locally possible but of secondary importance.

Limit equilibrium analyses were carried out for the most critical wedges under both static and seismic loading conditions. The results showed that overall stability is governed by a small number of geometrically well-defined blocks located above the main visitor paths, whereas the remaining parts of the cave roof exhibit significantly higher safety margins. Sensitivity analyses with respect to friction angle and seismic coefficient confirmed that uncertainties in mechanical parameters primarily affect these same critical wedges and do not change the ranking of the most unstable blocks. On this basis, a targeted stabilization strategy focused exclusively on these controlling wedges was adopted.

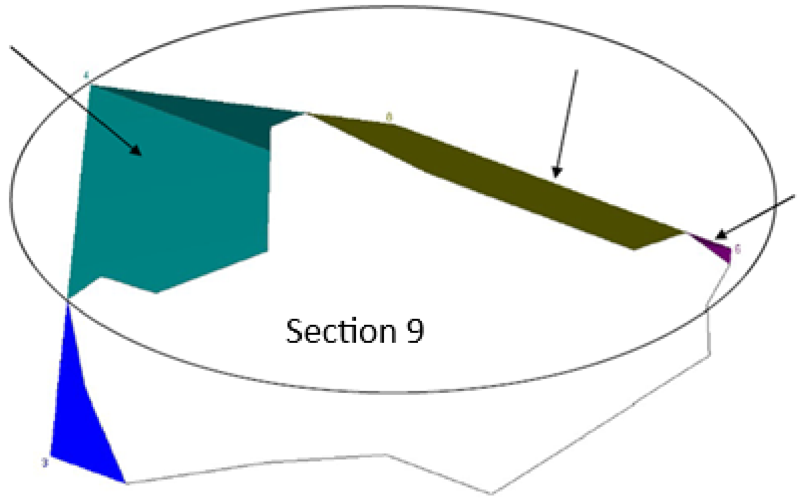

Figure 3. *Wedges susceptible to failure near Section 9 of Dikteon Cave (unaupported condition). 0.0 ≤ $FS_{min,Static\ Load}$ ≤ 1.2 and 0.0 ≤ $FS_{min,EQ}$=0.9.*

Stabilization measures

Stabilisation (Figure 4) was achieved through targeted interventions designed to confine the identified critical wedges. Fully grouted passive stainless-steel anchors made of AISI 316 steel with a diameter of 27 mm were installed to intersect the controlling discontinuities and provide internal restraint of potentially unstable blocks, as shown in Figure 5. The anchor configuration was defined by an inclination of 25° from the vertical, lengths ranging from 4 m to 8 m, and spacing varying between 2.00 × 2.00 m and 3.00 × 3.00 m. These parameters were optimised to ensure mechanical effectiveness while minimising visual intrusion and avoiding contact with sensitive speleothem surfaces.

This targeted approach made it possible to avoid any generalised lining or surface treatment and to restrict the intervention strictly to structurally necessary locations. All works were executed under strict archaeological supervision, with particular emphasis on vibration control, protection of speleothems, and detailed documentation of drilling, grouting, and installation procedures.

