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Anastylosis of the Western Stoa of the Gymnasium of Ancient Messene: Engineering Insights into an Archaeological Monument

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ABSTRACT

The structural assessment of restoration or anastylosis interventions in monumental dry-jointed stone structures, such as ancient Greek and Roman public buildings and temples, typically involves multidisciplinary surveys, documentation, and analyses to verify their safety and performance under static and seismic actions. Such engineering studies can also help archaeologists better understand the construction challenges faced by ancient builders, the structural solutions they adopted, and, in some cases, the underlying causes of observed damage or destruction. This presentation summarises the surveys and analyses carried out for the anastylosis programme of the western stoa of the gymnasium at Ancient Messene in southern Greece, highlighting key findings related to the original design of the stadium and surrounding stoas, as well as the likely mechanisms of their eventual collapse following abandonment.

Keywords: Anastylosis, Conservation, Ancient Columns, Seismic Response, Distinct Element Method.

INTRODUCTION

Restoration interventions on archaeological sites and monuments are typically conducted under the direction of archaeologists and architects responsible for the excavation, documentation, and interpretative study of the site. Within this framework, the early involvement of civil, structural, and geotechnical engineers is increasingly recognised as essential for fostering effective interdisciplinary collaboration. This integrated approach enables structural safety, seismic vulnerability, ground conditions, and foundation behaviour to be evaluated alongside considerations of archaeological authenticity and historical significance.

Engineering input from the initial stages of assessment and planning of an anastylosis programme, and throughout its implementation, is critical to ensuring the safety and durability of interventions. It also informs the design of compatible, minimally invasive, and reversible solutions, while contributing to a deeper understanding of original construction challenges and the strategies adopted by ancient builders in response to environmental and geotechnical constraints. In this context, targeted surveys, structural and geotechnical analyses, and analytical modelling establish a robust technical basis for interpreting deterioration processes and diagnosing damage or collapse, particularly when linked to natural hazards such as seismic activity, flood effects or ground instability.

The anastylosis of the Stadium and Gymnasium of Ancient Messene exemplifies the complexity of multidisciplinary conservation challenges, in which archaeological evidence, geotechnical conditions, and structural behaviour must be jointly assessed to ensure that interventions meet safety requirements while respecting the monument's authenticity, integrity, and improve legibility.

THE STADIUM AND GYMNASIUM OF ANCIENT MESSENE

The ancient city of Ancient Messene was founded in 369 BC and quickly developed into an important Hellenistic and Roman urban centre. The construction of the Stadium and Gymnasium, which are the subject of the present study, is dated to the late third or early second century BC (Themélis P., 2009). The Stadium served as a principal public space of the city and today stands as one of the most impressive architectural complexes of the site, in terms of both its scale and state of preservation. The northern, horseshoe-shaped section of the Stadium comprises 18 tiers of seating, arranged in 18 rows and separated by stairways. The Gymnasium is built around the Stadium and consists of Π-shaped stoas in plan, supported by single or double colonnades. Collectively, the stoas and the Stadium form a unified architectural complex, representing a distinctive feature among ancient stadia. The substantial quantity of building material from both the Stadium and the stoa colonnades, unearthed during excavations, enabled an extensive anastylosis programme, which today allows visitors to gain a clear understanding of the structure's size and appearance in antiquity. The current state of the site is illustrated in Figure 1.

***Figure 1**. The Stadium and Gymnasium of Ancient Messene after the completion of the archaeological excavations and the anastylosis program.*

An anastylosis programme, in addition to archaeological and architectural criteria, should be validated from a structural and geotechnical engineering perspective to ensure the safety and durability of the interventions. Prior to the commencement of the structural study, it is important to examine the monument's history through early reports and surveys, as well as other archaeological data, in order to understand the dominant damage and deterioration mechanisms and to identify geotechnical and structural vulnerabilities. In this particular case, information regarding the destruction and abandonment of the Stadium site is scarce; apart from the description of the city of Messene by Pausanias in the second century AD, when the stadium was fully operational, no evidence survives concerning the condition of the ancient city and its public buildings at later times. Archaeological findings confirm the decline and eventual abandonment of the city and its public spaces in the fifth century AD, while it is known that the Gymnasium was abandoned and fell into ruin as early as 360–370 AD (Themélis P., 2001).

Later observations and reports by nineteenth-century European travelers, such as Hallerstein, Stackelberg, Cockerell, and Pouqueville, provide only cursory accounts of the site's remains. The first systematic investigation of the Gymnasium was undertaken in 1829 by the French mission Expédition scientifique de Morée under the direction of Abel Blouet (1831), during which visible architectural members and colonnades were recorded. Documentation from the limited excavations carried out as part of this mission indicates that the depth of fill deposits in the area exceeded 2.50 m. Figure 2 illustrates the sketches and drawings produced during this early survey, in which the visible remains of the columns of the western and northern stoas are recorded using shaded markings, while open circles indicate column positions inferred in the absence of visible evidence at the time of mapping. In this map, seventeen columns of the western stoa are clearly identifiable, and the north-western corner is documented in detail through an excavation conducted as part of this preliminary investigation (figure 2 – (c) and (d)). It is also important to note that Blouet's published drawings depict a watercourse crossing the Stadium at the time of the survey. This stream was regulated in antiquity through the city's drainage system but reverted to its natural course following the decline and abandonment of the site.

More systematic archaeological excavations began in the early twentieth century and intensified after 1957 under the direction of Anastasios Orlandos, and subsequently, from 1986 onward, under Petros Themelis (Themelis 1999). By 1997, all three stoas surrounding the Stadium, as well as the Stadium itself, had been fully unearthed and documented, thereby clarifying the architectural layout of the complex, as illustrated in the aerial photographs in Figure 3. While some columns of the Gymnasium were uncovered in a partially standing and backfilled condition, many others were found toppled from their original positions in front of the stylobate, while others were completely disassembled and scattered along the original axis of the colonnade. In particular, the lower portions of most columns of the western and northern stoas remained standing in situ. In contrast, the eastern colonnade had collapsed, together with its entablature, and was found lying in front of its stylobate, to the west. A further observation from the aerial photographs in Figure 3 is the slightly divergent alignment of the western and eastern stoas, which gradually separate towards the south. This condition is also reflected in the architectural mapping of the remains (Figure 5).

