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Correlating damage condition with historical seismic activity in underground sepulchral monuments of Cyprus

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ABSTRACT

Severe and repeated earthquakes devastated Cyprus in antiquity, causing in many cases the abandonment of entire settlement sites. Yet, information regarding the level of seismic activity of historical seismicity in Cyprus is very limited and does not provide the evidence to arrive at reliable conclusions relative to hazard damage parameters such as the severity or occurrence frequency of a seismic event. Thereafter, the level of risk in which these monuments are exposed is unclear leading to an increased uncertainty regarding their safeguarding from future events.

The paper aims at investigating the correlation between damage observed in underground ancient tombs and the historical seismic activity at the area based on in situ observations and expert opinion analysis. In addition, the paper aims to simulate the current state of the tomb's structure, and predict, through a seismic scenario, the propagation of damage from future large earthquake events. Underground monuments are chosen since, due to the nature of the seismic force, they are further "protected" and capable of surviving strong ground motions as they follow the displacement of the soil surrounding them. Typical examples of such structures in Cyprus are the hypogea in the necropolis of the "Tombs of the Kings", located in Paphos area. Some of these monuments exhibit severe cracking of the rock-cut stone walls and evidence of collapse of vertical resisting members of skeleton structure. Paphos area is the most active seismic region in Cyprus based on the historical catalogue of events with evidence of a number of destructive earthquakes.

The framework presented herein utilizes information regarding the current geometry of these structures as documented from topographical surveys, their depth, area of opening, size of resisting members along with information regarding the geotechnical conditions at the site to arrive at estimates of the displacement demand under various seismic scenarios. The predicted shear strain levels on the walls are compared with the strain capacity under tension of the soil material to identify the possibility of propagation of cracking of the walls based on a specific seismic scenario.

1. Introduction

1.1. Archaeological and literary evidence

Contrary to studies related to historical seismic activity in Cyprus for the period beginning from the end of the 19th century onwards (Christofidou, 1969-1972; Ambraseys, 1992; Ambraseys and Adams, 1992; Gajardo et al., 1998), respective studies related to the ancient one are difficult to be found, mainly due to the intrinsic obstacles of the subject. An indexing including ancient seismic events concerning Cyprus has been formed by Ambraseys (1965) comprising in some instances the basis for archaeologists as well.

Literary sources are occasionally refer to distractive earthquakes stricken Cyprus, such as the 15 CE Paphos earthquake attested by the historian and Roman consul Dio Cassius (XXIII, 24, 7), the earthquake of 76 or 77 (Hill, 1949), the 365 CE Kourion earth quake (Am. Marc.) etc., while more abstract and generic references to seismic events related to disasters affected Cyprus are to be traced in ancient literature (Seneca, 1925: 91; Seneca, 2010: 6.25, 6.26.4; Orascula Sib. 3.395–396, 4.125–126, 5.449–454; Pas.Cr. 313C).

Ancient texts alongside archaeological evidence of ancient earthquakes consist of invaluable information guiding modern scientists' research enquiries. However, both the aforementioned resources are very limited in terms of concrete information and even though contemporary archaeologists are referring to ancient seismic events as the cause

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of destructions observed in several sites on the island, only few are to be validated through excavated archaeological material and consequently, datable with a certainty in context.

Unshaken archaeological evidence connected to ancient earthquakes derives from the area of ancient Kourion related to a great seismic event that possibly took place somewhere between the middle and the end of the 4th century A.D. (appr. 364–370 CE). This final earthquake, preceded by various shocks occurred through the years, befallen in a crucial historic *momentus* when Christianity was gaining power over paganism this great destruction was considered as a landmark that stigmatized once forever the shifting from one era to another (Soren, 1981; Soren, 1988; Soren and James, 1988. On the 365 CE earthquake see Am. Marc.; Sozomenus, n.d.).

Ancient earthquake manifestation in Paphos area has been revealed and documented through archaeological excavation in the Roman villa known as the House of Dionysos due to its magnificent floor mosaics. The house seems to have been destroyed and abandoned after the earthquakes of the 4th century A.D. During excavation the removal of the wall lying as it was fallen during the seismic event, revealed the skeleton of a man with his hands towards his head, documenting in a dramatic way his last moments. The study of the twelve coins that he was carrying with him permit a secure and a more or less absolute dating of the event. Based on the archaeological material the Paphos earthquake dates in the beginning of the 2nd century A.D., during the early reign of Hadrian (he reigned between 117 and 138 CE offering thus a terminus ad and postquem) (Michaelidou-Nicolaou, 1985). The earthquake attested by the excavation in Paphos was unknown to the scientific community of Cyprus prior 1985, date of publication of the excavation's results.

More seismic events affecting Cyprus are traced in ancient texts and possibly their material aspect is awaiting to be revealed through archaeological excavations.

1.2. Historical seismic activity in Cyprus

Despite all the gaps and weaknesses of the historical data, it is estimated that from 1500 BCE and until 1900 CE there were 30 destructive earthquakes of intensity 8 and above on the Mercalli scale, resulting in a statistical frequency of the order of 1 every 120 years (http://www.moa.gov.cy/moa/gsd/gsd.nsf/dmlHistEarthquakes_en/dmlHistEarthquakes_en?OpenDocument web-site of Geol. Sur. Dep.). By using the Ambraseys (1992) recurrence relationship this gives a return period of approximately 22 years, for an earthquake of magnitude 6 or more on the Richter scale. On the other hand the German re-insurance company Munich Re, in their Universal Map of Natural Disasters, gives a probability of 20% in 50 years for an earthquake with intensity 8 or more in the Mercalli scale (equivalent to about a magnitude 6 or more on the Richter scale) to occur in Cyprus. This means that by assuming a random distribution of earthquakes the return period for such an event is 224 years.

