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STUDY OF ANCIENT MONUMENTS' SEISMIC PERFORMANCE BASED ON PASSIVE AND REMOTE TECHNIQUES

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ABSTRACT

"Engineering structures are designed to be safe. The difficulty one trading in this regard is the desire to construct something for a specific purpose out of a material of which one can never know enough in terms of the material's properties as well as the environment the structure is going to operate in".

Even though this affirmation was initially drawn for modern structures, it however firmly describes the situation of the ancient ones. In the case of ancient monuments, the mechanical properties of the construction materials, their consistency and their homogeneity are highly unknown and can only be determined probabilistically through elaborate testing under legislative and protective to the monuments' restrictions. On the other hand, the environmental (weather) conditions and natural hazards to which those ancient masonry structures were and still are exposed is even more difficult to be determined with precision and thus monitored, but has certainly led to their degradation.

Towards this end, the present study discusses the potentialities of non-destructive passive and remote system investigations of monuments, trying to examine the benefits and drawbacks in relation to the result and in comparison to conventional structural control methods. A selection of the most credible methods for the investigation of monuments is described along with their potential applications.

The scope of this investigation is to acquire information regarding the subsurface condition and consequently the structural system of the monument and anticipate its future behavior in destructive earthquake events. This can be achieved through a simulation model, which can be as realistic as the information obtained and can be updated with more thorough information. To demonstrate the application of this updating process in obtaining the response of the monument, a case study tomb "Tomb 4" from the Hellenistic necropolis of the 'Tombs of the Kings', in

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Paphos Cyprus is examined, recapitalizing thus previous work of the team accomplished on the aforementioned monument. The seismic performance of the monument, located in a moderate earthquake hazard area, will be examined based on passive and remote data acquisition and simulation results will be shown.

Keywords: structural survey; underground monument; cultural heritage; passive and remote techniques; seismic analysis

1. INTRODUCTION

The intrinsic value of built cultural heritage is renown and accepted in all levels of related disciplines. However, ancient monuments are exposed to a variety of factors of anthropogenic and environmental nature, which along with natural aging affect their preservation. On this ground many initiatives in European level have been activated throughout the years, pursuing their protection (UNESCO 1972; Colette 2007). Within this context, a great attention is given to the investigation of the condition of preservation and monitoring of monuments, with the combined use of efficient and non-destructive technological tools, information and computational technologies, various observation floors (from satellite to ground).

The present study concerns the ancient necropolis known as “Tombs of the Kings”. The site dates back to the 4th century BC and is situated in NW Paphos District. Within the necropolis several tombs of the atrium type exist. These were carved out of the solid rock and feature open air porticoes supported by monolithic columns and/or masonry pillars. Many of the tombs incorporate alterations dating to the Roman and Medieval times. The site suffered extensive quarrying activity in modern times, while studies (Barker 2004) indicate that the area might have been simultaneously used as a necropolis and a rock quarry during ancient times. The aforementioned multiple use of the site, along with looting, contributed to the decay of the tomb monuments. Systematic cleaning and excavation of the site took place between 1977 and 1990 by the Cyprus Department of Antiquities. Since then, the funerary constructions preserved up to date have been declared Ancient Monuments, while in 1980 the archaeological site was included in the UNESCO list of World Heritage Monuments.

For this research, Terrestrial Laser Scanning, Ground Penetrating Radar measurements and Finite Element analysis have been merged in an effort of a multilevel analysis and approach of the monument’s state of preservation. These tools provided all necessary information for the development of numerical models and consequently analysis methods seeking possible documentation of the structural preservation of the monuments.

A geotechnical approach of the seismic response of the monument is hereunder considered with special focus, while the fusion of the post-processed results of the GPR and TLS surveys will be a subject of a future publication.

2. METHODOLOGY

The methodology followed for the investigation of the tomb included both in situ examination and desk-based processing. Field work was initiated by detailed visual inspection of the monument and documentation of its current state of preservation. Subsequently, the Terrestrial Laser Scanner (TLS) method was used for the geometric documentation of the tomb, while both TLS and Ground-penetrating radar (GPR) techniques were employed to map the monument’s state of preservation, primarily as far as its structural and superficial condition concerns.

TLS enables the 3D documentation of an object in a predefined distance using multiple laser beams and has thus been used for multiple purposes various applications worldwide (Assali et al. 2014; Ruther & Paloumbo 2012). Due to its enhanced time efficiency and ability to survey complex structures with high accuracy, TLS is increasingly employed in the domain of built heritage. Even though, the post processing of the acquired data for the formulation of a 3D model could be time consuming, the overall benefits of using a TLS for ancient monuments survey are multiple. The documentation of the geometry facilitates the architectural and structural understanding of a monument, while at the same time captures its state of preservation. Subsequently, a realistic 3D model of a monument and/or its environs, it is of great value for restoration and conservation interventions, considering both aesthetic and practical implications (Ruther et al. 2009).