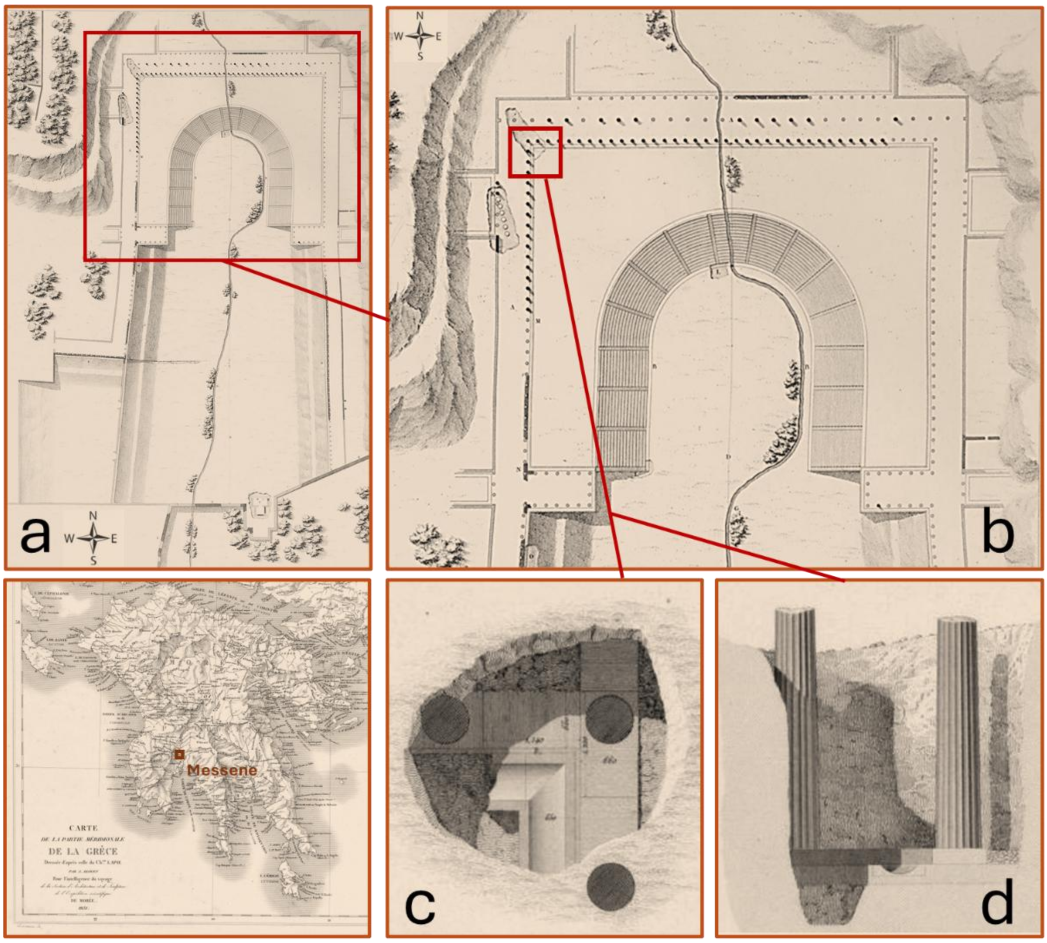

Figure 2. *(a) Remains of the stadium as documented by the 'Expédition Scientifique de Morée' (Blouet, 1831). (b) The stadium and the gymnasium colonnades black circles visible columns open circles inferred columns (c) plan view and (d) section of the findings on a small excavation at the NW corner of the gymnasium*

FLUVIAL ACTION AS A DETERIORATION MECHANISM

The anastylosis works of the complex were based on a comprehensive architectural survey and detailed documentation of the remains of the Stadium and the stoas of the Gymnasium, carried out following extensive excavations (Bilis 2015; Magnisali 2002), and complemented by subsequent architectural and archaeological studies. The position of the unearthed limestone blocks forming the seating tiers of the Stadium has been significantly affected by fluvial erosion and subsequent sedimentation processes following the abandonment of the site. As illustrated in Figure 4, the seating tiers were found to be severely displaced in certain areas, while differential settlement had also influenced their configuration at the time of excavation. Drag forces exerted by the torrential stream crossing the Stadium displaced many limestone blocks, while less intense but persistent flows progressively eroded and removed fine soil beneath the kerkis blocks, leading to the observed settlements. Similarly, the absence of standing columns in the Gymnasium stoas along the watercourse indicates that flooding and high-flow events were a major factor in the deterioration of the colonnades, highlighting the need for protective measures against water action. The reinstatement of the limestone kerkides was carried out using well-compacted granular fill to replace eroded material, in combination with geotextiles to prevent further loss due to groundwater flow.

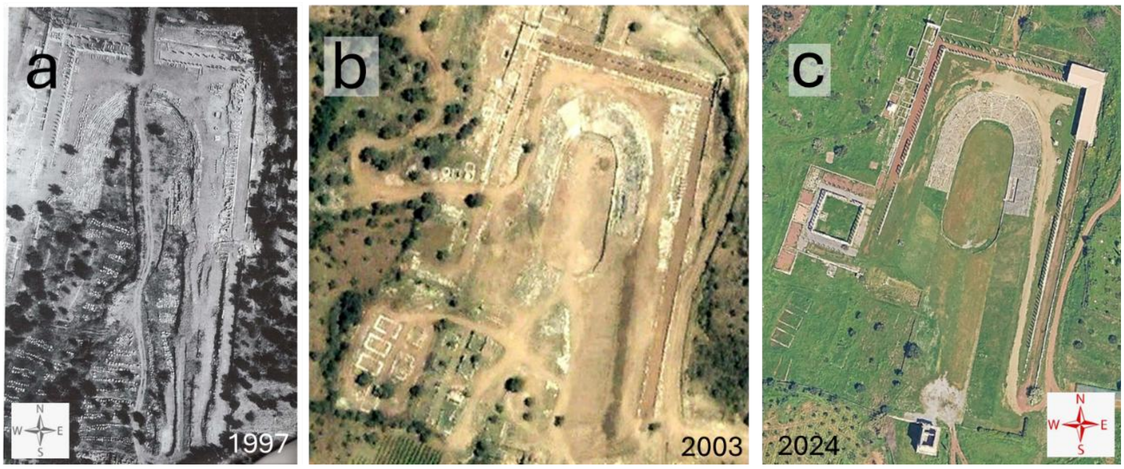

Figure 3. *Aerial photographs of the Stadium: (a) in 1997, prior to the start of archaeological excavations; (b) in 2003, during the anastylosis programme; and (c) in 2024, following the completion of the anastylosis.*

Groundwater drainage works were implemented both during and after the archaeological excavations. The rerouting of permanent water flows away from the Gymnasium and the Stadium was achieved through small ditches around the site and the construction of a larger culvert running beneath the Stadium, while, to some extent, ancient drainage systems were also reinstated. However, intense rainfall events continue to affect the area, as demonstrated by the extreme event of 6–8 September 2016, which flooded parts of the archaeological site. Menzafou et al. (2022) examined in detail the hydrology and drainage patterns of the watershed and streams crossing the site, proposing additional measures to reduce flood risk and highlighting that the impacts of climate change are likely to challenge the long-term effectiveness of such interventions. However, where complete flood prevention would require intrusive or disproportionate drainage works that could compromise the monument's authenticity, integrity, or archaeological context, the effects of temporary flooding should instead be managed through carefully targeted, minimally invasive, and reversible protective measures.

