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ENGINEERING-GEOLOGICAL AND GEOPHYSICAL SURVEYS FOR ARCHAEOLOGICAL RISK ASSESSMENT IN VIEW OF MITIGATION MEASURES AT AEGINA KOLONNA, GREECE

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EXTENDED ABSTRACT

Il sito archeologico di Aegina Kolonna, un importante patrimonio culturale in Grecia, occupa un promontorio costiero ed è minacciato da numerosi fattori ambientali e geologici, tra cui la continua erosione costiera, la sismicità locale e la diffusa instabilità delle scarpate costiere che delimitano il promontorio. Il progressivo arretramento delle scarpate che bordano il promontorio ha già causato, infatti, la perdita irreversibile di parte dei beni archeologici non ancora scavati, compromettendo severamente la preservazione del sito. Nell'ambito del Progetto Europeo TRIQUETRA (*Toolbox for assessing and mitigating Climate Change risks and natural hazards threatening cultural heritage*), è stato sperimentato un approccio interdisciplinare che integra geologica applicata, geofisica e archeologia per la valutazione dei pericoli geologici e della vulnerabilità del sito. Il progressivo arretramento della linea di costa dell'area di studio è determinato da una complessa interazione di fattori geologici e ambientali. L'assetto stratigrafico locale, che vede affiorare una formazione calcarenitica quaternaria sovrapposta ad argille plioceniche, rappresenta il fattore predisponente principale del processo di arretramento, essendo il motore di una dinamica di creep guidata da processi viscoplastici, che favorisce lo sviluppo di espandimenti laterali responsabili del progredire dei processi di instabilità delle pareti costiere. Nell'ambito delle attività previste dal progetto TRIQUETRA, è stata condotta una campagna di indagini geologico-tecniche e geofisiche, finalizzata alla ricostruzione del modello geologico-tecnico dell'intero promontorio. Oltre al rilevamento geologico dell'area, sono state eseguite 26 misure di rumore sismico ambientale a stazione singola per supportare la ricostruzione del modello geologico di sito e valutare la risposta sismica locale. I risultati ottenuti hanno evidenziato l'esistenza di due intervalli di frequenze di risonanza fondamentali di sito tra 0.4-0.7 Hz e 8-25 Hz, che sono indicativi di potenziali effetti di amplificazione stratigrafica (i.e., 1D) del moto sismico dovuti rispettivamente a un elevato contrasto d'impedenza con il substrato sismico profondo e a possibili contrasti tra gli strati più superficiali. Inoltre, dall'analisi del comportamento dinamico dell'unica colonna ad oggi integra del Tempio di Apollo, è stato possibile identificare due frequenze di risonanza strutturale a 5.1 e 8.2 Hz. Queste frequenze sono sovrapponibili alla frequenza di potenziale amplificazione sismica di sito e dunque non possono essere esclusi effetti di danneggiamento strutturale in caso di scuotimento sismico. Oltre alla valutazione della pericolosità geologica locale, il progetto TRIQUETRA si concentra anche sullo sviluppo di strategie per la conservazione dei siti archeologici di interesse culturale. Per il caso di studio di Aegina Kolonna, nell'area dei cosiddetti sobborghi preistorici dell'est, i precedenti interventi di restauro del patrimonio storico hanno previsto l'utilizzo di malte a base di cemento che nel tempo si sono deteriorate compromettendo la stabilità strutturale delle opere e causando perdita di materiale. Nell'ambito del progetto sono state implementate nuove misure conservative volte a stabilizzare il patrimonio scavato. L'analisi scientifica archeologica e la documentazione sistematica dello stato di degrado delle strutture, fra l'altro effettuata mediante fotogrammetria ad alta risoluzione, fornivano una base accurata per gli interventi successivi. Le malte cementizie deteriorate sono state sostituite con malte a base di calce, più compatibili con i materiali originali e in grado di garantire una maggiore durabilità. Inoltre, per mitigare il rischio di erosione e danneggiamento delle fondazioni murarie, è stato realizzato un consolidamento parziale, seguito da un rinterro delle trincee di scavo più profonde, stabilizzando e proteggendo le strutture. Infine, è stato implementato un programma di monitoraggio annuale delle strutture restaurate, finalizzato alla valutazione dell'efficacia delle soluzioni adottate e all'eventuale definizione di ulteriori strategie conservative. Dai risultati ottenuti emerge come l'utilizzo di un approccio olistico e sito-specifico sia necessario per la corretta gestione e valorizzazione del patrimonio storico e culturale esposto ai rischi geologici. Il progetto TRIQUETRA ha per questo sito l'ambizioso obiettivo di integrare l'analisi della pericolosità connessa a fattori geologici con l'utilizzo di tecniche di restauro e conservazione per sviluppare strategie di conservazione sostenibili del patrimonio archeologico custodito nel sito di Aegina Kolonna.

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ABSTRACT

The archaeological site of Aegina Kolonna, a prominent cultural heritage landmark in Greece, is increasingly threatened by geological hazards, including coastal erosion, seismic activity, and slope instabilities. The progressive retreat of the calcarenite sea cliffs has already led to the loss of unexcavated historical remains, posing a severe risk to the site's long-term preservation. Within the framework of the TRIQUETRA (Toolbox for assessing and mitigating Climate Change risks and natural hazards threatening cultural heritage) European Project, an interdisciplinary approach that integrates engineering-geological, geophysical, and archaeological investigations has been adopted to assess site vulnerability and implement targeted mitigation strategies. A comprehensive geological survey identified the primary factors driving cliff instability, while ambient seismic noise measurements helped characterize the subsurface conditions and assess local seismic amplification effects. The structural stability of key archaeological elements, such as the last standing column of the Apollo Temple, was also evaluated, revealing resonance frequencies in the range 5-8 Hz, which may influence its seismic vulnerability.

In addition to hazard assessment, the TRIQUETRA project focuses on heritage conservation of this site, particularly of the northeastern prehistoric settlement. Past restoration efforts relied on cement-based mortars, which have deteriorated over time, leading to structural instability. To address this, new interventions include detailed documentation, the replacement of degraded materials with lime-based mortars, partial backfilling to stabilize exposed foundations, and the implementation of long-term monitoring strategies. These measures aim to enhance structural resilience while adhering to international heritage conservation guidelines.

This study underscores the necessity of a holistic approach to cultural heritage management, demonstrating how scientific research and restoration practices can be integrated to mitigate geological and environmental risks and ensure the sustainable preservation of archaeological sites.

Keywords: *Aegina Kolonna, cultural heritage, risk assessment, geology, site conservation*

INTRODUCTION

The waters around Cape Kolonna, which is located in the north-west of the island of Aegina in the Saronic Gulf in Greece, are treacherous, and were feared as such already in antiquity: Pausanias, the Greek traveler of the 2nd c. AD, called Aegina as the most difficult island in Greece to access "for it is surrounded by sunken rocks and reefs which rise up" (Paus. 2, 29, 6). In modern times, the danger of access is levered by technology, but the waters are still a threat to Kolonna. The small peninsula, which covers an area of approximately 3.5 hectares, is home to the most significant archaeological site in Aegina (Fig. 1).