A study of the seismicity of Cyprus based on the earthquakes that occurred in this area the last 2000 years indicates that the most earthquake stricken area of Cyprus is the south-west coast zone, which stretches from Paphos through Limassol to Larnaca and reaches Famagusta. The south coast high seismicity zone is related to the Cyprian Arc, which is regarded as a diffuse boundary between the African and the Eurasian plates (Ambraseys and Adams, 1992). The structure of the Cyprian Arc is complex and the availability of information concerning it, is very poor. There is an agreement of opinions regarding the general shape of this arc, but there is not a clear view on whether it is a plate boundary (Ambraseys and Adams, 1992) (Fig. 1), or a broad zone of thrusting (Fig. 2) (Ambraseys and Adams, 1992).

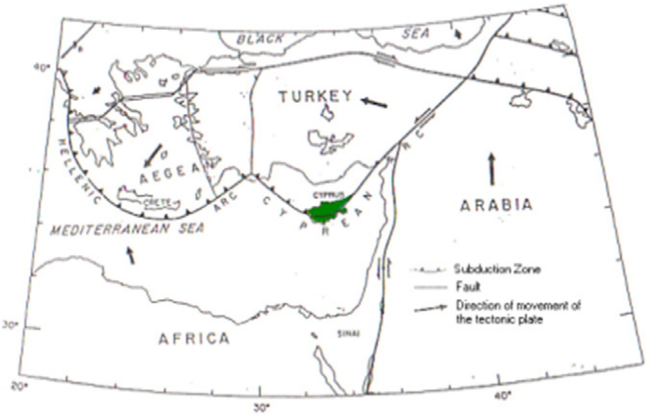

Fig. 1. Arrangement of the tectonic plates in the East Mediterranean. The Cyprian. Arc is shown as a plate boundary (after Ambraseys and Adams, 1992).

2. Methodology

In order to arrive at the analytical determination of the seismic vulnerability of the tomb a methodology was adopted based on the calibration of an analytical finite element model. The seismic hazard is introduced in the methodology in the form of a time-history acceleration record in order to account for its dynamic nature i.e. the frequency and magnitude of the oscillation. The adopted methodology includes both an observational part based on recordings and expert judgment and an analytical part. The first part relies on a thorough and detailed survey of the structure in order to identify its structural resisting system and map closely the cracking pattern on the walls. This investigation is conducted using a variety of methods from in situ topometric measurements, photographs, to more complicated and detailed digital image processing and standard topographic survey. The latest was accomplished with the use of the topographic equipment Leica 1203 + (accuracy < 1 cm). The total station was employed to record the current geometry and shape of the tomb, while special focus was given to some characteristic elements of the monument such as the pillars, the entablature and the entrance of the tomb. In addition, the equipment was used to capture the cracks presented in the tomb's vertical walls, as well as in the upper part of the portico. The geometry of the complex and the cracks were then drawn in a CAD environment and the retrieved product was used as a digital model for the structural stability test. Included in this part is the investigation, using the outcomes from

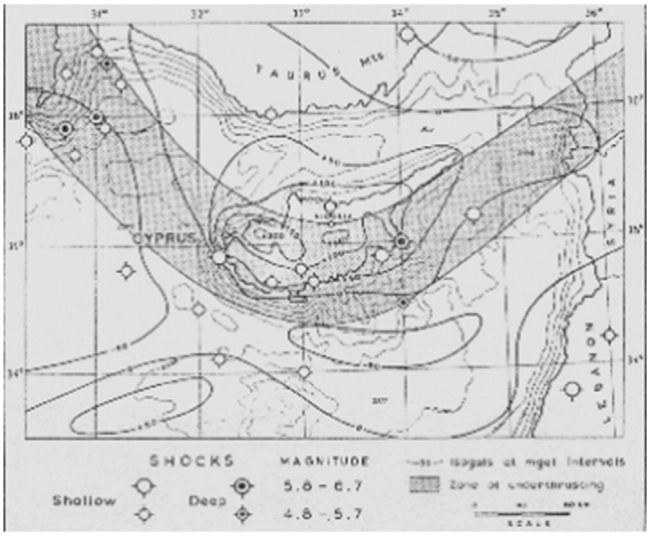

Fig. 2. The Cyprian Arc illustrated as a broad zone of thrusting (Galanopoulos and Delibasis, 1965).

these resources, of the damage patterns (cracking on the walls) and deterioration of the structural material. Possible sources that should be investigated is the differential settlement, the seismic loading, weathering causing shrinkage etc. The concluding section from this part should include an identification of the most vulnerable mechanism in the structure and the expected hazard which would cause increase in the loss of function and stability risk and might cause collapse of the structure.

