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Safeguarding archaeological excavations and preserving cultural heritage in cave environments through engineering geological and geophysical approaches

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ABSTRACT

Cave excavations pose several challenges, notably the stability of surrounding rocks crucial for archaeologists' safety and site conservation. Engineering geological modells, supported by geophysical investigations, provides effective solutions for rock stability assessment, pivotal in designing safety measures to protect archaeological sites, thereby enhancing accessibility for tourism purposes. This research dealt with a combined engineering geology and geophysics approach for rock stability assessments, incorporating the results into archaeological procedures at the Battifratta Cave (Central Italy). The rock mass characterisation was performed through direct geomechanical surveys and 3D photogrammetric reconstructions. Ambient seismic noise measurements were performed to identify potential subsurface cavities beneath the ground floor, while ambient vibration measurements highlighted prone-to-fall rock blocks. Geophysical techniques have been experienced as a monitoring strategy to support design for archaeological excavation project. More in particular, they allow identifying potential changes in dynamic properties or precursor signals of impending deformation in rock blocks posing a threat to the excavation area. Cross-fertilisation between the Earth Sciences and Cultural Heritage Sciences results in the definition of best practices to be applied in different archaeological contexts.

1. Introduction and research aim

Caves are by far the most evocative archaeological sites. Due to their predisposition to maintain a stable environment, they enable exceptional preservation of organic materials and rock art. These sites are frequently associated with ritual or funerary activities, preserving human skeletal remains, grave goods, and other evidence critical to understanding rituals, belief systems, and aspects of health, diet, and ancient lifestyles (Elster et al. 2016; Goude et al. 2020; Moyes 2012; Peterson 2018). Caves are also powerful archives of palaeoenvironmental records, retaining crucial information about past climates, vegetation changes, and geological events (Carrion et al. 2022; Pieruccini et al., 2022; Fairchild and Baker 2012; White 2007; Woodward and Goldberg 2001). Nevertheless, cave exploration and excavation pose significant challenges, including problems of access, conservation, and safety risks.

Several scientific studies discuss rock instability in caves, particularly concerning the preservation of the natural karstic environment (Van Beynen 2005) or the archaeological heritage (Leucci 2018). Specific attention is dedicated to safeguarding carved or painted rock art (Álvarez et al. 2018; Iriarte et al. 2010), while other studies emphasise the management of tourist flow within cave systems (Badge 2021; Parise 2011). More diffusely previous researches addressed the stability of exposed rock masses, which host in a natural contest an archaeological site, as in the case of caves, tombs, or on-rock artistic representations or sculptures (Hatzor 2003; Wang et al. 2021; Beni et al. 2023; Gallego et al. 2023, Fener and Varol 2024).

However, less emphasis has been placed so far on the safety issue,

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beginning with working conditions during archaeological excavation. Indeed, the issue of rock stability within caves and rock shelters is critical for archaeological exploration, with enormous implications for both the safety of field researchers and the preservation of invaluable cultural heritage.

The intersection of these concerns highlights the critical need for standard protocols dedicated to assessing and managing rock stability, a domain that, despite its obvious importance, remarkably lacks standardised methodologies in the archaeological field of application, especially during the excavation phases, or even earlier, in the planning stages of field research. To this aim, the development of comprehensive and standardised protocols for addressing rock stability during archaeological investigations would be a significant step forward. Such protocols would serve as the foundation for assessing, monitoring, and mitigating structural instability risks in cave or rock shelter environments.

Regarding archaeological deposits in caves, the conservation challenge needs to be tackled considering cultural and natural heritage aspects. Consequently, an interdisciplinary approach becomes essential for effective intervention, drawing on geology, engineering, and archaeology expertise. The risk assessment, monitoring, and research planning are components of the knowledge acquisition phase (Valagussa et al., 2021). Together with conservation, management, and fruition, these elements form the pivotal steps in cultural heritage management, which are inherently interconnected and are not to be considered independently (Margottini and Spizzichino 2015). Such a holistic approach can be particularly crucial for addressing safety challenges associated with jointed rock masses during archaeological excavation activities. For instance, the enhancement of these practices may range from the geomechanical characterisation of outcropping rock masses to the application of monitoring strategies encompassing ambient vibration and microseismic activity monitoring systems (Martorana et al. 2023). In particular, the definition of monitoring strategies suitable for the geologic context in which an archaeological site is found can drastically contribute to personnel safety and play a vital role in preserving the integrity of archaeological heritage sites. Ambient vibrations can be successfully used to detect signals indicating the progressive worsening in the area's stability conditions, especially in caves located in fractured rock masses (i.e., recognition of precursor signals of fracturing processes or change over time of the dynamic response of single rock elements). Near-surface geophysical applications have found broad application up to now for the analysis of microseismic events related to fracture propagation processes within rock masses or the detachment of rock blocks both in the natural environment (Arosio et al. 2018) and to monitor the stability of rocky materials during the excavation of tunnels (Tang et al. 2015), drainage plant (Dai et al. 2017), as well as for quarries and mines (Liu et al. 2020). Only in a few cases ambient vibration systems have been installed at archaeological assets to monitor damage induced by thermal or seismic actions (Bakun-Mazor et al. 2013; Alcaino-Olivares et al. 2021).

Ambient vibrations can also be used for the identification of dynamic structural properties of natural rock elements, such as modal frequencies, modal damping, and deformation patterns (i.e., mode shapes), that can be tracked over time for structural health monitoring (SHM) to detect and describe damage that may derive from natural and anthropogenic influences (Levy et al. 2010; Bottelin et al. 2013; Burjánek et al. 2018; Colombero et al. 2021; Geimer et al. 2022). These dynamic properties are, in fact, controlled by material properties and local boundary conditions, meaning that in-situ measurements can provide data useful for the creation and refinement of structural stability models. Besides, the non-invasive nature of ambient vibration measurements makes this geophysical method particularly suited for applications at cultural or natural heritage sites (Grechi et al. 2024; Ioannidis et al. 2024).

In this research, a challenge was to explore a multidisciplinary approach by combining archaeology, engineering geology, and geophysics, to develop best practices applicable to ongoing archaeological excavations in cave environments. This allowed us to highlight the innovative integration of these fields to address the critical issue of rock stability, with the aim of enhancing both the safety of excavation personnel and the preservation of archaeological sites. By integrating geomechanical surveys, 3D photogrammetry, and geophysical monitoring techniques, this study seeks to identify precursory signals of potential rock block instability in a cave environment object of excavation, a topic that has been underrepresented in previous literature. The here obtained findings aim at defining guidelines which can be applied across different archaeological contexts, enhancing their protection and management.