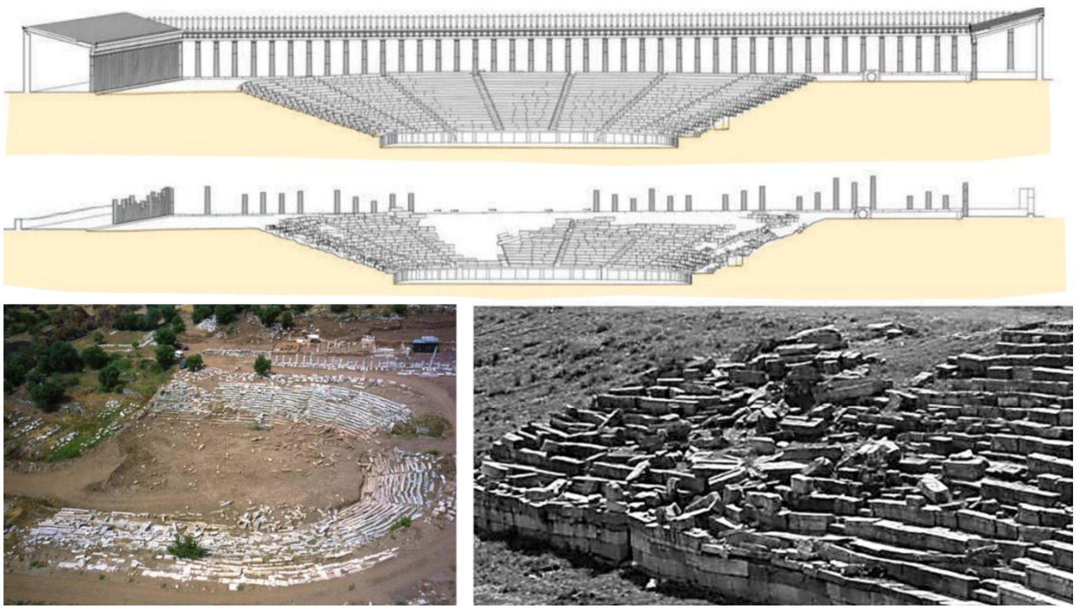

Figure 4. *Top: Archaeological reconstruction drawing of the Gymnasium, after Magnisali (2002), and its state of preservation at the conclusion of the archaeological excavations (ca. 2000), indicating areas affected by erosion along the course of the torrential stream crossing the site. Bottom: Photographs of the kerkides (stone seating tiers) showing erosion- and scour-induced dislocation of limestone blocks, as well as settlements resulting from fluvial action of the torrential stream.*

FOUNDATIONS OF THE GYMNASIUM COLONNADES

The restoration of the Gymnasium stoas involved the anastylosis of more than 160 columns, along with the reinstatement of original epistyles and frieze elements where available. The works aimed to re-establish continuous colonnades, enhancing both the visual perception of the monument and its interpretability for visitors. The project relied primarily on original building material recovered during excavation, supplemented by minimal new additions in accordance with principles of authenticity.

The structural assessment of the reinstated colonnades was supported by detailed geotechnical investigations, which also provided insight into ancient foundation practices and demonstrated the careful adaptation of the original design to local geomorphological and ground conditions. The stylobate is founded on dry rubble masonry constructed of flat, locally sourced stones, approximately 0.80 m thick and extending to depths of up to 2.0 m below ground level. Above this, the euthynteria comprises carefully dressed blocks forming the bearing surface of the colonnade (Figure 5). Borehole data indicate that the foundations rest on a relatively compact layer of man-made fill—composed of clayey or silty sand with gravel—used to form the artificial terrace, which in turn overlies a thin granular alluvial–colluvial deposit above weathered bedrock. Given the relatively low vertical loads and the competence of the foundation system, ground settlement is considered unlikely to have significantly influenced the structural behaviour of the colonnades.

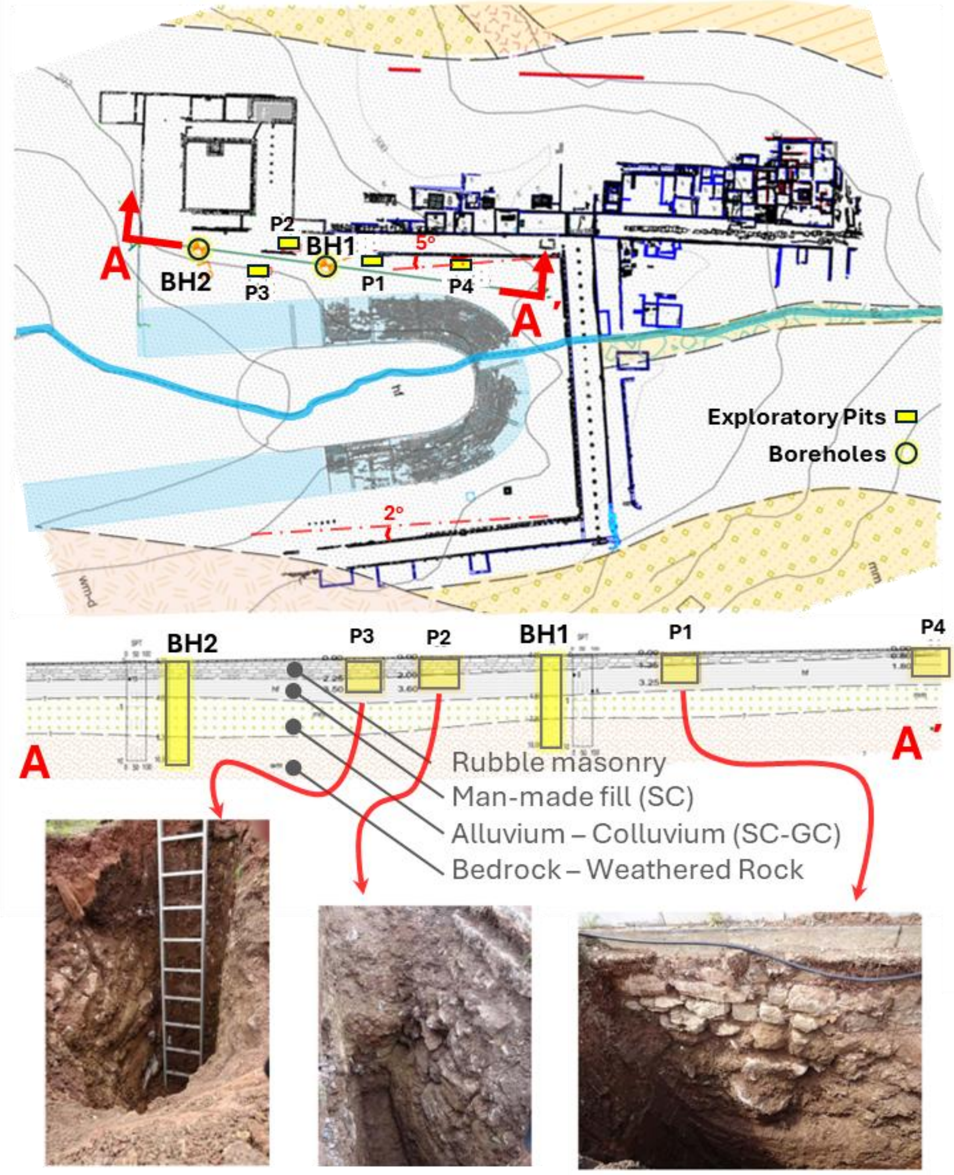

Figure 5. *Geotechnical conditions along the axis of the Western Stoa and ancient foundations of the stylobate.*

This survey highlighted that the ancient builders, in order to limit the thickness of recent fill and alluvial deposits beneath the foundations and to ensure firm and stable support for the colonnades, intentionally adopted a slightly divergent alignment of the eastern and western stoas relative to the rectangular geometry of the Stadium. The western stoa deviates from the stadium axis by approximately 5°, while the eastern stoa deviates by about 2°, allowing the structures to better adapt to the site's geomorphology and to achieve a stiffer subgrade. This arrangement is clearly illustrated in Figure 5.

