Finite element analyses of prehistoric walls under the loads of modern-day shelters. The case of the walls of the Phaistos Minoan Palaces

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ABSTRACT

The paper presents the analyses performed using the finite element method in order to test the ability of the prehistoric walls of the Old Palace and the Royal Chambers of the Palatial Complex in the Minoan City of Phaistos, Crete, to bear the loads calculated for newly designed shelters. Both the Old Palace and the Royal Chambers of Phaistos constitute unique prehistoric monuments with load-bearing masonry walls with soil-based mortars. Existing shelters built in the '60s have steel columns transferring loads locally to the walls of the monument. As part of the design of modern shelters to replace the existing ones it was investigated to use the positions of the existing columns as the positions for the new columns to be built. The strength and deformability of the masonry walls was assessed and finite element models for 2- and 3-dimensional analyses were designed in order to carry out analyses to estimate the effect of the calculated loads for the new shelters. Both types of analyses indicated that only a fraction of the calculated loads for the new shelters could be borne by the prehistoric walls at the positions of the existing columns. This result supported the decision to identify and propose new positions for the columns of the new shelters.
Keywords: Canopies, 2D & 3D FEA, allowable loads

INTRODUCTION

Prehistoric walls, from the Palaeolithic through the Neolithic, Bronze Age, and into the Iron Age, vary widely by region, culture, and purpose (dwellings, fortifications, palatial and government buildings, tombs, enclosures, or terraces). However, several common characteristics appear across many sites worldwide related to the materials used for the construction, the construction techniques, the design and the dominant cultures in specific regions and periods. The interest in this particular paper focuses on prehistoric masonry walls made of stone with soil-based mortar, a common type of walls found in the Minoan cities and palatial complexes. The reason for looking into the analysis of this type of walls was the design study of the new shelters to protect the remains of the palaces in the Minoan city of Phaistos (Fig. 1). Both the Old Palace and the Royal Chambers of Phaistos constitute unique prehistoric monuments with load-bearing masonry walls with soil-based mortars (Branigan, 1979). These remains are nowadays under shelters built in the 1960's which had their columns embedded in the walls of the palatial complexes. As part of the design of the new shelters, analyses were carried out to investigate whether the exact locations of the existing columns could be used to embed and found the columns of the new shelters with their anticipated loads as dictated by *modern-day regulations and codes in effect as part of the new design*. This investigation was part of an examination of the possible alternative of using the exact same locations of existing columns in comparison to founding the columns of the new shelters in new positions on the ground.

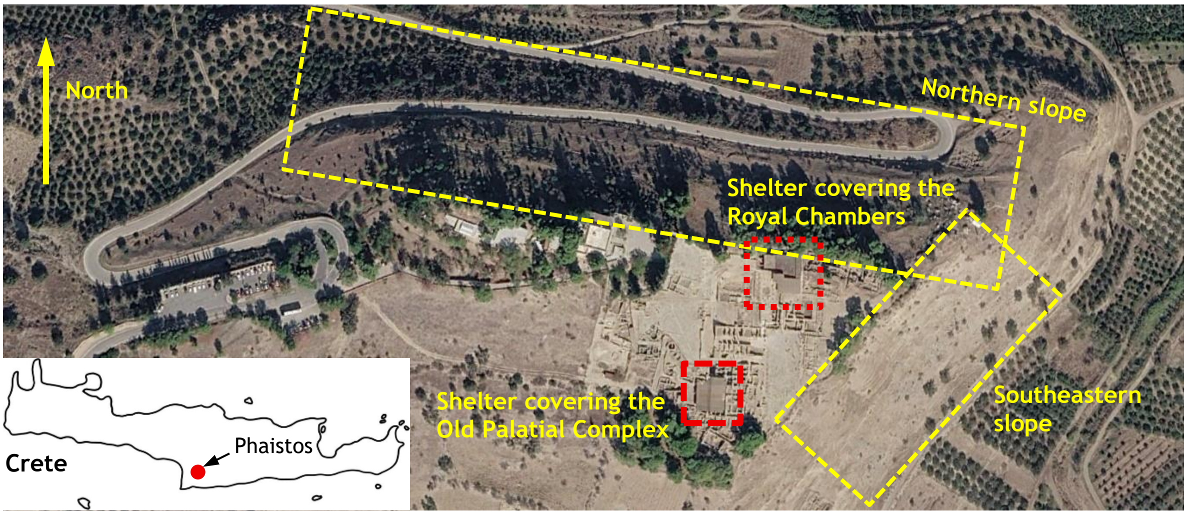

Figure 1. *Google Earth view of the Phaistos Hill in the valley of Messara, in Crete, Greece. Arrow indicating North, yellow, dashed line rectangles indicating locations of the Northern Slope and the Southeastern Slope (attracting interest due to slope instabilities), and light blue, dashed line rectangles indicating the locations of the Shelter covering the Royal Chambers (to the north) and the Shelter covering the Old Palatial Complex (to the south).*

SHELTERS FOR ANCIENT MONUMENTS. REGULATIONS AND LOADING CONDITIONS

The primary objective of shelters for ancient monuments in the form of canopy structures is the mitigation of environmental and mechanical actions acting on the archaeological remains, ensuring the long-term preservation of the authentic structural fabric while maintaining its integrity and durability. The design is governed by a performance-based approach, addressing both serviceability (protection from weathering, moisture ingress, and thermal effects) and structural safety (resistance to wind and seismic actions), while ensuring compatibility with the existing historic substrate.