2. Materials

2.1. Geological background and cave geomorphology of Battifratta Cave

The Battifratta Cave (LA 896) is located approximately 40 km NE of Rome, Italy, in the municipality of Poggio Nativo (RI), in the central Apennines in the Sabina Mts. that is part of the central Apennines fold-and-thrust belt built up mainly in the Neogene times (Cosentino et al. 2010) (Fig. 1a). The Meso-Cenozoic stratigraphical succession that crops out in the proximity of Battifratta cave is Umbria-Marche-Sabina shelf to a deep-water pelagic domain and Plio-Pleistocene continental deposits (Servizio Geologico d'Italia, sheet 357 Cittaducale). In particular, the stratigraphic succession surrounding the Battifratta Cave consists of the Upper Cretaceous to lower Eocene reddish marly limestone with chert bearing of Scaglia Rossa Fm. (SAA in the geological map) (~200 m, Lower Turonian-Ypresian) and marly limestone to marl mudstone with violet to black chert of Scaglia Variegata Fm. (VAS in the geological map) (~50 m Lutetian- lower Priabonian). The succession evolves to Palaeocene-lower Eocene marl and limestone marl locally bioclastic of the Scaglia Cinerea Detritica Fm. (CDZ in the geological map) (~100 m lower Priabonian-lower Rupelian). The Plio-Pleistocene succession is composed of conglomerates and sandy-silty layers of Monteleone Sabino Synthem (UMS in the geological map) (lower Pliocene), calcareous tufa and travertine of Poggio Moiano Syntem (UPM in the geological map), medium to fine sand deposits of Castelnuovo di Farfa Synthem (UVC in the geological map) and Holocene slope, fluvial and colluvial deposits (H in the geological map) (Fig. 1b). The Battifratta Cave is located on the left steep valley flank of the Riano River, a minor left tributary of the Farfa River that drains into the Tiber River. The cave develops within the "Poggio Moiano Synthema", consisting of lithoid travertine deposited in the Middle Pleistocene (Manfra et al. 1976; Cosentino et al. 2014). The natural entrance of the cave has the characteristics of a rock shelter developed due to slope retreat of the steep slope that exposes an ancient cave room with a stump of residual stalactite on the ceiling. The huge shape of the rock shelter (width 18 m, depth 8,5 m and height 6 m) was controlled by fractures and bedding plane of the travertine strata, with local widening due to the breakdown process from the vault and walls (freezing-thaw process) and by biological activity and alteration and micro pitting of roots. The configuration, orientation, and size of rock shelter permit to preserve from the outside climate or weather a wide spectrum of physical, organic, and archaeological deposits product of roof fall, wall collapse, infiltration and deposition of fine fraction and human-made objects (dark yellow area in Fig. 1c). In the past, the rock shelter was a cave mouth, with a diffuse water discharge point (spring) that influenced and reworked with different flood events the archaeological deposits (dark red area in the Fig. 1c). Moving the interior of the cave displays characteristics of a karst system, with linear to angular and poorly sinuous plan and eastward direction horizontal profile with a huge cave room filled with silty-clay and chemical cave deposits (speleothems) that correspond to one of recharge water points (reddish area in the Fig. 1c). The cross-sectional shape of the main cave passage or conduit (ca 60 m) records both phreatic and vadose conditions, with a rounded tube on top, entrenched by a vadose canyon in the floor (keyhole passages), filled with pale reddish to brown clay sediments and collapsed material. The formation of this type of passage occurred when the cave passed from phreatic to

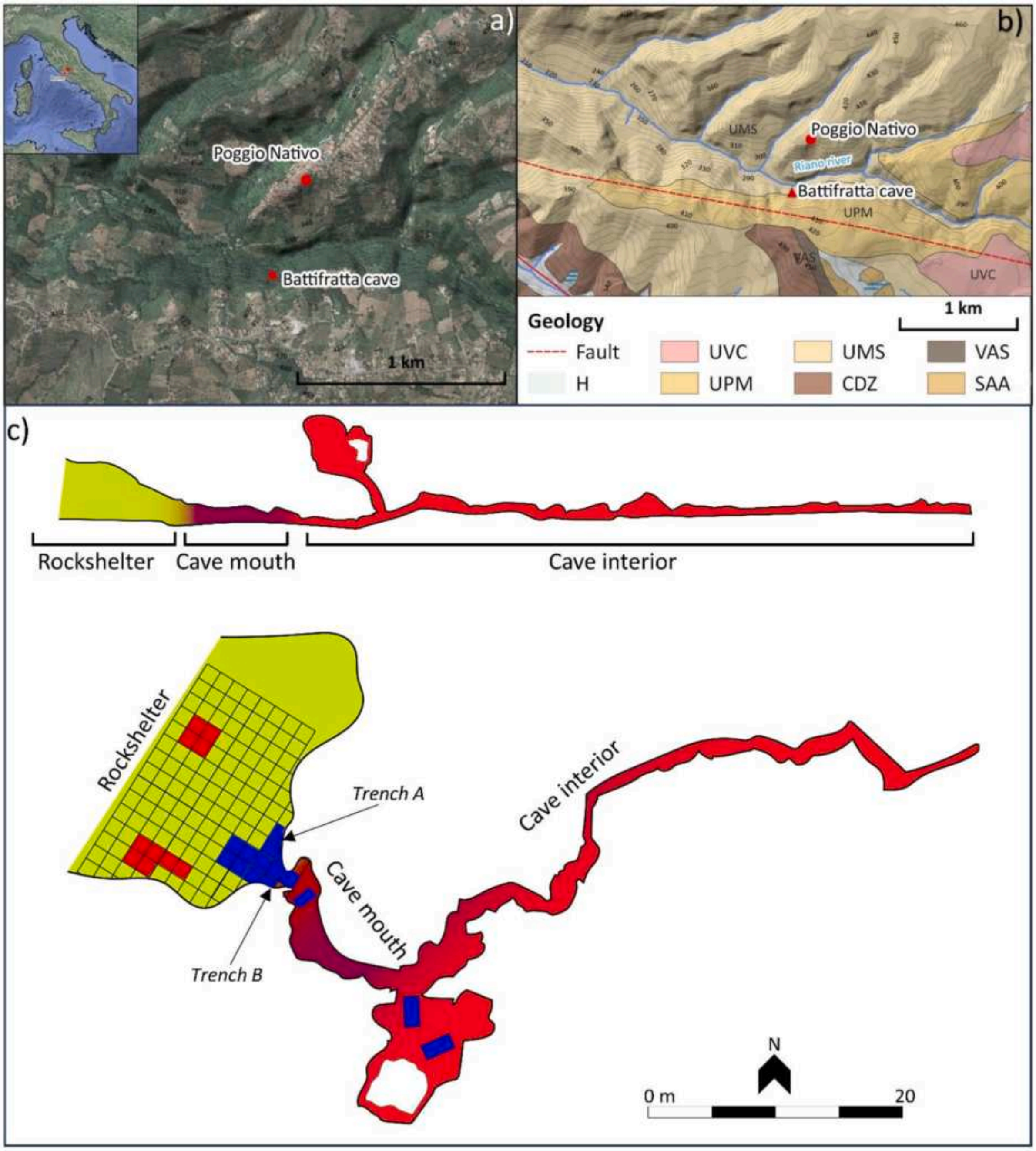

Fig. 1. Location of the Battifratta cave (42.209876 N, 12.792541 E – basemap Google Earth™) (a). Geological map of the area in which the main geological formations are reported (H, Holocene deposits; UVC, Castelnuovo di Farfa; UPM, Poggio Moiano Syntem; UMS, Monteleone Sabino Synthem; CDZ, Scaglia Cinerea Detritica Fm.; VAS, Scaglia Variegata Fm.; SAA, Scaglia Rossa Fm.) (modified from Servizio Geologico D'Italia, 2014, sheet 357 Cittaducale) (b). Plan and profile cave survey (modified from the cave survey made by the Gruppo Speleo Archeologico Vespertilio) with the position of different sectors of the cave and the archaeological excavation area: blue indicates those carried out, red indicates those interrupted due to safety issues (c).

vadose conditions due to a variation in the discharge of the cave (e.g., periodic flooding related to climate changes) and variation of the water table (Ford and William 2007; De Waele and Gutiérrez 2022). Therefore, the Battifratta cave displays both the characteristics of a karstic system, where different phases of floodwater with erosion and deposition of material occurred both within the karstic system and at the mouth of the cave and of a rock shelter in the outer portions of the system. (Fig. 1c).