SEISMIC ANALYSIS OF THE GYMNASIUM COLONNADES

The structural verification of the reinstated colonnades of the Gymnasium under static loading conditions involves assessing the bending stresses in the architraves, idealised as simply supported beams spanning between columns, while accounting for the influence of material discontinuities—such as joints, cracks, and fractures—both in the architrave blocks and in the column drums. While wind loading has a relatively minor effect on such structures, seismic actions are of primary importance and constitute the governing factor in their structural assessment.

Under earthquake shaking, free-standing columns respond through rocking and wobbling motions, involving uplift, rotation, pivoting, and repeated impacts at their interfaces. This behaviour is characteristic of dry-joint construction, in which the absence of mortar permits relative movement between blocks once gravity-induced contact stresses are exceeded (i.e. sliding or uplift), rendering simplified pseudo-static approaches unsuitable for seismic analysis and necessitating the use of dynamic time-history analyses. The structural safety of the Gymnasium colonnades was evaluated using discrete element models capable of capturing the relative movements of the articulated system and the dynamic interactions at contact interfaces.

The distinct element dynamic analysis is carried out using an explicit time-stepping scheme, in which the equations of motion are solved to compute the displacement and rotation of individual blocks. Contact detection is updated continuously as the blocks move, allowing new contacts to be formed and existing ones to be lost according to the relative positions of neighboring elements. Contact interactions are represented through normal and shear elasto-plastic springs and dashpots, combined with Coulomb friction, enabling the simulation of sliding, separation, impact, and energy dissipation at the interfaces. The modelling scheme is presented in Figure 6.The effectiveness of the Discrete Element Method (DEM) in the analysis of ancient columns has been extensively investigated and validated through comparisons with experimental results from shaking table tests (Papantonopoulos et al., 2002; Dasiou et al., 2009; Psycharis et al., 2014, among others). Additional confidence in the selected modelling parameters is provided by systematic sensitivity analyses (see Psycharis et al., 2000; Toumbakari & Psycharis, 2010).

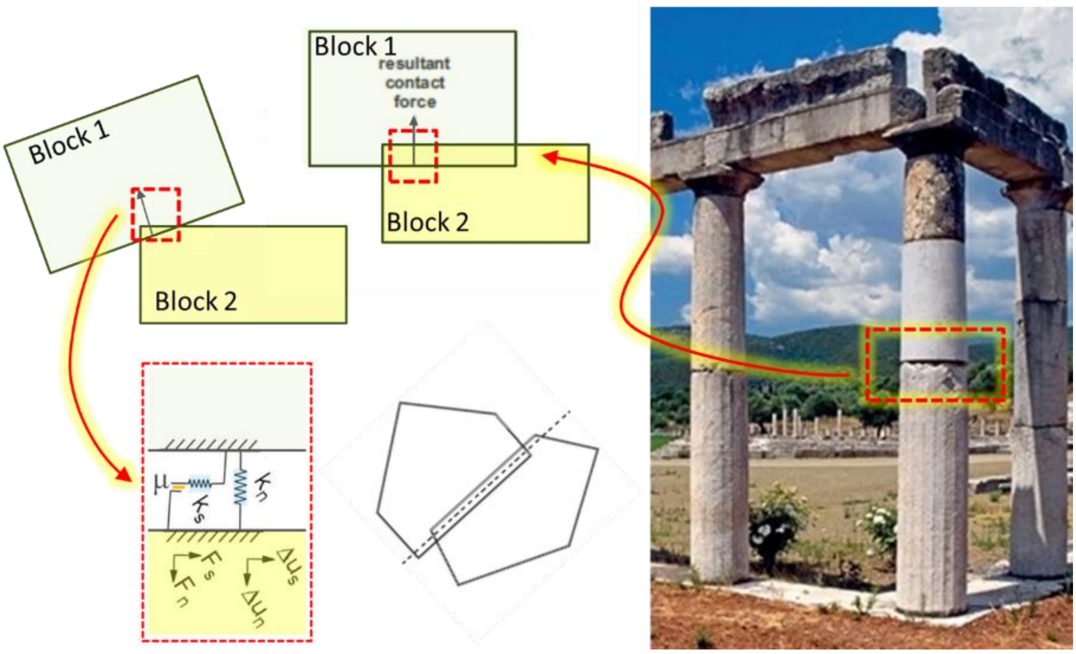

Figure 6. *Modelling of the colonnade using a distinct modelling approach.*

Explicit finite-difference scheme analysis, combined with the highly nonlinear character of the response of these structural systems, requires the selection of appropriate and representative accelerograms for time-history seismic analyses. The selection of accelerograms, in turn, requires a thorough understanding of the seismic and tectonic setting of the study area, allowing the identification of the seismic sources governing the seismic hazard and the definition of appropriate seismic scenarios. Figure 7 presents the seismogenic sources associated with shallow crustal earthquakes in the broader area of the archaeological site (after Sboras et al., 2014). The site of Messene is primarily influenced by nearby crustal normal-fault sources, including the Pamisos River and Kalamata seismic zones, which are capable of generating moderate-magnitude earthquakes. The Sphakteria source, associated with larger thrust-fault systems along the Hellenic/Aegean Arc, has a more limited influence on the site's seismic exposure because of its greater distance from Messene. Consequently, the site is expected to be more strongly affected by nearby shallow normal-fault earthquakes than by more distant, larger-magnitude events related to the Hellenic Arc. The contribution of intermediate-depth earthquakes is also considered in the overall seismic input through the selection of representative ground-motion records.

Seismic hazard studies for the Messinia region (see Kouskouna & Kaviris, 2014) indicate hazard levels broadly consistent with the design acceleration specified by the Greek seismic code for the area (EAK 2000/2003; PGA = 0.24 g), while peak ground velocity (PGV) values for a 10% probability of exceedance in 50 years are estimated to remain below approximately 20 cm/s. For the seismic analyses in the present study, a set of six strong-motion records recorded in southern Greece over the past 40 years was selected to represent different seismic scenarios. Most records correspond to small- to moderate-magnitude earthquakes at relatively short source-to-site distances, including near-source events, while the set also includes records from more distant, larger-magnitude earthquakes. The characteristics of the selected records are listed in Table 1, and the waveform of the stronger horizontal component of each record is presented in Figure 8.