The fundamental design principles are summarized as follows:
- *Contextual Integration*. Seamless integration of the new structures within the archaeological landscape, in alignment with internationally accepted conservation frameworks and best practices.
- *Preservation of Authenticity and Legibility*. Safeguarding the original material and structural system, ensuring that the intervention remains clearly distinguishable yet non-intrusive, preserving the readability of the historic fabric.
- *Structural Efficiency and Constructability*. Adoption of structurally efficient systems with rational load paths, enabling ease of fabrication, transportation, erection, and assembly, while minimizing construction impact on-site.
- *Reversibility and Minimum Intervention*. Implementation of non-invasive and reversible design strategies, allowing for future removal or modification without compromising the integrity of the archaeological substrate.

The structural design has been developed in accordance with the applicable European and national regulatory framework, adopting a limit-state and performance-based methodology, as outlined in Eurocode 0 (*Basis of Structural Design* -EN 1990), Eurocode 1 (*Actions on Structures* -EN 1991), Eurocode 3 (*Design of Steel Structures* -EN 1993), Eurocode 5 (*Design of Timber Structures* -EN 1995), Eurocode 6 (*Design of Masonry Structures* -EN 1996), Eurocode 7 (*Geotechnical Design* -EN 1997), and Eurocode 8 (*Design of Structures for Earthquake Resistance* -EN 1998), including the relevant National Annexes.

THE CASE OF THE MINOAN PALACES OF PHAISTOS

The existing shelters

The existing shelters within the archaeological site are classified into two categories:
a) Steel frame canopies with corrugated asbestos-cement sheet coverings, and
b) Reinforced concrete canopies of smaller dimensions.

Their construction is dated to the period 1961–1971, during which excavations were carried out by the Italian Archaeological School, under the direction of Doro Levi (Branigan, 1979). The main canopies cover the Royal Apartments in the northern part of the archaeological site (Fig. 2) and the Old Palace complex in the southern sector (Fig. 3). These are temporary structures composed of steel frames, typically consisting of circular hollow section columns measuring 80×2 mm and 60×2 mm, and beams of similar type and size, Ø35×2 mm (Fig. 4). Connections between members are executed by welding. In various parts of the archaeological site, supplementary reinforced concrete elements have been introduced, with reinforcement made of steel bars.

Figure 2. *Shelter canopies covering the Royal Apartments: partially a steel frame canopy with corrugated plastic sheet coverings (left) and reinforced concrete canopy of smaller dimensions (right).*

Figure 3. *Steel frame canopies with corrugated asbestos-cement sheet coverings over the Old Palace complex: view from west towards east (top) and from north to south (bottom).*

The steel canopies are supported by columns placed at intervals ranging from 2.5 m to 4.0 m. The support conditions of the columns are categorized as follows:

- Columns founded directly on ancient walls via surface contact (Fig. 5)
- Columns founded on ancient walls through the insertion of modern reinforced concrete elements
- Columns founded adjacent to walls on the ground using shallow reinforced concrete foundations
- Columns founded adjacent to walls on the ground via direct bearing

In total, 32 columns are used for the canopy of the Royal Apartments and 28 columns for the canopy of the Old Palace complex.

Figure 4. *A detail of circular hollow section beams.*

Figure 5. *Steel column founded directly on an ancient wall of the Royal Chambers via surface contact.*

The new canopies

The archaeological complex of Phaistos constitutes a site of exceptional cultural significance, where any structural intervention must comply with strict principles of reversibility, minimal invasiveness, and preservation of the stratigraphic integrity of the subsoil. Within this context, the installation of protective steel canopy structures necessitated the development of a foundation system that reconciles structural performance with archaeological constraints.

A foundation solution, explicitly tailored to the sensitivity of the site was designed. The design methodology was grounded in a performance-based approach, integrating geotechnical characterization, load-transfer mechanisms, and constructability limitations imposed by the protected environment.

The structural design emphasizes:

- Reduction of foundation footprint to mitigate interaction with archaeological layers
- Controlled load diffusion to avoid stress concentrations in heterogeneous soil conditions

- Reversibility of structural intervention, ensuring that the system can be removed without permanent alteration to the site

The resulting foundation system represents a calibrated engineering response, wherein modern structural design principles are adapted to the requirements of heritage conservation. The project exemplifies the integration of geotechnical and structural disciplines in achieving a solution that is both technically robust and compliant with international conservation standards.

The proposed design of the new canopies comprises a total of 28 columns (16 columns in the northeast sector and 12 columns in the southwest sector -Kasimis, 2024, Dede, 2024) -Fig. 6. The locations of the new columns are arranged either along the perimeter or adjacent to the existing archaeological structures. Under no circumstances is direct foundation on archaeological remains proposed.