Fig. 1 - Orthophoto of Aegina Kolonna in 2012

The western part of the site is extremely exposed to the environmental stressors above the shore (Fig. 13); steep cliffs mark the boundary of the archaeological zone, which in antiquity was larger than today. The ongoing process of erosion causes the fragmentation of the cliff face; unexcavated areas of the historical site have been lost already, and others are in danger of being severely damaged. Over the past few decades, there has been a discernible impact of natural hazards on the archaeological remains, as evidenced by systematic observations. This affects not only walls exposed to precipitation and significant daily and seasonal temperature variations, but also the geological and cultural layers that were excavated and subsequently broke off the steep cliff in the west (Fig. 2, Fig. 13).

Therefore, the progressive retreat of the calcarenite cliffs at Aegina Kolonna represents a critical geological process that has led to the loss of archaeological remains and continues to threaten the integrity of this heritage site. This phenomenon results from the combination of predisposing factors related to the geological setting of the Aegina Kolonna promontory, with preparatory actions linked to the mass rock creep process as well as with triggers related to sea wave impacts against the cliff and local seismicity. Furthermore, the role of floods connected to intense rainfall events as well as the possible overtaking of the sea cliff by anomalous waves, such as those connected to possible tsunamis, does not appear to be negligible. For this set of factors, the case study of the Aegina Kolonna promontory represents an interesting example of a combined geohazard (multiple hazard) as well as of a possible "domino effect" connected to triggering causes (cascading hazard). In both cases, the resulting hazard scenarios consist of the overlapping of effects in the promontory area that intensify the level of damage to the archaeological structures

Fig. 2 - Broken archaeological remains in the western cliff: a) well b) walls c) land loss between 2012 (outer red line) and 2024 (inner red line)

present therein. Such a complex geological context combining lithotechnical heterogeneity, structural discontinuities, and erosional mechanisms is responsible for accelerating the cliff degradation, determining its retreat and progressive demolition. Understanding the main drivers of this process is fundamental for assessing the local vulnerability and developing effective preservation strategies. To this aim, during the early stages of the TRIQUETRA project, the geological conditions of each pilot site have been characterized to determine the most significant geological hazard affecting the exposed cultural heritage. This was accomplished for the Aegina Kolonna case studies by developing a "Geohazard Severy Chart" (GSC), a matrix-based tool that assesses and categorizes the severity of geological hazards (Fig. 3). A GSC includes two components: type of process and time of recurrence. By combining these two components, the GSC assigns an intensity level to each potential geohazard scenario, categorizing them into predefined severity categories. This structured framework aids in geological risk assessment, prioritizing hazards, and developing mitigation strategies for cultural heritage sites and infrastructure (for more information, see Ioannidis *et alii*, 2024).

The geological hazards characterizing Aegina Kolonna are strongly related to the geo-structural setting of the Saronic Gulf and to the stratigraphic setting of the promontory. Engineering-

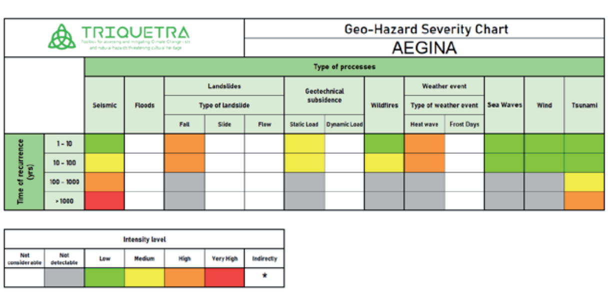

Fig. 3 - Geohazard Severity Chart (GSC) developed for the TRIQUETRA case study of Aegina Kolonna

geological and geophysical surveys were performed to constrain the local geological setting and create a base layer for a more comprehensive geological hazard and risk assessment analysis. This study attempts to establish the necessary groundwork for a site-specific hazard assessment by characterizing the local geological framework and identifying those factors controlling the cliff retreat process. Within the framework of the TRIQUETRA project, these findings will contribute to a broader methodological approach aimed at developing predictive models for site degradation and defining targeted mitigation strategies. The results will support long-term conservation planning and archaeological site management informed by site-specific geological risk.

Geological and geomorphological setting

The island of Aegina covers an area of about 87 km^2 and has 57 km of coastline. Aegina lies at the northwest end of the South Aegean Volcanic Arc (Mourtzas & Kolaiti, 2013), which spans from the Saronic Gulf in the west to the island of Nisyros in the east (Elburg & Smet, 2020). The island is one of the arc's volcanic centers, where volcanism first began (Vougioukalakis *et alii*, 2019). This volcanic arc was formed by the subduction and rollback of the African plate beneath the Aegean microplate (Papazachos & Comninakis, 1971; Pe & Piper, 1972; Royden & Papanikolau, 2011; Jolivet *et alii*, 2013; Foutrakis *et alii*, 2020) (Fig. 4a, b).

The Saronic Gulf is affected by an N-S extensional back-arc tectonism that reduces the crust thickness to 20 km and allows the mantle material to ascend (Georgiou *et alii*, 2021). The Saronic Gulf area has generally low seismicity, though strong earthquakes, both recent and historical, have occurred on the gulf's northern edge (Makropoulos *et alii*, 2012). This area has a complex fault pattern (Papanikolau *et alii*, 1988): active normal faults as well as strike-slip faults, have formed due to subsidence (Georgiou *et alii*, 2021). The island of Aegina is dominated by extensional tectonics, which have caused uplift and subsidence, resulting in the formation of horst and graben structures in addition to the emplacement of magma.

The geological basement of the island is constituted of Mesozoic limestones and Eocene flysch, which are only visible in the central-northern part of the island (Dorais & Shriner, 2002). Late Messinian transgressive conglomerates can be found above Eocene flysch in some northern coast outcrops (Dietrich *et alii*, 1993). The first volcanic phase ("Dacitic phase"; Dietrich *et alii*, 1993) started between 4.7 and 4.3 Ma (Francalanci *et alii*, 2005), initially overlapping the basement with rhyodacitic ashes and pumice. More recent andesitic-dacitic lava flows formed the central part of the island (Mourtzas & Kolaiti, 2013). Between 3.0 and 2.1 Ma, a low-rate eruption period likely occurred (Francalanci *et alii*, 2005), before and during which shallow marine sediments accumulated. This Pliocene sedimentary succession consists of silty clays and marls. The predominant feature is the occurrence of yellow to greenish marls, rich in fine-grained sandy intercalation. The greenish colors are the expression of a high content of chlorite, epidote, and serpentine minerals (Dietrich *et alii*, 1993). After this and during the second

