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Experimental and finite element assessment of stabilizing configurations for underground heritage sites

Sayed Hemeda[1*]

Abstract

Heritage sites in Alexandria, Egypt, are some of the UNESCO world heritage sites at high risk from geo-environmental hazards, in particular caused by sea level rise and heavy rain due to the climate change. Recently, safeguarding UNESCO world subterranean and built heritage draws more attention. After recent environmental catastrophies in Alexandria, sustainable conservation materials and stabilizing configurations of underground monumental structures has also become urgent and highly demanded. Based on typical damage due to the heavy weathering caused by the ground water table and salt, this paper offers a guide for engineers and conservators, where rock structures consolidation and stabilizing configurations to protect these structures in the static state and against strong seismic events is presented. In this paper, typical geotechnical problems and damage to the Catacombs of of Kom El-Shoqafa are presented first, followed by an experimental evaluation methodology that includes spectroscopic and morphological characterization in addition to the mechanical testing of untreated and treated rock samples with synthetic organosilicone and acrylic compounds. The effectiveness of the new silica-based consolidants was evaluated in terms of the amount of solid adsorbed, mechanical properties (e.g., surface hardness, ultrasonic velocity, modulus of elasticity and modulus of compressive strength), and resistance to salt crystallization. The treated groups showed better mechanical strength than the control group. The ability of the treated samples to resist climate change negative impact was also greatly improved. According to laboratory tests, new silica-based hardeners and hydrophobic materials have great potential for strengthening weathered Calcarenitic rock structures. It was observed that the rock samples containing the modified binder (MTMOS + Wacher BS 15) reach higher mechanical strength parameters. After the experimental study (testing procedures), FEM analysis was performed using PLAXIS 2D code to validate the silica-based consolidants and verify their efficiency in improving the response of rock structures in static and seismic states against strong earthquake events. The results of this work confirm the high potential of low-cost injection techniques and stabilizing configurations (pre- stressed anchors and concrete friction piles) technology, confirming the possibility of achieving significant improvement in the geotechnical properties of Calcarenitic rock structures and enhancing the seismic performance of underground archaeological structures using low-cost injection technology that is easy to manufacture.

Keywords Catacombs, Climate change, Environmental hazards, Experimental studies, Finite Element Method (FEM), Friction piles, Geotechnical properties, PLAXIS code, Pre-stressed Anchors, Rock bolts, Silica based Consolidants, Underground structures, UNESCO heritage sites

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Introduction

Climate change is increasing the number of natural disasters like flash flooding, heavy rain and sea level rise (S. L. R) and their intensive negative impact on UNESCO world natural and cultural heritage sites in Alexandria, Egypt in particular the subterranean Greek and Roman tombs and necropolis.

Recently, the increasing number of natural disasters linked to climate crises has put Alexandria's underground and above surface cultural built heritage at greater risk than ever before, which imposes new complex challenges on us to safeguard the historical urban fabric and built heritage in Alexandria, [1].

The petrophysical and geomechanical properties of these Calcarenitic rocks where the Greek and Roman monuments are excavated are affected by size, shape, grain packing, porosity, cement content and matrix, all of which are strongly controlled by depositional fabric and post-depositional processes [2, 3]. Ref. [4] reported that pore scale modeling, based on microCT images, allows direct identification and quantification of parameters related to pore structure and fluid properties to relate fluid rock flow properties to geological information and establish reliable rock classes.

The presence of water within the porous matrix of Calcarenitic rock materials of the Catacombs in Alexandria plays a major role in reduction of their mechanical performance and stability. As is known, the crystallization of salts and the migration of unwanted materials through water penetration can lead to the formation of cracks and level deformations, which severely affects the structural integrity of the building itself. Stone durability is a term that describes the extent to which a material retains its original physical and mechanical properties. As a result, it relates to several aspects such as texture, structure, and mineralogical composition, as well as quarrying and handling methods, applied loads, and environmental conditions to which the stone in question was exposed. In particular, during the past few centuries, porous limestone has been widely used as building materials in many areas of Alexandria. In these coastal urban environments, after a long period of exposure to heavy rains, flash floods and weathering, these stone patterns often undergo extensive disintegration due to the crystallization of soluble salt in the pores. Thus, for this type of natural building materials, the relationship between pore structure, water/moisture transport and salt crystallization has been extensively studied to understand the mechanisms and kinetics of degradation processes, [1, 5, 6].