The proposed structural system consists of columns and truss elements formed from circular hollow sections (CHS), specifically diameters of 168.3 mm with wall thicknesses of 10 mm or 12.5 mm, as well as CHS 193.7×8 mm and CHS 139.7×10 mm. Along the curved beams, RHS 80×40×5 mm members are utilized as secondary elements. The covering of the frame is done by layering a system consisting of trapezoidal steel surface in a curved shape, thermal insulation material, and final aluminum layering system (standing seam profile).

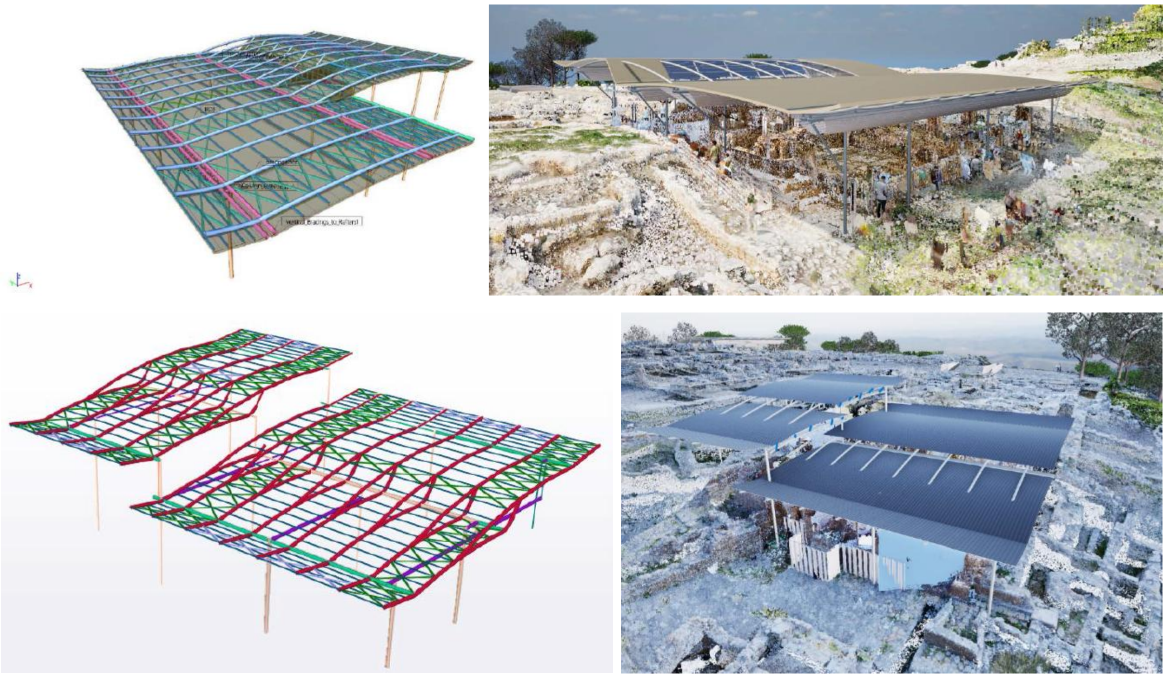

Figure 6. *3d canopies representation of structural elements and photorealistic view: canopy over Royal Chambers (top), and canopy over Old Palace (bottom).*

Design of column support on ancient structures

As part of an examination of the possible alternative of using the exact same locations of existing columns in comparison to founding the columns of the new shelters in new locations on the ground, a hypothetical case for assessment is shown in Fig. 7 which illustrates a conceptual approach for supporting steel columns on existing ancient masonry structures. The steel column is terminated by a base plate equipped with stiffening ribs to ensure adequate distribution of forces. The base plate is anchored through six steel anchor bolts into a reinforced concrete block, which provides the required fixation and stability at the column base.

The load transfer mechanism follows a vertical path from the steel column to the base plate, through the anchorage system and into the reinforced concrete element, which subsequently transmits the loads to the underlying masonry substrate. Particular attention is given to the assessment of local stress concentrations at the interface with the ancient material.