The primary objective of the seismic analysis was to determine the level of seismic excitation required to induce overturning of representative components of the restored structural system (e.g. individual columns and colonnade assemblies). This was achieved by progressively scaling the selected ground-motion records to increasing intensity levels. Comparison of the resulting overturning thresholds with seismic demand estimates derived from probabilistic seismic hazard analyses for the site (as reflected in design codes and relevant studies) provides the basis for assessing the safety level of the colonnades.

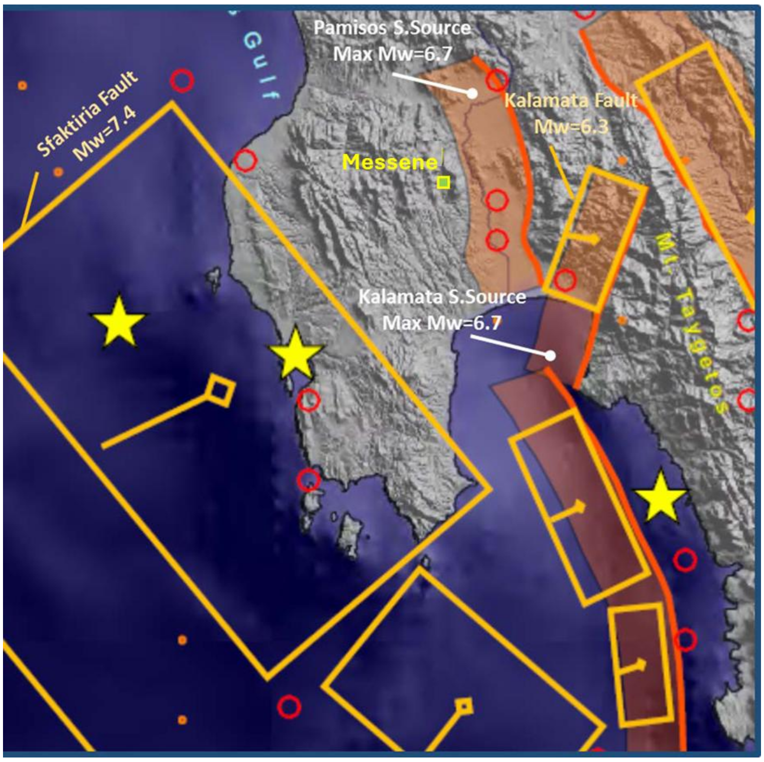

Figure 7. *Seismogenic sources of shallow crustal earthquakes in the broader area of Messene, as presented in the Greek Database of Seismogenic Sources (GreDaSS) (after Sboras et al., 2014).*

Table 1: *List of the accelerograms selected for seismic analysis of the colonnades.*

·	Earthquake event / Recording station	Earthquake Magnitude	Distance from Source	PGA (g)	PGV cm/sec
1	Alkyonides (1981) Xylokastro	Ms=6,7	R=31 km	0.289	22.72
2	Kalamata (1986) Nomarchia Bldng	Ms=6.2	R=9 km	0.266	31.51
3	Pyrgos (1993) OTE Bldng	Ms=5.3	R=10 km	0.434	18.74
4	Parnitha (1999) Sepolia Bldng	Ms=5.9	R=21 km	0.243	17.92
5	Lefkada (2003) Hospital Building	Ms=6.4.	R=8 km	0.416	31.71
6	Kithira (2006) Ag.Nikolaos Lakonia	Ms=6.9	R=79 km	0.150	15.13

The analysis focuses on the columns of the West Stoa of the Gymnasium as a benchmark case. The colonnade comprises 63 columns of relatively modest dimensions, each approximately 4.00 m in height, with a base diameter of 0.51 m and an upper diameter—just below the capital—of approximately 0.46 m. Most columns consist of two limestone drums, while approximately 20–25% comprise three drums and about 10% are monolithic. Numerical models of increasing complexity were developed based on the geometry of the colonnade (see Figure 9) and analysed parametrically using the selected strong-motion records to determine collapse thresholds. These models include: (i) single-column models with one, two, and three drums; (ii) a three-column assembly (including architraves and frieze elements) based on Section D in Figure 9; (iii) a six-column assembly based on Section C; and (iv) a 22-column model based on Section B. A comprehensive presentation of the full set of results is given in Alexandris and Papantonopoulos (2025), while only selected results are reported here.

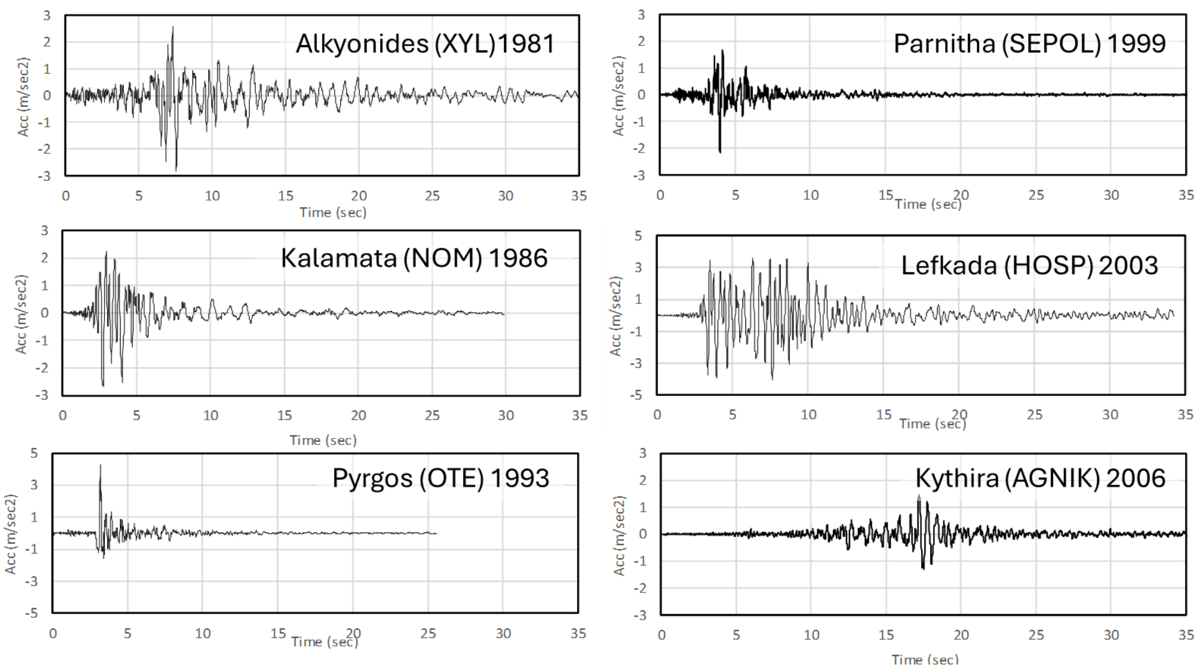

Figure 8*. Selected records considered in the seismic analyses of the Gymnasium colonnades.*

Figure 10 presents the results of the dynamic analyses for free-standing columns by varying the number of drums. The results indicate that the waveform characteristics of the input ground-motion exert a strong influence the overturning threshold of free-standing columns, with differences among individual records reaching up to an order of magnitude. Based on the analysis results, it is confirmed—consistent with findings reported in the literature—that long-period velocity pulses, typically associated with near-source forward-directivity effects and/or ground amplification, have a pronounced detrimental effect on the stability of such columns. This is clearly reflected in the present analyses by the lower overturning thresholds associated with records such as Kalamata (1986), Alkyonides (1981), and Lefkada (2003). In contrast, the remaining records are characterised by higher-frequency content, resulting in greater resistance to overturning.

