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Finite element assessment FEA of polymer anti-seismic piling techniques for protection of the underground culture heritage

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Abstract

Alexandria is one of the Mediterranean UNESCO World Heritage sites at risk from coastal flooding and Earthquakes. Nowadays, the safety of archaeological underground structures draws more and more attention. After many catastrophic events, the study of anti-seismic for underground structures has also become an important problem to be solved. Based on the typical underground structure seismic damage phenomenon, this paper summarizes the seismic characteristics, research methods and design methods of underground structures to offer a guide for engineers and conservators, where the polymer anti-seismic piling to protect the underground monumental structures against strong earthquakes is presented and validated in numerical analysis. In this paper, typical damages of archaeological underground structures are firstly presented, followed by the FEM analysis using the PLAXIS 2D code for the seismic response of Catacombs of Kom El-Shoqafa in Alexandria, Egypt with and without the anti-seismic polymer pilling techniques. Results of this work underline the high potential of these low-cost anti seismic technique, confirming the possibility of achieving a significant improvement of the seismic performance of archaeological underground structures by using the low-cost and easy to manufacture it.

Keywords: Seismic response, Anti-Seismic piling technique, Catacombs, Underground structures, Earthquake damage

Introduction

In the existing research results, the seismic performance and protection of archaeological underground structures is rarely researched. For the practical engineering of underground structures excavated in soft rock/ hard soil, there is no reference seismic experiment, reliable quasi-static calculation method, or seismic parameter-calculation method yet available. In order to obtain a reliable estimation of the seismic risk, it is desirable to perform full dynamical analyses that describe the effective transmission and dissipation of the energy coming from the ground motion into the underground structure. Luckily, when performing complete dynamical analyses it is often effective to adopt a two-dimensional model rather than a three-dimensional, even if the definition of a simpler model often requires a process of tuning in order to approximate as well as possible the features of the specific kinematics that is of interest. The approach followed was to create two-dimensional linear finite element models in order to find the most critical part of the underground structure of Catacombs of Kom El-Shoqafa.

Numerical modelling by means of FEM is often necessary to perform static and dynamic analyses that would be useful to detect causes of damage and to prepare efficient rehabilitation plans for underground and above ground historic structures.

Numerical modelling of monumental underground structures has been rarely presented and discussed in the literature, and the implementation of efficient and ready

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material models including nonlocal damage of these structures for application in commercial codes remains under development. Among the main problems observed when modelling monumental underground structures is their complex and irregular geometries, which are difficult to define, unknown building materials, mechanical properties and appropriate material models.

Based on the above problems, herein, a modified FEM model was proposed to verify the efficiency of Polymer Anti-Seismic Piling technique for Protection of the underground Monumental Structures against Strong Earthquakes. The modified FEM model offers good accuracy, a simple model, rapid modeling, and easy convergence. It provides engineering designers with a seismic design and analysis method for underground structures with convenient application and high precision. Therefore, the results obtained in this study can be considered useful to designers who are required to address the anti-seismic design of archaeological underground structures.

Damage of rock pillars and columns under earthquakes and in accidents due to fire and blast loading can lead to catastrophic failure of the entire underground structure. Columns are the main load bearing elements in the structural system and cannot undergo severe damages in order for the buildings to remain functional [1]. Earthquake damage to underground structures is thus mitigated, as the confining pressure exerted by the surrounding soil can improve the level of structural safety in the event of an earthquake. Hence, seismic calculations and seismic measures are not applied to the underground structures associated with subway systems. However, earthquake disasters in recent decades have affected thinking around this traditional concept, especially the Dahshuor earthquake 1992 which damaged the archaeological underground structures in Saqqara and Giza pyramids plateau GPP, indicating the possibility of subway underground structural damage and secondary disasters remains significant [2].

Seismic design has not been taken into consideration in the design and construction of most of the archaeological underground structures that have been built in ancient Egypt and roman times. Many underground structures were subject to different degrees of damage, particularly some Catacombs in Alexandria and Saqqara. This had aroused the attention of scholars and research Institutions from all over the world to such issues.

Historic earthquakes like 1303 AD and in recent years, several strong earthquakes in Egypt, such as the Dahshuor earthquake in 1992 and the Aqqaba Earthquake in 1995, have caused great damages to underground structures.

Some researchers [3], suggest that use of SMA restrainers and the rubber bumper together at the joints could be the most effective in mitigating the damaging impact as well as the large separation between the adjacent structures.

Results of RHAs showed that Recycled Rubber Fiber Reinforced Bearings (RR-FRBs) can be an excellent technology for protecting buildings from strong earthquakes. They are capable of reducing the base shear, the interstory-drifts, and the floor accelerations. Results of RHAs showed the good performance of these bearings in terms of collapse prevention and reduction of damage to structural and nonstructural elements of a building after major earthquakes, [4].

Geosynthetics reinforced interposed layers can protect structures on deep foundations against strike-slip fault rupture, and the recent studies referred that the bottom geotextile layer sustained higher tensile stresses induced by fault rupture and differential settlement between pile and soil, [5].

Earthquake risk assessment of Alexandria

Throughout historical and recent times, Alexandria has suffered great damage due to earthquakes from both near- and far-field sources. Sometimes, the sources of such damages are not well known. During the twentieth century, the city was shaken by several earthquakes generated from inland dislocations (e.g., 29 Apr. 1974, 12 Oct. 1992, and 28 Dec. 1999) and the African continental margin (e.g., 12 Sept. 1955 and 28 May 1998).

Alexandria is the Egypt's second largest city and largest seaport. It is located along the coast of the Mediterranean Sea in the north central part of the country. The city is built on a narrow and partially elevated coastal ridge facing the sea and has historically expanded in a linear fashion with very high densities along its waterfront. Greater Alexandria currently spans over 230,000 ha with its 2006 population estimated at 4.1 millions by the national census. The current boundaries of the urban agglomeration of Alexandria consist of seven districts, Al-Montazah, Shark (East), Wasat (Middle), Gharb (West), Al-Gomrok, Al-Amriya, and Borg Al-Arab.

Alexandria was also known for the Pharos (Lighthouse of Alexandria) one of the Seven Wonders of the Ancient World. The lighthouse continues to be mentioned in Roman writings and traveler accounts. An earthquake shook Alexandria in 956AD but caused little damage to the lighthouse. It was later in 1303 and in 1323 that two stronger earthquakes considerably damaged the structure. Very little of the ancient city has survived. Most of the royal and civic quarters sank beneath the sea, due to the subsidence caused by earthquakes.

The city is exposed to different kinds of hazards including the following: marine submersion, coastal erosion, earthquakes, and flooding. The earthquake, as a natural hazard, is one of the great threats to human beings. As the occurrence of an earthquake can be neither controlled nor even predicted exactly, what we can do are designing and constructing facilities with enough strength to withstand the effects of earthquakes. However, stronger facilities require additional costs, and large earthquakes are very seldom to occur. We are required to decide an adequate strength level to be given to facilities. In this context, the risk-based design or risk management procedures may be useful, where the earthquake risk is balanced against the costs of the facility [6].

It should be stated that geophysical studies (e.g., microtremor) that can be applied without damaging the existing structure and geophysical methods (e.g., electrical resistivity, seismic refraction) to be used to determine the groundwater level and pressure should also be used and the studies conducted in Egypt should be given as recent references, [7–9].

Typical earthquake fdamages of archaeological underground structures (catacombs of Kom El-Shoqafa)

Alexandria city is located approximately three plate boundaries that interact with each other generating a complex system of major and local faults close to Alexandria offshore. These faults are associated with small to moderate earthquakes. The focal mechanisms and the waveforms of the offshore events reflect the complexity of this tectonic zone. Because of this complexity, it was very difficult to represent the moderate earthquake of 1998 by one source and fit both P and SH waves.

Some of the historical earthquakes information approximately Alexandria is probably missing. As the underwater archeological remains in Abou kir bay strongly support, either local or remote earthquakes destroyed the city.

Offshore events have strong and short duration of shaking at Alexandria city. The energies of the main peaks are of low frequencies (less that 4 Hz) that have the maximum response spectra from the site. While those in remote areas have a very long duration of shaking, however their peaks are relatively weak. These peaks are also of a very low frequency, which is coherent with the response spectra.

In history of Alexandria, countless underground structures have been damaged in different degrees during the activities of earthquake, which caused the most severe damage to underground structure in Alexandria. Table 1 summarizes the seismicity and strong earthquakes struck Alexandria through its history. Many columns collapsed. Roof collapses and large cracks appeared on the sidewalks, causing the large-scale settlement above the underground structures.