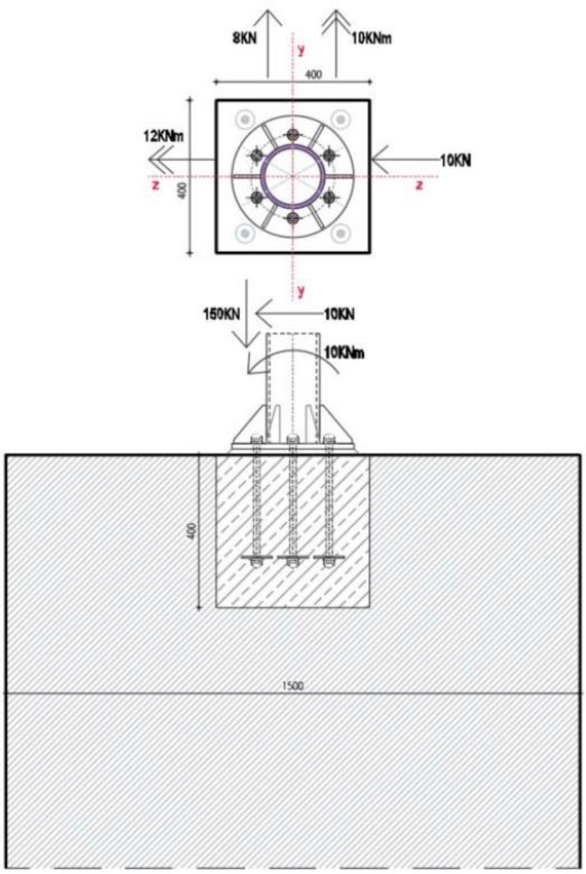

Figure 7. *Illustration of a conceptual approach for supporting steel columns on existing ancient masonry structures (details shown as calculated for the Old Palace).*

ANALYSES OF EXISTING WALLS WITH THE NEW LOADS

Assumptions, Loads and Geotechnical Model

In order to examine the bearing capacity of the prehistoric masonry walls under the loads of the new shelters deriving from contemporary standards, two-dimensional and three-dimensional finite element analyses were performed, with RS2 and PLAXIS3D software respectively. They were performed as paer of the Geotechnical Design Study of the Foundations of the New Shelters (Bardanis & Tsoutsas, 2024).

The design load combinations resulted from static, seismic and wind actions, while the parameters of the materials resulted from lab testing and statistical evaluation of the results. It is noted that the masonry walls at the Old Palace area display different geometrical and structural properties than the prehistoric walls at the Royal Chambers area. As such, three series of analyses were executed for each area and characteristics. The structural parts were modelled assuming Tresca failure criterion parameters and linear isotropic elastic behaviour. The model parameters of the masonry walls were estimated according to the lab tests results (Bardanis, 2024a) and the Code for Assessment and Structural Interventions to Existing Masonry Structures (EPPO, 2023). It is noted that the uniaxial compressive strength of the masonry walls at the areas of the Old Palace and Royal Chambers were estimated to be of the order of 550 kPa and 750 kPa respectively (Bardanis, 2024a). The mechanical and physical properties of the concrete base for the columns of the new shelter were derived from the structural properties of concrete C30/37, according to Eurocode 2. The Mohr- Coulomb failure criterion properties of the marly foundation rockmass of the masonry walls were estimated according to the geotechnical evaluation of the laboratory tests executed for the purpose of the study (Bardanis, 2024b). Due to uncertainties that are inherent to conversions from compressive strength values to tensile strength, all materials modelled were considered to have zero tensile strength.

All of the above are presented in Figures 8 and 9 and Table 1.

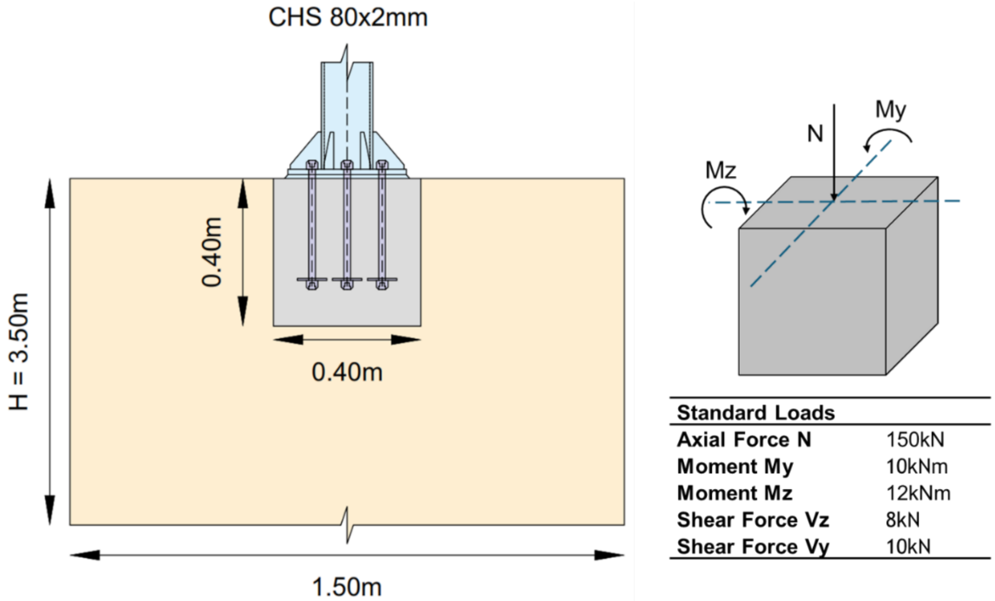

Figure 8. *Geotechnical model for the analyses executed for the foundation of the new shelters on the prehistoric masonry wall at the Old Palace area and the loads transferred from the columns according to contemporary design standards.*