The second part of the methodology relies on an analytical assessment and determination of the vulnerability of the structure through sophisticated finite element analysis. This part relies on the formulation of a detailed simulation model of the structure calibrated on experimental data of the mechanical characteristics of the structural material. Further to the modelling of the structure, the support and connection details of the structure to its surrounding environment need to be included in the model in order to identify the influence of the surrounding soil conditions and the interaction between the various sections of the structure. The simulation model is analyzed for a number of seismic scenarios which are selected as representative of the local seismotectonic environment and the response of the structure both in terms of displacement and stresses on the rock walls is recorded. The selected scenarios should account for the design earthquake in the region usually with a 10% probability of exceedance in 50 years but also for an earthquake with very large recurrence rate (a suggestion for ~2500 years) since the life-span of monuments is such that they are expected to sustain damage from very rare events.

In order to obtain information for the vulnerability of the structure, the processing of the results from the analysis should identify the following key damage states: (1) The attainment of the material capacity in tension cracking; (2) The penetration of cracks through the whole width of the wall; (3) The formation of independent rock section between the through cracks; (4) The loss of contact between adjacent rock masses at the cracked surfaces and creation of independent sections connected between them only through friction; (5) Rocking of independent sections to the seismic excitation and (6) Cracking at the base of the rock mass and increase of rocking displacements.

At the final stage and in order to identify the loss of stability initiation, static non-linear analysis can be used to obtain the relationship between horizontal force and displacement at the top of each section. This analysis will indicate the maximum top displacement prior to the overturning of the sections i.e. collapse of parts of the monument.

3. Case study

3.1. The "Tombs of the Kings" necropolis

The ancient necropolis known as "Tombs of the Kings" is situated in NW Paphos District and comprises the north part of a vast cemetery, once surrounding the ancient city of Nea Paphos, extended outside the city walls (Fig. 3). Within the necropolis a variety of architectural tomb types coexist with the most magnificent one to be that of the atrium tombs, after which the ancient cemetery gained its modern denomination.

The necropolis dates back to the Hellenistic period with extensive reuse during the Roman times, detectable among other in the architectural remodeling of some of the tombs. During Medieval times on wards the large spacious atrium tombs have been used for several other purposes causing in some instances alterations. The site suffered extensive quarrying activity in modern times and apparently since antiquity, while it has been suggested its deliberate use both as necropolis and quarry from its foundation (Barker, 2004).

The aforementioned multiple use of the site caused several and severe alteration to the tombs further contributing to their natural decay often aggravating secondary failures, while rendering tricky/complex the diagnostic phase of their state of preservation and/or the origin of certain failures.

Fig. 3. Aerial photo of the 'Tombs of the Kings' necropolis 2010. Direction North-South. Photo by © Thomas Sagory 2010, Archive of the Department of Antiquities of Cyprus.

Between 1977 and 1990 the Department of Antiquities of Cyprus undertook systematic cleaning and excavation (under the form of trenches since the tombs were already looted and/or opened in the past) of part of the site (Short essays on the cleaning/excavation seasons held by the Department of Antiquities of Cyprus are to be found in the *Annual Reports of the Director/of the Department of Antiquities* uninterruptedly for the years 1977 until 1992, as well as in the *Bulletin de Correspondence Hellénique* for the corresponding years, reproducing more or less the same information).

The funerary constructions preserved up to date have been declared Ancient Monuments by the Department of Antiquities and the archaeological site has been included in the UNESCO list of World Heritage Monuments since 1980. However, apart from sporadic publications, individual thematic articles and short reports (Cesnola, 1877: 223–234; Jeffery, 1915: 167–169; Megaw, 1952: 17), while short essays on the cleaning/excavation seasons held by the Department of Antiquities of Cyprus are to be found uninterruptedly for the years 1977 until 1992 in (Karageorghis, 1978a; Karageorghis, 1978b; Hadjisavva, 1982; Hadjisavvas, 1985a: 343; Hadjisavvas, 1985b: 262; Hadjisavvas, 1988: 236; Młynarczyk, 1990: 197–200; Papageorghiou, 1990) not a complete study and publication has been hitherto accomplished in relation to this unique royal cemetery.

3.2. The "Tombs of the Kings" necropolis – tomb 4

One of the most impressive and unique tombs within the ancient necropolis is tomb no 4 (T.4) (Hadjisavva, 1982: 8–9) (Fig. 4). The access to the tomb is achieve through a stepped *dromos* consisting of a flight of 13 steps (today covered by a wooden staircase), forming a right

Fig. 4. T4 'Tombs of the Kings', Paphos.

angle leading down to the *atrium*. What is seen today is a rock-cut underground tomb of the peristyle type around a central *atrium* yard utterly hewn out of the bedrock. The uniqueness of T.4 lies among other in the fact that the portico is supported both by columns (north, south and east side) and square pillars (west side), reentering thus in the architectural type of the composite peristyle atrium tombs hitherto a singular example on the island (Lysandrou, 2014). The colonnade supports a *Doric* style entablature with alternating *metopes* and *triglyphs* in relief. Almost opposite the entrance of the tomb and in the center of the east portico one faces the one and only burial chamber of the tomb. Besides the intrinsic historic and aesthetic values to be traced in the monumental tomb under consideration, an added reason for its study in terms of risk assessment embeds to the fact that is one of the best preserved atrium tombs in Cyprus, both in terms of architectural integrity (as a structure) and architectural decoration (entablature etc.) a fact that implies that its thorough study will provide archaeologists with valuable information for understanding the less well-preserved atrium tombs on the island. Further to that and in means of understanding its structural stability alongside to the potential lurking hazards due to its sensible geographical location, considering further the fact that the tomb belongs to one among the top visited archaeological sites of the island, the protection of this monument is among the priorities of the local authorities responsible for the preservation of cultural heritage on the island.