2.2. Archaeological background

In the 1980s, the Italian Institute of Human Palaeontology conducted two test pits at Battifratta Cave identifying a stratigraphic sequence with archaeological material ranging from the Early Bronze Age to the Recent Neolithic (Segre Naldini, Biddittu 1985, 1988). The cave investigation resumed in 2021 in the framework of the "Farfa Valley Project. Caves, People, and Past Environments", a multi-scale and interdisciplinary study aimed at reconstructing the pre-protohistoric landscape of Sabina (northern Latium) and its transformations over time (Conati Barbaro 2021–22; Conati Barbaro et al. 2024). The excavation has been carried out systematically and extensively within the cave mouth and in the rock shelter. The ongoing archaeological research revealed that the cave was frequented with different intensities and for various purposes in the

Middle Palaeolithic, Neolithic, Middle Bronze Age, and in the 16th century. This archaeological evidence is distributed discontinuously within the cave mouth and rock shelter. The Middle Palaeolithic layers were concentrated in the rock shelter area (Trench A). They consist of lithic assemblage characterised by the Levallois technique as well as faunal remains, including large-sized animal bones, such as *Bos primigenius*. The Neolithic period (late 6th to early 5th mill. B.C.) is recorded within the cave mouth (Trench B), where there is a stratigraphic sequence of sandy sediments interspersed with abundant charcoal fragments, faunal remains, lithic assemblage, and pottery. The general arrangement of the stratigraphy suggests occasional episodes of reactivation of the karstic system with several floodwaters. The associated ceramic repertoire features shapes and decorations typical of Central Adriatic (Ripoli-style painted motifs) and Tyrrhenian (incised linear motifs) Italy. The cave was used for funerary purposes during the Neolithic period, as evidenced by the discovery of two burials. A clay figurine was also found, an extremely rare find for this region of the Italian peninsula. Two millennia later, during the Middle Bronze Age, the cave was in use again, as is evident from a hearth associated with archaeological material at the entrance to the cave and a few vessels in the innermost parts. Finally, around the 16th century BCE, violent floodwater eroded the upper part of the pre-protohistoric stratigraphy, sealing a large portion of the rockshelter with mud. Three more test pits were conducted in the outermost part of the rock shelter but were later abandoned for safety reasons (Fig. 1c, red square). In two cases, the collapsed vault blocks prevented going deep with hand excavation, and problems with rock instability were advised against using the jackhammer or other potentially hazardous systems. In the other case, the position of the trench beneath a dislocated rock block was considered too dangerous for the archaeologists' safety. With these constraints, the available space for archaeological investigation is significantly reduced. Furthermore, even in the most extensively investigated areas, removing the soil that filled that portion of the cavity revealed unstable rock walls.

3. Methodology

An integrated engineering geological characterisation of the outcropping rock mass was performed by coupling geomechanical field surveys, both from direct inspection and remote sensing, as well as near-surface geophysical monitoring. Geomechanical surveying aimed at identifying potentially unstable rock blocks, i.e., delimited by fractures − technically called joints − which interrupt the continuity of the intact rock, to be considered for parametric stability analysis and, therefore, designing any necessary support structures aiding in safety conditions at the site. To investigate the stability conditions of the identified rock blocks, explorative ambient vibration measurements were performed to identify their modal properties (i.e., resonance frequencies, modal damping ratios and mode shapes).

Several subjective geomechanical surveys were carried out and allowed the identification of five discontinuity joint sets intersecting the rock mass and, based on this evidence, to perform kinematic and dynamic compatibility analyses respect to rock block failure mechanisms though the traditional Markland test (Markland, 1972). Moreover, key parameters describing jointing conditions such as orientation (by using the compass), spacing, JRC (Joint Roughness Coefficient, by using Bartn Comb profilograph), JCS (Joint Compressive Strength, by using Schmidt hammer sclerometer) and volumetric joint density (Jv) were derived from field measurements according to the ISRM (1978) recommendations. These parameters are fundamental for retrieving shear strength values for each discontinuity joint set using Barton and Choubey failure criterion (Barton and Choubey, 1977).

The joint sets isolate medium- to high-volume rock blocks predisposed to fall (Hungr et al. 2014): eight potentially unstable rock blocks located above the excavation area were recognised, and their volume was computed (Fig. 2). Intact rock properties such as the bulk unit weight (γ_n) and the uniaxial compressive strength (UCS) were determined from laboratory tests (i.e., hydrostatic weighing and point load test) performed on rock samples representative of the outcropping lithotype, according to specific ASTM standards (American Society for Testing and Materials, D7263-21 and D5731-08 respectively). As soon as the volume of the rock blocks and the specific weight of the outcropping lithotype were measured, it was possible to estimate the weight of each of the eight rock blocks. For each of these critical elements, specific stability analyses were performed, following a "joint driven" conceptual approach at limit equilibrium, to quantify the safety factor (SF) under several conditions (i.e., static, hydraulic, and seismic conditions).

To support direct geomechanical surveying of the rock mass through the remote characterisation of discontinuity joint sets, we performed a drone-based photogrammetric survey to obtain a high-resolution point cloud of Battifratta cave using the structure-from-motion software Agisoft Metashape (www.agisoft.com) (Fig. 2a). Since a good satellite signal was not available inside the cave and the lack of a georeferenced model, we deployed seven ground control points (GCP) for model scaling and orientation. By measuring orientations and relative distances between the GCPs, it was, indeed, possible to remove scale and orientation ambiguities of the photogrammetric output. The resulting raw point cloud was further processed in CloudCompare (www.cloudcompare.org), and the general model refinement was achieved using a series of statistical outlier removal and noise reduction filters. The resulting point cloud was then analysed using the MATLAB Toolbox DSE 3.0 (Discontinuity Set Extractor), which allows for the automatic identification of discontinuity sets from point cloud data through a kernel density estimation and density-based cluster algorithm (Riquelme et al. 2014, 2017) (Fig. 2j).

The possible presence of cavities below the ground floor of the cave was investigated through twenty ambient seismic noise measurements using three-component SARA SL-06 velocimeters and adopting a regular array grid of approximately 3x3m (Fig. 3a, b). One hour-long single station measurements were performed, setting the instruments to a sampling frequency of 200 Hz. The analysis was performed following the Horizontal-to-Vertical Noise Spectral Ratio (HVNSR) approach, analytically implemented by Nakamura (1989), for evaluating the resonance frequency of a given site. In particular, the HVNSR function represents the ratio between horizontal and vertical Fourier amplitude spectra at each natural frequency, and a strong drop of the function below one might indicate the presence of shallow underground cavities due to low stratigraphic contrast of impedance. Furthermore, to better understand the dynamic behaviour of the unstable rock blocks above the excavation area, two daily surveys were performed using two instrument types characterised by different flat frequency response ranges and sensitivities.

Due to the explorative nature of these surveys, the employment of different sensor types was considered mandatory to identify frequencies of interest within a broad frequency range and related to the dynamics of rock blocks characterised by varying sizes. In the first survey, six Bruel&Kjaer Type-8344 one-component piezoelectric accelerometers (flat frequency response 10–2000 Hz and 2500 mV/g sensitivity), cable-connected to a HBM signal amplifier and digital acquisition system (SomatXR MX1601B-R and SomatXR CX23-R, respectively) were used in a block-to-reference setting (Fig. 3c, d). Such a configuration was adopted to highlight signals related to modal resonances of the rock blocks. The bottom sector of the cave was selected as a fixed local reference due to its low fracturing degree, while active sensors were paired and installed on five rock blocks using steel omega-shaped support brackets. Continuous ambient noise vibrations were recorded for two hours at a sampling rate of 2400 Hz. During the second survey, we deployed two GEOSPACE 4.5 Hz geophones (flat frequency response 5–200 Hz and 100.4 V/m/s sensitivity) connected to a 24-bit digital acquisition system and recorded three-component ambient vibration data at 500 Hz (Fig. 3e). We collected ambient vibration data during a two-hour monitoring window using the same previously described block-to-reference configuration.