Table 1 Historic Seismicity and strong earthquakes struck Alexandria through its history, Egypt

Date	Location of epicenter	Epicentral intensity	Alexandria (locational) intensity	Remarks
2200 BC	**Tall Basata**	**VI**	–	**M = 5.8. Deep fissures and soil cracks in Tall Basata**
27 BC	**Theban area**	**VI**	–	**Destruction of most temples in Theban**
24–20 BC	**Alex offshore**		–	**Strong sea waves**
320	**Alex offshore**	**VII**	**VII**	**Many houses destructed**
796	SE Mediterranean Sea	VI	–	Felt at different localities of Egypt, partial damage of Alex Light House
5/26/1111	East Cairo	VII	VII	Destruction of Rehachope Temple
8/8/1303	Fayum	VIII	VII	M = 6.5. Severe earthquake: many places in Cairo were destructed, affected the Nile Valley till Quoos
1326	**Alex offshore**	V	–	Light house was shocked, felt in many places
1687	**Alex offshore**	VI	VI	Alexandria was vibrating for 10 ~ 12 days
9/1754	Tanta	VIII	VII	Two-thirds of Cairo buildings damaged. 40,000 fatalities'
8/7/1847	Fayum	VIII	VI	3000 houses and 42 mosques destroyed. 85 fatalities
1870	**East of Mediterranean**	X	–	M = 7. Severe earthquake, felt in vast area 32° N, 30° E
1908	**Alex offshore**	–	–	Strongly felt earthquake
10/ 1/1920	29.4° N 31.0° E	VII	V-VI	M = 5.8
10/12/1992	29.89° N 31.22° E Dahshuor	VIII	VII	Ms = 5.8 HL, = 5.9
				Mo = 8xl017 N-m
				Depth 25 km
				445 dead and 6512 injured

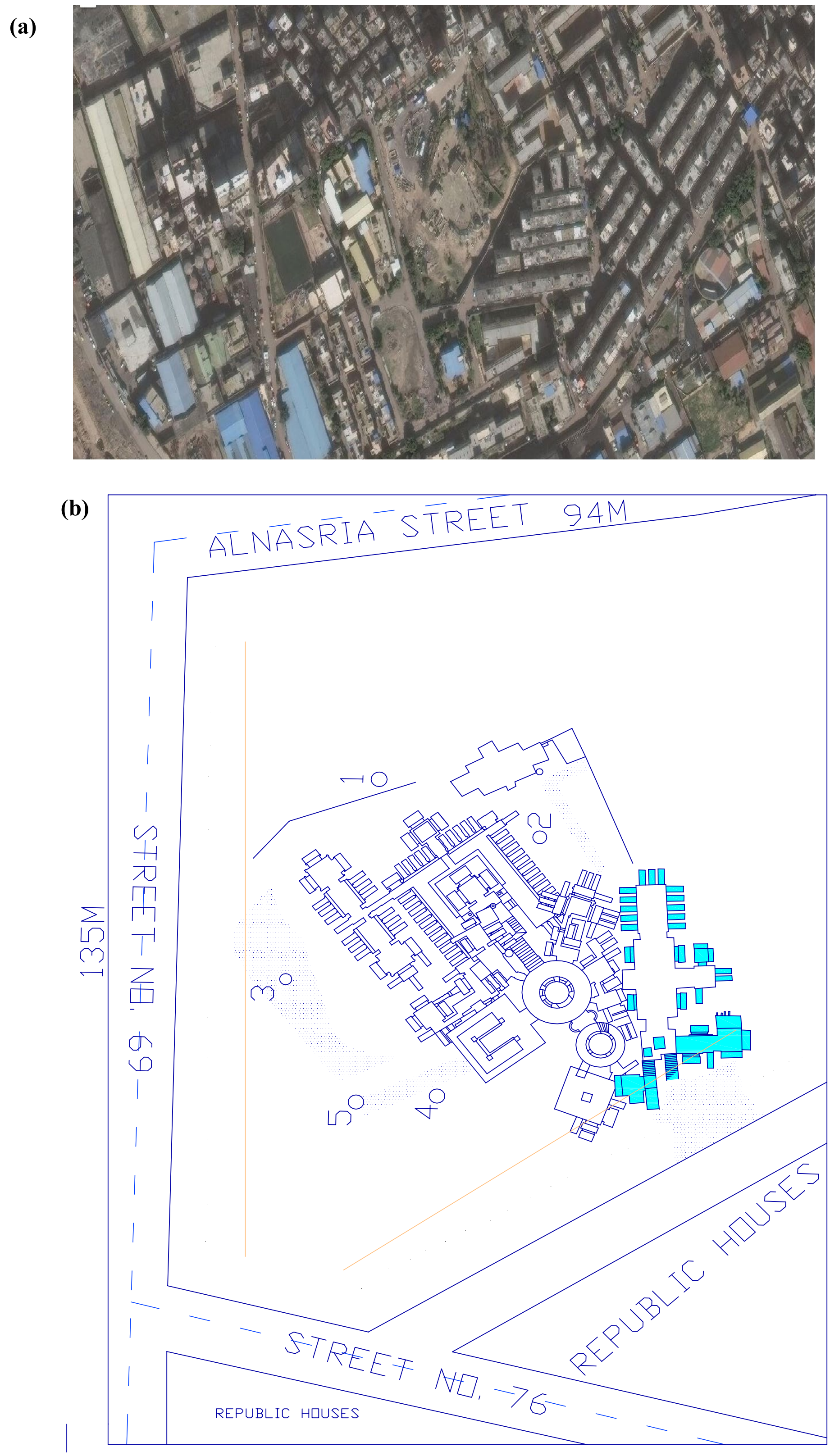

Fig. 1 **a** Descriptive satellite imagery with the general location of Catacombs of Kom El-Shoqafa. [Source: USGS powered by ESRI]. **b** Layout and location map of Catacombs of Kom El-Shoqafa

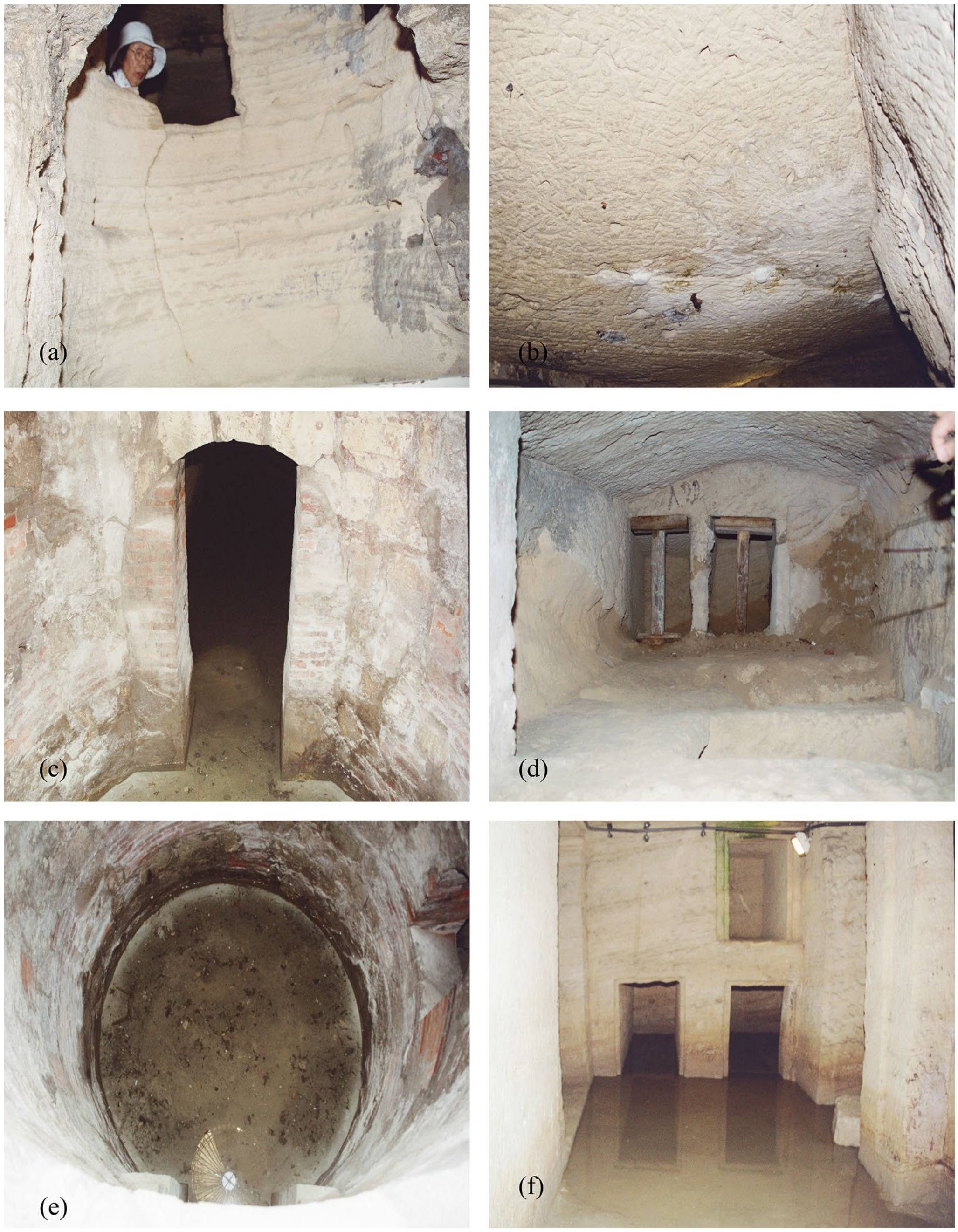

Fig. 2 **a**–**f** Catacombs of Kom El-Shoqafa. State of preservation

It showed cracks and spalls of the side walls and rock columns, damages of the entrances and exits, bulging and bending of the reinforcement, and displacement of the walls. The cracking of the floor and the collapse of the underground structures also occurred due to slope failure.

The site

The Catacombs of Kom El-Shoqafa lies in the district of Karmouz on the south-west of Alexandra, not far from the so-called Pompey,s pillar, on the south slope of the hill. The area was called Kom El-Shoqafa or a pile of shards. This catacomb lies at about 2–2.5 km from the seashore, and it is higher in topography than Amod El-Sawari area, Fig. 1a and b.

The structure

The Catacombs under study was most likely initially a private tomb and later converted to a public cemetery. It consists of three levels cut into the rock, a staircase, a rotunda, the triclinium or banquette hall, a vestibule, an antechamber and the burial chamber with three recesses in, where in each recess there is a sarcophagus.

The Catacombs also contains a large number of Luculi or grooves cut in the bedrock. As shown in Fig. 1b.

Material and structure pathology and causes

The Alexandria Catacombs show some clear indications of yielding and partial collapse at several locations, Weathering as indicated by in particular honeycomb, stone surface scaling, disintegration of construction material, intense rock meal damp surfaces in particular for semi-sheltered parts of the excavation, white salt efflorescence and yellowish brown iron staining can be noted at many parts.