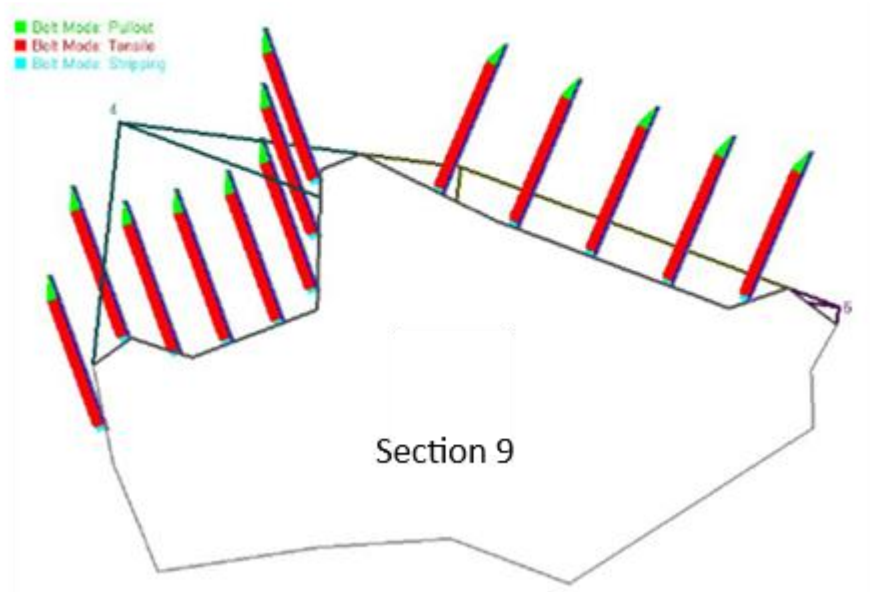

Figure 4. *Wedges susceptible to failure near Section 9 of Dikteon Cave (stabilisation measures). $FS_{min,Static\ Load}$=1.78, $FS_{min,EQ}$=1.12.*

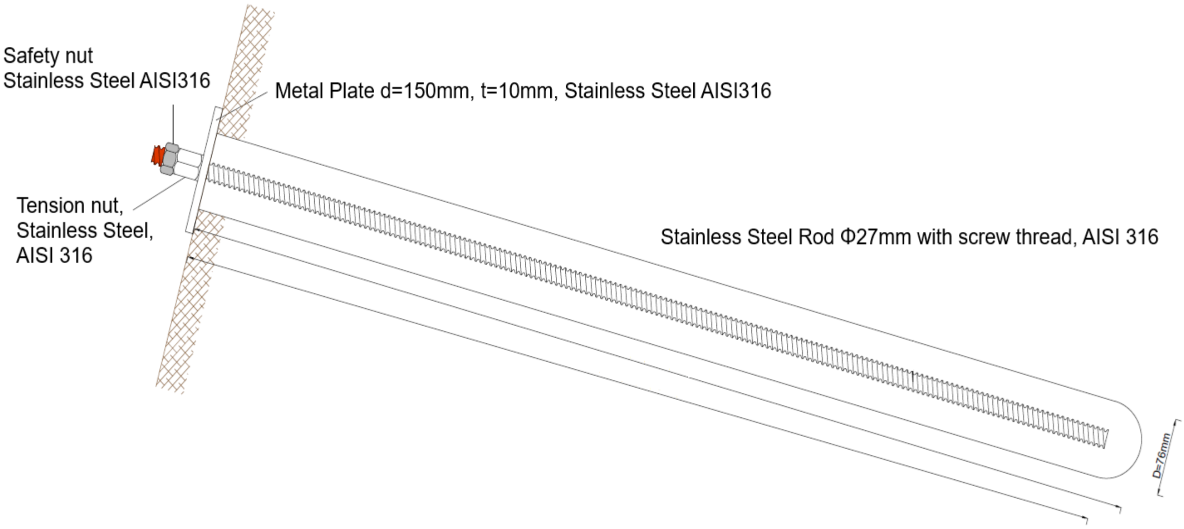

Figure 5. *Typical passive anchor arrangement and installation detail for Dikteon Cave.*

CASE STUDY: THEOPETRA CAVE (TRIKALA, THESSALY)

Geomorphological setting and Rock Slope instability Hazards

Theopetra Cave is located near Kalambaka in Thessaly, at an elevation of approximately 280 m. The cave entrance is an arched opening about 17 m wide and 3 m high, leading to a main chamber of roughly 500 m². Visitor access follows a developed route situated directly beneath steep limestone slopes whose heights locally reach approximately 90 m (Figure 6).