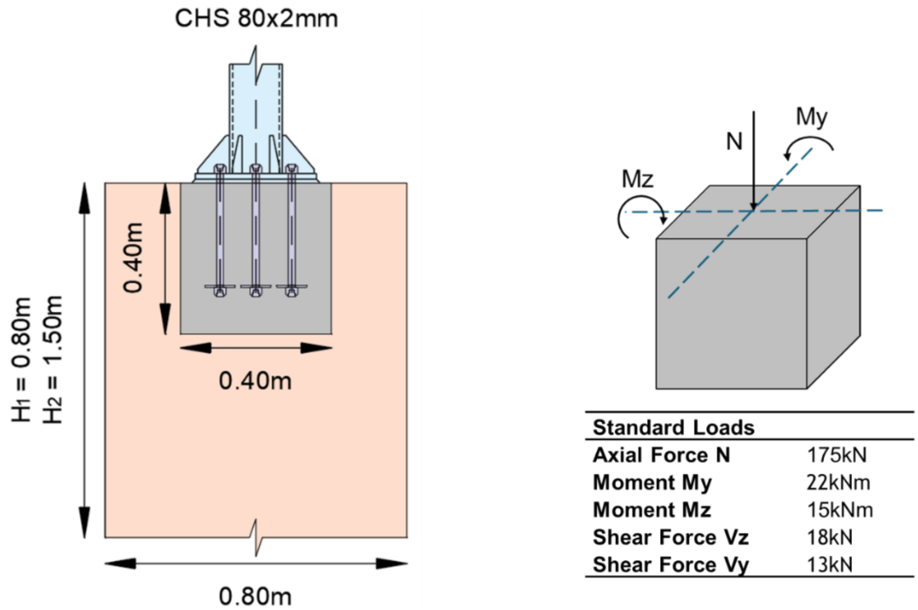

Figure 9. *Geotechnical model for the analyses executed for the foundation of the new shelters on the prehistoric masonry wall at the Royal Chambers area and the loads transferred from the columns according to contemporary design standards. Two wall heights (H_1 and H_2) were examined.*

Table 1. *Physical and mechanical properties of the geotechnical model for the finite element analyses.*

Description	Colour	Unit Weight, γ (kN/m^3)	Cohesion, c (kPa)	Angle of shearing resistance, φ (°)	Modulus of Elasticity, E (MPa)
Foundation Ground	-	20	200	45	2000
Old Palace Walls		20	275	0	450
Royal Chambers Walls		20	375	0	600
Concrete C30/37		25	15000	0	32800

Two-Dimensional Analyses Results

The non-convergence of the model after the application of the full load was briefly noticed. As such, the loads were applied by progressively reducing them until the model marginally converged. In Figures 10, 11 and 12 it is evident that, when the results are displayed in major principal stress terms, the structural integrity of the prehistoric masonry walls is compromised due to a wedge-type failure developed as a result of stresses building up on the edges of the concrete base which led to tension failure.

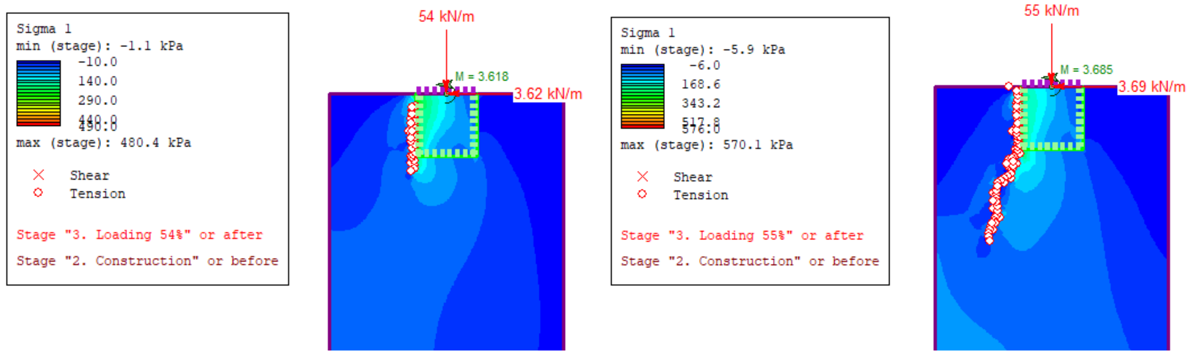

Figure 10. *Two-dimensional finite element analyses' major principal stress results for the Old Palace area when 54% of the standard loads are applied (left) and 55% of the loads are applied (right). The development of wedge failure is shown by the extent of the yielded elements due to tension stresses.*