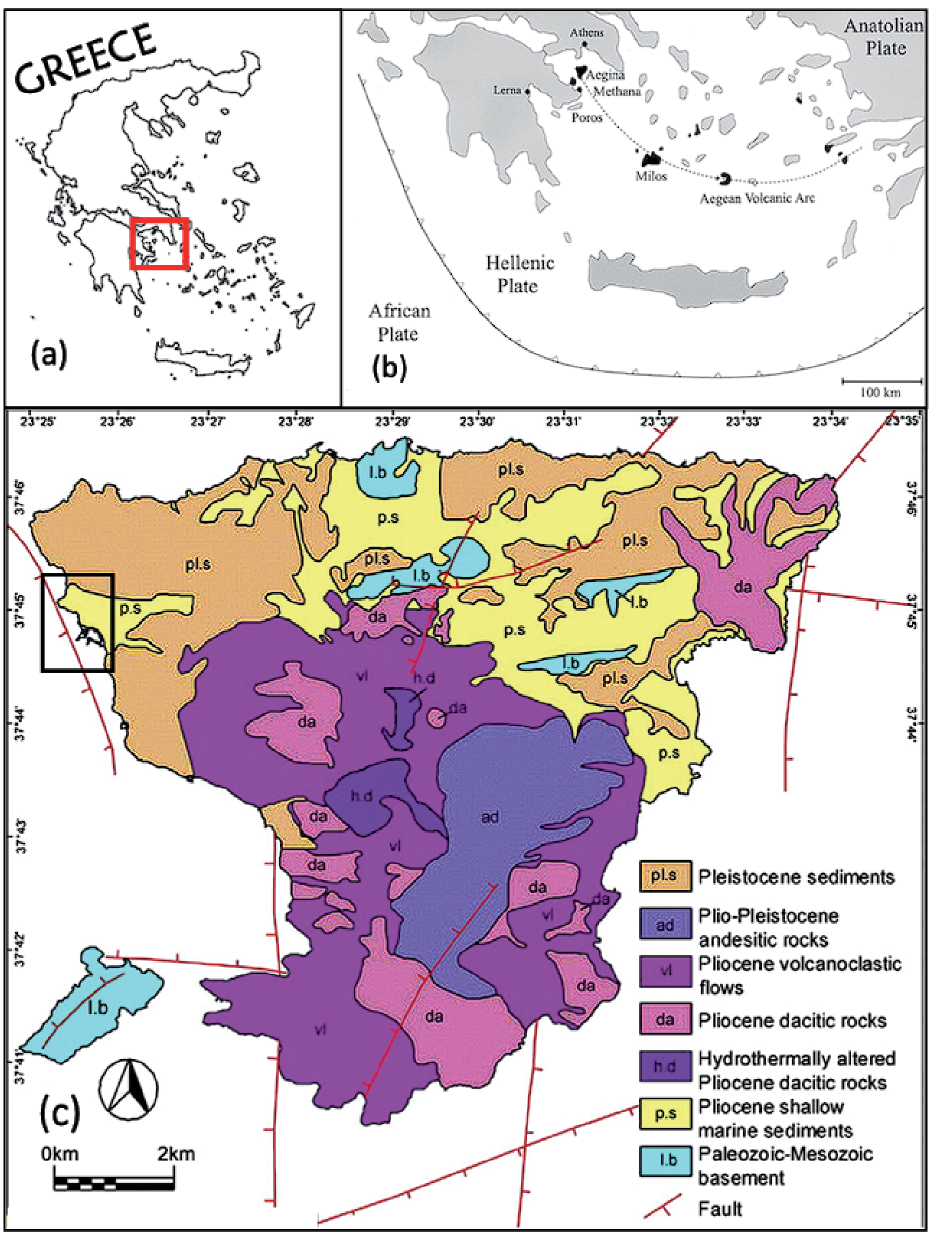

Fig. 4 - a) Geographic location of the Saronic Gulf; b) location of the South Aegean Volcanic Arc with the principal volcanoes and c) geological map of the island of Aegina indicating the study area (rectangle). [mod. after Dorais & Shriner (2002) and Mourtzas & Kolaiti (2013)]

volcanic phase ("Andesitic phase"; Dierich *et alii*, 1993), minor amounts of pyroclastics and flows of basaltic andesites, high-alumina basalts, and andesites were produced, thus forming the south part of the island. This was followed by subsidence of the north part of the island and the deposition on the north coasts of hard, white, sandy–marly limestone of marine origin (Mourtzas & Kolaiti, 2013) ("Poros Formation") (Fig. 4-c).

Aegina Kolonna is a minor promontory, reaching a maximum elevation of about 15 m above sea level, that gradually merges with the inland while exhibiting a quite steep sea cliff on its westernmost section (that reaches a maximum height of about 8 m). The dominant morphogenetic control on the landforms in the promontory is represented by the gravity-induced processes (landslides) and by the sea. Many rock blocks are present below the sea cliff, depicting a predominant process in terms of cliff's edge retreat and geological risk. The main process that occurs in the area is the lateral spreading caused by the peculiar stratigraphic setting (stiff Quaternary calcarenite overlaying ductile Pliocene clays). Such rheological contrast is responsible for the deformation process that currently affects the western portions of the promontory and is reflected in rock toppling and falls (Hungr *et alii*, 2014) that periodically affect the cliff. The sea, through the process of wave refraction, contributes to the evolution of the cliff. The energy of the sea waves tends to concentrate at the westernmost portion of the promontory, causing the erosion of the marly horizon and the creation of a basal notch.

Historical and archaeological outline of Aegina

The island of Aegina is located in the middle of the Saronic Gulf, in proximity to Piraeus, Athens and Attica (from about 19 km), to Salamis (appr. 12 km) and even closer to the peninsula of Methana on the Peloponnese in the south-east (appr. 8 km). Its vicinity to the mainland, coupled with its advantageous access to the Aegean Sea, has attracted people to settle since the Neolithic period (at least since the 4th millennium BCE). Cape Kolonna, on the well-protected western side of the island, with the two natural harbour bays, and endowed with a fertile hinterland, offered the island a particularly suitable environment for habitation. Consequently, it is home to the largest fortified Bronze Age settlement on the island, dating back to the 3rd and 2nd mill BCE. Its economic prosperity is reflected in the continuous expansion of the settlement eastwards from the fortified center (Gauss, 2010). In historic times (7th c. BCE - 3rd c. AD) Kolonna housed a prominent sanctuary with a well-visible temple, built around 530/520 BC.

The construction of the large central Doric peripteral temple (so-called temple of Apollo) with its surrounding temenos wall represents a highlight in the history of Kolonna (Felten, 2007). Its massive foundations are rooted in the walls of the earliest settlement revealing the intertwined and complicated history of the site. The appellation 'Colonna' was bestowed by the Venetian sailors, who utilized the two remaining columns as a point of orientation, of which one collapsed in the 19th c. Nowadays, the last column of the temple dominates the hill. It is visible from all directions and thus gives the cape its name.

Towards the end of the 6th c. AD, new settlers from Corinth arrived in Aegina and transformed the site into a new, early Byzantine town that survived until approximately AD 1000 (Pennas, 2005; Felten, 2007). The building activities undertaken by the most recent settlers resulted in significant disruption to the older architectural remains and structures. They levelled the site and reused older stones and components (*spolia*) for their new buildings. This has had a profound effect on the architectural remains, with the structures of the sanctuary in particular being severely affected.

The site has been studied in the project Aegina Kolonna, its excavations going back to the 19th c. The University of Salzburg has carried out excavations of the archaeological site on an annual basis since 1966; the current focus of research concentrates on the Bronze Age settlement and the Byzantine occupation as well as on the digitization of the excavation (project: "Mapping Kolonna" to support geophysical investigations and the modelling of the site, Sporn *et alii* 2017, Sokolicek, 2023; see: www.aegina-kolonna.at).

The Inner Suburb of the prehistoric settlement on the hill of Aegina Kolonna was one of the first targets of archaeological interventions at the site in the late 19th and early 20th centuries. Excavations in this area were mainly carried out between the First and Second World Wars and continued until the early 1980s (Stais, 1895; Wolters, 1925; Sporn *et alii*, 2017). Work on the site was completed around 1990 with partial consolidation using cement mortar.