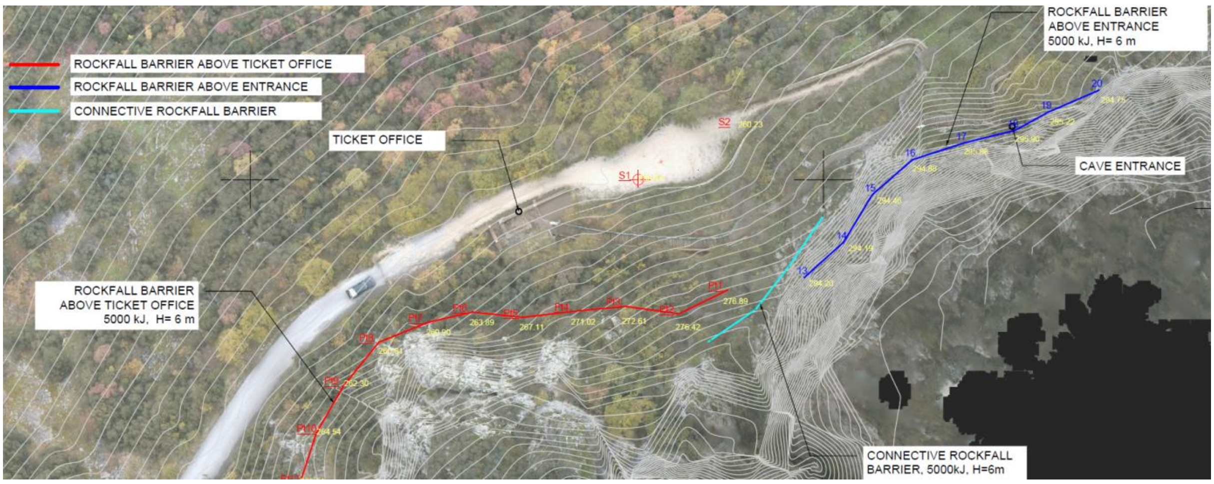

Figure 6. *Topographical Survey of the archaeological site of Theopetra Cave, and as-built location of rockfall protection barriers.*

In contrast to Dikteon Cave, the dominant hazard at Theopetra does not originate primarily from the cave interior but from the surrounding rock slopes. Recurrent rockfalls and block detachments from the external slopes threaten both the cave entrance and the visitor access route. Field evidence confirms that this instability is active and ongoing and must be addressed at the scale of the slope rather than solely at the cave opening.

Structural Geological Survey and Stability Evaluation of Internal Rock Wedges

Inside the cave, detailed discontinuity surveys revealed several persistent joint sets capable of forming wedges, planar sliding surfaces, and locally toppling-prone blocks. Regarding the area outside of the cave, kinematic analyses were used as a first-level screening tool to identify potentially unstable rock blocks both near the cave entrance and on the slopes above the access route. Subsequent limit equilibrium analyses were carried out for the most critical blocks and wedges under static, saturated, and seismic loading conditions.

The investigation and design basis follow the geotechnical–rock mechanics implementation study (Egglezos, 2018).

Figure 7 displays the formed wedges inside the cave and the results of the wedge analyses for both the untreated and treated conditions. These analyses showed that, in the untreated condition, several wedges in the vicinity of the cave entrance exhibit very low safety margins, with computed factors of safety under static conditions locally ranging between 0 and approximately 0.6, depending on joint persistence and water conditions. After the implementation of stabilization measures, the corresponding values increase to the range of approximately 2.0 to 4.1, confirming that local block stability can be effectively restored through targeted reinforcement.