GPR is a RAdio Detection And Ranging technology designed to detect and localize targets hidden below the air-soil interface or in optically opaque materials. It exploits microwaves, i.e. signals belonging to the portion of the electromagnetic spectrum ranging from 10^8 up to 10^{10} Hz, and the ability of these signals to penetrate into non-metallic objects. Accordingly, GPR can be regarded as a non-invasive geophysical prospecting technology and it is commonly adopted in several applications among which structural surveys, devoted to retrieve information on the internal features of masonry or pillars, including the presence of cracks, voids and defects. In particular, this method is very useful in the field of heritage diagnostics, restoration and conservation (Masini et al., 2007).

A time-domain standard GPR system transmits a modulated time domain pulse and collects the reflected energy as a function of time, which represents the travel-time of the wave along the transmitter-target-receiver path. It is worth noting that the target is a generic variation of the electromagnetic properties (dielectric permittivity, electrical conductivity, and magnetic permeability) occurring into the probed medium. Hence, GPR allows the identification of internal layers as well as the detection of local reflectors referable to decay pathologies such as voids, cracks and fractures (Persico 2014). More precisely, by shifting the transmitting and receiving antennas along a line and joining together the gathered traces at all the antenna positions, a spatial-time image is built, which is referred to as raw-data radargram or B-scan. Being the round-trip travel time a function of the distance occurring among antennas and targets, the radargram provides a distorted image of hidden objects, which appear as hyperbolas whose characteristic features (i.e., vertex and eccentricity) depend on position, shape, size of the objects as well as on electromagnetic properties of the probed medium. As a consequence, advanced data processing approaches, among which microwave tomographic approaches (Soldovieri 2011), are commonly adopted to improve the imaging capabilities and obtain easily interpretable images. Herein, a microwave tomographic approach, which is based on a linear model of the scattering phenomenon underling the GPR survey is exploited (Catapano et al. 2012).

3. CLOSE RANGE SURVEY TECHNIQUES RESULTS

3.1 Terrestrial Laser Scanning survey

For the TLS survey the Leica ScanStation C10 laser scanner was used. The capacity of the machine permits a scanning of up to 50,000 points per second, while the accuracy is of the level of ±6mm/50m distance. The field of view (FOV) of the Scan Station is of 360^o x 270^o which provides huge flexibility in close-range applications such as the current case study.

For the purposes of the present study the monument was scanned under a medium resolution analysis (i.e. points every 1mm at 10 m distance). Due to the complexity of the monument, six different scan stations were positioned providing equivalent number of point clouds. For registration purposes of the individual point clouds, special reflector targets were used. Coordinates of the targets were estimated using the reflector-less total station Leica 1203+. The Root Mean Square (RMSE) registration error was reduced at 1cm, an acceptable error for the purposed of the present study. The registration of the individual point clouds was based upon the ICP (Iterative Closest Point) algorithm.

Amongst the aims of the TLS survey were to capture the geometry of the monumental complex, to digitally map the cracks present on the vertical walls of the tomb and the columns/pillars, and thus facilitate the monitoring and observation of the phenomenon over the time, in case that changes occur. In addition, through the digital documentation of the monument the state of preservation as for the weathering of the rock surface could be mapped and quantified, supporting any future conservation intervention (Figure 1).