This Inner Suburb was built in the Middle Bronze Age outside the existing settlement. It consists of a series of rooms built against a new fortification wall, some of which had been preserved to the level of the door lintel (Fig. 5a). As is characteristic of the Bronze Age, they are built of local rubble stones and clay mortar (Fig. 1; Fig. 5a). This type of construction is very sensitive to the elements, especially rainwater, which washes out the joints and leads to instability of the walls. Unsurprisingly, already a few decades after the excavation, in the 1920s, parts of the constructions were lost, leading to the present situation. The rubble walls were originally covered with a protective layer of lime plaster, parts of which are still preserved in a room with a pottery kiln. This room is covered by a modern porch roof, a measure carried out during a previous restoration around 1990 (Fig. 5b).

ENGINEERING-GEOLOGICAL AND GEOPHYSICAL SURVEYS

In the framework of the TRIQUETRA project, engineering-geological surveys of the study site were carried out in July

Fig. 5 - Inner Suburb with room with pottery kiln from the west. a) around 1900 (Photo archive of the German Archaeological Institute Athens, D-DAI-ATH-Aegina-0017); b) in 2024

2023 and 2024 to identify and delineate the main engineering-geological units and geomorphological features of the Aegina Kolonna promontory. The field investigations focused on reconstructing and mapping the geological contacts between the stiff Pleistocene calcarenites and the underlying deformable marls, a lithological contrast that plays a fundamental role in the slope instabilities affecting the western sector of the promontory. In this area, instability mechanisms - mainly rockfalls and block topples - are actively driving the retreat of the cliff edge, thereby threatening the integrity of the archaeological remains. The interaction between structural discontinuities and wave-induced erosion is promoting the progressive failure of the cliff, leading to basal undercutting and notch formation in the marly substratum, which further destabilizes the overlying calcarenite cap-rock. In this framework, a detailed engineering-geological field survey was carried out mapping and characterizing the outcropping geological units. A geomechanical characterization of the Pleistocene calcarenite was performed following ISRM (2007) standards, including the assessment of joint distribution, persistence, and infilling conditions. A scanline survey was also conducted in sectors where the calcarenite was most exposed, allowing for the quantitative evaluation of the rock mass fracturing conditions.

In addition to the engineering-geological surveying, single-station ambient seismic noise measurements were taken at 26 different locations, covering the entire archaeological area (Fig. 6a), to constrain the subsurface geological setting by identifying fundamental site resonance frequencies (f_0) through the HVSR technique (Nogoshi & Igarashi, 1970; Nakamura, 1989). The HVSR analysis is particularly well-suited for site characterization when marked seismic impedance contrasts exist between low shear-wave velocity layers and the underlying seismic bedrock, and peaked frequencies in the HVSR function can be interpreted as resonances of the soft surface layers (Bonnefoy-Claudet *et alii*, 2006; Iannucci *et alii*, 2018). For each measuring station, the ambient vibrations were recorded for 1-hour at a sampling frequency of 200 Hz using a SARA SL06 three-component velocimeter (2.0 Hz nominal frequency) equipped with an in-built

24-bit digitizer. In the framework of the TRIQUETRA Project, a dedicated MATLAB toolbox was developed to process ambient vibration data and retrieve H/V functions for each recording station. The data processing workflow followed a systematic approach to ensure the reliability of the computed spectral ratios. At first, basic time series and spectral analyses were performed to evaluate data quality and verify the absence of significant disturbances in the recordings (e.g., anthropogenic noise, earthquakes, and strong winds). After data validation, preprocessed was conducted on all signals by removing the mean, linear trend, and correcting for the instrument response via spectral division, finally band-passing data between 0.05 and 50 Hz. Following, the Welch's method (Welch, 1967) was used to estimate power spectral densities (PSD) and Fourier amplitude spectra (FAS), with stacked Fast Fourier transforms (FFT) of 60 s Hanning-tapered windows with 50% overlap to reduce variance (Fig. 5b). To further reduce spectral variability, each FAS was smoothed using the Konno-Ohmachi filter with a b-value of 40. The horizontal components were averaged using the geometric mean (Bard, 2005), and the HVSR functions were computed as the ratio between the average horizontal and vertical FAS for each window (Eq. 1).

$$HVSR(f) = \frac{\sqrt{FAS_{NS} * FAS_{EW}}}{FAS_{UD}} \quad (1)$$

The average HVSR function and its standard deviation were computed over all windows to provide a robust estimate of site-specific spectral amplification characteristics (Fig. 6c). Finally, to investigate the directionality of the H/V functions, the H/V ratios were computed for multiple azimuthal orientations by systematically rotating the horizontal components of each station (Fig. 6d). A strong azimuthal variation may be the first indication of nonuniform source distributions and/or the presence