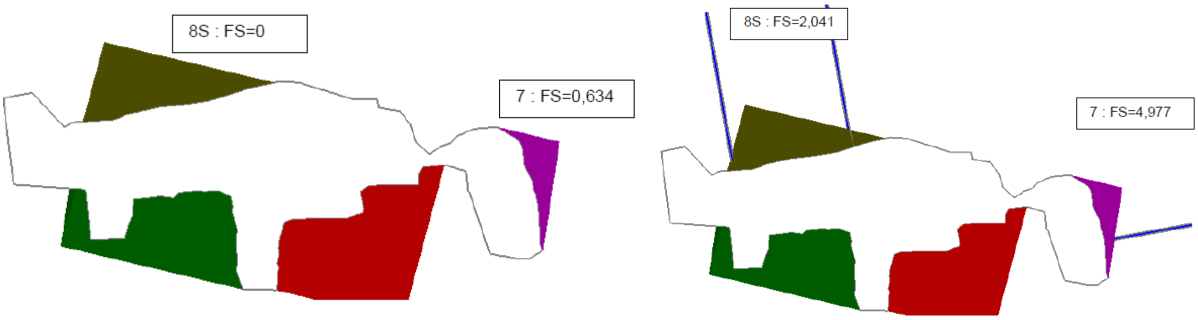

Figure 7. *Safety factor of wedges inside the cave near the location of section D30, under Static Condition with great joint advancement (Left: FoS=0~0.634), Static Condition after measure implementation (Right: FoS=2.041~4.077).*

Rockfall Trajectory Analysis

The potentially unstable blocks located outside the cave (above the entrance and along the visitors' route) higher on the slopes could generate rockfalls capable of reaching the visitor areas. This became clear from the early stages of the study during the in-situ inspection. Therefore, the local reinforcement of the roof wedges inside the cave could not be sufficient to ensure the safety of the visitors during their tour inside the area of the archaeological site.

For this reason, a detailed kinematic rockfall analyses were carried out for the steep rock slopes located above and around the cave entrance. The analyses were based on representative geometric models of the slope profiles and aimed at simulating the possible trajectories of falling blocks from likely release zones down to the accumulation areas near the visitor route.

Conservative assumptions were adopted for the initial detachment conditions, including block size and initial release velocity, consistent with gravity-driven failure mechanisms. The simulated motion included successive phases of free fall, impact, bouncing, rolling, and sliding, taking into account the local slope geometry and the mechanical response of the ground surface. For each investigated cross-section, 200 trajectories were simulated in order to capture the inherent variability of block paths and impact locations.

The results were evaluated in terms of maximum runout distance, bounce height, impact energy, and spatial distribution of trajectories. Particular emphasis was placed on the envelopes of kinetic energy at critical locations along the slope, especially at positions where protective measures could realistically be installed. The analyses showed that a limited number of sections concentrate the highest rockfall intensities and therefore govern the overall design of protection works. On this basis, a design kinetic energy of approximately 5,000 kJ and a required barrier height of 6.0 m were adopted for the main protective structures. The essential parameters used in the rockfall simulations are summarised in Table 3.

Table 3. Essential parameters used in the rockfall analyses

Parameter	Symbol	Value	Unit	Remarks
Block mass	m	up to 10000	kg	Representative unstable block size
Initial release velocity	v_0	0.1	m/s	Conservative detachment condition
Normal restitution coefficient	R_n	0.4	-	Controls rebound height
Tangential restitution coefficient	R_t	0.8	-	Controls post-impact rolling
Friction coefficient	μ	0.5	-	
Number of simulated trajectories	N	200	-	Statistical sampling
Design kinetic energy	$E_{k,design}$	5000	kJ	Governing value for barrier design
Barrier height	H	6.0	m	Selected from trajectory envelope

Integrated Stabilization and Rockfall Protection Strategy

Based on the above analyses, an integrated stabilisation strategy was adopted, combining local reinforcement measures with slope-scale rockfall protection systems. The roof wedges inside the cave were stabilised using fully grouted, mechanically anchored stainless-steel anchors of 27 mm diameter, installed at a length of 8 m and a spacing of 2 m. Outside the cave and close to the entrance area, the potentially unstable blocks were similarly stabilised using fully grouted, mechanically anchored stainless-steel anchors of the same diameter, with a length of 12 m and a spacing of 3 m. In both cases, smaller unstable fragments were removed where feasible and where such actions remained compatible with monument protection requirements.