The structural damage is represented by ceiling cracking, vertical cracks on the walls, stone surface decay and partial collapse of some parts of the ceilings and walls, rock exfoliation especially noted in the ceiling of the narrow corridors that are found at the deepest parts and mass wasting from its ceiling and walls of corridors.

During the site visit to this large underground monument, some evidences of problems of instability, especially near the entrances of the three floors, due to weathering and the structural discontinuities of the soft oolitic sandy limestone, which loses its strength, when saturated, were observed. It is also noted that fractures, spalling and slabbing occurred at the roofs and on the pillars (Fig. 2) are the indicators of yielding of rock mass in certain locations. It is clear that the underground openings are subjected to material decay due to weathering caused by environmental conditions and long-term loading. Nevertheless, the effect of temperature and humidity variations on the underground structures should be quite small since they do not show very large fluctuations of the temperature and humidity.

Deformations of underground openings in squeezing grounds may prolong for a considerable period. One of the reasons for time-dependent behaviour may be resulting from dissolving of binding minerals in rocks and the presence of great amount of free silica like sand grains. Nevertheless, the deformation due to swelling probably accounts for a small fraction of the total deformation. The second, which is probably the most significant one, is the degradation of deformability and strength characteristics of rocks with time. Many researchers proposed a method to predict the squeezing potential of rocks during excavations. However, this method could not cover the time-dependent behaviour of squeezing rocks. An extension of this method to time dependent domain of rocks to assess long-term performance of these openings is given. Due to the above-mentioned possible rock engineering problems based on the observations, investigation of the long-term performance of these openings can be considered as an important research topic.

The mechanical stability of Catacombs of Kom El-Shoqafa is not likely to be dominated by sliding on structural features, other factors such as excessively high rock stress; weathering and/or swelling rock and excessive groundwater pressure or flow become are important and can be evaluated by means of a classification of rock quality.

Table 2 Material properties of rock material and polymer piles

Material	Name	Rock construction	Polymer pile (PVA)	Unit
Parameter				
Type of behaviour	Type	Elastic	Elastic	
Normal stiffness	EA	2.270E+06	2.150E+04	kN/m
Flexural rigidity	EI	–	8867	kNm2/m
Equivalent thickness	D	–	2	m
Weight	W	18	5.40	kN/m/m
Poisson's ratio	v	0.28	0.00	–
Rayleigh α			0.00	
Rayleigh β			0.00	
Shear wave velocity	Vs	715	80	m/s

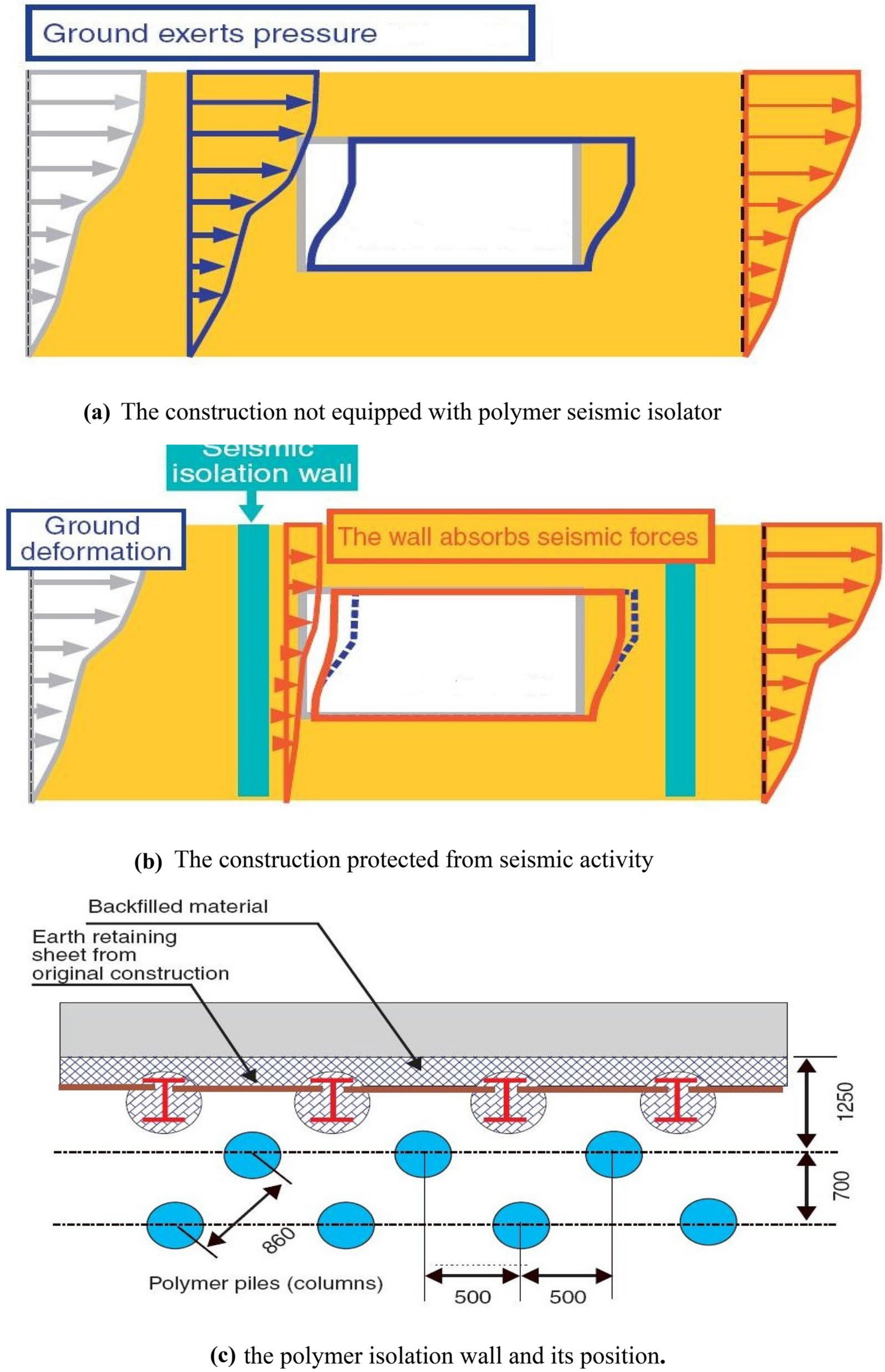

Fig. 3 **a**–**c** Polymer seismic isolation method (Conceptual diagram), [11]

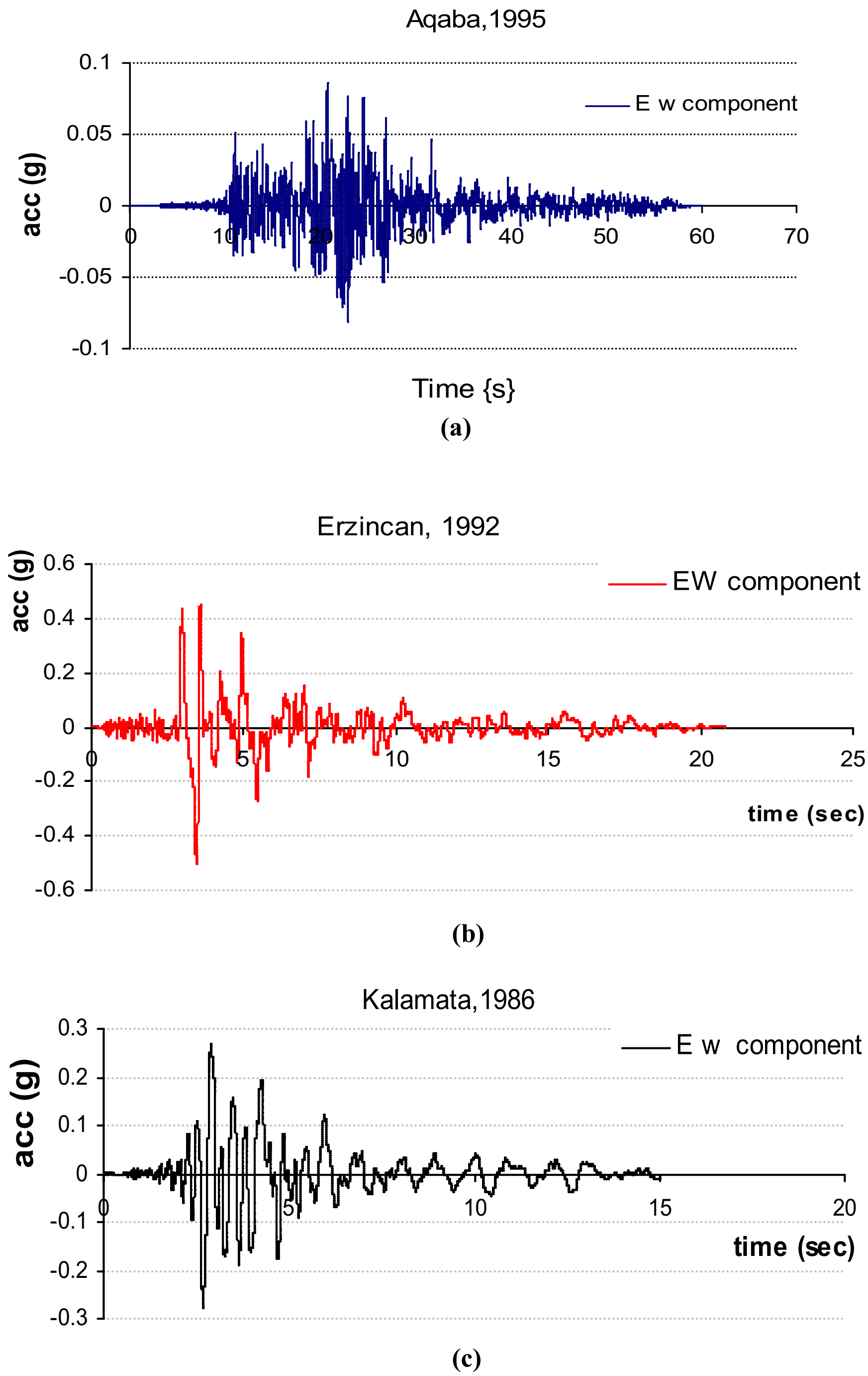

Fig. 4 Seismic excitations at the bedrock for the reference ground motions (acceleration-time history). **a** Aqaba, 1995; **b** Erzincan, 1992; and **c** Kalamata, 1986