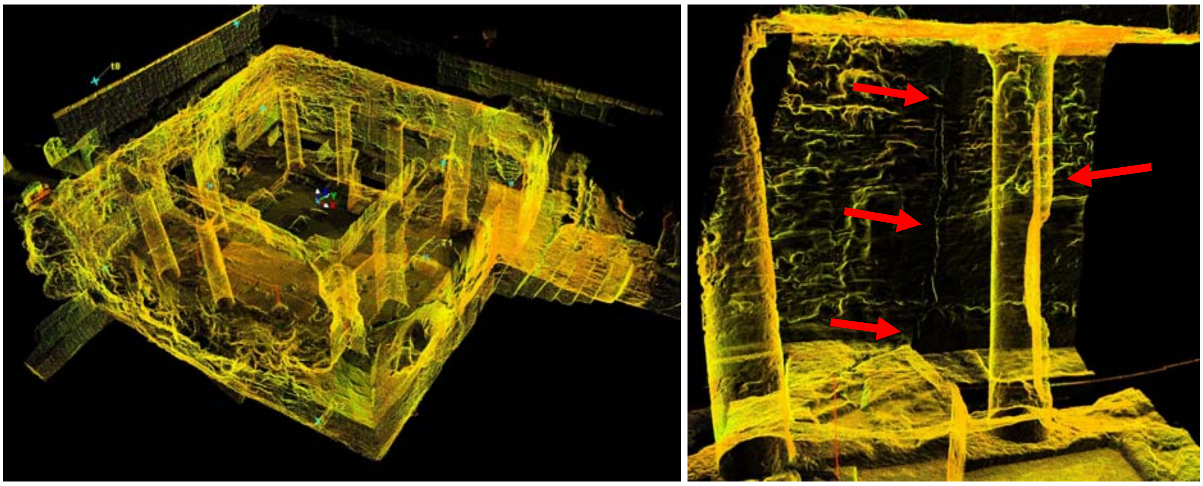


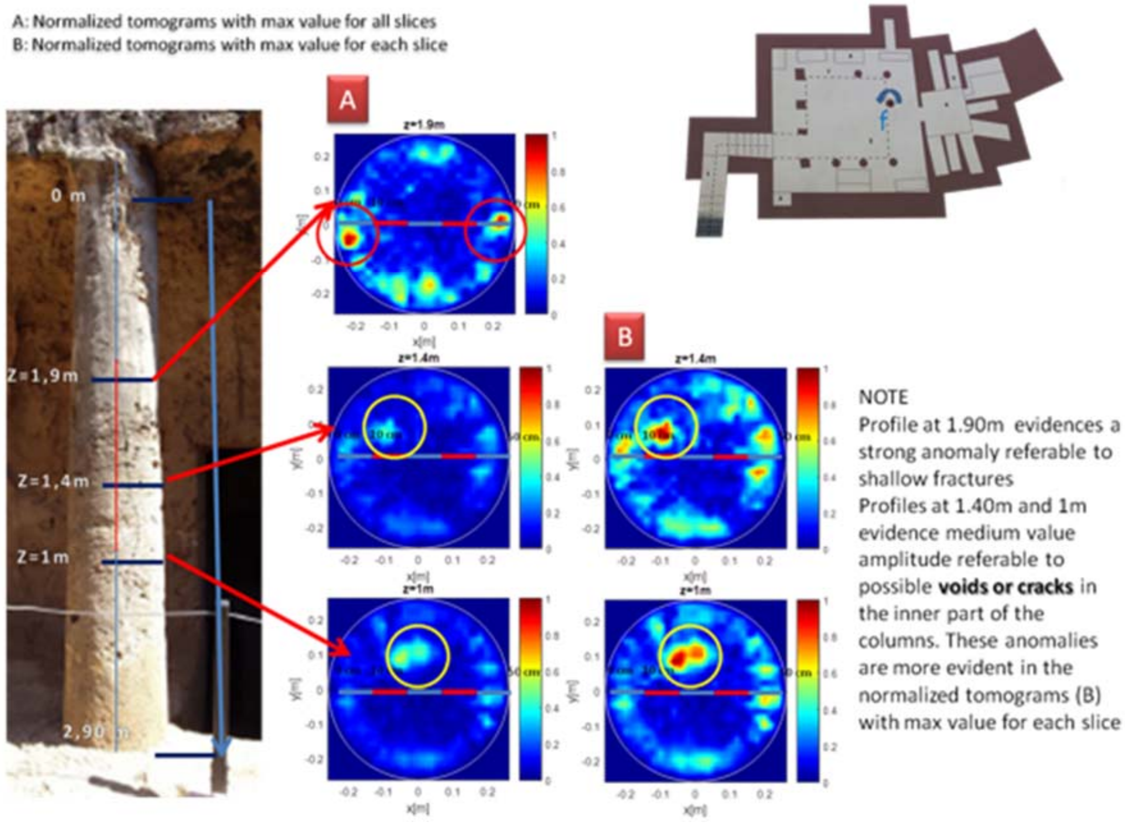
Figure 1. General preview of the point cloud (left); detail indicating cracks along the east wall and column of the tomb (right).

3.2 GPR survey

The GPR survey carried out on the pillars of Tombs of King n. 4, was performed with the time domain Ris Hi-Mod GPR system, manufactured by IDS System, equipped with a single fold shielded antennas, whose nominal peak frequency is equal to 2GHz. All the GPR profiles have been acquired by considering a 32 ns observation window discretized by 1024 time samples for each measurement position. Each column/pillar examined was probed along parallel vertical and horizontal scans along the circumference.

As said, GPR data processing can identify interfaces between the local reflectors referring to voids, fractures or inhomogeneities and improved results are obtained by exploiting microwave tomography. Specifically, we have processed the gathered data by using a linear microwave tomographic approach (Catapano et al. 2012). This approach faces the imaging as the solution of an inverse scattering problem, exploits the Born approximation to define the mathematical model describing the relationship between data (i.e. the gathered radar echoes) and unknowns (i.e. the contrast function, which accounts for the occurring electromagnetic variations) and it adopts the Truncated Singular Valued decomposition to obtain a reliable solution. The output is a spatial map, named tomographic image, showing, pixel by pixel, the absolute value of the retrieved contrast function, whose expression can be given as normalized to its maximum value into the overall investigated region or slice by slice. Accordingly, the significant values identify the location of targets and give information about their geometry. Figure 2 shows the tomographic images obtained by processing data acquired along horizontal scans at different high from the column top. These images allow the clear visualization of localized anomalies, which infer the presence of a number of reflectors referable to cracks and material discontinuities, some of them not visible by means of a visual inspection of the column.