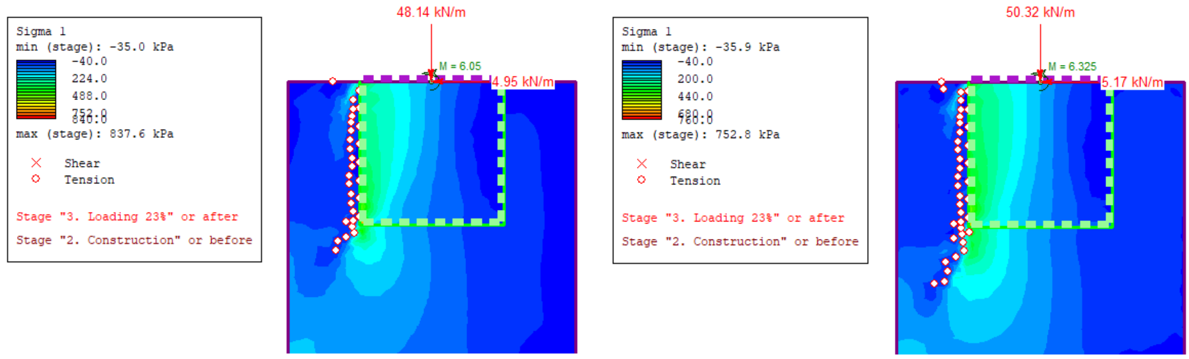

Figure 11. *Two-dimensional finite element analyses' major principal stress results for the Royal Chambers area (wall height equal to H_1 = 0.80m), when 22% of the standard loads are applied (left) and 23% of the loads are applied (right). The development of wedge failure is shown by the extent of the yielded elements due to tension stresses.*

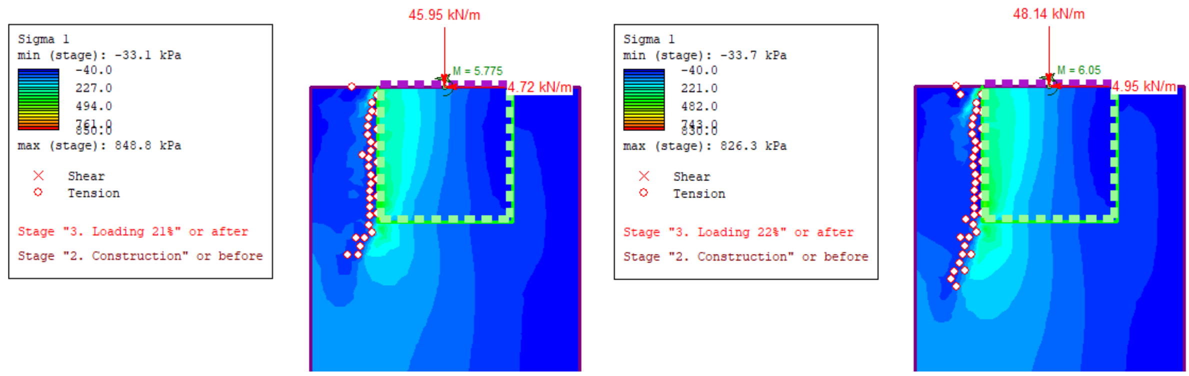

Figure 12. *Two-dimensional finite element analyses' major principal stress results for the Royal Chambers area (wall height equal to H_2 = 1.50m), when 21% of the standard loads are applied (left) and 22% of the loads are applied (right). The development of wedge failure is shown by the extent of the yielded elements due to tension stresses.*

Three-Dimensional Analyses Results

Similarly, the finite element model did not converge when the full loads were applied, and the same methodology was followed for three-dimensional analyses. The results are shown in Figures 13 and 14. These results concern the calculations executed for the Royal Chambers walls of 1.50m height. The results of the rest of the analyses were similar.