The tomb has been directly linked to the Hellenistic funerary complexes of the Alexandrian Mustapha Pasha (Mustapha Kamel) cemetery and specifically with Tomb I (Fedak, 1990: 131; Guimier-Sorbets and Michaelides, 2009: 219; Venit, 2002), while great similarities are to be found to some atrium tombs in Cyrene (Stucchi, 1975: 149–160).

4. Observed damage and structural stability

4.1. Observed damage

The instrumental mapping, the descriptive drawings and in situ observations were used to identify sources of weakness and assess the existing structural condition of the tomb under examination with regard to its stability. At this stage the assessment was based on expert judgment and the conclusions drawn aided the construction of a mathematical simulation model capable of predicting the monument's behavior to future seismic events.

The tomb is located at a depth of approximately 3 m underground. The opening of the tomb is supported at its four sides by rock-masses, which can be regarded as infinite in thickness at the two sides (south and east) and having finite thickness at the remaining two sides. This irregularity in plan is expected to affect the inflicted seismic damage on the tomb walls. The two unrestrained to movement sides of the tomb are its north and west sides as shown in Fig. 5. They are regarded as unrestrained since a finite width of the wall provides the stiffness to resist the horizontal force of the earthquake in that direction whereas the other two sides are embedded in large volumes of rock-mass (at least of few meters width of rock mass). It is obvious that regarding its vulnerability, the difference in stiffness will lead to a corresponding difference in seismic force i.e. the unrestrained sides and the north-west corner will attract more seismic energy during an earthquake due to its release in movement as compared to the much stiffer (infinite stiffness) opposite sides of the tomb. This first main observation of an inherent irregularity in plan provoked the investigation of the existing damage pattern on the walls in light of the assumption of the unrestrained movement at the north side. Careful investigation of the cracking on the walls showed excessive vertical and diagonal cracks on the north wall some of which are mirrored on the south one. The existence of diagonal cracks directed towards both ends of the walls and concentrated near corners is an evidence of reversal of load during an earthquake. These cracks extend at the whole height of the wall especially at the corners of the walls in both diagonal directions (towards the west and east sides). Some of the cracks on the north wall mirror on the south one (Fig. 6a), which leads to the conclusion that seismic force was the hazard causing the deformation of the ground in this direction (north-south). The latter observation in particular indicates the possible existence of a seismic fault under the tomb moving (thrusting) in the north-south direction causing deformation of the rock-mass in that direction. Thus cracking of the rock-mass is expected to extend along the whole length of the quarry. All the above mentioned observations need to be verified through a detailed geological study. As far as the width of the cracks is concerned cracking on the north wall appears to extend in depth through the wall's width. The same appears to be the case for the west wall and also severe cracking is concentrated close to the north-west corner. Thus it is obvious from the observations that the north-west part of the tomb due to its freedom in movement in both the horizontal directions has been damaged extensively from previous seismicity, which led to the disintegration of the rock mass due to the through cracks (through the whole width of the wall). Therefore the most vulnerable part of the tomb's structure to seismic forces and movements is the north-west one and this is the one selected for the analytical investigation later on.

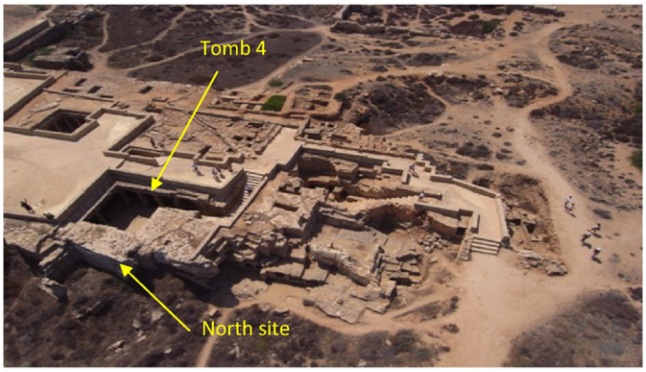

Fig. 5. Aerial photo of T4.
Photo by Thomas Sagory 2010, Archive of the Department of Antiquities of Cyprus.

Further to the determination of the cracking pattern on the walls, the in situ survey concluded that the rock mass has suffered severe deterioration of the surface wall material due to weathering and drainage problems. The deterioration in the material composition loosens its cohesion and amplifies the crack width. Also in some areas of the wall loss of material is evident leading to the creation of large voids (Fig. 6b) that aid the penetration of moisture and other micro substances causing a rapid deterioration.

5. Response to earthquake loading

5.1. Finite element modelling

In order to numerically examine the seismic behavior of the tomb T4, a 3D Finite Element (FE) model was developed in Abaqus/CAE (Fig. 7) and was subjected to non-linear dynamic and static analyses.

The part of the tomb hereby examined consists of orthogonally connected stone walls approximately 1.50 m thick and 3 m high. Above the walls 0.40 m thick and 1.80 m wide stone slabs were carved on the rock material. The edges of the slabs are supported by stone columns of rectangular and circular cross-sections. The widths and diameters of the columns are 0.40 m and 0.35 m, respectively. The distance between consecutive vertical supports is approximately 1.60 m. Only four of the six original columns survive nowadays. Moreover, the stone walls and slabs exhibit cracking and extensive weathering.