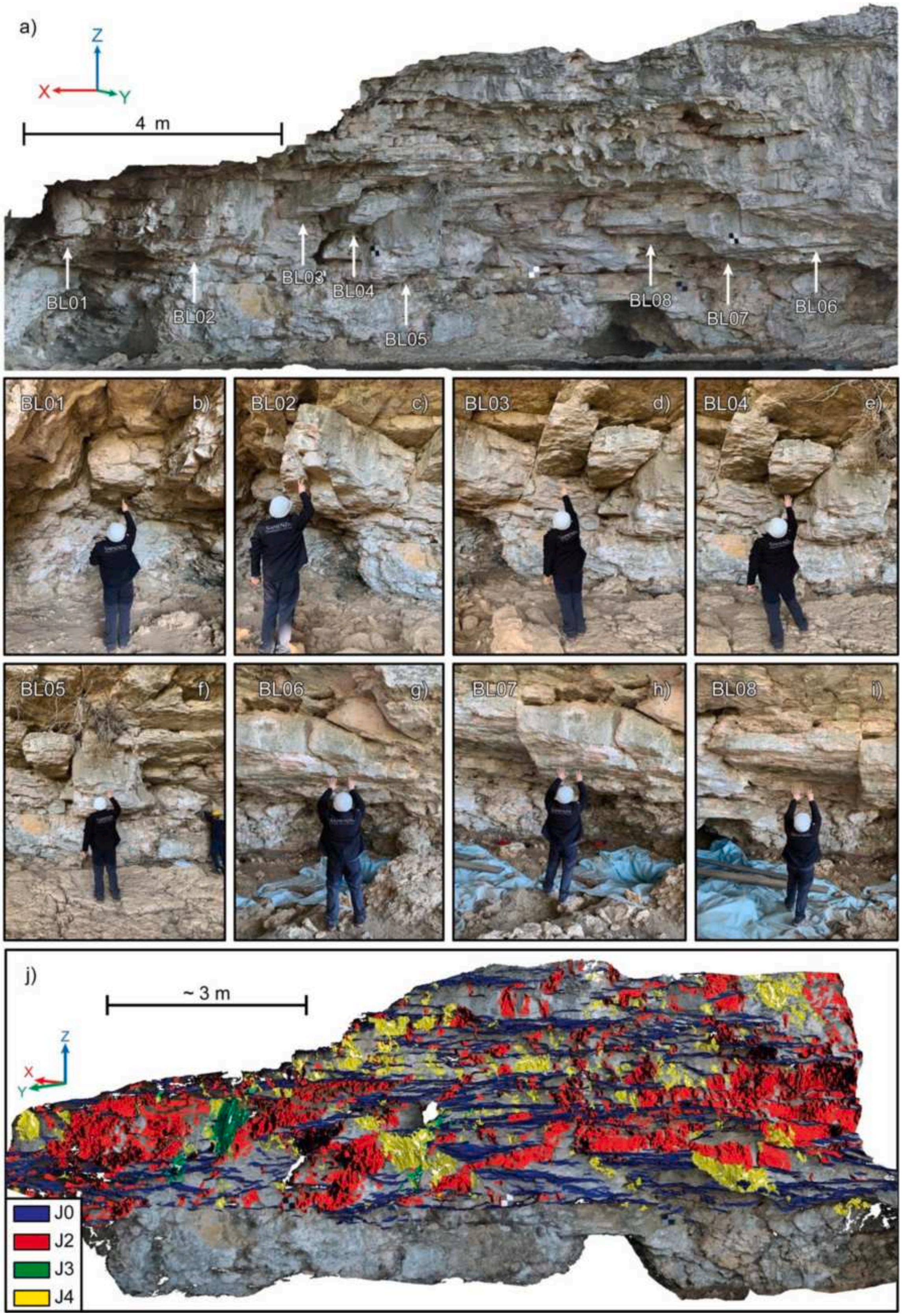

Fig. 2. Orthoview of Battifratta cave where the location of the eight rock blocks poses a potential threat to the excavation area safety (a). Detailed view of each rock block identified via visual inspections and direct geomechanical surveys (b–i). Classified point cloud obtained through the discontinuity set analysis performed in MATLAB; only four out of the five manually identified discontinuity sets were correctly identified and classified on the point cloud (j).

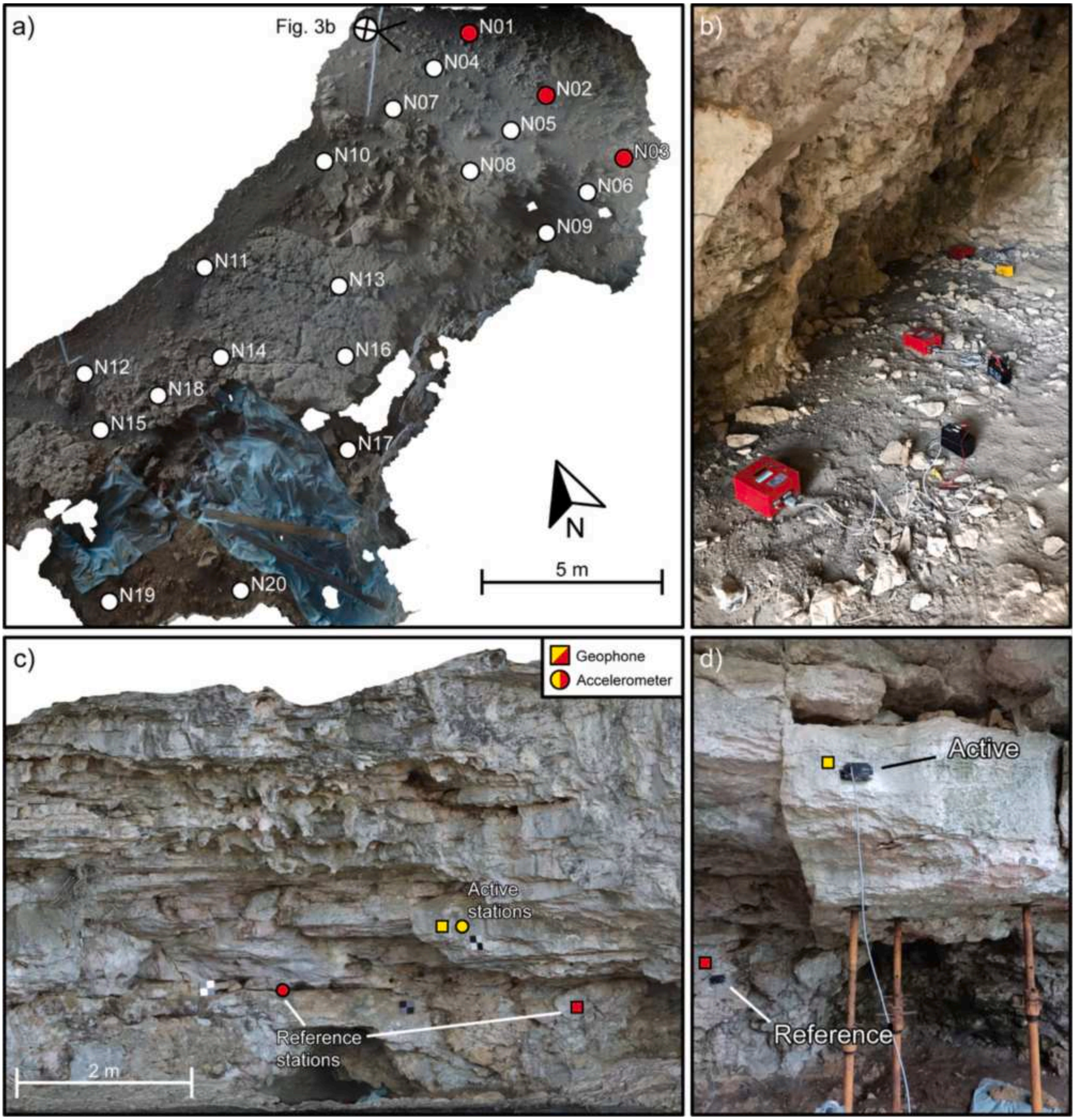

Fig. 3. Orthophoto of the Battifratta Cave excavation area with the location of the ambient seismic noise measurement locations (a) Red circles highlight the location of seismometers shown in panel b. SARA SL-06 three-component seismometers deployed inside the excavation area (b). Location of geophones (squares) and accelerometers (circles) installed on one target rock block to investigate and monitor its modal properties (c). Red and yellow markers refer to reference and active stations, respectively. Detailed view of the active and reference geophones (d).

The dataset of ambient vibration records was analysed in the frequency spectral domain to identify resonance modes (i.e., eigenmodes) related to the rock block dynamics. The collected dataset was first examined to extract the longest undisturbed continuous time block for time-series processing. We then removed the mean and linear trend and applied the instrument response correction via spectral division, high passing signals above 5 Hz. Power Spectral Density (PSD) estimates of velocity and acceleration were computed for the trimmed dataset and on hour-long data blocks following McNamara and Buland's (2004) approach. We used Welch's method (Welch 1967) with stacked fast Fourier transforms of 60 s Hanning-tapered windows with 75 % overlap to reduce variance and smoothing over 0.1 Hz windows.