A: Normalized tomograms with max value for all slices
B: Normalized tomograms with max value for each slice



NOTE
Profile at 1.90m evidences a strong anomaly referable to shallow fractures
Profiles at 1.40m and 1m evidence medium value amplitude referable to possible **voids or cracks** in the inner part of the columns. These anomalies are more evident in the normalized tomograms (B) with max value for each slice

Figure 2. Tomographic images from horizontal scans using GPR

4. ANALYSIS OF SEISMIC RESPONSE

4.1 Finite element modelling

The seismic analysis of underground monuments such as the tomb under study poses a real challenge. Unlike surface structures which are directly subjected to ground excitations and experience amplification of their shaking motion depending on their own vibratory characteristics, underground structures primarily sustain racking deformations/distortions imposed by the seismic motion of the surrounding medium (i.e. soil or rock) (Wang 1993). Focus should therefore be placed on evaluating the distribution of free-field displacements within the ground layers and on examining their effect on the various members of the underground structure (St John & Zahrah 1987).

In light of the above, the seismic response of the ancient tomb is hereby examined using a quasi-static approach. The adopted method involves simulating the effect of an earthquake with an equivalent seismic load that is statically applied to the structure as a distribution of free-field cumulative displacements. For this purpose, a Finite Element (FE) model was developed based on the geometry of the tomb and the geotechnical characteristics of the area, while 1D numerical analysis was performed to calculate the ground deformations generated during seismic motion. It is worth noting that although this methodology has been extensively used for the design of tunnels and culverts (e.g. Fabozzi et al. 2017; Argyroudis & Pitilakis 2012; Zurlo 2012; Hashash et al. 2001), this study comprises one of the few efforts to extend its application to the appraisal of underground monumental structures and is regarded as complimentary to the study of Kyriakides et. al. 2017, which focused on the 3D time-history numerical analysis under acceleration seismic excitation.

The geotechnical characteristics assumed for the site where the monument is located are based on the field investigation of Veldemiri et al. (2016) who performed a detailed seismic ground response analysis for the wider region of the city of Paphos. The latter included the implementation of boreholes at several locations and the execution of Cross-Hole and Down-Hole tests which enabled determining soil profiles and evaluating their dynamic properties. Results obtained from a certain borehole (A13) at the vicinity of the monument, indicate that the tomb was carved into a 10 m deep layer of calcarenitic sedimentary rock, having a shear wave velocity of 500 to 650 m/s. Underneath the rock layer, clayey silt deposits that extend up to a depth of 140 m exist. The shear wave velocity of these soils increases progressively from 250 to 560 m/s. According to Veldemiri et al. (2016) the presence of calcarenite rock above considerably less stiff layers of soil is a particular characteristic of the specific area examined and can affect the seismic performance of structures. The assumed rock-soil layering and shear wave velocity profile are shown in Figure 3.

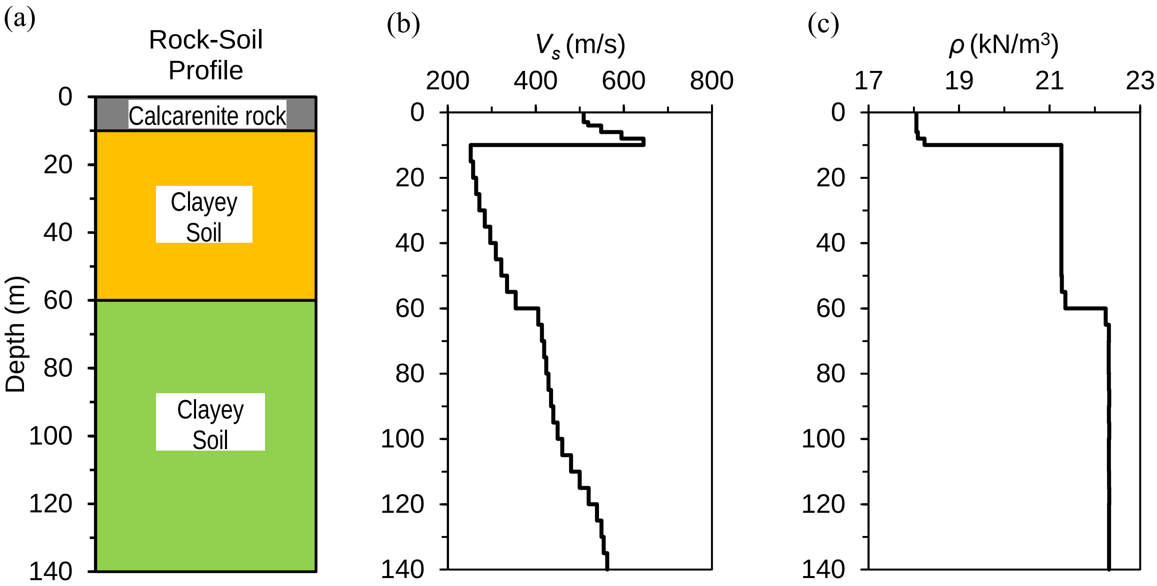


Figure 3. Assumed profile of rock-soil layers (a) and corresponding variations of shear wave velocity (b) and unit weight (c) based on the data reported in (Veldemiri et al. 2016).