(See figure on next page.)
Fig. 5 Deformed mesh and peak total displacement, the final step: **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. The PGA = 0.24 g. Initial models, Catacombs not equipped with polymer seismic isolator

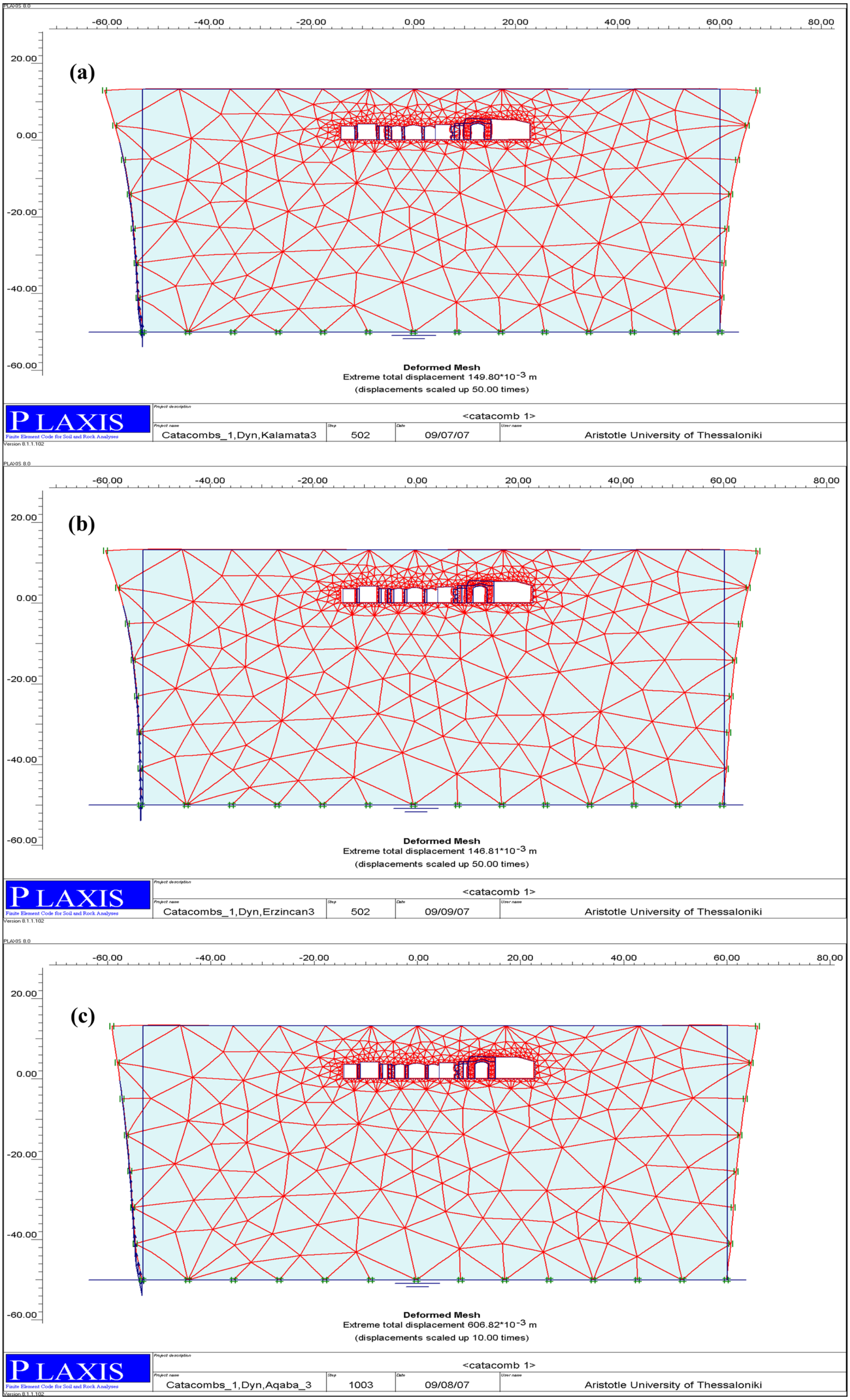

Fig. 5 (See legend on previous page.)

The majority of structural damages and instability have been caused from the combination of the following factors:

Progressive weakening of rock material due to intrinsic sensitivity to weathering factors especially salt weathering, wetting, and drying as noted from the field study and laboratory analysis. Generally associated with poor rock, but instability may also occur in isolated parts of otherwise sound rock. The rock salt content and salt type at these sites indicate how intensity salt weathering acting on such weak sedimentary rock, the main salt weathering mechanisms are: salt crystallization, salt hydration, thermal expansion, in addition to chemical effect of salts. The rate of weathering is 1.52 mm/year for areas close to seashore (Necropolis of Mustafa Kamil and El-Shatbi Necropolis), and 1.36 mm/year for those away from seashore (Catacombs of Kom EL-Shoqafa and Amod EL-Sawari or Pompey's Pillar archaeological area).

Excessively high rock stresses. Unusually weak rock conditions can also give rise to stress-induced instability.

Excessive underground water pressure or flow can occur in almost any rock mass, but it would normally reach serious proportions if associated with one of the other forms of instability mentioned above.

Earthquake damages "seismic loadings under repeated earthquake activity".

Permanent deformation of the rock mass under long-term loading.

Natural wear of material. Where the rock mass, which the catacombs are excavated in, is sandy oolitic limestone with high free silica content and high porosity and this rock characterized by very low mechanical strength.

The long construction history in the area. Rocks are very sensitive to pressure changes. Additional loads due to new residential development may induce the strain–stress redistribution in the rock.

Dynamic effects generated by human activities: Dynamic effects generated by human activity (technical seismicity-man-made tremors, blasting, vibrations from heavy traffic, induced seismicity) reach in some cases the intensity of natural earthquakes.

In conclusion, the present state of conservation of the great Catacombs of Kom El-Shoqafa, the best-known and most highly prized testimony of Alexandrine funerary architecture culture is now at the utmost limit of degradation as shown in Fig. 2.

Seismic response characteristics of monumental underground structures

The seismic behaviors of the underground structures in general are quite different from that of the upper structures. The characters of responses in both structures and their main differences are introduced as follows:

1. The deformation of underground structure is restrained by the surrounding soil, and the dynamic responses of the structures are not largely influenced by its free vibration characters, while that of the upper structures are dependent on its free vibration characters, particularly the influence of the low modes.
2. The presence of an underground structure has very little influence on the vibration of the surrounding base (when the ratio of the size of the underground structure to the seismic wavelength is small). However, the existence of the ground structure causes a great disturbance to the seismic oscillation of the free field.
3. The vibration form of underground structure is greatly influenced by the direction of seismic wave. The deformation and stress of each point of underground structure can change greatly even when the incident direction of seismic wave changes little. The vibration form of ground structure is affected relatively slight by the direction of seismic wave incidence.
4. There are obvious phase differences of the underground structure in earthquake. While the phase difference of the ground structure in the vibration is not obvious.
5. In general, the main strain of the underground structure in vibration is not obviously related to the magnitude of earthquake acceleration, but it is closely related to the strain or deformation of surrounding rock and soil medium under earthquake action. As for the upper structure, seismic acceleration is an important factor affecting the dynamic response of it.
6. For both underground structures and over-ground structures, the interactions between them and their foundations have an important influence on their dynamic responses, yet with different extent in various ways.

(See figure on next page.)

Fig. 6 Deformed mesh and peak total displacement, the final step: **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. The PGA = 0.24 g. Catacombs protected from seismic activity