4. Results

Based on the evidence collected from the geomechanical surveying, performed at the archaeological site of the Battifratta Cave, three litotechnical units have been recognised. The firs litotechnical unit corresponds to the ceiling of the cave, characterised by a high degree of rock mass fracturing with jutting out blocks on the underlying ground. The second litotechnical unit is represented by the ground floor of the cave, in the area not involved in the excavation (where blocks numbered 1 to 5 are located), consisting of residual blocks that remained after previous collapses and currently constitute the cave's ground floor. The third litotechnical unit is represented by the ground floor of the cave which is involved in the archaeological excavation (where blocks numbered 6 to 8 are located), which is composed of finer material belonging to silts and clays. In this third lithotechnical unit, the archaeological layer is abundant.

Five main joint sets were identified on the cave rock mass by comparing and integrating results from direct geomechanical and photogrammetric surveying (Table 1). The physical–mechanical parameters of the recognised joint sets, relevant for performing specific rock block stability analyses, were assessed.

The intersection of the joints acribable to these sets locally isolates eight protruding blocks, which have been considered prone to fall respect to the whole cave rock wall. Through the standardised Markland Test and given the shape of the cave vault, no further kinematic mechanisms of rock instability appear to be compatible (i.e., planar sliding, rock wedge sliding, toppling). The size and volume of the 8 protruding blocks were analytically determined. The bulk unit weight was also known through hydrostatic weighing conducted in a geotechnical laboratory (Table 2).

Considering a basic friction angle (ϕ_b) equal to 32°, according to an average value provided by literature for the involved lithology, a stability analysis under static conditions was performed for each block by applying the equation (1):

$$SF = [C + (Ntan\phi)]/W \tag{1}$$

Where C is the force of cohesion, due to the cementation inside the opening of the joints that bounded each block and predispose it to fall, N is the normal force to the joint that predisposes each block to the fall, W is the weight force, ϕ is the peak friction angle evaluated for each joint of interest by applying the equation (2):

$$\phi = JRC \bullet (JCS/\sigma_n) + \phi_b \tag{2}$$

Where σ_n is the normal strength acting on the considered joint plane, and ϕ_b is the basic friction angle (i.e. referred to a perfectly smooth surface).

The so performed stability analysis, under static conditions, returned a safety factor (SF) value for each rock block. In three cases only, the SF values were very low, i.e., failure conditions are close to occurring; two of these blocks are just projecting above the archaeological excavation area (SF = 1 means failure condition, SF > 1 means stable conditions, SF < 1 means unstable conditions). Table 3 summarises the parameters adopted for the stability analysis under static conditions and the SFs obtained.

Once the stability analysis under static conditions had been performed, sensitivity analyses were carried out for each block, considering a different percentage of cementation of the joint predisposing to the fall and the action of the destabilising factors. About these two last variables, the following two conditions were considered: i) the presence of a hydrostatic thrust, which refers to the force exerted by water pressure on joints, and ii) the presence of a dynamic input. More in particular, to quantify the SF value considering the hydrostatic thrust, equation (1) is modified as shown in equation (3):

Table 1
Average attitude of the five joint sets identified, expressed as dip direction and dip. The roughness and the Uniaxial Compressive Strength (MPa) of the joint surfaces are also highlighted.

Joint Set ID	Dip direction (azimuth)	Dip (degree)	JRC	JCS (MPa)
J0 (attitude of strata)	135	4	12–14	44
J1	323	53	14–16	101
J2	178	80	14–16	60
J3	227	86	8–10	41
J4	272	76	14–16	111

Table 2
Physical parameters characterising each of the 8 identified blocks.

Block ID	Height (m)	Length (m)	Width (m)	Volume (m^3)	γ_n (kN/m^3)	Weight (kN)
BL01	0.95	2.60	1.00	2.50	25.71	63.50
BL02	1.40	5.00	2.60	18.20	25.71	467.92
BL03	0.80	1.80	0.90	1.30	25.71	33.32
BL04	0.65	0.90	1.90	1.10	25.71	28.58
BL05	1.35	2.10	2.20	6.20	25.71	160.35
BL06	0.80	3.20	0.50	1.30	25.71	32.91
BL07	0.90	3.90	1.90	6.70	25.71	171.46
BL08	0.50	2.90	2.60	3.80	25.71	96.93

$$SF = [C + (Ntan\phi)]/(W + U) \tag{3}$$

Where U represents the hydrostatic thrust, in turn, calculated according to the equation (4):

$$U = \frac{1}{2} \bullet (h_w)^2 \bullet \gamma_w \tag{4}$$

Where γ_w is the unit weight of water and h_w refers to the wetted height relative to the extension of the joint being considered.

Similarly, considering a dynamic input (i.e., earthquake) expressed as PGA (Peak Ground Acceleration), whose maximum permissible value is given by the probability of exceeding 10 % in 50 years with a return period equal to 475 years (https://esse1-gis.mi.ingv.it/), the value of the SF is given by equation (5):

$$SF = [C + (Ntan\phi) - (k_h \bullet W)]/[W + ((k_h \bullet cos\alpha) \bullet W)] \tag{5}$$

Where k_h is the horizontal pseudostatic seismic coefficient expressed in terms of PGA (measured in g) and refers to the dip of the joint that predisposes the block to failure (joint behind the block).

The stability chart in Fig. 4 combines the sensitivity analysis to seismic action and hydrostatic thrust for each block. This chart allows identifying the combination of the triggering actions (in terms of their intensity) suitable for causing the rock block failure. In particular, blocks 6 and 8, directly projecting onto the excavation area, become unstable due to a seismic action equal to 0.175 g and a return period equal to 475 years, thus making them the two blocks with the highest hazard regarding seismic action. However, it results that the rock blocks stability is less sensible to the hydrostatic thrust due to their volume; the height of the water inside the joints such that there would be a water pressure valuable for inducing instability of the blocks should be, indeed, greater than the height of the blocks themselves, thus making this action not admissible. Moreover, presence of water inside the joints seems unlikely as they can be considered a highly pervious system, due to their attitude and opening.

Focusing on the outputs of geophysical surveys, the HVNSR analysis is performed on the seismic ambient noise measurements to evaluate the possible presence of a fundamental site resonance frequency (f_0) or further voids beneath the cave floor. The HVNSR results are all characterised by a function that did not reveal clear resonance peaks or a function dropping below 1 that could suggest the presence of voids below the ground level, i.e., related to possible cave existence. In particular, all the measurements carried out along the external alignment of the cave, whose opening is exposed to the northwest, and along the central alignment show a flat trend of the HVNSR function (Fig. 5b, c). Only the measurements conducted along the internal alignment of the cave show a slight peak in the HVNSR function, between 1.3 and 1.6 Hz, but with values not exceeding 2.5–3 (Fig. 5a; see Fig. 3a for check sensors' location). Furthermore, these peaks do not appear stratigraphic as they are not 1D but are all polarised in an azimuthal direction between 90° and 120°, i.e., towards the inside of the cave.

For structural health monitoring, ambient vibration monitoring was employed to identify and characterise resonance modes of unstable rock

Table 3
Parameters considered for the rock block stability analysis for each block and SFs obtained.