The underground tomb monument was simulated in 2D using the FE code Abaqus/CAE (Simulia Corp. 2009). A plane strain model representing a longitudinal cross-section of the tomb and horizontally layered rock and soil strata was developed. The lateral extent of the calculation domain was set as 180 m, in order to ensure that the distance of each side from the central axis of the tomb is at least equal to three times its total cross-sectional width (i.e. 30 m), so as to minimize boundary effects (Argyroudis & Pitilakis 2012). Since the monument was entirely hewn out of the rock, the perimeter of the tomb's modelled section was connected to the surrounding rock and soil layers via common nodes. The typical plane strain thickness was set to 1 m for all regions of the model, except of the two parts representing the atrium pillars where a 0.3 m thickness was defined in accordance to the geometrical characteristics of the monument. The FE mesh consisted of 15091 4-noded bilinear quadrilateral elements with reduced integration and hourglass control (CPE4R), resulting to a total of 31338 degrees of freedom (Figure 4). The maximum size of the elements' length at the regions of the model representing the soil layers was set as 5 m. A denser mesh composed of elements with side lengths ranging from 0.1 to 0.25 m was assigned at the tomb's area. Vertical displacement of the nodes along the two sides of the model was constrained ($u_y = 0$), while both translational degrees of freedom at the bottom of the mesh were fixed ($u_x = u_y = 0$).

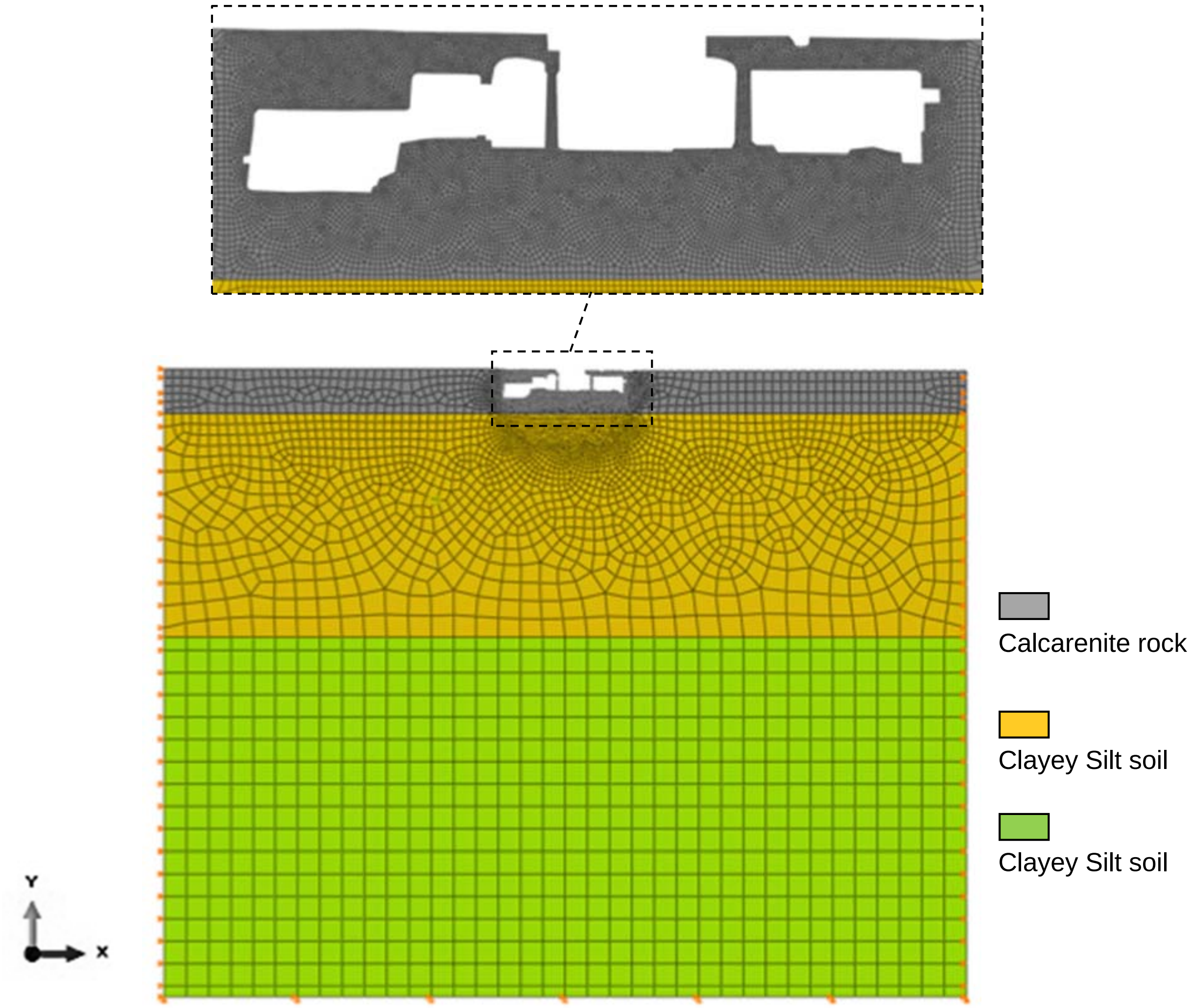


Figure 4. Plane strain FE model developed in Abaqus/CAE for examining the seismic response of the underground monument and mesh at the calculation domain corresponding to the tomb's cross-section.