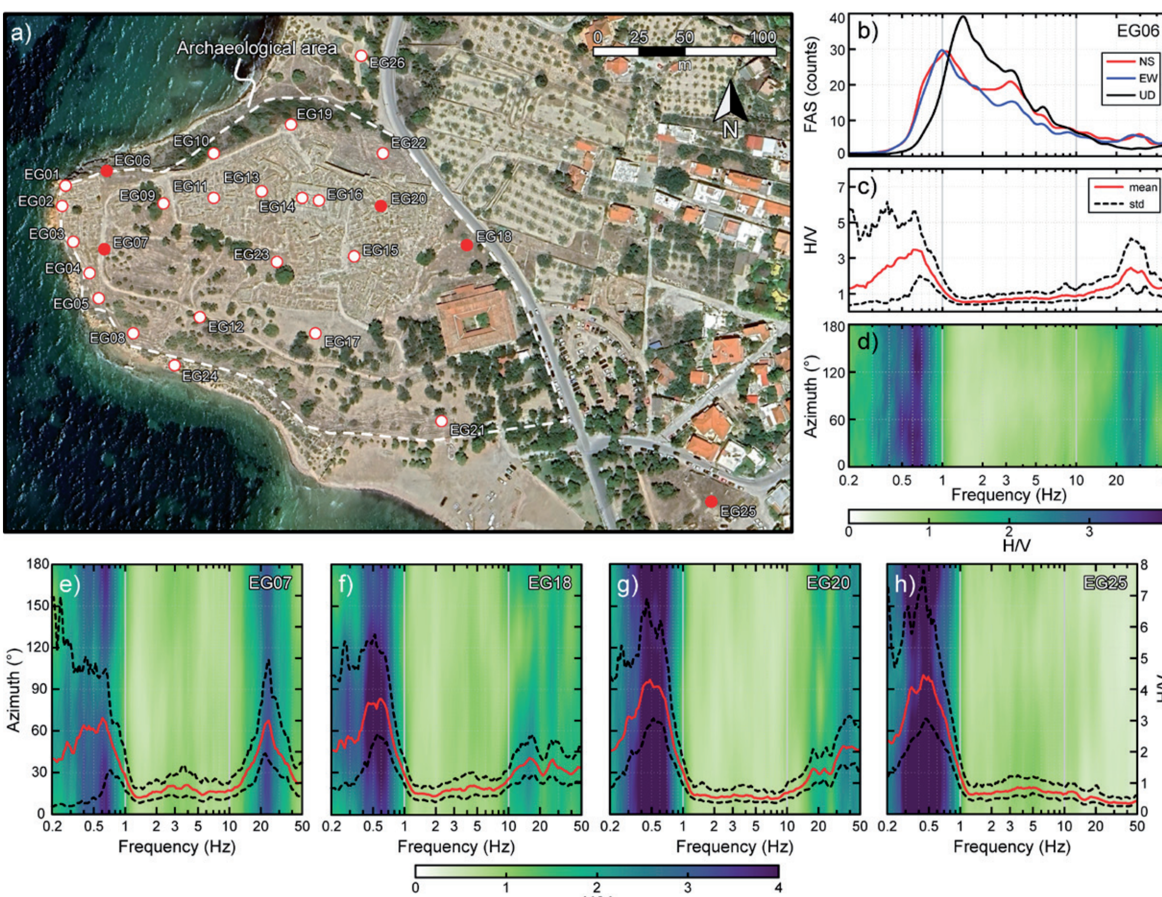

Fig. 6 - a) Satellite view of the archaeological area of Aegina Kolonna with the location of all ambient seismic noise measurement stations. b) Example of Fourier Amplitude Spectra (FAS) for station EG06, showing spectral amplitudes for the North-South (NS), East-West (EW), and vertical (UD) components. c) Corresponding HVSR function for EG06, with the mean HVSR curve (red) and standard deviation (black dashed line). d) HVSR rotate analysis for EG06, illustrating the directionality of the HVSR ratio as a function of frequency, where azimuthal variations highlight the potential polarization of site resonance. e)–h) Composite plots showing results for additional stations (EG07, EG18, EG20, and EG25), showing dominant resonance peaks and their directional characteristics

of subsurface geological heterogeneities (Wathelet, 2020), providing preliminary insights into site-specific characteristics. Besides conducting ambient seismic noise measurements to characterize the local seismic response of the promontory, we also recorded ambient vibrations at the base of the last standing column of the Apollon Temple. A seismometer was deployed close to the column's base and continuously recorded ambient vibrations for 3 hours, with the aim of investigating the dynamic behavior of the structure. This preliminary survey serves as a reference for future analyses aimed at assessing its stability and vibrational response to environmental and seismic excitations. Data were analyzed for both spectral content and polarization attributes. Spectral analysis following the already described processing steps, have been performed and the resulting PSDs were analyzed to identify spectral peaks potentially related to resonance modes of the column. To further characterize the identified peaks, frequency-dependent polarization analysis was performed on the dataset (Koper & Hawley, 2010). This technique can aid in the interpretation of spectral peaks as resonance modes by allowing for the extraction of the degree of polarization, polarization azimuth and dip with respect to the horizontal plane.

MAIN OUTCOMES

The detailed engineering-geological survey allowed to constrain the geological and geomorphological setting outcropping of the study area. A total of five engineering-geological units were recognized across the promontory (Fig. 7a):

- Clay unit: the oldest engineering-geological unit outcropping in the promontory and consists of medium-to-high consistency silty clays and yellow-greenish marls (Lower Pliocene-Upper Pliocene).
- Calcarenite unit: rock mass unit composed of calcarenite layers up to 120 cm thick, thin sandstone and marl layers, and intervals up to 50 cm thick of poorly sorted, grain-supported breccias in a sandy-silty matrix. Aeolian deposits with good cementation can also be found at the top of the unit (Lower Pleistocene). This unit is associated with the Poros Formation and constitutes the primary lithology forming the Aegina Kolonna sea cliffs.
- Eluvial-Colluvial unit: silty-clayey deposits constituted by weathered material and detrital deposits transported by sheet waters (Olocene).
- Backshore unit: sandy-silty transitional deposits that can be found between the mainland and the shoreline (Olocene).
- Anthropic unit: constituted by both the archaeological remains and waste deposits of the different archaeological excavations in the area.

The geomechanical characterization of the Pleistocene calcarenite revealed the presence of three joint sets, including sub-horizontal bedding (J_0) and two steeply dipping sets (dip direction/dip, Fig. 7a): J_1 (308°N/74) and J_2 (158°N/87). In particular, the orientation of J_1 matches a mapped fault offshore of the Kolonna promontory (Fig. 4c), and it is thus likely related to that structural lineament.

Results from ambient seismic noise measurements helped constraining the thickness of the identified engineering-geological units and preliminary assessing the site-specific seismic response of the investigated area. Results from HVSR analysis reveal a consistent and prominent peak across all stations in the frequency range 0.4-0.7 Hz (Fig. 6, 7). This HVSR peak was interpreted as resulting from a very deep seismic impedance contrast between the Eocene flysch or Mesozoic limestone, that constitutes the seismic bedrock, and the Pliocene Clay unit outcropping in the area. This HVSR peak features a broad or "plateau-like" shape (Fig. 6e-h), generally originated by seismic noise wavefield diffraction, that suggests the existence of an inclined or irregular contact between the soft-soil deposits and the underlying seismic bedrock (Uebayashi, 2003). No significant directionality is observed in the HVSR functions within this frequency range, thus suggesting a depth-controlled (*i.e.*, stratigraphic) or 1D seismic response model for the area. Besides, all stations located above the Calcarenite unit show HVSR functions that are characterized by a sharp amplitude drop up to values < 1 in the frequency range 1-10 Hz. This marked decrease in the HVSR amplitude results from the higher amplitude of the vertical component relative to the two horizontal ones, suggesting the existence of a shear-wave velocity contrast between the soft clays and the overlying stiff calcarenite unit, that can also be appreciated in correspondence of eluvial-colluvial and anthropic deposits. This evidence further helped reconstruct the engineering-geologic model of the study area by constraining the spatial distribution of the Calcarenite unit. It is worth noting that some stations highlighted clear peaks in the HVSR functions in the frequency 8-25 Hz (Fig. 6e, 7b). Although these peaks are not consistent across the entire promontory area, we interpreted them as deriving from local resonances of shallow deposits (*e.g.,* Eluvial-Colluvial and Anthropic units). Similarly, a few stations close to the western edge of the promontory show HVSR peaks at frequencies higher than 40 Hz that can be potentially associated with local resonances of calcarenite blocks partly dislodged from the cliff by subvertical fractures.