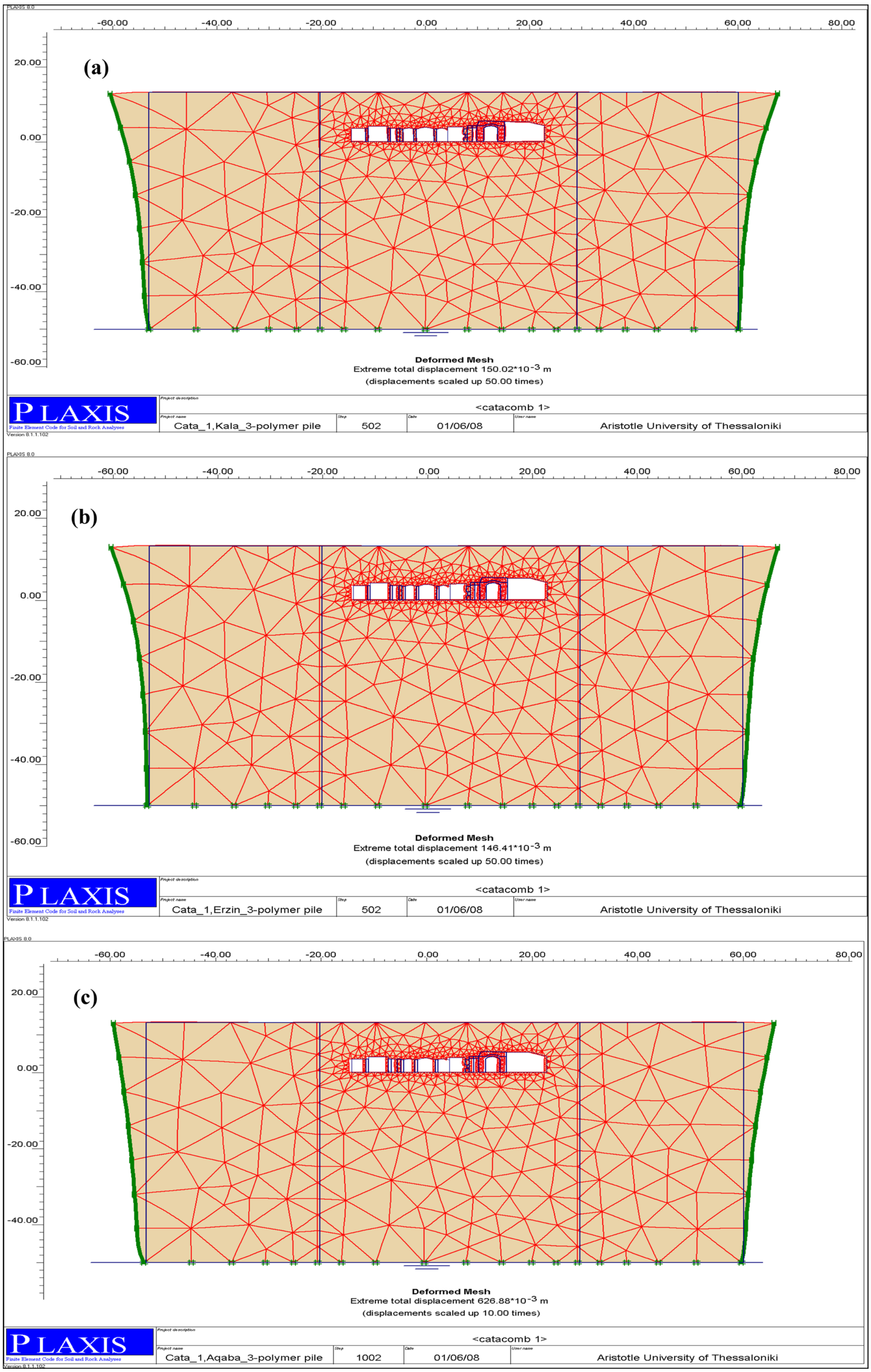

Fig. 6 (See legend on previous page.)

7. In general, for underground structures, the main contributing element to the reaction is the kinematic characteristics of the surrounding soil, and changes in structural shape generally have relatively little effect on the reaction [10].

Research method of seismic resistance of underground structures

The major means to study the seismic performance of underground structures are prototype observation, model experiment and numerical calculation:

Prototype observation

The prototype observation method refers to the actual observation of the dynamic response and seismic damage of underground structures under seismic action, thus revealing the seismic response characteristics of underground structures, the seismic performance and the mechanism of earthquake damage.

Model experiment

The model test method is usually used to study the response characteristics of underground structures through the shock test. It can be divided into artificial source experiment and shaking table experiment. It is the most direct method to study the structure seismic response and failure mechanism in laboratory.

Numerical calculation

In this method, the entire site is divided into numerical grids with corresponding boundary conditions, then seismic waves are input and dynamic response analysis is performed, then the deformations, stresses and strains in the soil and underground structures will be obtained.

In summary, there is no single means to fully realize the complete and true interpretation and simulation of the dynamic response of underground structures, the seismic performance analysis is developed based on all these three methods [10].

Simplified design method for seismic design of underground structures

In order to satisfy the development of underground engineering, simplified seismic analysis method of underground structures were proposed based on the previous researches.

Seismic coefficient method

Time dependent seismic forces were firstly equaled to static seismic load, and then static calculation models were used to analyze the internal force and deformation of the structure under seismic loading.

Free field deformation method

In this method, the free field deformation of the surrounding soil under seismic was directly applied to the structure as the structural deformation. Then the internal force of the structure was calculated, and the structure was designed.

Flexibility coefficient method

In practical engineering, the stiffness of underground structure and the stiffness of surrounding soil are often different.

Response displacement method

In this method, the underground structure was assumed as an elastic foundation beam, and the response of underground structure was obtained according to the method of statics.

Reaction acceleration method

In this method, only inertia force is considered, which depends on the mass distribution and acceleration of the system. As the mass distribution of the system is definite, it is only necessary to determine the acceleration distribution. Therefore, compared with the reaction displacement method, this method is simpler to use.

Pushover analysis method of underground structure

The method is to apply an increasing horizontal load to a structure with a certain height distribution structure until a predetermined target structural displacement to analyze the nonlinear response of the structures [10].

Polymer anti-seismic piling

An attempt has been made to employ the new developed polymer seismic isolation method, which has been employed successfully to retrofitting the Nakagawa underground station in Yokohama city [11], to protect the underground structures of Catacombs of Kom El-Shoqafa against strong earthquakes, more than PGA = 0.24 g. This method is suitable for the seismic protection of the underground monuments because the application of this method is completely non-destructive,

(See figure on next page.)

Fig. 7 Effective shear stresses σ/xy—time histories on the base of rock Pier _1 (at the right side of rotunda). **a** Kalamata RQ; **b** Erzincan; **c** Aqaba RQ. The PGA value = 0.24 g. Before and after the installation of polymer anti-seismic piling

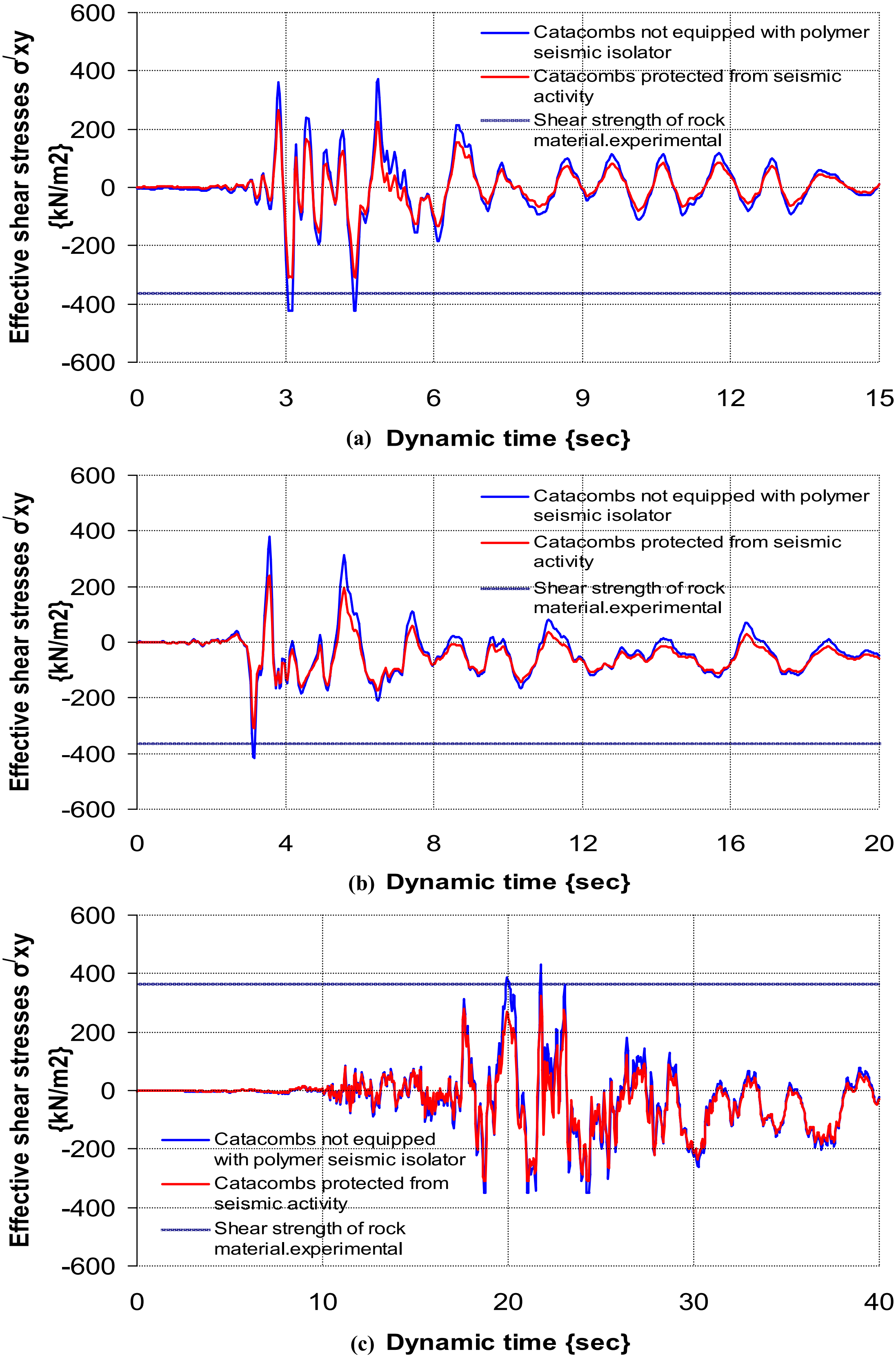

Fig. 7 (See legend on previous page.)

do not involve any change in the original materials of the monuments; in addition do not employ new materials or constructions to the monumental structures.

The newly developed 'polymer seismic isolation method' involves the construction of polymer walls on both sides of underground structure in order to reduce the seismic actions transmitted from the surrounding ground onto the structure. The stiffness of the polymer material should be about 1/10 to 1/100 that of the surrounding ground. Table 2 summarizes the material properties of rock material and polymer piles used in this numerical analysis. This method is not intended to prevent or control the seismic ground deformation itself, but to isolate structures from seismic forces transmitted from the surrounding ground. As shown in Fig. 3. The polymer seismic isolation method has the following advantages over conventional anti-seismic methods (such as the steel jacket method):

i. The polymer reduces the seismic force transmitted from the ground, thereby reducing relative deformation of the structure. A steel jacket, for example, would reinforce only one part of the structure, whereas the polymer reduces the cross-sectional force on all structural parts, improving the seismic performance of the structure.
ii. Use of a polymer with a stiffness of one-tenth of the shear wave velocity of the surrounding ground will, depending on certain conditions, reduce the shear force by up to half.
iii. The polymer is installed from above ground, near the underground structures, so the work can be done at any time. This shortens the retrofitting period, thereby reducing cost considerably.
iv. There is no need to drill holes in the existing structure, thereby it is completely non-destructive [11].