The Kom El Shoqafa groundwater reduction project, which began on October 12, 2017 and was, completed on March 13, 2019, aims to address these issues by reducing the risk of water leakage. Between 2 December 2017 and 27 September 2018, field archaeologists were present at the site to monitor and record any archaeological remains at risk of impact (removal) due to project construction activities, especially under earthworks.

The Kom El-Shoqafa groundwater lowering system was designed to collect and convey about 600 to 700 m^3/hr of groundwater. Collection entails six pumped deep wells, designed to draw down the groundwater to a target elevation of − 4.2 m Below Sea Level, 2 to 3 m below the lowest (3rd) level in the catacombs.

An earthquake measuring 5.3 Magnitude struck yesterday, Sunday, July 21, southwest of Greece at exactly 7:01 am and was identified as a Mediterranean earthquake. The danger of this earthquake is that it is a surface earthquake with a depth of only 31 km. The earthquake occurred in the Mediterranean Sea and struck a number of Greek cities, most notably Crete, Chania and Gialos. The epicenter of the earthquake is located only 99 km from the Greek coast. Also Libya also felt it.

This type of surface earthquake that occurs inside the sea is considered one of the most dangerous types of earthquakes because it results in or associated with a Tsunami or a rise in sea levels for neighboring countries, including Egypt in particular, which is the closest country to Greece in the southern Mediterranean. It is noticed that the distance between Alexandria and Crete is just 654 km, which is less than the distance between Cairo and Aswan, which is approximately 699 km. This is the reason for the state's warnings today and its request to close all beaches overlooking the Mediterranean Sea in Egypt from July 22 until further notice, but it did not explain the reasons. Indeed, the beaches of Port Said and Damietta were closed today, and tomorrow all beaches will be closed. I warned of the possibility of a Tsunami and the sinking of a large part of the eastern coasts of Alexandria in a number of my research published in 2021, 2023, and finally 2024.

The areas of eastern and central Alexandria are more exposed and vulnerable to the danger of rising sea levels than the areas of western Alexandria, which are topographically elevated due to the Calcarenite structures that are more than 8 meters above sea level.

Alexandria has been exposed to more than 30 strong earthquakes and 2 Tsunamis throughout its history, and the epicenters of these earthquakes were often the island of Crete as well. The Lighthouse of Alexandria was completely destroyed as a result of the 1303 AD earthquake and Tsunami. This earthquake or tsunami resulting from this earthquake will have a limited impact, just a rise in sea level not exceeding half a meter, but the danger is that it is the beginning of several successive earthquakes and Tsunamis after that over several years. The sinking of the city of Heracleion in Abu Qir Bay at the east

Fig. 1 The geo-environmental conditions inside the Catacombs of Kom El-Shoqafa; **a** the 1st level, the main tomb and Caracala hall, **b** the 3rd level of Catacombs. After the Groundwater Lowering Project—which began on October 12, 2017 and was completed on 13 March 2019—aimed to address these issues by reducing the threat of water infiltration

of Alexandria, Cleopatra's Palace and the other sunken monuments in the eastern port are also the result of an unspecified marine event that Alexandria was exposed to 1500 years ago, most likely as a result of a Tsunami. Alexandria was exposed to a minor Tsunami last year, the effect of which appeared in the Sidi Bishr area, following the earthquake in Turkey in November 2023.

Figure 1 represents the geo-environmental conditions and intensive mechanical and chemical weathering of the rock materials and structures (i.e. stone bleeding and honeycomb weathering) due to the salts crystallization activities and drying processes inside the Catacombs of Kom El-Shoqafa after the groundwater Lowering Project which began on October 12, 2017 and was completed on 13 March 2019 aimed to address these issues by reducing the threat of water infiltration. (a) The 2nd level, the main royal tomb and Caracala hall, (b) the 3rd level of the Catacombs. Photos were taken in January 12, 2024.