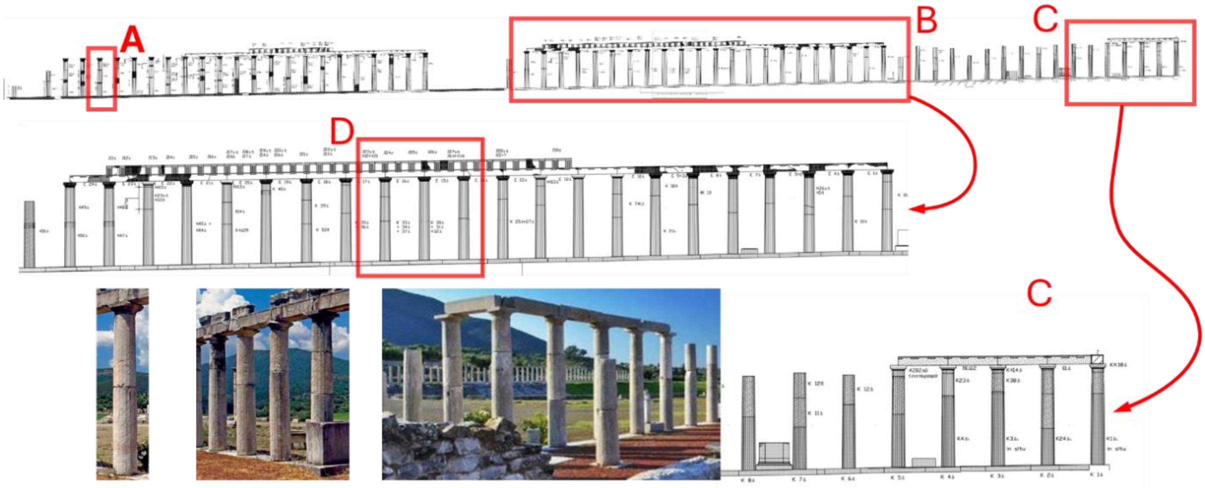

Figure 9. *Anastylosis of the Western Stoa colonnade; Structural assemblages of varying complexity.*

A comparison of the seismic resistance of the Gymnasium columns with that of columns from ancient Greek temples—such as the Parthenon (Papantonopoulos et al., 2002), the Temple of Zeus at Nemea (Psycharis et al., 2000), and the Temple of Zeus at Olympia (Alexandris et al., 2014), among others—indicates that the former are significantly more vulnerable to dynamic loading. This increased vulnerability is primarily attributed to their smaller dimensions and more slender geometry, whereas temple columns are generally nearly twice as tall and of larger diameter, resulting in a more favourable dynamic response and enhanced seismic stability. This comparison is illustrated in Figure 11, where the size and slenderness of the columns of the stoas of the Gymnasium of Messene are presented at the same scale as those of a number of well-known ancient Greek temples, some of which have been studied with respect to their seismic response.

Figure 12 presents the same results for more complex structural systems, namely colonnades consisting of 3 and 22 columns arranged in a row. By comparing the seismic response of the colonnades with that of free-standing columns, it is observed that the additional mass introduced by the architraves has a significant positive impact on seismic resistance. This effect has been rigorously identified and analysed through simplified planar models by Makris (2014); the present results confirm that the same behaviour also applies to realistic three-dimensional structural systems.

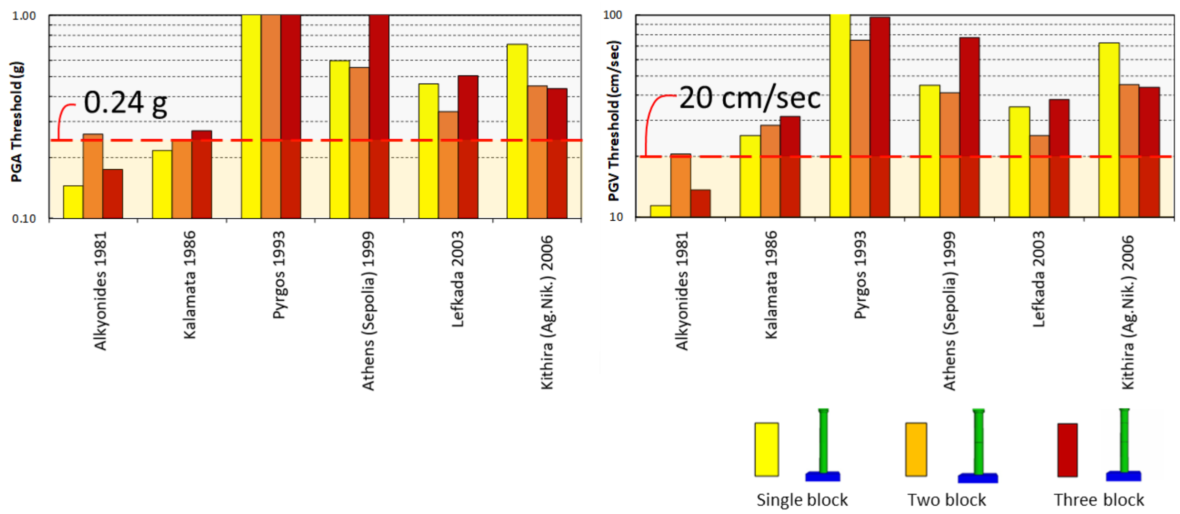

Figure 10. *Comparison of collapse threshold of monolithic, two-drum, and three-drum columns. Larger number of drums generally improves stability conditions for records that have the lowest failure thresholds (Alkyonides/Kalamata/Lefkada).*

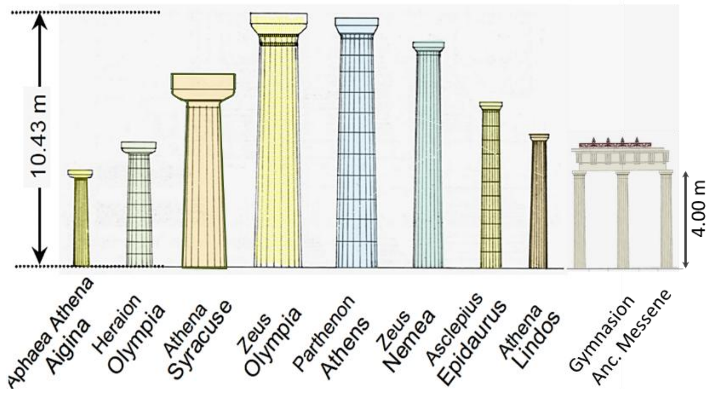

Figure 11. *Comparison of the size and slenderness of the columns of the Gymnasium of Messene with those of well-known ancient Greek Doric temples, some of which have been analysed for their seismic response (figure modified after Müller-Wiener, W., 1988).*