At the same time, rockfall protection measures, including high-energy absorption barriers and anchored meshes, were installed at selected locations along the slope above the cave entrance and the visitors' route in order to intercept falling blocks before they could reach the accessible areas and the cave entrance (Figure 8). The main barrier was designed for an energy absorption capacity of 5,000 kJ and a height of 6.0 m, as dictated by the rockfall analysis. All measures were designed and implemented so as to remain visually discreet and compatible with the monumental character of the site.


Figure 8. *Left: The protective barrier above the entrance and the visitor walkway on the near-vertical slope. The protective barrier (6m; 5000kJ) above the ticket office and the visitor walkway is nearly hidden by the tree-line. Right: Anchors (AISI316; Ø27~28) on the wedge above the cave entrance (inside), right before non-destructive tests.*

CASE STUDY: PETRALONA CAVE (CHALKIDIKI)

Geotechnical Challenges of Archaeological Excavation Faces in Weak Infill Deposits

Petralona Cave is internationally known for its paleoanthropological and archaeological importance. The geotechnical problem addressed in this case does not concern the stability of the cave as a whole, but the stability of the steep to locally near-vertical faces created by the archaeological excavation of the cave infill deposits, which are located in close proximity to visitor pathways (Figure 13). In contrast to Dikteon and Theopetra, where instability is governed by discontinuity-controlled mechanisms in limestone, the controlling processes here are associated with the time-dependent behaviour and progressive degradation of weak and heterogeneous infill materials.

Accordingly, the design approach was governed by three principal constraints: (i) reduction of risk to visitors, (ii) preservation of the stratigraphic readability and scientific value of the exposed section, and (iii) application of technically necessary stabilization measures with controlled spatial extent and careful integration within the archaeological environment.

The investigation and design basis follow the geotechnical–rock mechanics implementation study (Geo.Per. S.A., 2021).

Material characterisation and modelling approach

The exposed profile consists of heterogeneous infill deposits with variable degrees of cementation and complex internal stratigraphy. For engineering purposes, these materials were grouped into a limited number of representative units, including: (i) fine-grained, matrix-supported horizons prone to ravelling under moisture variations, (ii) mixed sandy and gravelly horizons exhibiting variable apparent cohesion, and (iii) locally cemented lenses or blocky horizons capable of producing small-scale detachments.

The governing instability mechanism is progressive rather than sudden and is characterised by ravelling of fine material, development of shallow local shear zones, and detachment of small cemented fragments. On this basis, the assessment focused not on the possibility of a single large-scale collapse, but on the long-term mechanical performance of the excavation under adverse combinations of moisture conditions, time-dependent degradation, and seismic loading.

Limit Equilibrium Stability Assessment and Evaluation of Stabilization Effectiveness

In its original configuration, the mechanical behaviour of the excavation was controlled almost entirely by the low strength, pronounced heterogeneity, and high deformability of the infill deposits. Two-dimensional limit equilibrium slope stability analyses showed that, under several representative loading scenarios, including seismic action, the excavation developed sliding surfaces that were incompatible with long-term stability requirements (Figure 9). In several critical cross-sections, the computed safety factors approached the lower bound of acceptability. This behaviour demonstrated the limited robustness of the original geometry and confirmed the need for systematic stabilization.

Following the implementation of the stabilization works, the mechanical response of the excavation changed fundamentally. The combined application of low-pressure grouting, selective reinforcement, and limited local geometric modification is expected to lead to a substantial increase in the stiffness and strength of the infill mass and to a more confined and coherent mechanical behaviour.

For all critical sections examined, the computed safety factors under both static and seismic loading conditions satisfy the applicable design criteria (Figure 10).