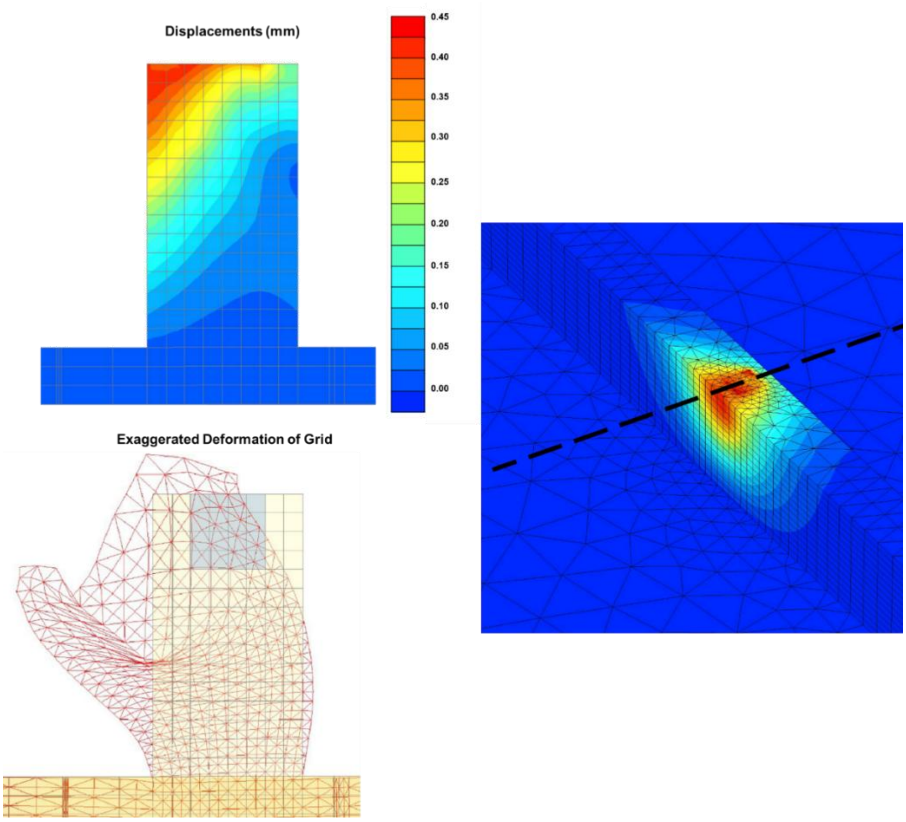

Figure 13. *Distribution of displacements and deformed grid of the structure at the maximum borne loads (left). Distribution of displacements on the 3-D grid at the maximum borne load and location of cross section (right).*

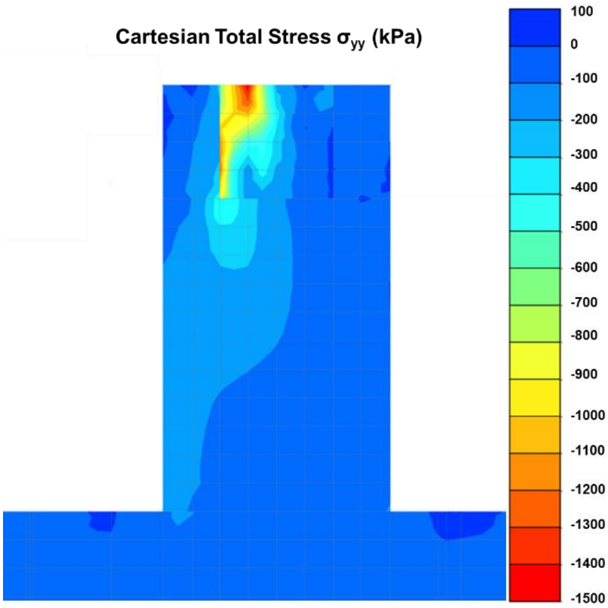

Figure 14. *Distribution of major principal stresses of the structure at the maximum borne load. The wedge-type failure being developed is of similar geometry to the ones observed during the evaluation of the results of the two-dimensional analyses.*

DISCUSSION & OPTIMIZED PROPOSAL

From the results of the finite element analyses presented in the previous section, the loads of modern-day shelters designed with contemporary standards cannot be borne from the prehistoric masonry walls of the Old Palace and Royal Chambers areas. It is noted that this was not a consequence of the bearing capacity of the in-situ foundation rock mass, but rather of the structural integrity of the walls, and that the foundation scheme was selected in order to rationally replicate the previously installed shelter arrangement and prevent damage to the monument.

Furthermore, as shown below in Table 2, 3-D finite element analyses display improved results over 2-D analyses, yet still inadequate. This improvement was expected as the load transfer from the columns to the walls is a strongly 3-dimensional phenomenon. The strength that the wall contributes under the load from the columns is in fact larger than that in the plane-strain conditions considered in 2-dimensional analyses. As columns load the walls, a finite wedge is formed in the body of the wall with mobilised strength resisting to its movement developing all over the surface of the wedge. In 2-dimensional analyses the counterpart of this “wedge” is essentially a triangle with mobilised strength considered only across its base.

Table 2. *Summarized results of finite element analyses executed as percentage of standard loads that the walls were able to bear.*

Area examined	Height H (m)	Width W (m)	W/H Ratio	2-D FEA Analysis	3-D FEA Analysis
Old Palace	3.50	1.50	0.42	54%	62%
Royal Chambers, H_1	0.80	0.80	1.00	22%	45%
Royal Chambers, H_2	1.50	0.80	0.53	21%	38%

Given this, the following concept and installation methodology were proposed and designed (Fig. 15):

- The support of the new columns is achieved by shallow reinforced concrete pad foundations of typical dimensions 40 × 40 × 40 cm. The foundation units are installed through controlled partial embedment into the subsoil (approx. 30 cm), ensuring adequate bearing conditions while minimizing disturbance to the surrounding ground.
- Concrete casting is performed within a geotextile membrane (100 g/m²), lined with a 2 mm polyethylene sheet, ensuring full isolation of the foundation element from the natural soil. This approach prevents direct interaction with the ground and enables complete future removability, in accordance with the principle of reversibility and minimum intervention.
- Stability against sliding and overturning actions is ensured through the installation of four fully bonded stainless steel ground anchors (Ø25 mm), embedded within the geological substrate. The anchors are installed in Ø75 mm boreholes, subsequently filled with cement grout to achieve adequate bond and load transfer.
- Drilling operations are carried out using portable light-duty drilling equipment, suitable for restricted-access archaeological environments, with a maximum drilling depth of approximately 3.0 m. The equipment is transported in modular components and assembled on-site, allowing precise positioning even in confined areas.
- A targeted geotechnical investigation program has been conducted at each column location, including surface-level assessment of the local geological formations. The results are incorporated into the design assumptions and the detailed foundation design.