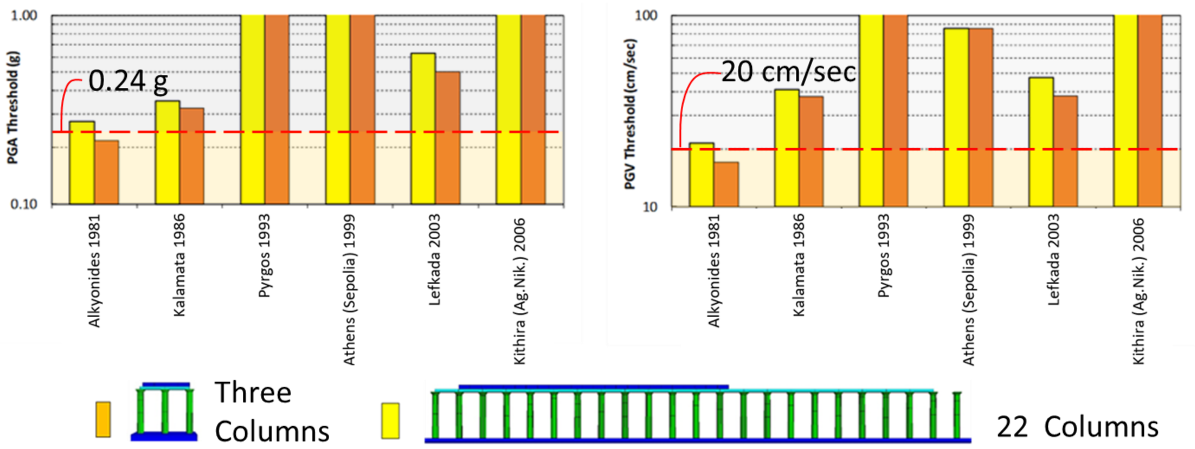

Figure 12. *Failure threshold of the full colonnade model with connectors at the entablature, compared to the corresponding three-column model. An increase in the toppling threshold is observed with the coupling of a larger number of columns.*

Figure 13 presents the rocking response and collapse mode of a six-column system arranged in a corner configuration. The results indicate that the corner geometry generally enhances the seismic resistance of the system by promoting asynchronous motion of the columns along the two principal axes. As illustrated in Figure 13, the column on the northern side (to the right in the figure) tends to move out of phase with the rest of the colonnade, thereby limiting rocking amplitudes and improving the overall response. It is also noteworthy that the dominant failure mode develops in a direction perpendicular to the axis of the longer colonnade.

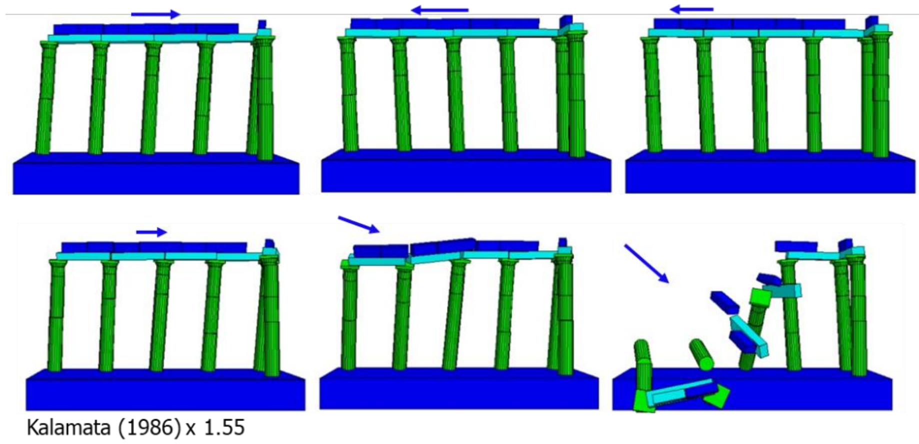

Figure 13. *Snapshots of the response leading to collapse of the six-column model under the Kalamata (1986) ground-motion record, scaled to a peak ground acceleration of 0.41 g.*

The swaying and rocking response of a 22-column colonnade under the scaled Kalamata record is illustrated in Figure 14. For comparison, a free-standing column is also included at the far right end of the model; it can be observed that this free-standing column overturns earlier than the remaining interconnected columns of the colonnade, highlighting the lower resistance of isolated columns compared to those linked by architraves. In the same sequence of snapshots, out-of-plane overturning is seen to initiate at the far-left end column, which carries a smaller load, and subsequently propagate along the colonnade dragging it into an out-of-plane overturning.