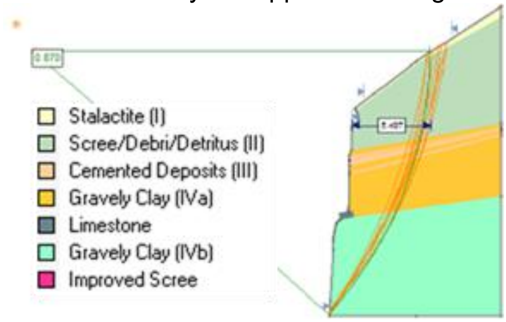

Figure 9. *Seismic stability analysis (Janbu, 1973 method), downward vertical acceleration component, existing configuration;* F_s*,min = 0.87; sliding surfaces with FOS < 1 (Geo.Per. S.A., 2021).*

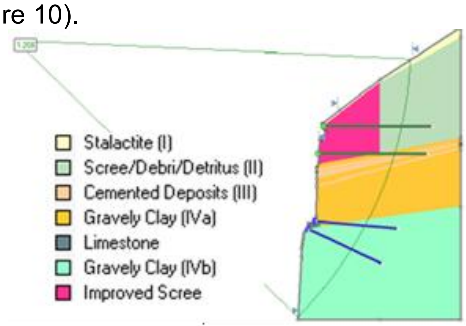

Figure 10. *Seismic stability analysis of the stabilization measures using the Janbu, 1973 method – downward vertical acceleration component;* F_s*,min = 1.21 (Geo.Per. S.A., 2021).*

Finite Element Elasto-Plastic Seismic Analysis

Following the limit equilibrium assessment, two-dimensional pseudo-static analyses were performed to further investigate the stress–deformation response of the system and to quantify displacement demand under seismic loading. The analyses were carried out using an elasto-plastic continuum model for the infill material, coupled with linear elastic behaviour for the surrounding rock-mass. Seismic action was introduced through horizontal pseudo-static coefficients consistent with the adopted design spectrum, while pore pressure conditions were modelled explicitly. The results (Figure 11) are evaluated in terms of global stability indicators and permanent displacement metrics.

Following the implementation of the stabilization works, the calculated permanent displacements are reduced to clearly acceptable levels. For all critical sections examined, the computed safety factors under both static and seismic loading conditions satisfy the applicable design criteria (Figure 12).

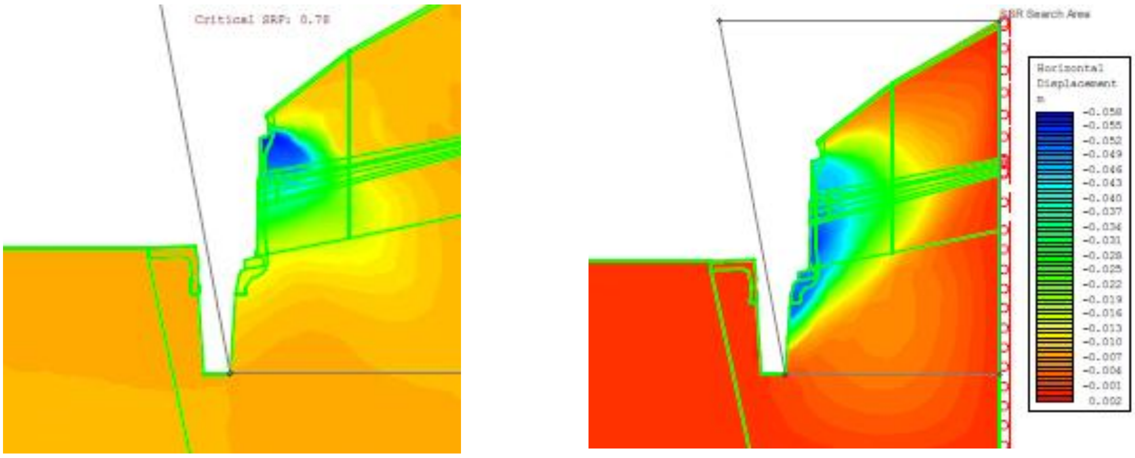

Figure 11. *Left: Seismic 2D elasto-plastic stability analysis with finite elements – downward vertical acceleration component – existing configuration –* F_s*,min = 0.78. Right: Seismic 2D elasto-plastic stability analysis with finite elements – downward vertical acceleration component – existing configuration – maximum permanent horizontal displacement Δh = 0.058 m (Geo.Per. S.A., 2021).*