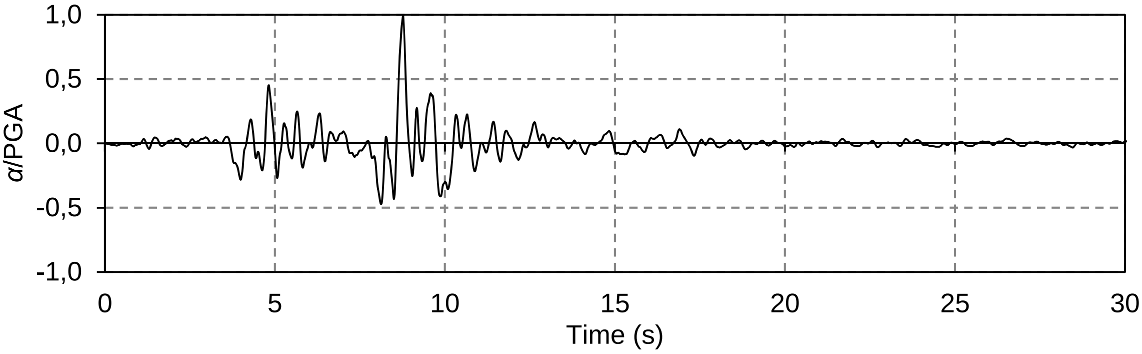


Figure 4. Accelerogram of the 1978 Thessaloniki earthquake used in the seismic analysis of the tomb monument.

The seismic input motion used for the analysis of the tomb is based on a record of the 1978 Thessaloniki earthquake (Figure 5). The accelerogram was scaled to a Peak Ground Acceleration (PGA) of 0.25g, which corresponds to the design value prescribed in the Cyprus National Annex to Eurocode 8 for the Paphos region. The quasi-static seismic ground displacements resulting from the action of the selected earthquake motion were computed following the 1D EQL approach by assuming an equivalent linear elastic soil behavior, using the code EERA (Bardet et al. 2000). The variations of the calcarenite rock's and clayey silt soil's shear moduli G/G_{max} and damping ratios D with respect to the shear strain level γ were defined according to relevant data from the literature (Vinale 1988; Seed & Sun 1989; Idriss 1990) (Figure 6). For carrying out displacement calculations, the rock-soil profile was discretized into a total of 31 layers, each with a thickness of 1 to 5 m. In the iterative procedure, the ratio between the effective and maximum shear strain was taken as 0.65. Cumulative displacements at different depths were estimated as a function of the computed peak shear strains. The computed profiles of peak shear strain, cumulative displacement and mobilized value of shear stiffness are shown in Figure 7.

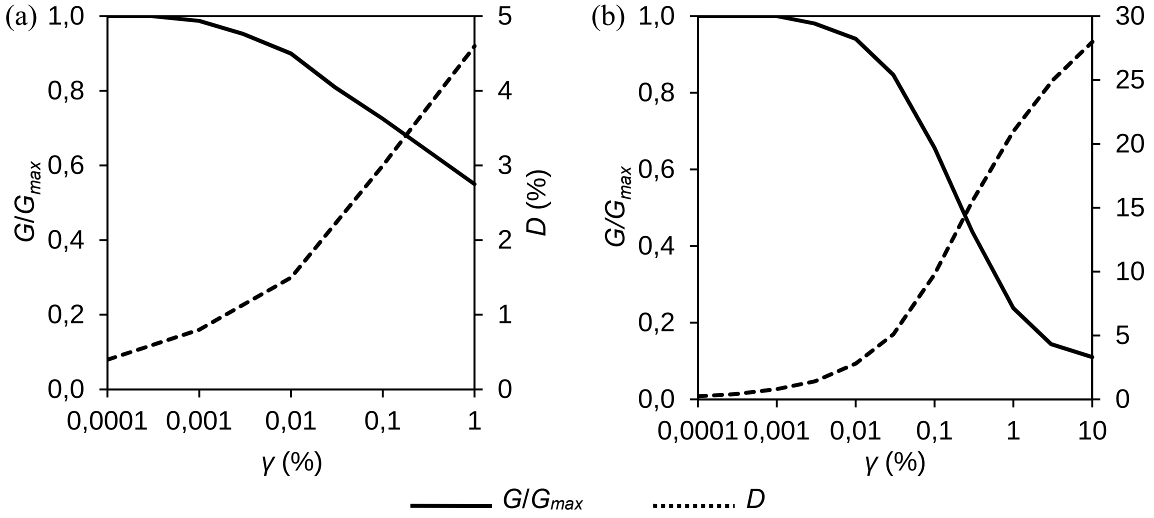


Figure 6. Shear modulus reduction ($G/G_{\max}$) and variation of damping ratio (D) with shear strain (γ) assumed for the calcarenite rock (a) and the clayey silt soil (b).