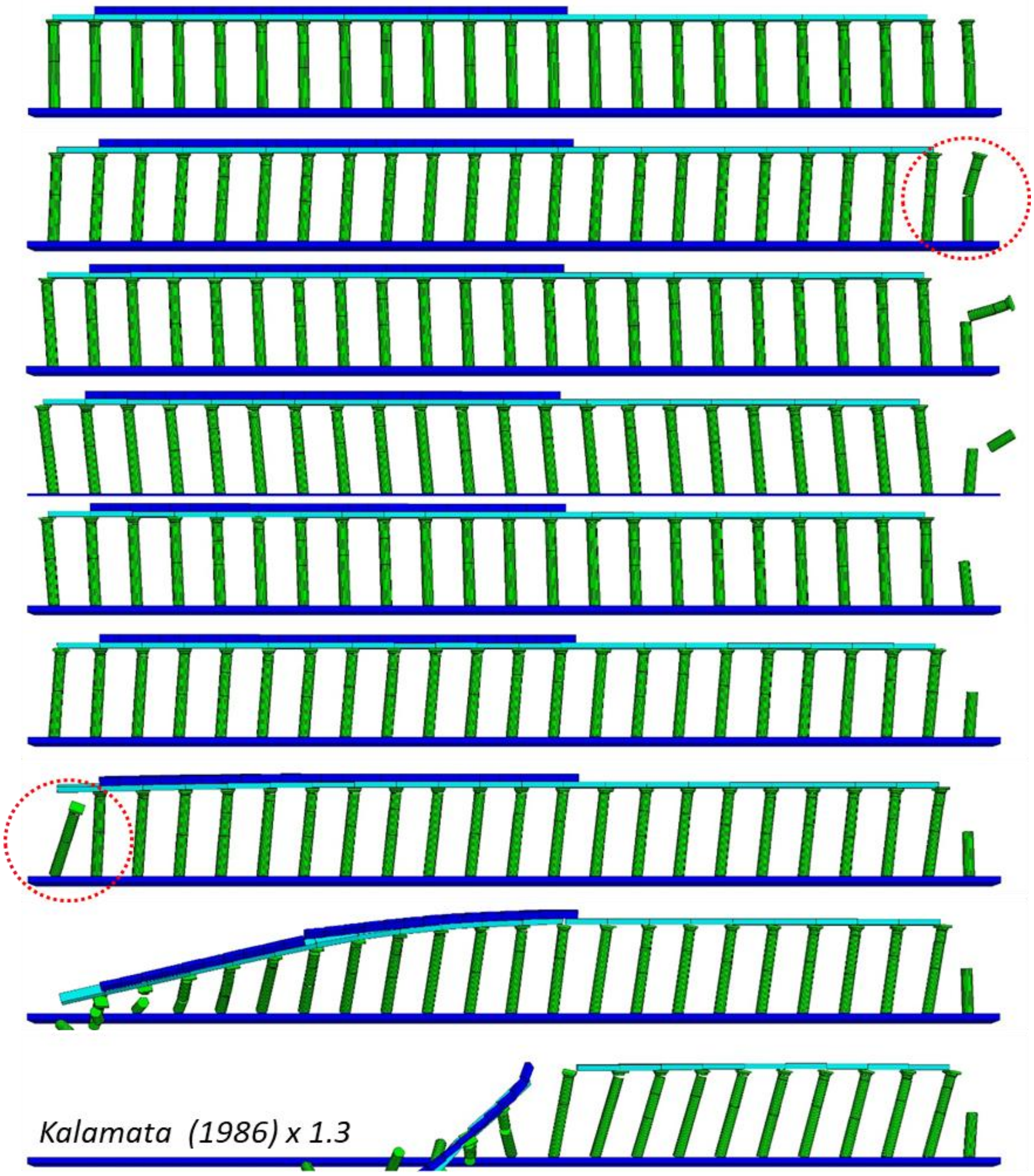

Figure 14. *Response of the multi-column model under excitation from the Kalamata (1986) accelerogram, scaled to 0.35 g.*

The analysis results of the long-colonnade model indicate a collapse mode and a pattern of fallen blocks broadly consistent with those documented for the columns of the Eastern Stoa during the archaeological excavations depicted in Figure 15. Based on these similarities it cannot be excluded that, following the abandonment of the site and the gradual deterioration and collapse of the wooden roofing of the stoas, the area was subjected to repeated flooding events, resulting in progressive sediment accumulation along the western and northern stoas. Before this sedimentation reached the Eastern Stoa, it is plausible that a strong earthquake—comparable to the Kalamata event, namely a moderate-magnitude event occurring relatively close to the site—may have caused the toppling of the still-standing colonnade, which was subsequently buried by the accumulating sediments.

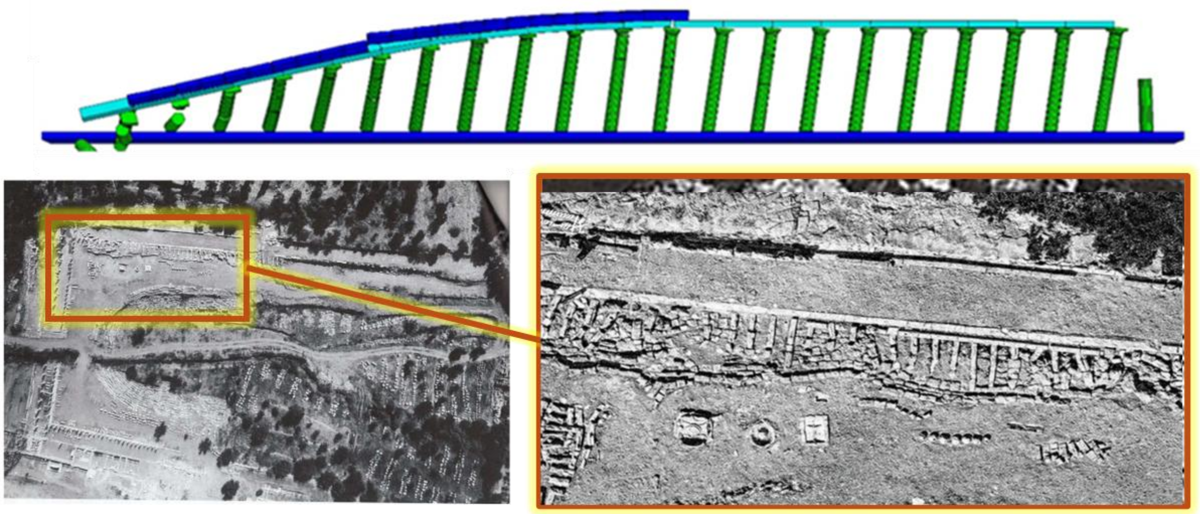

Figure 15. *Mode of collapse of a continuous colonnade compared with the position of columns found during the excavations along the Eastern Stoa of the Gymnasium.*

No earthquakes are reported by historical sources or other archaeological evidence in the area after 360 AD, a period during which the Stadium and Gymnasium of Messene are known to have been abandoned and destroyed. Shortly thereafter, the major earthquake of 365 AD, associated with the Hellenic Arc and likely originating from a source between Crete and the Peloponnese, affected large parts of the Eastern Mediterranean. The event generated a large sea wave that inundated coastal settlements in Egypt, the Peloponnese, and Sicily, causing severe damage. Ambraseys (2009) estimates a very large magnitude for the 365 AD earthquake ($M_w \approx 8.0$), sufficient to explain both tsunami generation and the widespread felt area, although ground shaking likely produced limited damage in many regions reporting the event.

It is plausible that such a large-magnitude earthquake along the Hellenic Arc could have triggered seismicity within the interior of the arc through crustal stress redistribution. These moderate- to small-magnitude events, potentially following the larger thrust earthquake along the arc, may not have been documented in contemporary literary sources, which were typically produced only in major urban centres and often relied on indirect information. Furthermore, the dramatic impact of the associated sea wave likely dominated historical accounts, potentially obscuring the effects of subsequent local earthquakes in the southern Peloponnese.

DISCUSSION AND CONCLUSIONS

The anastylosis of the Stadium and Gymnasium of ancient Messene serves as an illustrative case highlighting the benefits of early involvement of engineering specialists during the technical surveys and planning of anastylosis programmes. This approach enables the effective integration of expertise across the full spectrum of engineering disciplines, ranging from hydraulic and hydrological engineering to geotechnical, materials, and structural engineering.

A sound understanding of the hydrological regime, natural ground relief, drainage system, and geological and geotechnical setting of the monument or site is essential for establishing the required background data. The factors and mechanisms responsible for structural deterioration and damage, whether associated with flooding, geotechnical hazards, or earthquakes, should be investigated and explicitly taken into account in the design of the anastylosis programme. Foundation analysis is also essential to ensure that any reinstated structure will remain unaffected by natural geotechnical or hydraulic processes. Seismic effects are of particular importance for dry-stone structures, such as ancient Greek and Roman colonnades, and require rigorous assessment by specialised engineers. Although such analyses may be complex, they are highly valuable, as they provide insight not only into the structural safety of the proposed intervention but also into the potential causes of the damage patterns observed in the archaeological record.

ACKNOWLEDGEMENTS

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