Nevertheless, the installation of these measures need free space around the underground monuments also to be sure that there are no underground monumental structures in the area of the application of the piles.

Finite element modelling and numerical analysis

The numerical model of the Catacomb of Kom El-Shoqafa and the mechanical analysis were performed using PLAXIS 2 D code [12] in Aristotle University of Thessaloniki, Civil Engineering Department. The whole numerical model is built of 4-node linear tetrahedral volumetric finite elements with one integration point and three degrees of freedom in each node-type C3D4 [13]. The total number of finite elements in all the analysis cases equals approximately 3.5 million. The FE mesh density was determined in a parametric study based on convergence analysis of the cracked form. The numerical model is loaded only by its self-weight. The geometrically nonlinear analysis was performed using a dynamic explicit procedure [14], as it is computationally efficient for the analysis of large models with relatively short dynamic response times and for the analysis of extremely discontinuous events or processes. In the proposed numerical solution (quasi-static technique), the load is applied smoothly; consequently, slow deformation triggers a low strain rate. This type of analysis allows for using a consistent, large-deformation theory. In view of the above, the proposed method of analysis is highly effective for studying the damage and degradation of monumental underground structures. Due to this approach, one can track very carefully the propagation of gradually occurring damage (like cracking and crushing) under an increasing load value, regardless of the type of loads. The PLAXIS package apparently offers several other methods performing dynamic analysis of nonlinear problems, such as implicit dynamic analysis [15].

This study presents the typical damages of archaeological underground structures by the FEM analysis using the PLAXIS 2D code for the seismic response of Catacombs of Kom El-Shoqafa in Alexandria, Egypt with and without the anti-seismic polymer pilling techniques.

Seismic reinforcement of catacombs of Kom El-Shoqafa

Design calculations

A seismic performance assessment of these monumental underground structures discovered that the shear force caused by a possible earthquake could exceed the bearing force capacity of the sidewalls and center pillars. The center pillars could be reinforced adequately by the steel jacket method, but there was no conventional effective method to reinforce the sidewalls of the catacombs. The decision was therefore made to install polymer anti-seismic piling.

Numerical analyses were carried out in order to determine the properties of the polymer isolation wall and its position.

The analyses led to the decision to use a polymer material with a rigidity of approximately one-tenth of the shear wave velocity of the surrounding ground. The analyses also determined that the polymer isolation piles

(See figure on next page.)

Fig. 8 Acceleration -time histories on the top of Catacombs. **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. PGA = 0.24 g. Before and after the installation of polymer anti-seismic piling

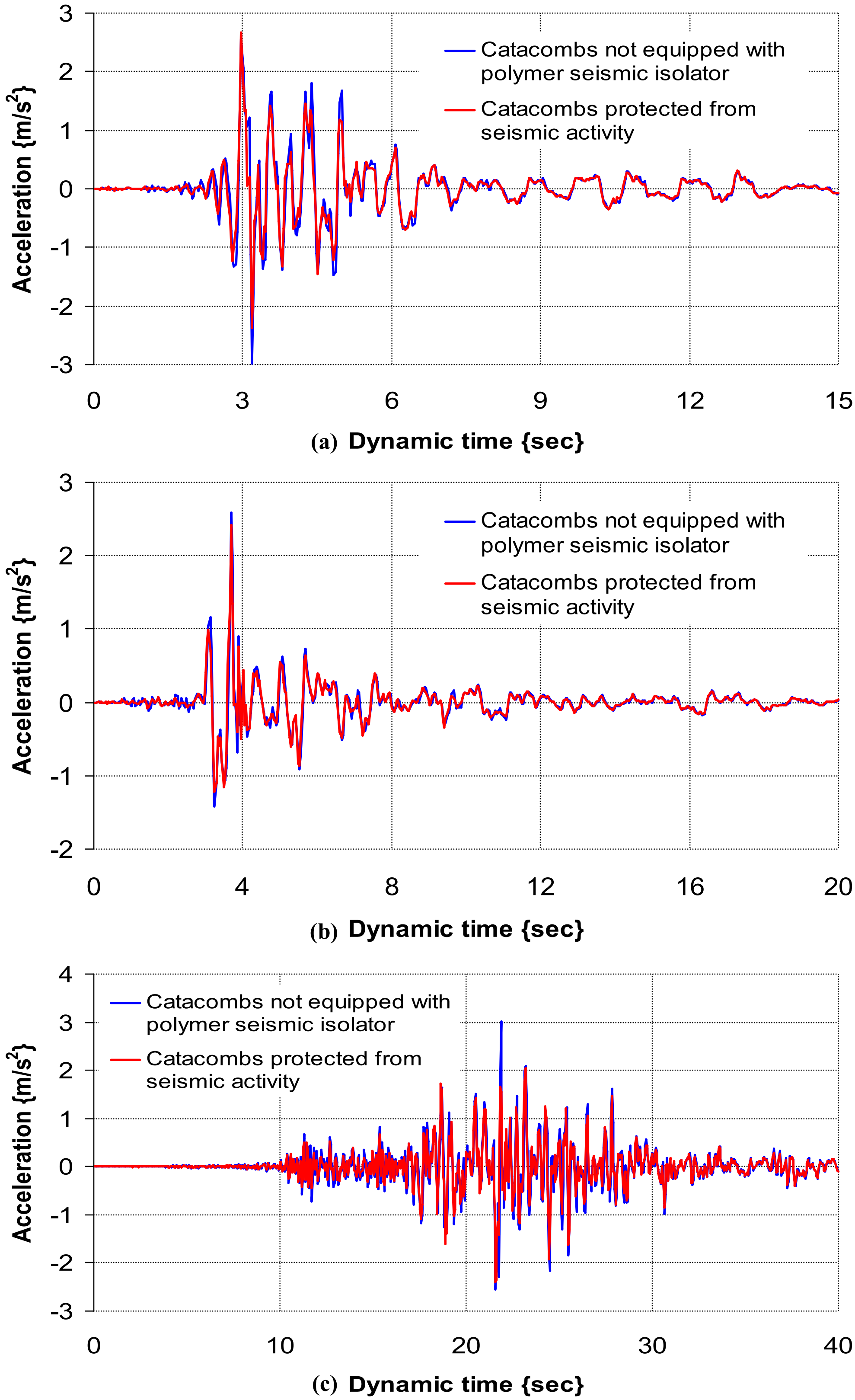

Fig. 8 (See legend on previous page.)

(columns) should be arranged as indicated in Fig. 3. These decisions were reached after considering the existence of the sheet piles and other structural components, and after it was determined that the installation of polymer piling at a certain distance from the catacombs walls would still be effective. The seismic performance of the retrofitted structure was evaluated under these conditions.

The evaluation indicated that the relative deformation would be reduced by 10%, and that the shear force on the sidewalls would remain within safety levels even in the event of a major earthquake [11].

Installation

Retrofitting measure could be conducted in these three phases:

i. A small ground stabilization machine equipped with an auger screw could be used to bore holes in the ground and remove earth.
ii. Polyethylene bladders could be inserted against the walls of the drilled holes and a PVA polymer liquid will be poured in to fill the bladders, to make the polymer anti-seismic piles.
iii. The top 2 m of the holes may fill not with the polymer material but with a sandy soil (May from the same soil in the site).

Future potential

Relatively serious earthquakes have struck different parts of Alexandria, Egypt over the last few years, prompting the public to show greater interest in anti-seismic measures. We expect the above-mentioned polymer seismic isolation method to contribute effectively to the reinforcement of underground monuments, especially the royal cemetery of Alexandria as the pilot monuments in Ptolemaic Alexandria.

Seismic input

In the present study, we have selected three reference earthquakes: (i) Aqaba, Egypt, 1995; (ii) Erzincan, Turkey, 1992; and (iii) Kalamata, Greece, 1986. The time histories of these earthquakes representing different seismtectonic settings and frequency content were scaled to three peak ground acceleration values equal to 0.08 g, 0.16 g, and 0.24 g respectively. And they are used as input motions at the bedrock. The design acceleration in Alexandria according to the Egypt code is 0.08 g.

We believe that with the advances in computational methods it is now possible to predict with reasonable accuracy the seismic demands on these geometrically complex monuments. Specially, computer modeling and simulations are very useful tools for identifying regions of stress concentration where only non-invasive techniques are allowed. Accurate quantification of stresses are also useful for understanding the direction of cracks propagation and for quantifying the seismic demands on whatever new materials may be introduced in the retrofit program. Three earthquakes were chosen:

Aqaba: 22/11/1995, M = 7.1, Ml = 6.2: Station Eilat. Distance (km): Closest to fault rupture (93.8).

Erzincan: 13/3/1992, Mw = 6.9, Ms = 6.8. Station: 95 Erzincan, Rrup = 2 km, Re = 1 km.

Kalamata:13/9/1986.17:24:35, Ms = 5.8. Mw = 5.9, Ml = 5.5. Station: Old telecommunication building, Re = 10 km.

22 November 1995, an major earthquake (Aqaba earthquake) with a magnitude of 6.2 on the local scale ML, and a moment magnitude of MW D 7:1, (PDE bulletin, 1996), struck the shorelines cities of the Gulf of Aqaba, such as Aqaba (Jordan), Eilat, Hagel (Saudi Arabia) and Nuweiba (Egypt), Damage occurred in many parts northeastern Egypt as far as Cairo. This major event was followed by 2089 earthquakes ranging in magnitude from 2 to 5.5 on local magnitude (ML) recorded and/or analyzed by the Jordan Seismological Observatory (JSO bulletin, 1998). This seismic swarm activity began on 22 November 1995 and continues at least until the end of December 1997.