For the purpose of the numerical study, the cracks detected at the sections under study were considered to extend throughout the thickness of the rock material dividing the structure into a series of individual blocks. This is regarded as a valid assumption based on the in situ

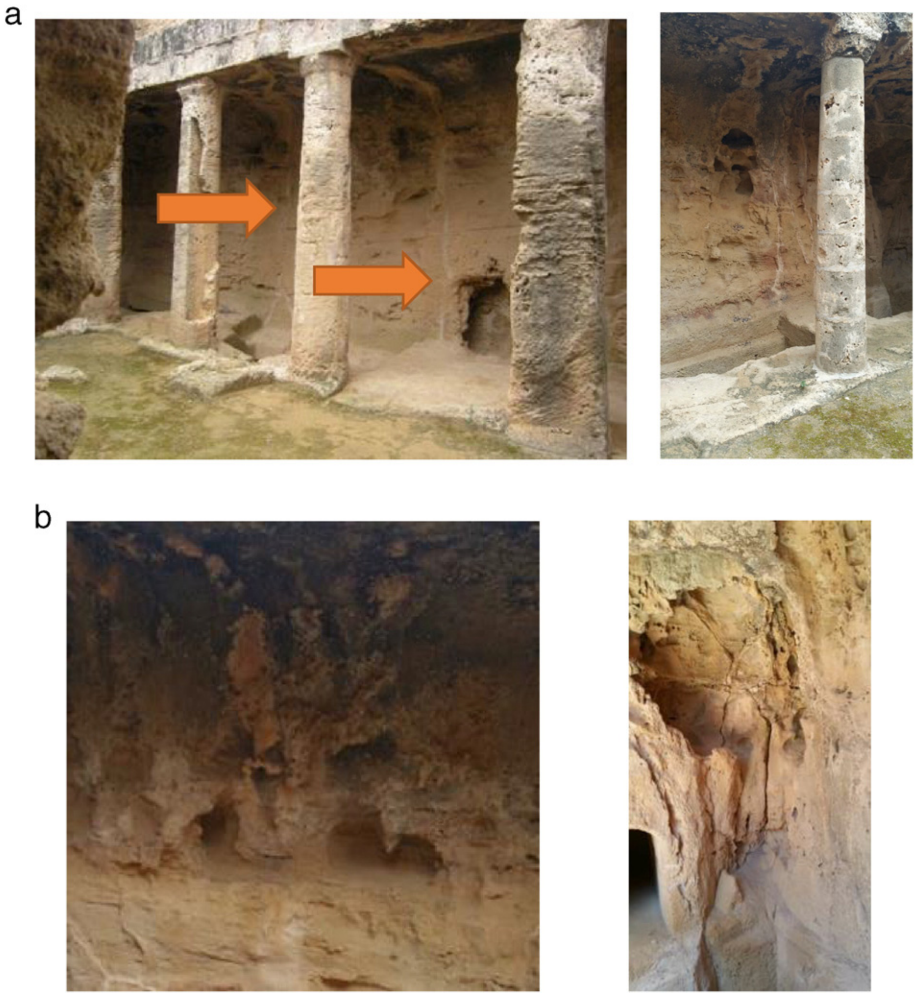

Fig. 6. a. Cracks on north and south walls located along the same north south trajectory. b. Material loss and surface deterioration due to rock weathering.

observations. Even if there is a small connection between the individual blocks through rock mass this will be cracked and eliminated at the beginning of any severe shaking. In the absence of adequate geological data, it was assumed that cracking has affected only the tomb structure and does not extend to the underlying bed-rock. The tomb was therefore modelled as a series of interacting stone blocks attached to a 3 m high homogeneous bed-rock layer.

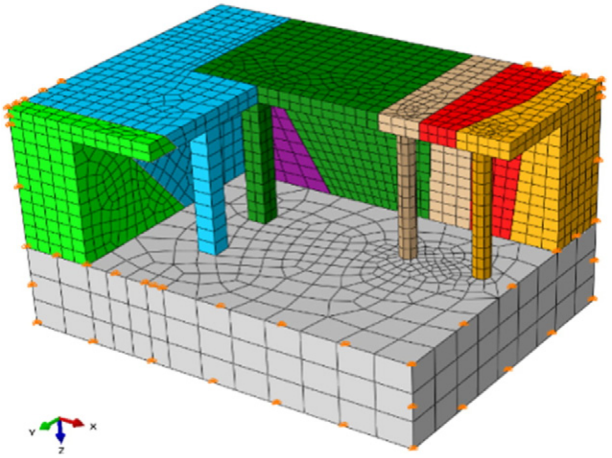

Fig. 7. 3D FE model developed for examining the seismic behavior of the T4 tomb. Interacting stone blocks separated by cracks are shown in different colors.