These results deriving from passive seismic investigations based on environmental seismic noise recordings, allow us to associate a conceptual model of seismic response to the promontory of Aegina Kolonna which, in agreement with Martino (2024), varies from "depth controlled", in the innermost area of the promontory, to "volume controlled", in the perimeter area. In the first case, the stratigraphic resonance connected to the geological setting of the

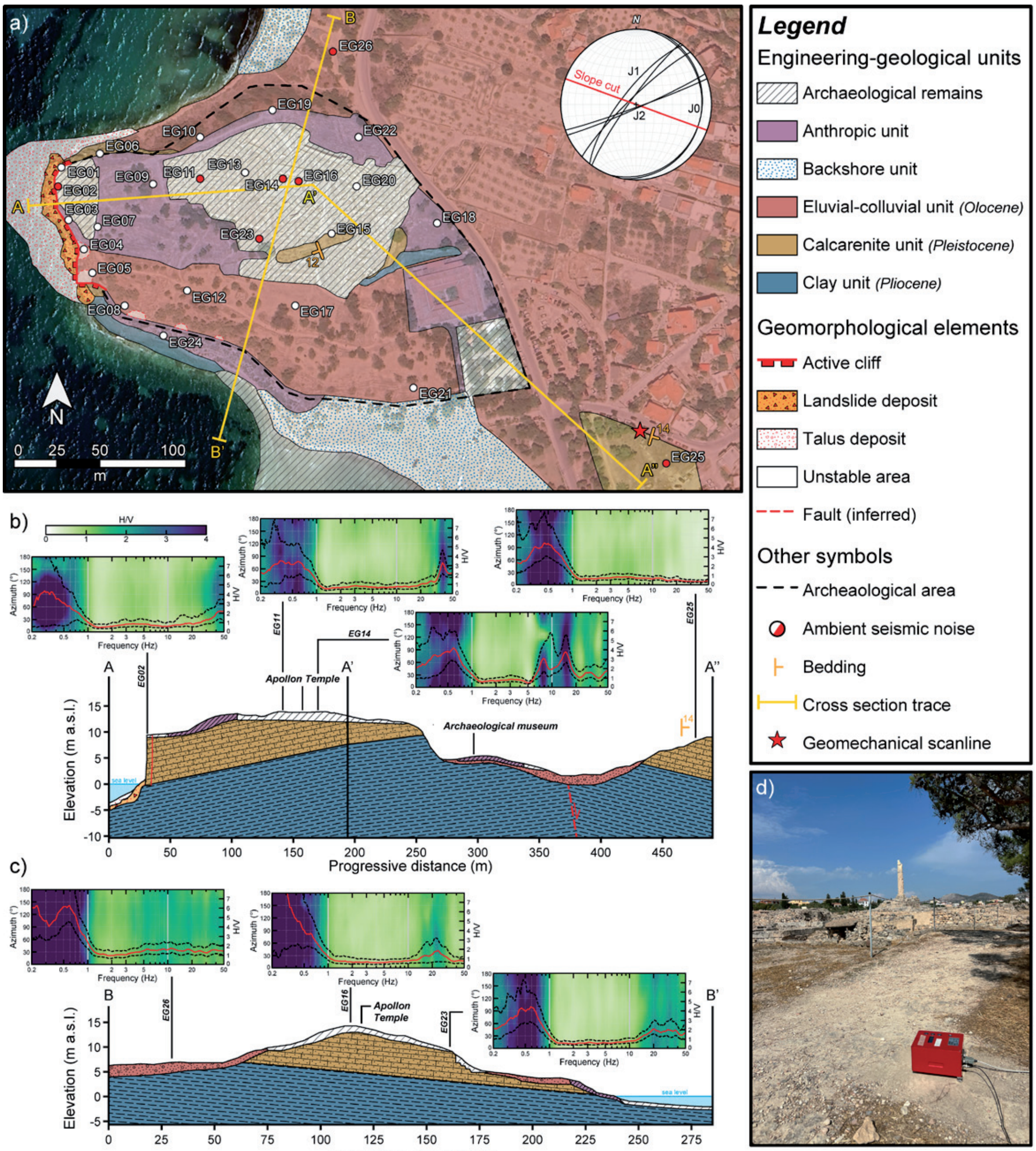

Fig. 7 - a) Engineering-geological map of the study area, showing the main geological units, geomorphological elements, and ambient seismic noise measurement stations. The cross-section traces A-A'-A" b) and B-B' c) are indicated in yellow, while the location of the geomechanical scanline is marked with a red star. Composite HVSR plots for selected measurement stations (red circles in panel a) are shown along both cross sections to highlight the seismic site response. The stereoplot in the upper-right corner of panel (a) shows the principal joint sets identified in the area. d) Example of an ambient seismic noise measurement station, showing the field setup used for recording ambient vibrations to infer local site response characteristics

area is substantially evident, while in the second case, this effect is superimposed by the specific presence of eigenmodes connected to blocks of rock isolated by fractures forming along the perimeter of the sea cliff, especially in its westernmost portion.

The ambient vibration data collected at the base of the column allowed us to preliminary characterize its dynamic behavior (Fig. 7). From spectral analysis, two prominent peaks were manually identified at 5.2 Hz (f_1) and 8.1 Hz (f_2), corresponding to local maxima in the PSDs (Fig. 8a), that were interpreted as resonance frequencies of the column. In fact, these frequencies feature a degree of polarization that peaks close to unity in the probability density function (Fig. 8b), confirming that particle motion is well-organized within a narrow frequency range. Results from polarization analysis show that f_1 is EW-oriented, with an incidence angle of 30°, thus indicating a potential bending mode with significant vertical component. Conversely, f_2 suggests a nearly horizontal, SW-NE bending mode with minimal vertical component participation (Fig. 8c, d). Additionally, a broad spectral peak, dominant on the EW component, is observed in the PSD plot. However, this frequency does not exhibit a significant degree of polarization, indicating that particle motion is more scattered and lacks a well-defined resonance pattern. This suggests that the observed peak may derive from non-structural factors, such as local site effects or external disturbances, rather than a fundamental resonance mode of the column.

PREVIOUS RESTORATION WORK IN THE INNER PREHISTORIC SUBURB AND ACTIONS UNDERTAKEN AS PART OF THE TRIQUETRA PROJECT

Apart from a few photographs, there is no documentation of the earliest consolidation and restoration work. However, some initial work was carried out in selected restricted areas in the 1920s, and more extensive work was carried out in the late 1980s. As was characteristic of the time, cement mortar was used. However, excavation continued, even below the foundations, leaving the lower parts of the walls unprotected and exposed to the elements. In addition, the cement mortar on many of the walls has become detached over the years, requiring new interventions. More recently, following the first comprehensive documentation of the current state, some exceptionally heavy winter rains have caused damage in the form of partially