The proposed system is designed to ensure full reversibility of the intervention. In the event that future removal of the new structures is required, all structural components can be systematically dismantled, while the reinforced concrete foundation elements may be extracted through controlled fragmentation and localized removal techniques. The entire process is conceived to be non-invasive to the surrounding archaeological fabric, ensuring that no damage or alteration is induced to adjacent historic structures, in accordance with the principles of minimum intervention and material preservation.

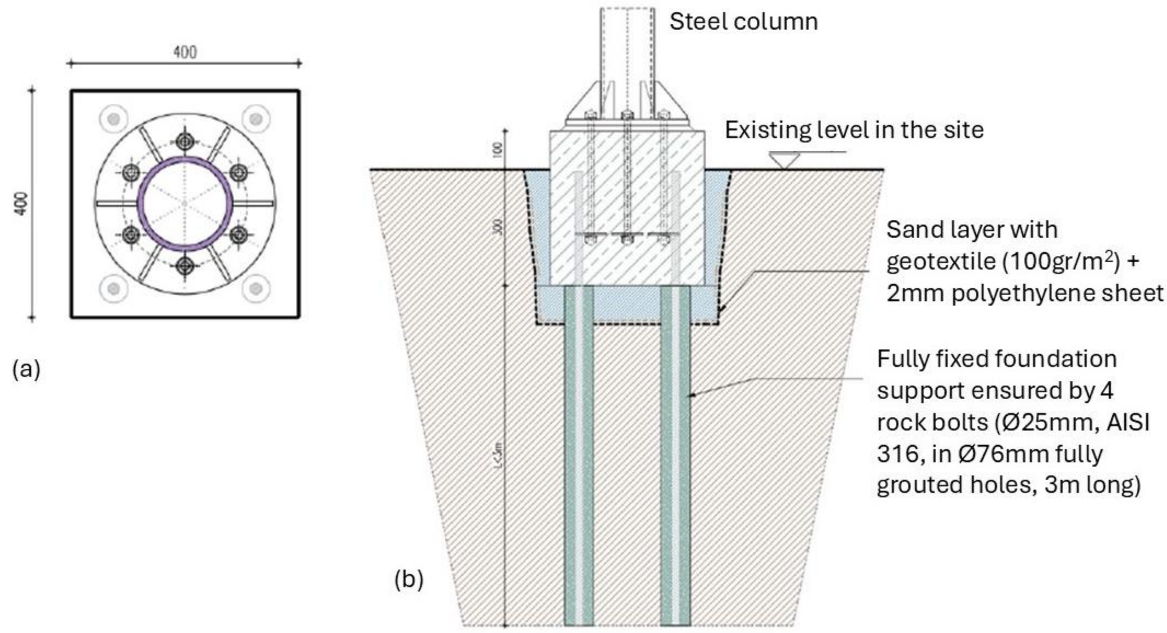

Figure 15. *Detail of proposed and designed column foundation for the new shelters: a) plan view of column fixation to its concrete base, and b) section showing the foundation design (all dimensions in mm, unless otherwise shown) -Kasimis, 2024.*

CONCLUSIONS

New shelters were designed for the Royal Chambers and the Old Palace of Phaistos. Both of these remains are currently under shelters built in the '60s with steel columns embedded in existing prehistoric walls of the remains. Given the loads imposed by the existing regulations for new shelters an exercise was performed; to test whether the existing prehistoric walls of the remains with steel columns of the existing frames could bear the loads that the steel columns from the new shelters would transfer onto them. 2-dimensional and 3-dimensional finite element analyses were performed on characteristic critical sections from both the Old Palace and the Royal Chambers. From the results of the finite element analyses performed, the loads of modern-day shelters designed with contemporary standards cannot be borne from the prehistoric masonry walls of either the Old Palace or the Royal Chambers. It is noted that this was not a consequence of the bearing capacity of the in-situ foundation rock mass, but rather of the structural integrity of the walls, and that the foundation scheme was selected in order to rationally replicate the previously installed shelter arrangement and prevent damage to the monument. The results of this exercise dictated the need to design new foundations of the steel columns directly on the ground, fully fixed by means of rock bolts to be drilled down to depths identified by geotechnical investigation at the exact spot of each foundation. This work makes a point about the engineering need to remove possible similar foundations of existing shelters on remains when it comes to the construction of newly designed shelters, as loads dictated by contemporary standards seems that they cannot be borne by the remains of masonry walls remains like those in the case of the Phaistos Palatial Complexes. 3-dimensional analyses seem to model more adequately the transfer of loads from the columns to the remains of the masonry walls in comparison to 2-dimensional analyses. Further development of this kind of calculation exercise could involve more advanced and complex models for the masonry walls and other types of foundation connecting the column with the existing remains. Still the calculation results seem to support the concept of relieving remains from playing the role of bearing elements in favour of new foundations on stable ground.

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