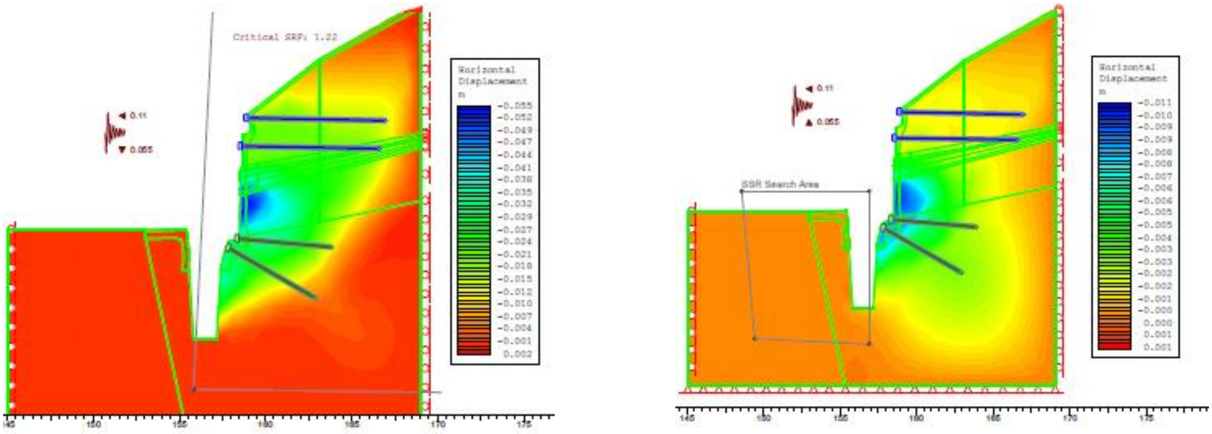

Figure 12. *Left: Seismic 2D elasto-plastic analysis using the SSR method (finite elements) – stabilization measures – downward vertical acceleration component –* F_s*,min = 1.22 Right: Seismic 2D elasto-plastic stability analysis of the stabilization measures with finite elements – downward vertical acceleration component – maximum permanent horizontal displacement Δh = 0.011 m (Geo.Per. S.A., 2021).*

A key outcome of the analyses is that the treated configuration exhibits a qualitatively different mechanical behaviour compared to the original state. Instead of showing a tendency toward progressive degradation and localised instability, the improved infill mass responds in a more uniform and controlled manner, with significantly reduced sensitivity to unfavourable combinations of actions. The intervention strategy therefore achieved not only an increase in formal safety margins, but also a fundamental improvement in the overall robustness of the excavation.

Characterisation, implementation, and verification

Because of the extreme archaeological sensitivity of the site, intrusive investigations were strictly limited. Material characterisation therefore relied primarily on detailed stratigraphic logging, selective sampling, and conservative parameter selection. Stability assessment was focused on progressive ravelling and moisture-driven degradation processes rather than on sudden, large-scale collapse mechanisms.

Stabilization measures consisted mainly of low-pressure grouting to improve local cohesion and continuity of the infill mass, combined with highly discrete reinforcement in strictly limited locations where this was permitted. Post-intervention verification is based on systematic visual inspections and repeat photographic documentation, which confirm a clear reduction in ravelling rates and the stable long-term preservation of the exposed stratigraphic section.