The rock material was simulated using a damaged plasticity constitutive model (Lee and Fenves, 1988; Lubliner et al., 1989). This model uses concepts of isotropic tensile and compressive plasticity to represent the inelastic behavior of quasi-brittle materials. The parameters required for the formulation of the constitutive law were based on experimental data obtained from compression and tensile splitting tests on stones originating from the same geological formation. The results of the test are not published yet but are available at the Strength of Materials laboratory of the University of Cyprus. Density was defined as $\rho = 1550\ \mathrm{kg/m^3}$. Young's modulus was set as $E = 1800$ MPa and Poisson's ratio was set as $v = 0.20$. Response to compression was defined using a parabolic stress-strain relation. A value of $f_c = 1.80$ MPa was specified for the rock's compressive strength, which is in line with similar results from rock testing discussed in Chrysostomou et al. (2013b). In tension, the medium's response was considered to be elastic up to the maximum allowable stress. Linear softening was assumed

Table 1
Input parameters used for the simulation of the rock material.

Property	Value
Friction coefficient among interacting rock blocks	0.6
Density	1550 kg/m^3
Young's modulus	1.8 GPa
Poisson's ratio	0.20
Compressive strength	1.8 MPa
Tensile strength	0.4 MPa
Tensile fracture energy	5 N/m

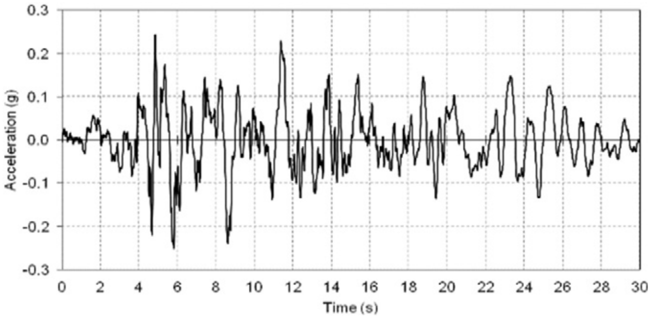

Fig. 8. Accelerogram of the Hercegnovi earthquake used in the dynamic analysis of the T4 tomb.

after cracking. Uniaxial tensile strength was set as $f_t = 0.40$ MPa. The tensile fracture energy controlling the post-cracking loss of strength was defined as $G_f = 5$ N/m. To account for the effects of material degradation due to cracking, the values assigned to the Young's modulus and the compressive and tensile strengths were assumed equal to 30% of the corresponding average experimental results based on code guidelines for the reduction in the strength of cracked concrete (1/3 of uncracked strength value). The rock's dilation angle was set as $\psi = 15°$, while the flow potential eccentricity was set as $e = 0.1$ (Simulia Corp., 2009). The ratio between the initial equibiaxial compressive yield stress and the initial uniaxial compressive yield stress was defined as $\sigma_{b0}/\sigma_{c0} = 1.16$ (Simulia Corp., 2009). Parameter K_c that relates the second stress invariant on the tensile meridian to the equivalent invariant on the compressive meridian was defined as $K_c = 2/3$ (Simulia Corp., 2009). The main input parameters used for the simulation of the rock mass are given in Table 1.

Interaction among the adjacent surfaces of the different stone blocks in the normal direction was modelled using "hard" contact pressure-overclosure relationships that allowed for the transfer of any stress under compression but enforced separation under tension. In the tangential direction, a finite-sliding formulation based on the Coulomb theory was adopted assuming a friction coefficient of $\mu = 0.6$ (Barton, 2013). Tie constrains were defined between the bases of the stone blocks and the underlying bed-rock layer.

All parts of the model were discretized into 8-noded brick elements with reduced integration and hourglass control (C3D8R). In the case of the bed-rock layer the approximate global size of the elements' sides was set as 0.75 m. A more dense mesh composed of elements with an approximate side length of 0.25 m was used for the tomb structure's stone blocks.

Translational constraints along the x, y and z axes were imposed along the perimeter and the base of the bed-rock layer. Displacements in the x, y and z directions were also constrained at the two edges of the structure which are connected to the rock mass of the surrounding hill.

5.2. Numerical analysis and results

Response to earthquake loading was initially examined by performing a non-linear time-history analysis on the model representing the interacting stone blocks separated by cracks. The dynamic simulation was completed in two successive steps taking into account geometric non-linearity effects. At the first step, the structure was analyzed under dead loads using a general static solution procedure. Then, the seismic load was imposed adopting a dynamic implicit procedure with direct integration. Upon the transition from the static to the dynamic step, all translational constraints along the y axis were removed and a ground acceleration acting in the same direction was applied to the nodes at the base of the bed-rock layer. The amplitude of the seismic acceleration was defined in accordance with the accelerogram recorded during the Hercegnovi earthquake (Fig. 8) adapted to Eurocode 8 (CEN, 2004b) response spectrum. This recorded was regarded in the literature (Chrysostomou et al., 2013a; 2014) as representative of expected large seismic events with more than one peak and was adopted due to the lack of local recordings of such events. The duration of the selected seismic record was scaled to 30 s. The Peak Ground Acceleration (PGA) was set as 0.25 g which is the design value prescribed in the Cyprus National Annex to Eurocode 8 (CEN, 2004b) for the Paphos region. Scaling to a higher peak ground acceleration value for analysis purposes was avoided in this paper since scaling techniques need to be examined closely in order to arrive at realistic input motions and most importantly because the non-linear properties of the rock material on site need to be verified through local geophysical studies in order to simulate the response accurately. Subsequent research on the same case study tomb is expected to examine the above in detail and apply the proposed methodology to obtain results for higher earthquake excitations. The computed distribution of maximum principal stresses at the various stone blocks of the tomb is shown in Fig. 9. As expected, significant concentrations of tensile stresses occur at the upper parts of the stone blocks which are not supported by columns. Furthermore, stress concentration is noted at the interface between the two stone blocks of the tomb's south side. This is due to the fact that the relative displacement of the two stone blocks during the earthquake results to collisions which generate relatively high stresses. The magnitudes of the tensile stresses attain their highest value at 5.82 s, when the peak ground acceleration is imposed. The FE model predicts that a maximum tensile stress of 0.304 MPa will develop during the seismic scenario examined. Although, this is lower than the 0.40 MPa tensile strength (capacity in tension) assumed for the rock material, some concerns regarding the development of cracks at the unsupported horizontal members of the blocks are raised due to the observed stress localization. Therefore, for the particular earthquake scenario, the various parts