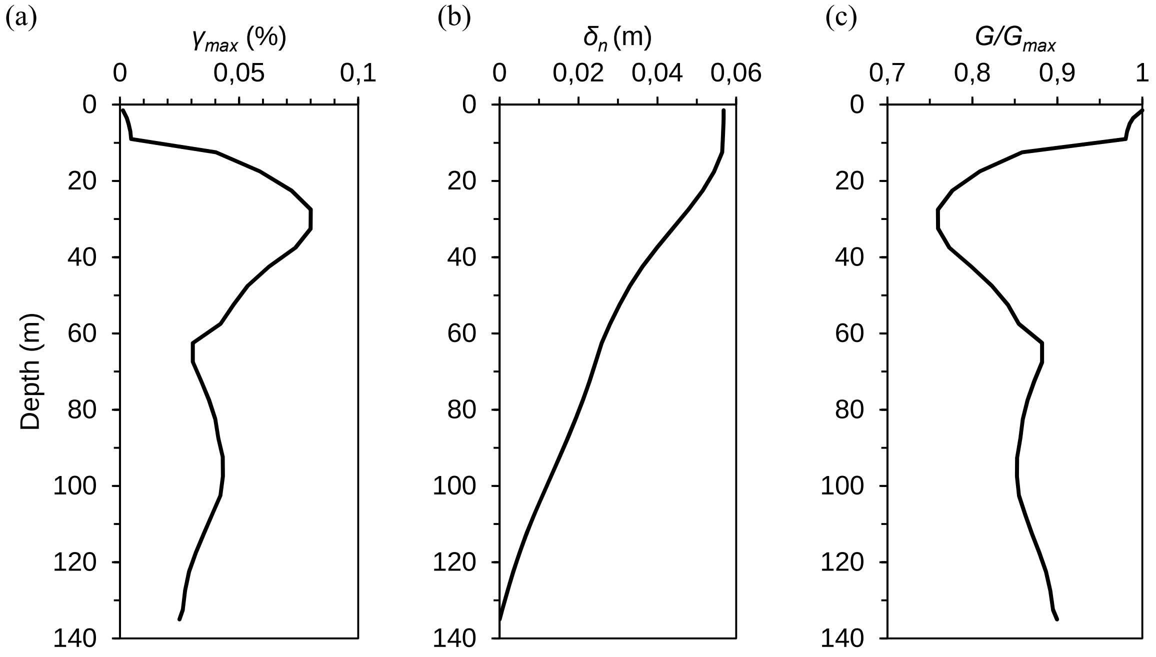


Figure 7. Results of 1D ground response analysis with EERA: variation of peak shear strain (a), cumulative displacement (b) and mobilized value of normalized shear stiffness (c) with respect to depth.

The outcomes of the 1D ground response analysis were also used to evaluate the moduli of elasticity that were assigned to the FE model for the simulation of the rock and soil. Both materials were hereby modeled as linearly elastic. The modulus of elasticity (E) at each depth level was defined in accordance to the variation of the equivalent shear modulus (G) computed from the free-field analysis (Figure 7c) as:

$$E = 2 \cdot G \cdot (1+v) \qquad (1)$$

In the above equation v is the Poisson ratio; assumed to be constant and equal to 0.2 and 0.3 for the calcarenite rock and clayey silt soil, respectively.

FE numerical analysis was completed in two consecutive steps using a general static procedure with a full Newton solution technique. At the first step, a gravitational load was imposed at all parts of the model in order to simulate the initial static conditions of the problem. Subsequently, the calculated profile of peak horizontal displacements corresponding to the free-field ground response under the scaled accelerogram was applied to the side boundaries of the FE model.

4.2 Results of FE analysis

The outcomes of the FE analysis are presented in Figure 8 which shows the deformed mesh shape of the tomb's simulated cross-section along with the computed distributions of displacements in the *x* direction and of maximum principal tensile stresses.

According to the estimated displacement magnitudes, in the event of an earthquake generating a PGA of 0.25g, the columns supporting the tomb's atrium are expected to sustain a lateral drift in the region of 0.4%. Based on the provisions of FEMA 356, masonry piers subjected to in-plane loads have a nominal yielding drift of 0.1%, while at drifts ≥ 0.3% significant damage develops and at drift levels exceeding 0.4% the collapse prevention limit state is reached. This suggests that the stone columns can suffer from extensive cracking due to seismic action, which may even jeopardize their structural stability. Bearing in mind that most of the monument's columns are monolithic (i.e. entirely hewn out of the bedrock) and do not incorporate any joints allowing for slippage or rocking motion during dynamic excitations, it can be argued that these members may exhibit brittle behavior characterized by sudden tensile or shear failure.