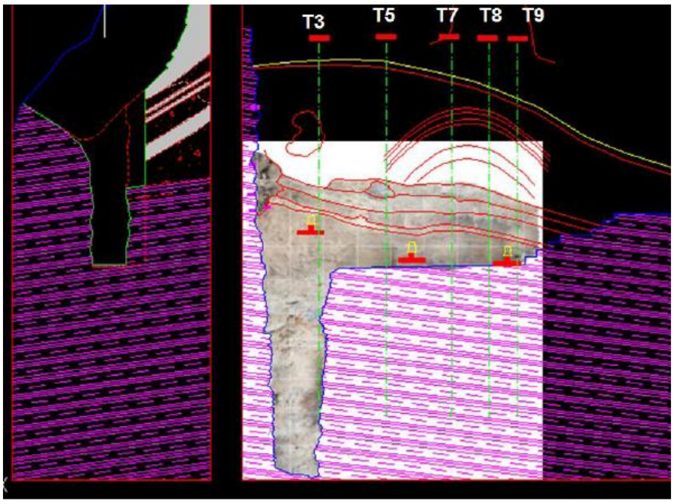

Figure 13. *Left: Cross-section and Right: Front view of the Vertical archaeological section in Petralona Cave (Geo.Per. S.A., 2021).*

COMPARATIVE DISCUSSION

Although the three caves are characterised by different geological materials, geometries, and types of hazard, their stabilization was guided by a common engineering logic: identification of the governing instability mechanisms, selection of analysis tools consistent with these mechanisms, and definition of targeted interventions compatible with the constraints of monument preservation.

In Dikteon and Theopetra, instability is primarily controlled by the structural fabric of the limestone Rock-mass, leading to wedge, planar, or block-type failure mechanisms. However, even within this apparently similar geological context, the scale and nature of the hazard differ fundamentally. At Dikteon, the problem is local and internal to the cave and can be addressed through the confinement of a limited number of critical roof wedges. At Theopetra, in contrast, the dominant hazard originates from the surrounding slopes and is slope-scale, and local reinforcement alone is insufficient; the stabilization strategy must therefore combine selective anchoring with rockfall protection measures designed on the basis of kinematic and runout analyses.

At Petralona, the governing mechanisms are fundamentally different. Here, instability is not controlled by discontinuities in competent rock, but by the time-dependent and moisture-sensitive behaviour of weak and heterogeneous infill deposits. The problem is therefore not one of preventing a single, well-defined collapse mechanism, but of controlling progressive degradation, ravelling, and localised shear over long periods of time. Treating this situation as a variant of a “rockfall problem” would be conceptually incorrect and could lead to inappropriate and overly intrusive interventions.

Taken together, the three case studies demonstrate that apparently similar “safety problems” in show caves may in fact be governed by very different mechanical processes, and that effective stabilization requires the explicit recognition of these differences. The unifying element is not the type of measure adopted, but the mechanism-driven workflow that links investigation, analysis, design, and implementation.

CONCLUSIONS

This paper shows that the safe and sustainable stabilization of show caves of monumental value can be achieved through a mechanism-driven geotechnical workflow that explicitly respects the constraints imposed by heritage protection and public accessibility. The three case studies illustrate how this general approach must be adapted to fundamentally different geological conditions, material behaviours, and scales of hazard.

At Dikteon Cave, where instability is governed by discontinuity-controlled wedges in the cave roof and entrance area, the problem can be effectively addressed through discrete passive anchoring systems that provide the required level of safety with minimal visual and physical intrusion. At Theopetra Cave, the dominant hazards originate from the surrounding slopes rather than from the cave interior, and stabilization therefore requires an integrated strategy combining local reinforcement with rockfall protection measures designed on the basis of kinematic analysis, stability checks, and runout and energy assessment. At Petralona Cave, where hazards are controlled by the behaviour of weak and heterogeneous infill deposits, the governing problem is progressive degradation rather than sudden large-scale failure, and stabilization must accordingly be gentle, staged, and supported by monitoring rather than by aggressive structural interventions.

Across all three cases, a number of common principles proved to be essential: conservative characterisation under severe investigation constraints, explicit consideration of seismic effects where relevant, preference for targeted and reversible interventions over generalised treatments, and systematic documentation and verification of the works. More generally, the presented case histories show that, in complex underground monuments, engineering success depends less on the application of standardised solutions than on the rigorous identification of the controlling mechanisms and on the disciplined adaptation of design and construction strategies to the specific character of each site.

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