Block	ϕ_b (°)	JRC	JCS	Weight (kN)	ϕ (Eq. (2))	C (kN)	N (kN)	tan ϕ	SF (Eq. (1))	SF class
BL01	32	15	111	63.44	52	224.27	5.25	1.26	3.6	Medium
BL02	32	15	111	467.45	31	487	169.38	0.61	1.3	Low (critical)
BL03	32	15	111	33.29	45	159	12.50	0.99	5.2	High
BL04	32	15	111	28.55	51	105	3.86	1.24	3.9	Medium
BL05	32	15	111	160.19	36	453	81.01	0.73	3.2	Medium
BL06	32	15	60	32.88	44	159	8.13	0.95	5.1	High
BL07	32	15	60	171.29	38	201	21.45	0.78	1.3	Low (critical)
BL08	32	15	60	96.83	51	124	1.61	1.22	1.3	Low (critical)

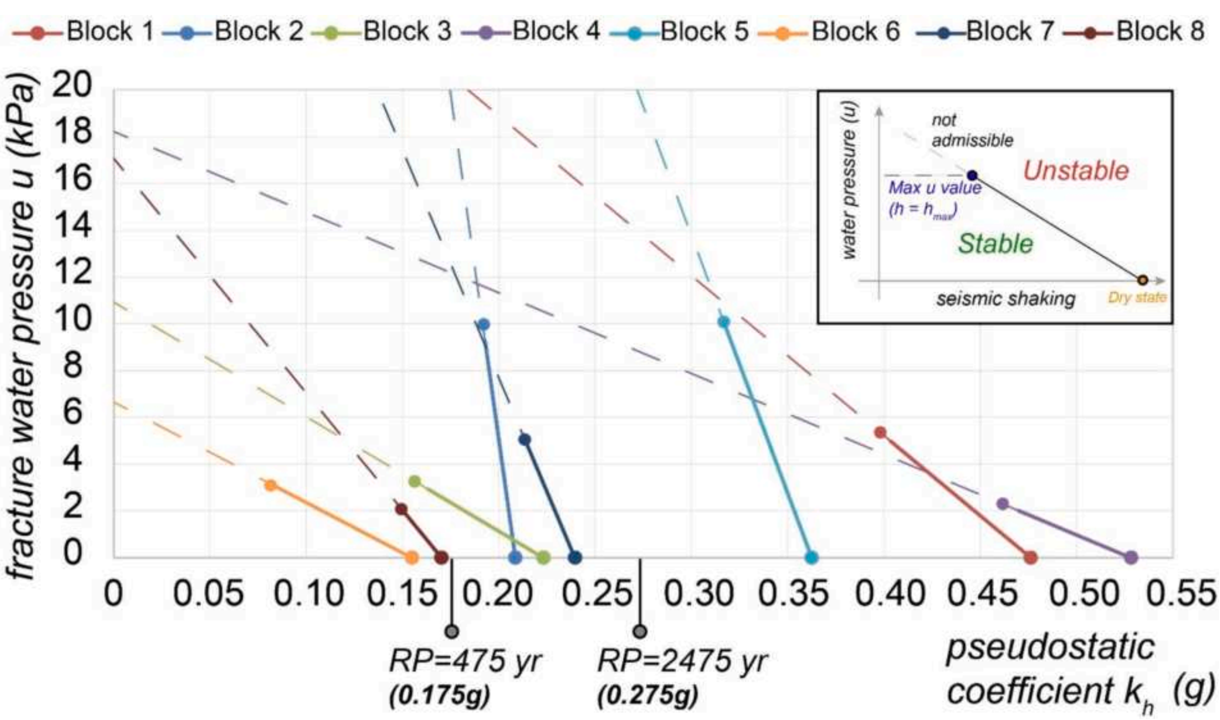

Fig. 4. Stability chart showing the safety conditions of each block to the seismic action and to the hydrostatic thrust chart. Solid lines indicate FS equal to 1. As visible in the conceptual sketch, the area under the line indicates stable conditions, while the area over the line indicates unstable conditions. Dashed lines report not admissible conditions for the hydrostatic thrust.

blocks located on the cave vault. The deployment of accelerometers and geophones allowed for comprehensive coverage across a broad spectral range (i.e., 5–1000 Hz), but no frequencies related to natural modes of vibrations were detected. The analysis of background noise levels in the time domain (i.e., mean and standard deviation) for geophones highlighted no significant differences in ground motion amplitude on all recording channels between the reference and the unstable rock blocks (Fig. 6b). The same result was obtained after processing the accelerometric dataset. From spectral analysis, no frequency peaks potentially related to natural modes of vibration of any rock block were identified in the dataset. The analysis of PSD estimates and spectrograms highlighted the existence of continuous, evenly-spaced narrow peaks spanning the entire frequency spectrum (Fig. 6c, d). These spike-like spectral peaks show similar features for geophones and accelerometers (e.g., constant spacing and high amplitude), and were found to be constant during each monitoring period (Fig. 6d). Recurrent spikes characterised by constant frequency spacing and high amplitude can be indicative of instrumental noise dominance. This scattered pattern is typical of a systematic influence on the data, which is often associated with the characteristics of the recording instrument rather than with natural environmental or seismic signals. The physical and mechanical characteristics of the employed sensors could be responsible for the impossibility of identifying natural signals related to the resonances of the rock blocks. For example, the comparison between PSD estimates and the residual inherent noise of the accelerometers shows a low signal-to-noise ratio, especially at low frequencies (5–50 Hz), which suggests the recorded data may be dominated by residual inherent noise or instrumental noise.

Instrumental noise can derive from various factors, among which ground loops (i.e., electric currents flowing in the shield of accelerometer or geophone cables) and triboelectric noise (i.e., disturbance induced by the mechanical motion of cables) affecting long cables can be dominant. Moreover, their contributions to the overall residual noise of the acquisition chain can completely mask natural, low-amplitude signals (Serridge and Licht, 1987).

5. Discussion

As mentioned above, the instability of the rock walls and vault was the most compelling and complex issue that needed to be addressed from the beginning of the excavation activity at Battifratta Cave. Consequently, it was considered necessary to adopt a multidisciplinary approach by involving experienced geologists in the field of geological engineering and geophysics within the research team.

The key objectives of this study were to i) assess the stability of the rock blocks, ii) design the securing, and iii) develop a fieldwork strategy

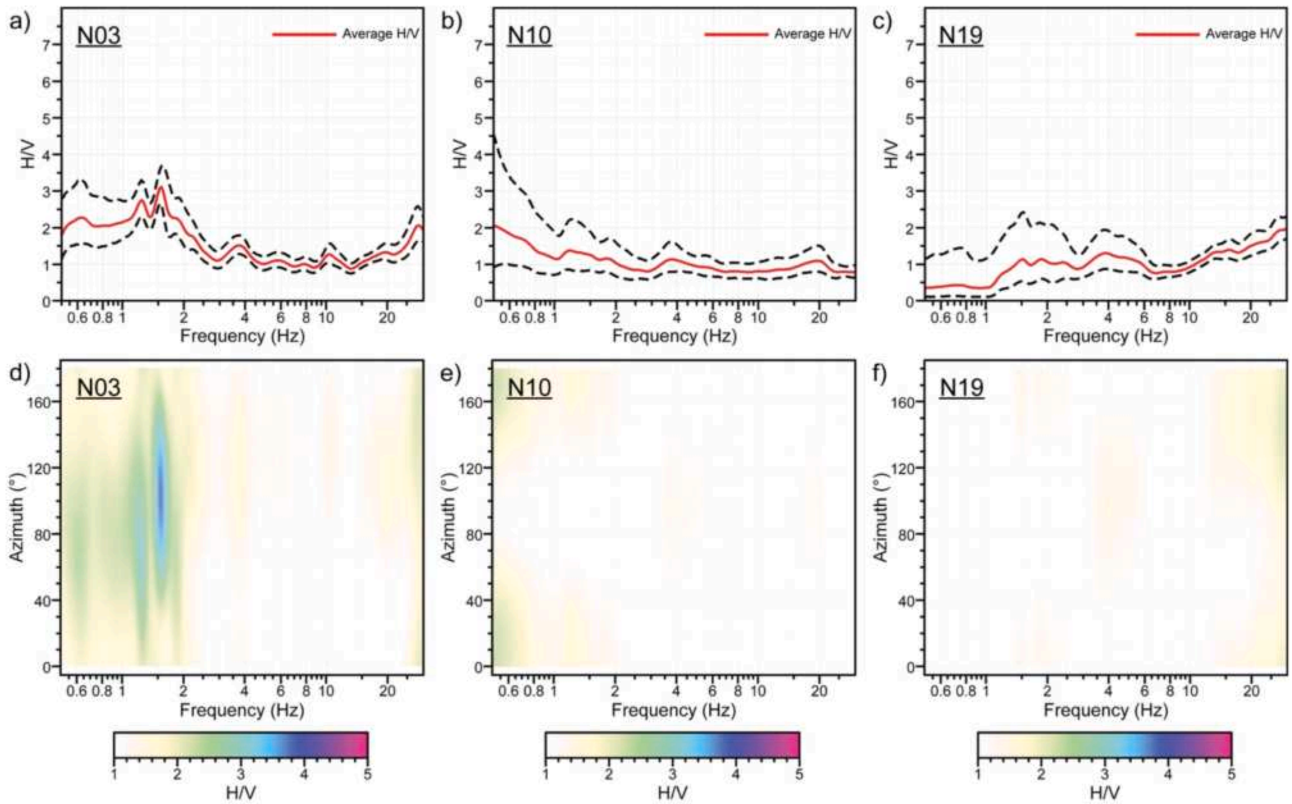

Fig. 5. Summary of HVNSR results obtained at different measurement locations inside Battifratta cave (see Fig. 3a). Mean (red lines) and standard deviation curves (black dotted lines) define the HVNSR functions at stations N03 (a), N10 (b) and N19 (c). HVNSR rotate plots were obtained at the same stations, and the colour bars indicate the HVNSR amplitude.