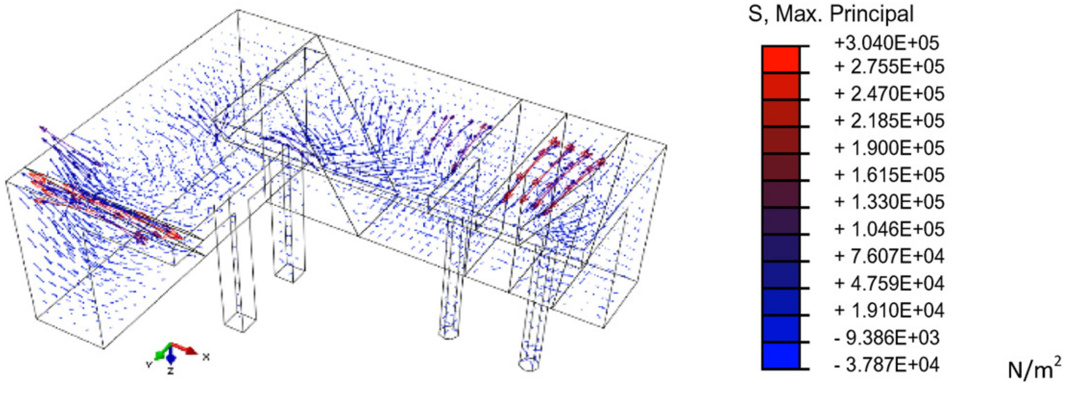

Fig. 9. Tensor diagram showing the computed distribution of the maximum principal stresses when the peak ground acceleration is imposed.

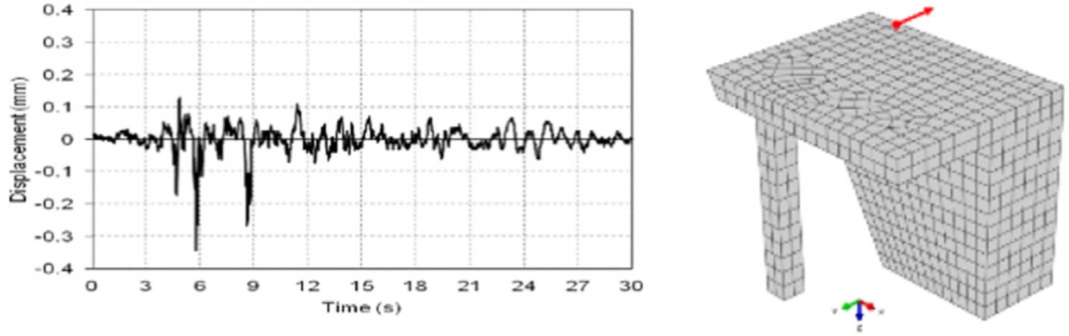

Fig. 10. Time history of the relative displacement measured during the dynamic analysis at the upper section of the west side's central stone block.

of the structure between the existing cracking patterns are expected to remain elastic and not to undergo severe damage or crushing. It should be noted though that the small difference between the tensile stress developed and the capacity of the rock in tension may indicate the initiation of newly developed cracks. From the results of the analysis, it is obvious that higher stresses are formed at the base of the stone blocks and thus their detachment from the foundation may take place leading to rocking behavior.

Fig. 10 presents the variation of the relative out-of-plane displacement measured at the upper section of the west side's central stone block over time. Relative displacements were estimated by subtracting the translation of the bed-rock layer's basal nodes along *y* axis from the corresponding total lateral displacement of the control nodal point at the top. Since the stone block structures examined are quite stiff and have rather limited height, the applied dynamic excitation results to comparatively small lateral displacements. The maximum relative displacement in the *y* direction is 0.35 mm which accounts for an out-of-plane drift of 0.01%. Such small drifts are not expected to cause instability and overturning of the stone blocks. However, at higher magnitudes of seismic acceleration increased relative movement is expected to lead to the development of local kinematic mechanisms.

In addition to dynamic analysis, non-linear static analysis under horizontal loading was conducted in order to obtain information regarding the collapse mechanism and the deformation capacity of the west side's central block. The seismic behavior of this particular part was considered critical because at this area the structure is not restrained against out-of-plane movements. The corresponding section of the FE model was hence isolated and examined individually. A two-step analysis was again performed in the general static solution procedure. After the application of the dead load, a mass-proportional distribution of progressively increasing lateral forces was imposed along the *y* direction to all nodes of the section under study. There are critical limitations associated with the assumption used for a single mode response, but this analysis was conducted solely for the purpose of obtaining an order of magnitude approximation of the displacement capacity of the structure. The outcomes of the pushover analysis are given in Figs. 11 and 12. The predicted distribution of plastic strains (Fig. 11) indicates that failure of the particular block examined will occur due to tensile cracking at the base of the stone wall and detachment of the supporting column from the stone slab. The maximum load resistance of the block is in the region of 240 kN (Fig. 12) and accounts for approximately 70% of its self-weight. Loss of the load-bearing capacity occurs at an out-of-plane displacement of 1.5 mm (i.e. at a drift of 0.05%). Despite the abrupt drop in lateral strength noted after the yielding point, a significant force is still required to cause overturning of the block due to its considerable weight. The computed force-displacement response verifies that, provided the stone block is firmly attached to a homogenous bed-rock layer, collapse is not expected to occur at the design peak ground acceleration.