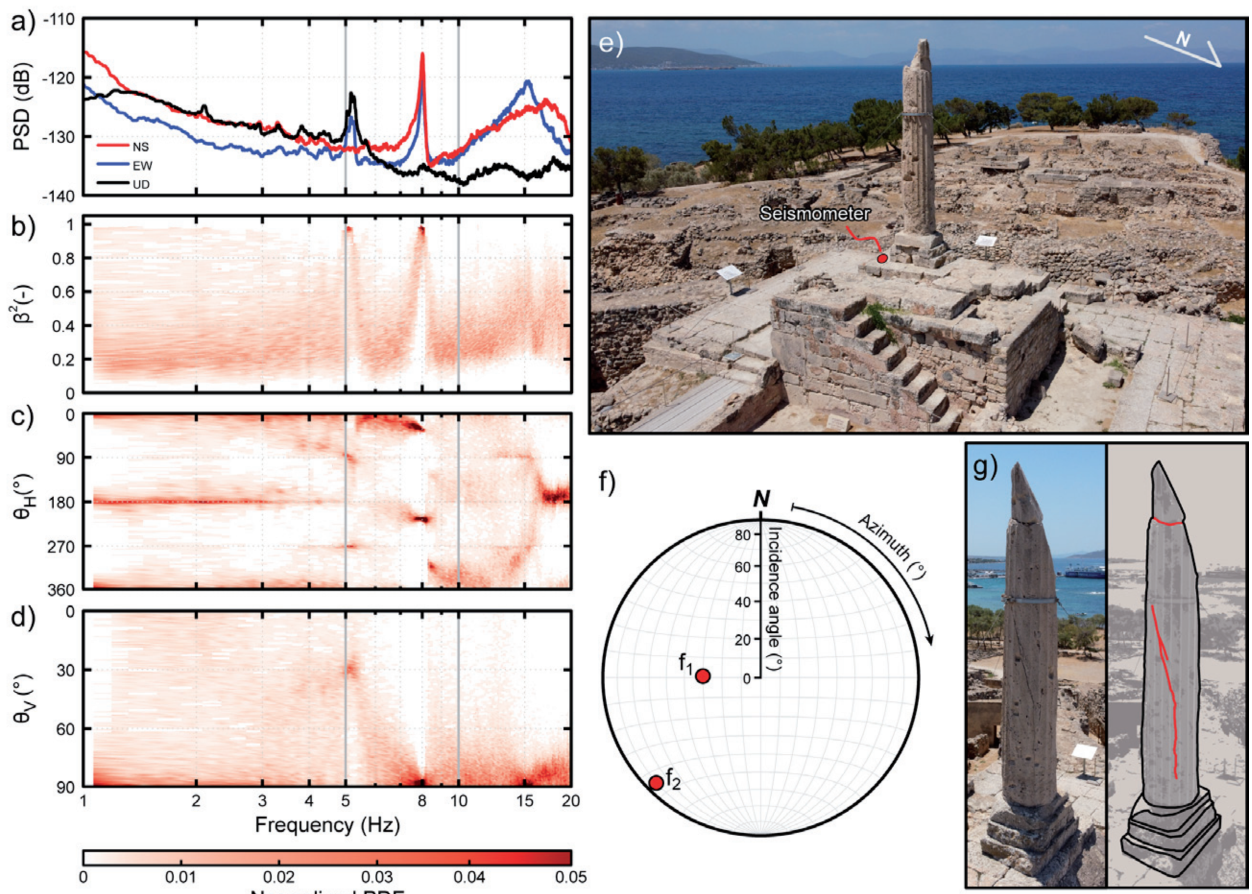

Fig. 8 - Results of spectral and frequency-dependent polarization analysis for the ambient vibration data recorded at the base of the standing column. a) Velocity power spectral density (PSD) estimates where decibel powers are relative to 1 $m^2 s^{-2} Hz^{-1}$. Probability density functions (PDFs) of b) degree of polarization (β^2), c) polarization azimuth (θH), and d) incidence angle (θV). e) Panoramic view of the standing column with the location of the seismometer at the base (red circle). f) Lower hemisphere stereographic projection of polarization vectors for the identified resonance frequencies of the column. g) Close view of the column and schematic interpretation of the observed structural damage, with red lines indicating fractures and potential failure planes

collapsed walls due to undermining of the wall foundations.

A 2011-2014 survey has already systematically documented all the structures in the area to the north and east of the Temple of Apollo, including the Inner Suburb: a new detailed stone-by-stone plan, photographs, a 3D model, as well as mapping of damage and previous restoration, followed by an architectural analysis, including archival images (Sporn *et alii*, 2017). This was used as the basis for an emergency restoration in the following years, accompanied by trials of different types of mortar. Subsequently, a consolidation and restoration concept was designed in 2017 and implemented in the following years, with annual adjustments and annual monitoring. This included partial backfilling, particularly of deep trenches (Tanner, 2020).

In the framework of the TRIQUETRA project, a new photogrammetric 3D model and orthoimages of the site undertaken by the Lab. of Photogrammetry of the National Technical University of Athens serves as up-to-date documentation. The researchers were able to draw on their long-term documentation of the walls and their experience over the past decade in consolidating and restoring rubble structures, including trained local masons. Finally, as part of the TRIQUETRA project, the area of the lower parts was filled in throughout the area.

In general, the conservation and restoration works must be coordinated with the principles of the Charter of Venice, which serves as a basis for the national laws on the preservation of monuments and sites (Charter Of Venice, 1964).

"Art. 9. ...The restoration in any case must be preceded and followed by an archaeological and historical study of the monument.

Art. 10. Where traditional techniques prove inadequate, the consolidation of a monument can be achieved by the use of any modern technique for conservation and construction, the efficacy of which has been shown by scientific data and proved by experience.

Art. 12. Replacements of missing parts must integrate harmoniously with the whole, but at the same time must be distinguishable from the original so that restoration does not falsify the artistic or historic evidence."

Fig. 9 - Types of damage a) Washed-out joints. b) Undermined foundation and fallen stone. c) Detached cement mortar. d) Vegetation

The first step in the former project, after the archaeological and architectural study, was to map and assess the damage. The main types of damage are washed-out joints, washed-out wall foundations with stones that have fallen out of place, detached old cement mortar and vegetation on the walls (Figs. 9a-d). This led to the development of a restoration plan, which included the measures for the walls such as restoration, covering with earth or leaving in their original state, where possible (Tanner, 2020).

For the consolidation and restoration, a restoration mortar was developed by testing different types of lime. According to this preliminary test series, a lime mortar consisting of natural hydraulic lime and river sand gave good and long-lasting results, which we have been applying since then. The damaged walls were subsequently restored with this lime mortar using the documentation. Once the walls had been cleared of vegetation, earth and, where present, old, detached cement mortar, they were restored one by one, accompanied by documentation.

The washed-out joints were filled with mortar. Undermined foundations were underpinned by newly constructed rubble walls, set back slightly and covered with plaster. With the help of the photographic documentation, stones that had fallen out were replaced in their original positions. Gaps were filled with stones for stability reasons. All the new stones were covered with plaster, in accordance with *Article 12* of the Charter Of Venice (Figs. 10a, b).

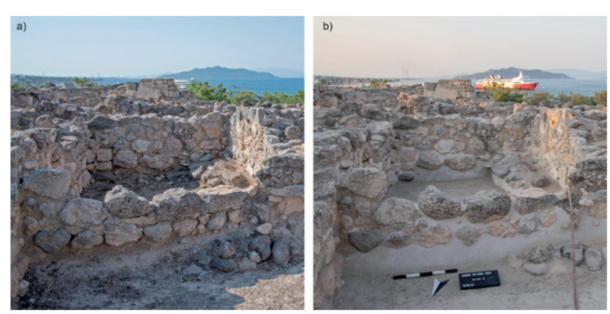

Fig. 10 - Restoration of wall M1451 in the Inner Suburb. a) Undermined foundation due to deep excavation. b) Partial restoration, especially of the lower part

In particular, low-lying structures in deep trenches and high-lying exposed walls need protection at the base, as undermining by rain will occur again. Partial backfilling is therefore the best way to protect the monuments against meteorological hazards. It serves the following purposes:

1. To protect the walls and other structures (they will still be visible on-site panels with plans);

2. To level the ground for visitors and to facilitate the maintenance of the site (cutting the grass);

3. To reduce the growth of vegetation in the stony material (gravel and sand). This last point is still under observation.

While the Outer Suburb, which was the subject of the previous project, had hardly been conserved at all and had some very deep trenches, the area of the Inner Suburb was on a level surface and had already undergone the consolidation measures mentioned above. During the last years (2022-24) it was therefore essential to consolidate the unprotected foundations of the walls in the area of the Inner Suburb (Fig. 11). This was achieved by the construction of substructures and partial consolidation of the lower parts of the walls.