considering the various risk factors involved. For this latter purpose and considering the results obtained from the characterisation and stability analysis of the protruding blocks, it is possible to intervene in the short and medium term. It is, however, necessary to keep in mind that of the eight blocks identified, only three directly involve the excavation area, while the other blocks are above a part of the cave exploited for logistic operations only. Two of the three blocks above the excavation area show very low SF values (i.e., ≈ 1, close to the failure), under static conditions. Furthermore, they show conditions close to SF equal to 1, even for seismic actions with a return period of 475 years. Instead, the action of the hydrostatic thrust saturating the joints as a possible destabilising action was discarded due to their very pervious conditions.

Based on the stability charts obtained for the individual blocks surveyed in the cave, in the absence of saturation of the joints, two blocks would be unstable due to seismic actions of the order of a hundred years (PGA between 0.15 and 0.2 g) while six blocks would be unstable due to seismic action of the order of thousands of years (PGA higher than 0.25 g). This would mean that during the time of use of the cave (starting from the Middle Paleolithic), these conditions of instability would have occurred on a multi-century basis, but they would have affected a percentage of no more than 25 % of the types of blocks present in the cave. Seismic actions occurring over a millennial basis, however, could have induced instability conditions for over 50 % of the blocks present in the cave.

The results obtained from the slope stability analyses for the protruding blocks which are located on the cave vault, led to the consideration of engineering solutions that could ensure the stability of these blocks during excavation, as well as the safety of the personnel working on the cave floor. Additionally, the proposed solutions were differentiated between the section of the cave directly involved in active excavation and the section used for archaeological material processing (sieving, bagging, labelling), field documentation, storage of excavation equipment.

Adopting high load-bearing capacity props was considered the most affordable engineering intervention to stabilise unstable rock volumes during the excavation stages, i.e., taking into account short time windows, thus ensuring the safety of the archaeologists involved in the excavation. These props were sized in terms of load-bearing capacity and number for each block, using the weight and volume values determined for each individual block. At the same time, still considering a short time window, the solution adopted for the safety of the five blocks that do not project onto the excavation area is passive. In fact, to maintain an acceptable cost/benefit ratio, it was considered sufficient to prohibit people's transit in that area. These solutions have been sized and verified by drafting an executive project, the project drawings of which are summarized in Fig. 7.

Focusing on a medium time window, a strategy to be considered for guaranteeing safety during the archaeological excavation, along with the shoring, is vibrational monitoring of protruding blocks. This may have the dual purpose of studying the dynamics of the jutting blocks and identifying any microseismic emissions related to micro fracturing events of the rock mass and of the rock bridges, which guarantee cohesion between the blocks and the rock mass itself, which can represent precursor signals of deformation on the largest scale until the failure time is reached. With this aim, we started using ambient vibration monitoring for structural health assessment of multiple unstable rock blocks threatening the archaeological excavation area. Despite the adopted ambient vibration monitoring strategy enabling the investigation of a broad spectral range (5–1000 Hz), the absence of frequencies related to natural modes of vibrations in the recorded data is noteworthy. The observed limitations in identifying natural signals related to natural resonance modes of unstable rock blocks may be attributed to the physical–mechanical characteristics of the employed sensors that determine instrumental noise dominance. Nonetheless, the encountered

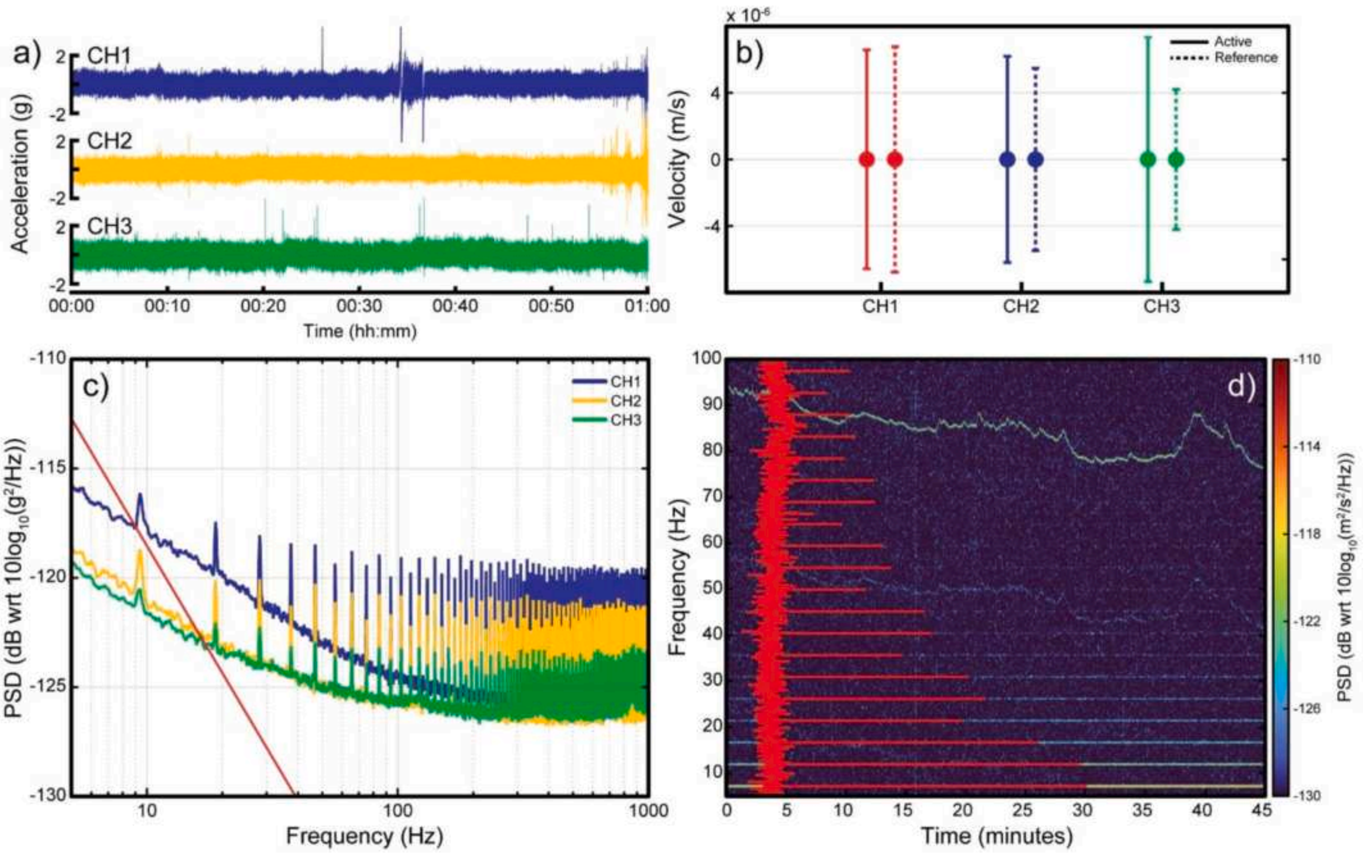

Fig. 6. Example of 1-hour time history recorded by three accelerometers (a). Mean and standard deviation background noise levels were recorded during the monitoring period in which reference (dotted lines) and active (bold lines) geophones were deployed (b). Acceleration power spectral density estimates and residual spectral noise curve (red line) for the employed Bruel&Kjaer Type-8344 accelerometers clearly show the existence of constant disturbances that appear as evenly spaced spikes in the frequency domain (c). Recurrent spike-like spectral peaks can be appreciated from the observation of the velocity power spectral density estimate over-imposed to a spectrogram for one of the deployed geophones (d).