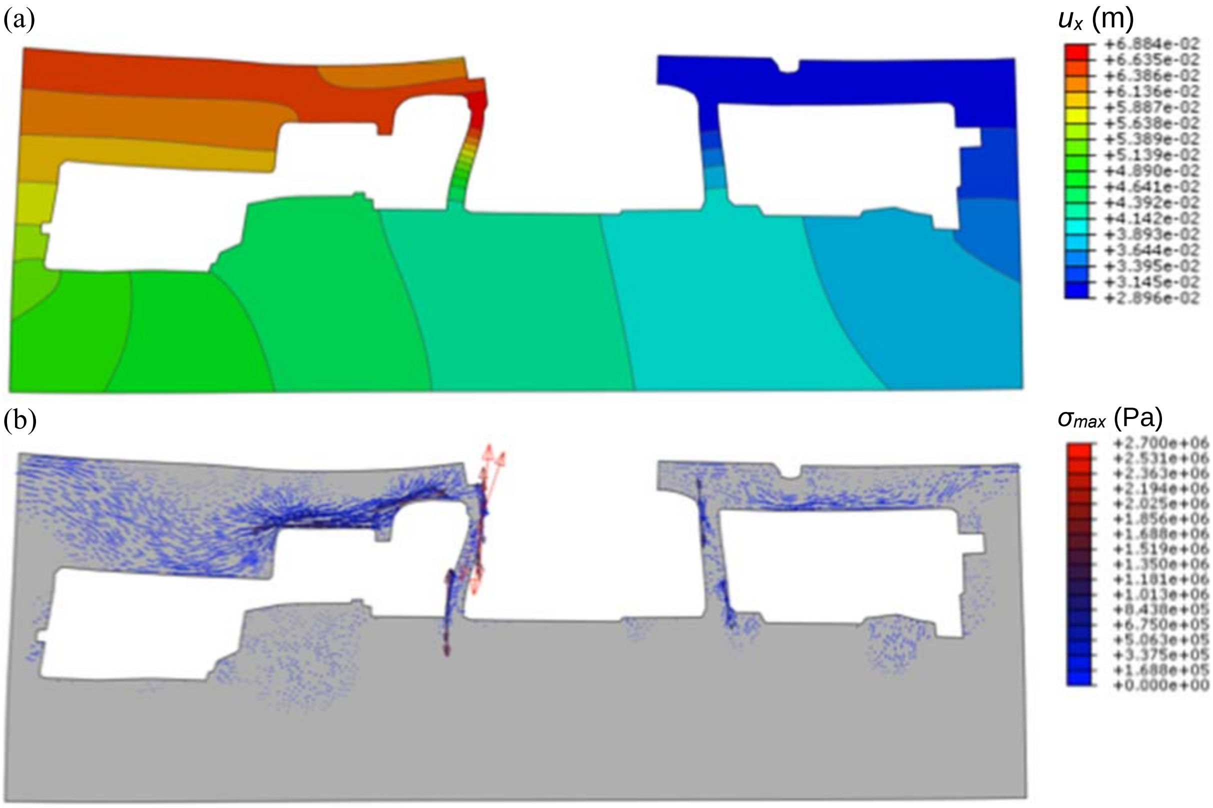


Figure 8. Deformed mesh shapes (displacements scaled up 25 times) of the tomb showing a contour distribution of displacements in the *x* direction (a) and a vector distribution of principal tensile stress (b).

The development of seismic damage at the column sections is further implied by the computed stress distribution. The analysis shows the generation of tensile stresses > 1 MPa at the base and upper part of these elements. Significant concentrations of analogously high tensile stresses occur along the chamber section, at the eastern part of the tomb. A laboratory investigation carried out by (Modestou et al. 2016) concluded that local carbonate rocks have rather high porosity and relatively low tensile strength that can range from 1 to 4 MPa, depending on their mineralogical composition. Considering that the rock composing the members of the monument is exposed to the elements and has been affected by long-term weathering which has reduced its mechanical properties, it is rather safe to assume that cracking will develop at areas where tensile stresses between 1 and 3 MPa occur.

Indeed, the predicted damage distribution is, to a certain degree, verified by the crack pattern observed at the actual monument. A number of columns at the tomb's atrium exhibit fracturing at their base or incorporate cracks which extend throughout their height (Figure 9a). In addition, fissures are noted at both the exterior and interior of the chamber compartment (Figure 9b and c), at approximately the same areas where the analysis predicts the development of tensile stresses > 1 MPa. Correlation between the numerical results and the physical damage observed at the tomb indicate that cracking/fissuring was possibly caused by past seismic activity.

Figure 9. Pilasters and columns at the atrium of the tomb that exhibit cracking and fracturing at the base (a) and fissures at the exterior (b) and interior (c) of the chamber compartment.

5. CONCLUSIONS

A field survey involving the use of advanced TLS and GPR methods was undertaken to examine the condition and analyze the pathology of an ancient monumental tomb complex located in Paphos, Cyprus. Processing of the data obtained from the in situ investigation enabled the formulation of a 3D digital model that accurately captures the geometry of the site. Detailed mapping of the cracks present on the surface of the tomb's architectural members was also performed. Furthermore, the study resulted to valuable information regarding the occurrence of anomalies within the mass of the structure's stone elements. These provide indications concerning the development/propagation of cracks and the existence of discontinuities within the rock material.

Using relevant data from the literature a seismic analysis of a specific tomb structure was carried out. For this purpose, a 2D plane strain model was developed and was subjected to linear static loading by imposing the free-field cumulative displacements generated by an earthquake motion scaled to the design PGA of the particular area under study. The analysis predicted the development of high tensile stresses at certain areas of the tomb, implying the occurrence of cracking damage. Interestingly enough, these areas practically coincide with sections of the actual monument where physical damage is observed. Further research is in progress to evaluate all aspects of the monument's seismic behavior.

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