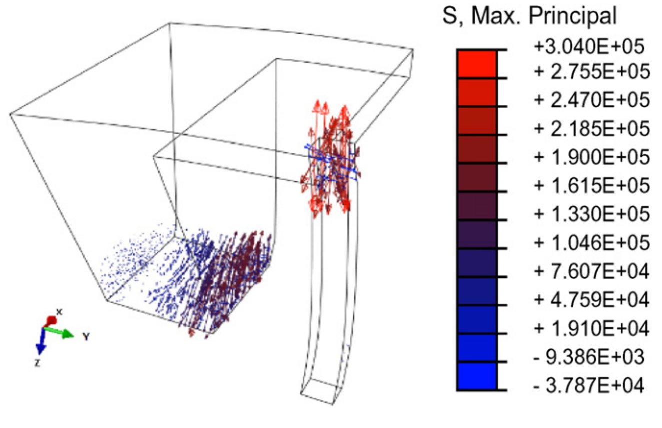

Fig. 11. Tensor diagram of computed plastic strains obtained from the pushover analysis of the west side's central stone block.

It must be stressed out that the numerical results hereby presented have been based on a series of modelling assumptions which need to be examined through further in situ investigations. More specifically, a thorough geotechnical study should be carried out to determine the boundary conditions present at the physical structure, to estimate the depth at which the cracks extent within the mass of the stone blocks and to assess the condition of the rock and/or soil layers upon which the tomb is constructed. Particular attention should be given on examining whether any underground geological faults exist, because such discontinuities in the foundation material can affect both the static and seismic response of the structure.

6. Discussion

The aim of the paper was to investigate the correlation of existing damage patterns on underground tombs with the severity of historic seismic events based on local observations and expert judgment and predict through sophisticated finite element (F.E.) analysis the response of the existing cracked structural system of the tomb during future severe earthquake events. The methodology used was based on both in situ measurements and observations at the first stage and detailed F.E. analysis of the most vulnerable part of the tomb at the second stage. The observations were analyzed based on expert judgment and were used to calibrate the simulation model for the F.E. analysis. Of equal importance to the calibration of the model was the use of experimental data for the mechanical properties of the rock material. The simulation of the seismic hazard was conducted through the use of a real record representative of large events with more than on peak in their history that have yet to be recorded at the local environment, which was amplified up to the level of the anticipated hazard in the area. Such earthquake records are expected to inflict more damage to the structure than single peak records of the same magnitude. The record was applied in the north-south direction as anticipated by the local tectonic environment. The results from the F.E. analysis showed that for a PGA = 0.25 g, which is the design value for the Paphos area, severe cracking may takes place at the base of the isolated blocks especially at the blocks on the

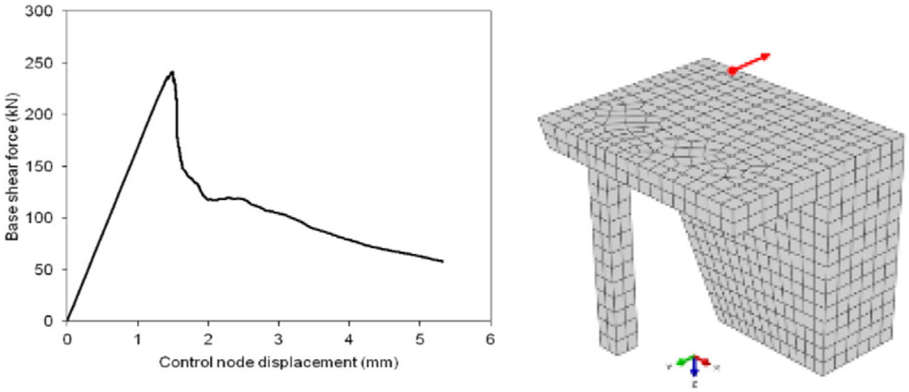

Fig. 12. Pushover curve obtained from the non-linear static analysis of the west side's central stone block.

north wall. This cracking leads to loss of the connection between the block and its base (foundation) and thus rocking of the block is expected to take place. The last part of the analysis used static non-linear analysis to push the isolated block and examine its overturning tendency. It is clear from the results that during the selected earthquake, the displacement at the top of the rocking block will reach a value close to the overturning limit but a severe force is required to actually cause overturning. It should be noted though that during such an excitation, the rocking of the blocks and their disintegration through cracking would lead to the creation of small loose rock masses that might fall due to gravity.

The judgment from the observations and the results from the analysis are based on a number of credible assumptions that need to be verified through local geological studies using a number of techniques to obtain information about the material composition, the length and direction of the cracks in the rock-mass and the direction of the local seismic faults.

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