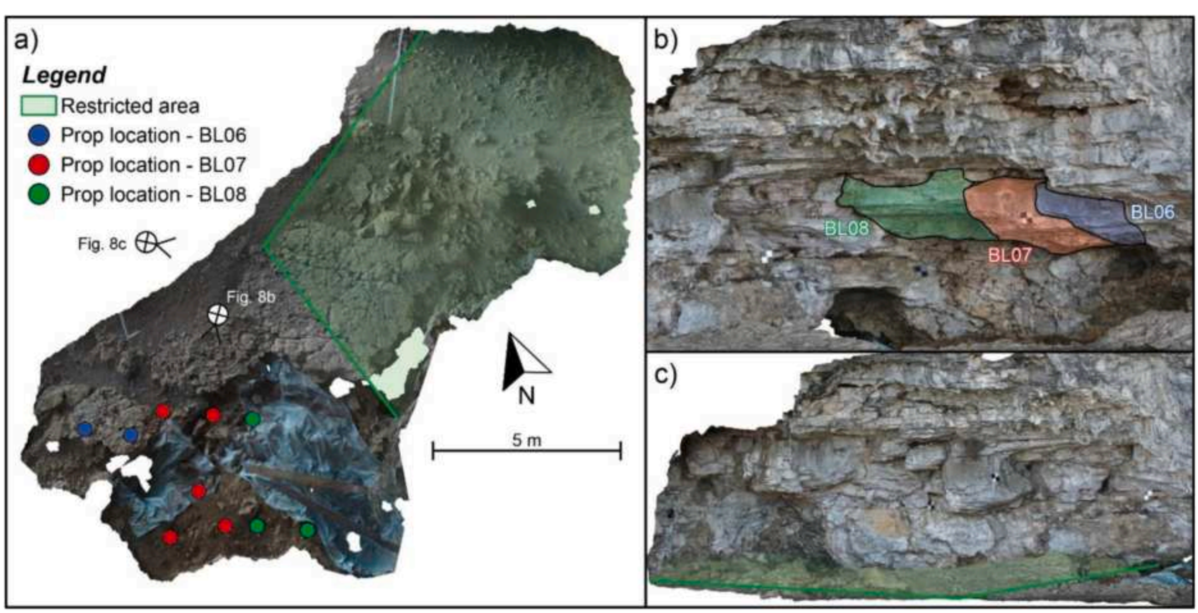

Fig. 7. Orthophoto of the Battifratta Cave excavation area (plan view) with the location of the props to stabilise blocks 6–7-8; the prohibited area at the people transit is also shown (a). 3D point cloud of Battifratta Cave rock shelter which shows the propped-up blocks (b) and the area closed to the transit of people (c).

instrumental shortcomings may also represent a result with direct implications for the analysis of the stability conditions of the examined blocks. This limitation suggests the presence of very low-amplitude vibrations characterising the dynamic behaviour of the rock blocks (i.e., vibrations falling below the sensitivity threshold of the employed high-sensitivity sensors). The absence of detectable natural vibrations, hidden by instrumental noise, could be interpreted as deriving from a general state of equilibrium, thereby implicitly providing valuable insights into the overall stability conditions of the rock blocks located on the cave vault and threatening the excavation area. Understanding instrumental limitations is crucial for refining monitoring strategies and ensuring the reliability of data interpretation in the context of safety excavation in archaeological sites. Future efforts could focus on addressing and mitigating instrumental noise sources to improve the efficacy of ambient vibration monitoring for structural health assessments in similar geological settings.

The experience gained in Battifratta Cave leads to state that the short- and medium-term interventions ensured the safe execution of two excavation campaigns and will be beneficial for future research activities. Furthermore, the methodology applied, and the achieved outcomes will have long-term value by aiding in planning more substantial and enduring interventions to preserve and establish visitor pathways for public access. In this regard, the multi-disciplinary approach performed in this case study represents one of the first contributions in the scientific literature where the engineering geological characterisation and geophysical monitoring of archaeological excavation areas not only aim to ensure and monitor the integrity and stability of the archaeological site itself over time (Bakun-Mazor et al. 2013; Alcaino-Olivares et al. 2021) but also contribute to guarantee the safety of excavation personnel exposed to potential geological risks (as is often the case in cave context). In light of the results, it can be stated that the objective of ensuring safety during excavation was fully achieved through the application of geomechanical investigation and geophysical monitoring. This represents a novel contribution compared to the existing background on the topic, as presented in the introduction of this paper, laying the foundation for the adoption of best practices that address not only the protection of sensitive archaeological assets but also the safety of excavation personnel. Beyond this specific example, it is important to focus best practices on modifying the excavation solutions used in the field to reduce the impact of archaeological activities, not only with respect to the archaeological asset itself but also to the geological environment that hosts it.

6. Conclusion

The importance of incorporating engineering geological approaches into archaeological excavation sites has been demonstrated through this research as it represents a very encouraging practice that gains traction at a few ancient sites with the primary goal of safeguarding cultural resources and providing secure public access. In fact, in the archaeological site of the Battifratta Cave, the engineering geological characterisation of the rock mass and the geophysical investigation techniques have allowed the identification of potentially unstable blocks projecting over the excavation area, the evaluation of their susceptibility to fall both in static and dynamic conditions as well as to monitor them during the presence of the excavation personnel.

In particular, an engineering geological survey was performed on-site, both directly and remotely, using a drone that allowed the reconstruction of a 3D photogrammetric model of the rockshelter. Based on the identified joint sets, eight kinematically compatible blocks prone-to-fall were identified. Dimensioning and stability analysis were performed for each block, considering both static conditions and the possibility of seismic input, revealing those with a safety factor closer to instability conditions and in which return period regarding a dynamic shaking. This led to the selection of a risk mitigation strategy, involving the implementation of different solutions depending on the time scale. These ranged from the installation of high-capacity load-bearing props in the short term to the adoption of microvibrational geophysical monitoring in the medium and long term. Additionally, HVSNR geophysical investigations ruled out the presence of further voids beneath the cave ground floor.

The research enabled the development of shoring projects for specific locations, allowing for safe working conditions. This preparatory phase comes before the ultimate securing of the vault, which is required to open the site to the public. This has aided in the efficient planning of excavation operations.

The experienced approach emphasises the key role of including geological engineering analyses since the beginning of an archaeological project due to the potential difficulties that may develop if these procedures are implemented at a later, more advanced level. Scenarios in which shoring, containment, or safety measures may be compromised due to circumstances such as excavation area extension, the presence of structures, or architectural installations linked to display pathways.

Risk mitigation related to a cave working environment often faces challenges due to constrained financial resources, environmental impact concerns, and logistical limitations. On the other hand, providing a risk mitigation strategy since the beginning of an archaeological project represents a good opportunity to apply more efficient safety measures. This also allows optimising the cost-to-benefit ratio of the entire design.

Developing standardised protocols to assess rock stability during archaeological exploration also improves the preservation strategies required to protect the cultural heritage embedded within these vulnerable geological contexts. Its adoption would represent a significant step forward in balancing safety concerns with conscientious conservation efforts, thereby significantly contributing to these invaluable archaeological sites' responsible and sustainable exploration.

CRediT authorship contribution statement

Cecilia Conati Barbaro: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Matteo Fiorucci:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Guglielmo Grechi:** Writing – review & editing, Visualization, Software, Resources, Investigation, Formal analysis, Data curation. **Luca Forti:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation. **Gian Marco Marmoni:** Writing – review & editing, Visualization, Software, Investigation, Formal analysis, Data curation. **Salvatore Martino:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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