The Kalamata earthquake was recorded on hard ground at a distance of about 9 km from the epicenter and its magnitude was Ms = 6.2. The record samples the near field strong motion that caused considerable damage to the buildings of the city of Kalamata. The duration of the strong motion is about 6 s and the maximum accelerations are 0.24 g in the N-S direction and 0.27 g in the E-W direction. The corresponding peak velocities are 32.0 and 23.5 cm/s, respectively.

The 13 March 1992 Erzincan earthquake, M = 6.8, occurred in the eastern half of the Erzincan basin. The largest aftershock took place near Pülümür on 15 March 1992. No clear surface breaks were observed, although teleseismic studies suggested that it was a strike-slip earthquake striking parallel to the North Anatolian fault, with a focus of approximately 10 ± 2 km depth, 30 km rupture length, 95 cm of slip, and a 1.16×1026 dyn.cm

(See figure on next page.)

Fig. 9 Horizontal displacement -time histories on the top of Catacombs. **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. PGA = 0.24 g. Before and after the installation of polymer anti-seismic piling

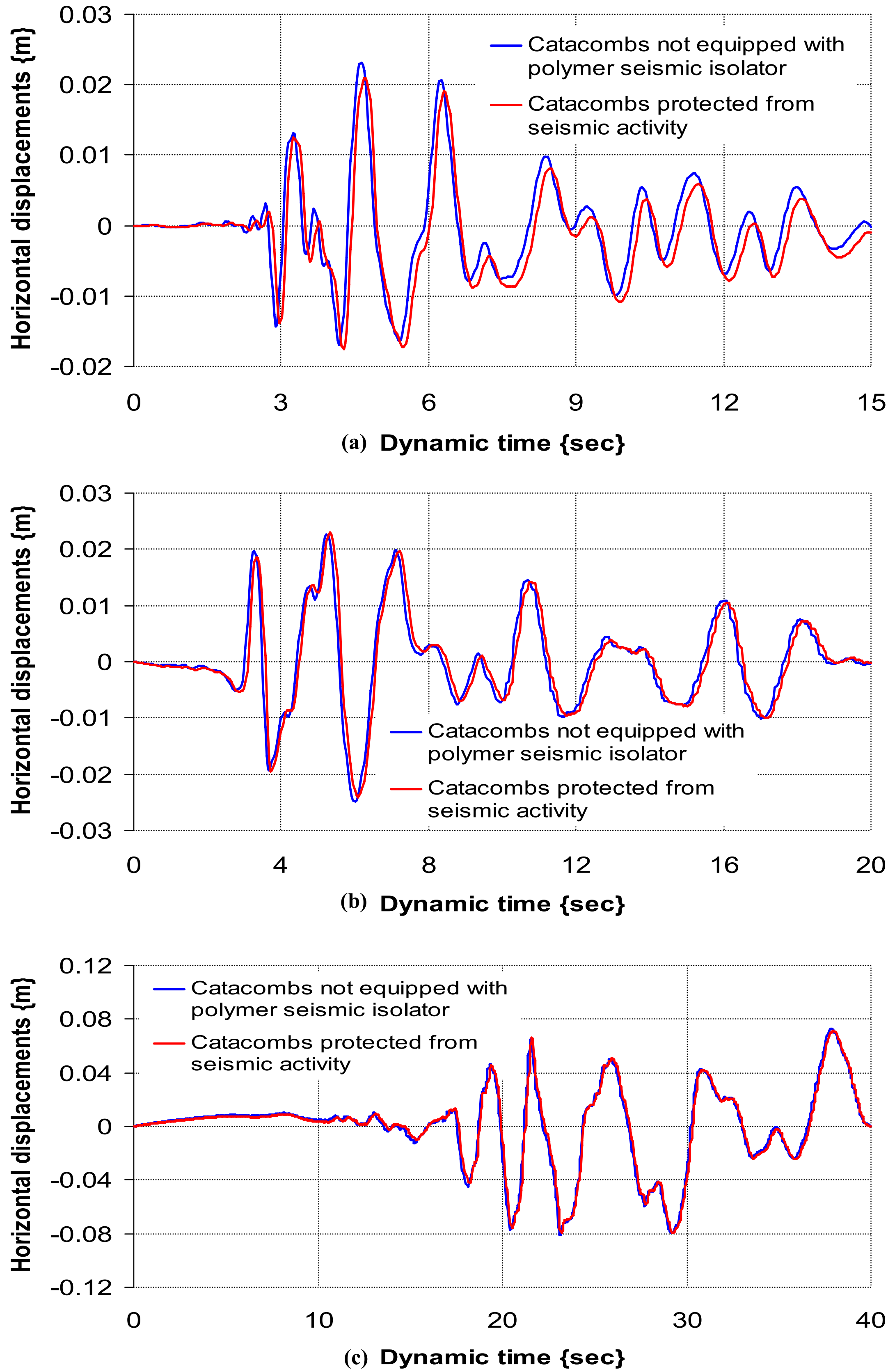

Fig. 9 (See legend on previous page.)

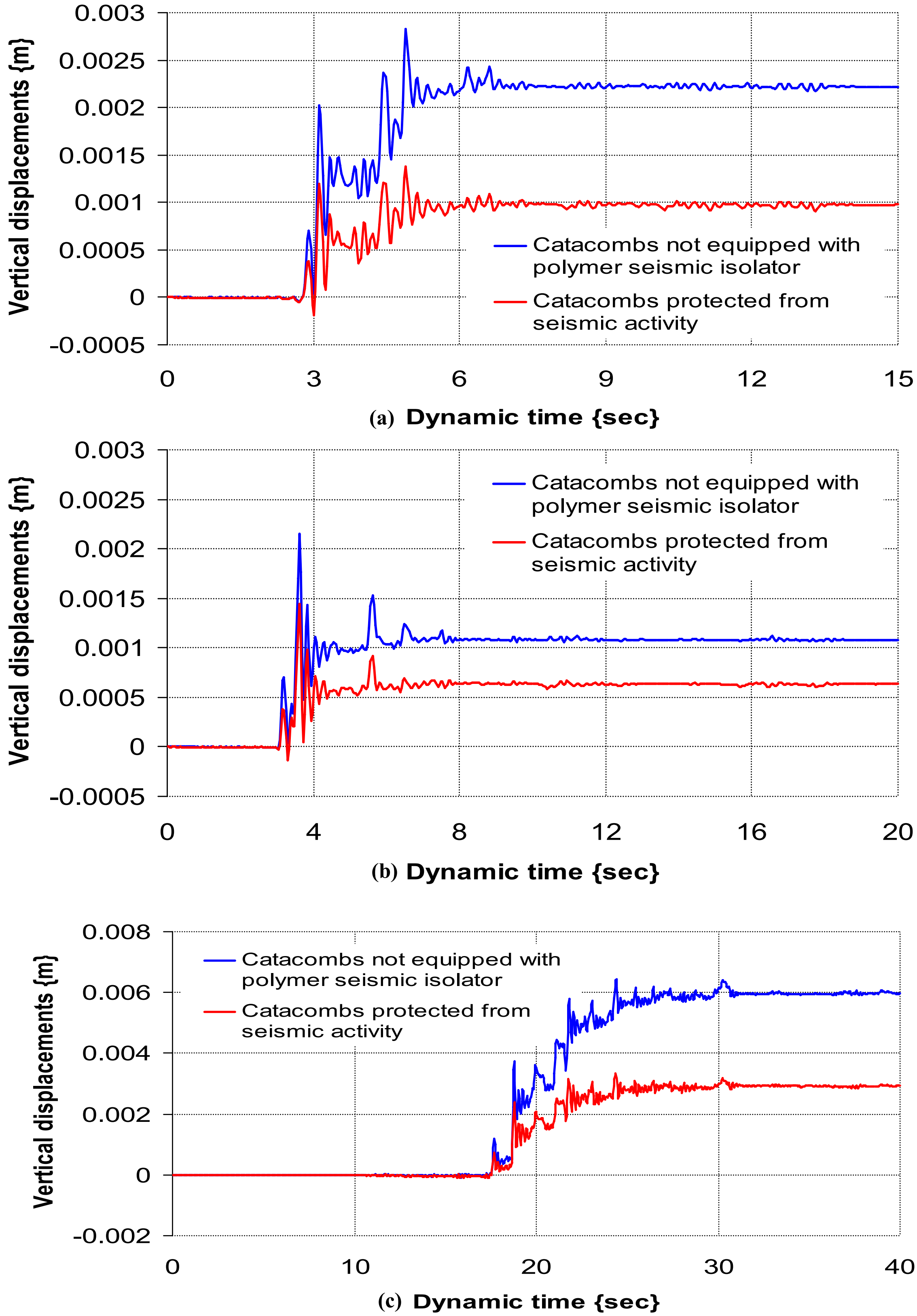

Fig. 10 Vertical displacement-time histories on the top of Catacombs. **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. PGA = 0.24 g. Before and after the installation of polymer anti-seismic piling