As a final and most protective measure, a 10 to 25 cm infill of gravel and sand was spread during the summer 2024 field campaign in order to raise the ground level above the foundations in this area (Figs. 11, 13 b-d).

The area will continue to be monitored and repaired annually as necessary. In addition, maintenance of the area requires annual cutting of the grass on the ground, while the plants are also detrimental to the walls. It is expected that these measures will reduce the growth of vegetation in the future, making the conservation and maintenance work easier (Fig. 12 a).

Fig. 11 - Restoration plan 2024 with the areas of the Inner and Outer Suburbs in the northeastern prehistoric settlement

Fig. 12 - Overview of the Inner Suburb from the west. a) April 2024, before the grass was cut in spring. b) August 2024, after cleaning the area at the beginning of the campaign. c) September 2024, during the restoration work and infilling with a layer of coarse gravel on a permeable geotextile. d) September 2024, at the end of the campaign, after the wall restoration and backfilling (Infilling with a layer of sand up to the lower edge of the wall)

CONCLUSIONS

The Kolonna promontory in Aegina hosts the most significant archaeological site on the island, situated on a small peninsula of about 3.5 hectares. The western part of the site is extremely exposed to the elements above the shore (Fig. 13), causing continued fragmentation of the cliff face. Over the past few decades, there has been a discernible impact of natural hazards on the archaeological remains.

The engineering-geological surveys carried out at the Aegina Kolonna promontory in the TRIQUETRA project framework have highlighted how the cause of the evident retreat of the sea cliff can be attributed to a combination of stratigraphic setting, i.e. stiff calcarenite overlapping ductile clayey marl, responsible for the activation of a creep processes which induces the lateral spreading of the rock plateau of calcarenite, and external forcing such as marine actions due to the sea waves, and earthquakes, the latter connected to the high seismicity of the Saronic Gulf area. Factors capable of predisposing the site to a combination of geohazards as well as to their concatenation. It is possible to assume the eventuality that impact chains are generated by the effect of earthquakes capable of generating tsunami waves and consequently flooding of the promontory, as well as the impact of sea waves on the steep sea cliff can cause its collapse in blocks with the consequent retreat of the edge of the promontory, a phenomenon this prepared over time by the slow deformations due to creep that involve the summit calcarenite in contact with the underlying clayey marls.

Results from the noise measurement campaign have highlighted the presence of at least two ranges of fundamental resonance frequencies: one related to broadband peaks in the range 0.4-0.7 Hz, and the other between 8 and 25 Hz. The first frequency range suggests the existence of 1D site amplification effects related to the local stratigraphy that can determine, in the event of earthquakes characterized by very-low frequency content (e.g., far-field conditions), an increase in the seismic shaking transmitted to the existing archaeological structures, thus increasing potential damage. It should also be noted that given the not-flat morphology of the area and the deep not-horizontal contacts among the reconstructed geological-technical units, further two-dimensional amplification effects within different frequency ranges may occur. In particular, ambient vibration measurements at the base of the standing column of the Temple of Apollo have identified two resonance frequencies at 5.2 and 8.1 Hz (Fig. 8). Given that resonance phenomena can amplify structural responses, seismic excitations with peak spectral content overlapping the dynamic range of the columns may induce significant amplification effects, increasing the risk of structural instability and potential failure.

These findings emphasize the necessity of implementing preventive monitoring and mitigation measures and site-specific seismic hazard assessments. Furthermore, the interaction between local stratigraphic amplification and the dynamic response of the column should be quantitatively investigated through numerical modeling, which will provide insights into the soil-structure interaction effects governing the seismic behavior of this archaeological landmark.

Therefore, in the continuation of the TRIQUETRA project, numerical modelling of seismic response will be carried out in correspondence with the geological-technical sections to quantify the seismic amplification both for the purpose of evaluating the possible soil-structure interactions with particular reference to the Aegina column and to evaluate the seismic action with respect to the instability of the part of the promontory subject to falls and topples that determine the progressive retreat of the slope, threatening the conservation of the archaeological remains present. For this last purpose a stability analysis of the cliff will also be carried out to define the current safety conditions and the eventual necessity of risk landslide mitigation interventions. It is imperative to continue removing harmful vegetation and conserving the architectural features to prevent the site from effects due to damaging. Permanent heritage conservation and its monitoring make a significant contribution to the sustainable preservation of cultural heritage monuments and sites.

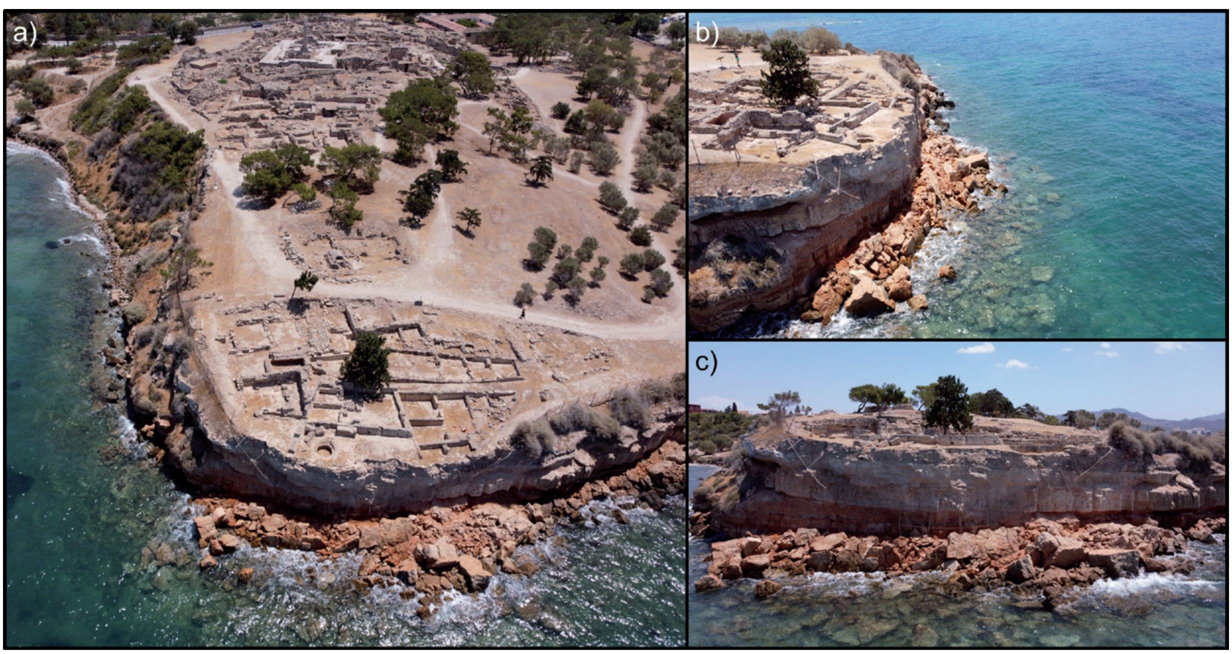

Fig. 13 - a) Aerial view of the western sector of Aegina Kolonna promontory where the cliff retreat process threatening the archaeological remains is clearly visible. b–c) close views of the unstable cliffs and related landslide deposit

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