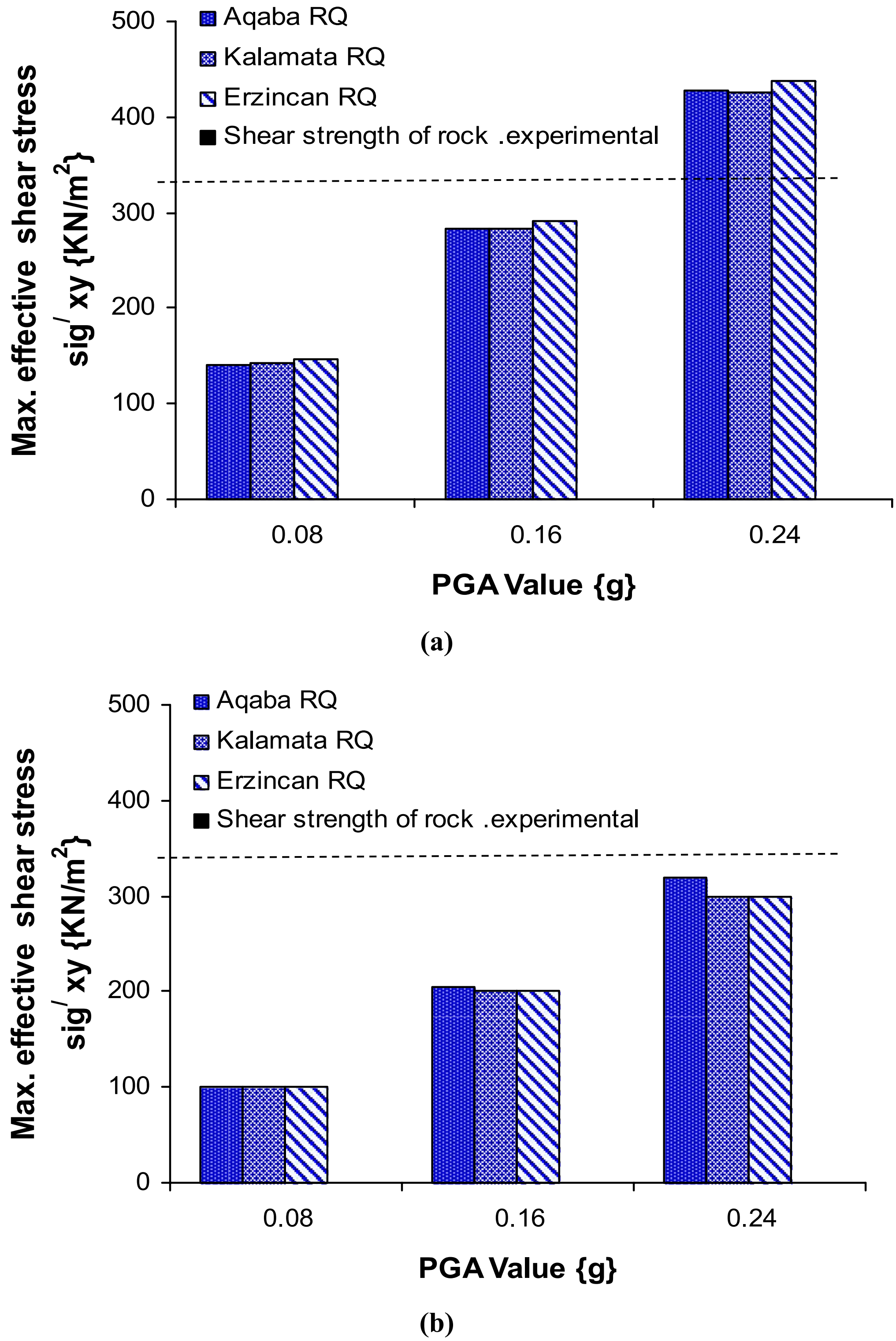

Fig. 11 Maximum effective shear stresses sig/xy on the base of rock pier_1, for Aqaba, Erzincan, and Kalamata earthquakes, scaled to several values of PGA. **a** Initial model, **b** After the installation of polymer anti-seismic piling

seismic moment. The aftershock distribution concentrated at an area of the intersection between the North Anatolian fault and the Ovacik fault. These results indicate that the previously suggested seismic gap along the North Anatolian fault, east of Erzincan, remains unruptured.

The criterion for this choice was their different frequency content, as they will give information about the response of these structures in different period ranges Fig. 4 shows one of the horizontal components of acceleration for each record. The records were retrieved from PEER and ESMD online database.

In order to estimate the threshold PGA values to collapse, a set of parametric analysis was carried out. These structures were subjected to increasing level of horizontal accelerations.

Seismic analysis results and discussion

After the installation of polymer anti-seismic piling method (the catacombs equipped with polymer seismic isolation), the shear forces on the rock pillars and the sidewalls of the catacombs, which is the most vulnerable parts inside the catacombs, reduced by up to half in the cases of the three earthquakes scenarios, as shown in Figs. 5, 6, 7, where the effective shear stresses on the pillars reduced from 410 to 250 kN/m^2 in the case of Kalamata earthquake at PGA = 0.24 g, from 400 to 280 kN/m^2 in the case of Erzincan earthquake at PGA = 0.24 g, and from 430 to 300 kN/m^2 in the cases of Aqaba earthquake at PGA = 0.24 g.

The decreasing of the acceleration was obvious in the three earthquakes scenarios, for example the horizontal acceleration on the top of the catacombs decreased from 3 to 2 m/s^2 in the case of Aqaba earthquake, from 2.6 to 2.3 m/s^2 in the case of Erzincan earthquake at PGA = 0.24 g, as shown in Fig. 8.

The relative deformation would be reduced by 10% where the horizontal displacements on the top of catacombs decreased from 24 to 20 mm in the case of Kalamata earthquake, from 25 to 21 mm in the case of Erzincan earthquake, also from 80 to 78 mm in the case of Aqaba earthquake at PGA = 0.24 g, as shown in Fig. 9.

For the vertical displacements on the top of catacombs decreased from 2.8 to 1 mm in the case of Kalamata earthquake, from 2.4 mm to 1.5 mm in the case of Erzincan earthquake, also from 6 to 2.5 mm in the case of Aqaba earthquake at PGA = 0.24 g, as shown in Fig. 10.

The preliminary seismic analysis of the Catacombs with three seismic scenarios of different PGA values proved that the some critical supporting parts of the catacombs structure (i.e., rock piers) are safe, without any strengthening measures, only for PGA values lower than 0.08–0.10 g, which is rather low considering the seismic activity and the past seismic history of the city. Retrofitting and upgrading is hence considered necessary.

The present integrated study may be considered as a preliminary pilot study for future conservation efforts of these historical monuments, in order to assess the vulnerability of these underground structures to different hazards and to propose appropriate strengthening retrofitting measures especially to reduce the seismic risk.

Polymers anti seismic pilling techniques are extremely appealing due to their lightweight and low cost characteristics. These techniques could be widely employed as an effective seismic risk mitigation technology for the archaeological underground structures, as well as for retrofitting existing above surface historic buildings. Developing countries could take advantage from these techniques to reduce the earthquake vulnerability of large urban underground areas. A case study describing the application of these devices to a benchmark underground structure of catacombs of Kom El-Shoqafa representative of high valuable monuments is discussed in this work. Results show a significant reduction of the seismic demand on the underground structure when polymers anti seismic pilling techniques are adopted.

It is obvious, that the seismic stability of the catacombs has been upgraded after the installation of the polymer anti-seismic piling method, now the supporting rock piers which is the most vulnerable parts inside the catacombs are safe at PGA values more than 0.24 g. whereas the polymer reduces the cross-sectional force on all structural parts, improving the seismic performance of the structure, as shown in Fig. 11.

Generally, the evaluation indicated that the relative deformation would be reduced by 10%, and that the shear force on the sidewalls would remain within safety levels even in the event of a major earthquake.

We expect the above-mentioned polymer seismic isolation method to contribute effectively to the reinforcement of the pilot underground monuments.

The relative stiffness of the structure, compared to the surrounding soil, as stiffer structures appear to produce lower amplifications.

The horizontal component of motion can be amplified from 20 to 40%. The vertical component of motion reaches values from 1/3 to 1.5 times the value of the horizontal free-field component.

The value of the relative stiffness does not alter the affected surface area. The horizontal component of motion can be amplified by 20–85% within. A distance of eleven radii from the tunnel axis ($0 < x/ < 11$).The ground response is further complicated by the appearance of a parasitic vertical component of motion, [16].

Due to the special properties of loess, the modified FEM is suitable for the seismic response analysis of underground structures in soft rock/ hard soil area. However, whether it is applicable to other soils remains to be studied in future research [17, 18].

Based on the finite element analysis method, a practical table of horizontal relative displacements of strata in loess areas, and the comprehensive recommended equation of foundation reaction spring stiffness, was provided. The practical table and the comprehensive recommended equation provide a method of estimation of those seismic calculation parameters required by designers of underground subway stations in loess areas, [19–21].

The performances of polymer anti seismic piling techniques are generally as good as those of conventional devices.

The results of this work can apply to new underground structures and to the seismic retrofit of brittle and poorly built underground structure that were designed with no specific provisions for lateral loads.

Conclusion

The paper summarizes the seismic characteristics, research methods and design methods of underground structures to offer a guide for engineers and conservators, where the polymer anti-seismic piling to protect the underground monumental structures against strong earthquakes is presented and validated in numerical analysis.

In Catacombs of Kom El-Shoqafa, the field observations and the data analysis have shown that geotechnical instability problems of these Catacombs are mainly due to the permanent deformation of the rock mass, the progressive weakening of rock material due to intrinsic sensitivity to weathering factors especially the underground water and salt weathering effect and Earthquake damages.

These Catacombs are carved in oolitic sandy limestone (Calcareous cemented sand); it is yellowish white massive, fine to medium grained cross-bedded sandstone cemented with calcareous cement. Intersected conjugated joints filled with very fine friable sand saturated with water in the lower parts. This unit is underlined by loose calcareous sandstone.

The soil which includes the Catacombs area with Marriut Lake is calcareous sandy soil with great depth and high porosity. The durability of the rock is moderate to low due to its high silica content. The strength of the sandy limestone where the catacombs are carved is low. Considering all other affecting factors and the specific geometry of the complex, this low rock strength affects seriously the safety of the catacombs both under static and seismic loading conditions.

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Declarations

Competing interests
The author declare that he has no competing interests.

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