In fact, these Calcarenitic rock structures are particularly susceptible of deterioration especially due to the

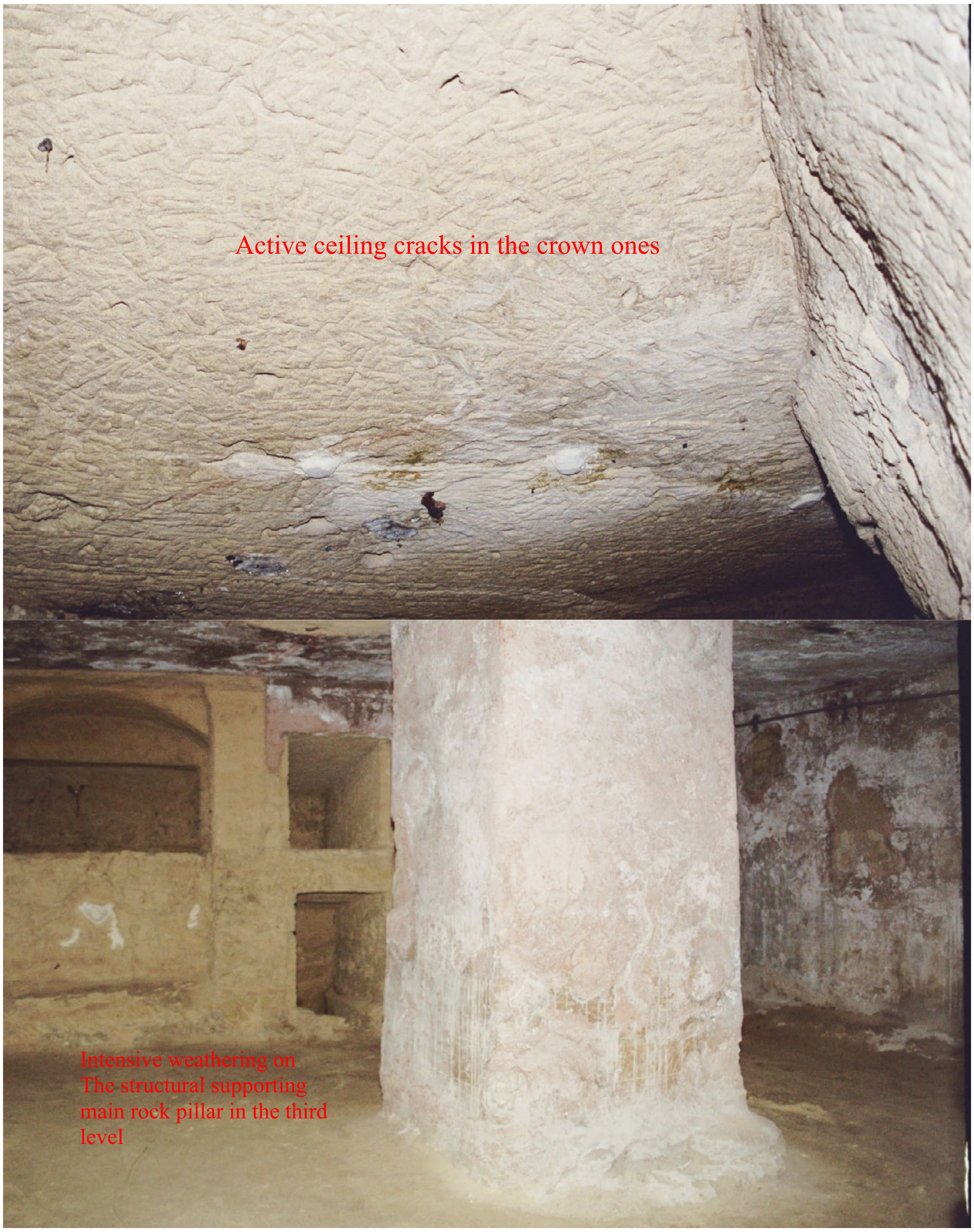


Fig. 2 Catacombs of Kom El-Shoqafa, represents state of conservation. **a** the in plane deformation and crack patterns in the crown zone of the 2nd level due to the geostatic loading and reduction of the strength the rock materials. **b** The intensive weathering of structural supporting main rock pillar at the 3rd level due to the ground water level rising

heterogeneous and porous structure of this rock material. The rock texture varies from fine to coarse grain size with different crystalinity of its components and bioclasts (fossils) more resistant to weathering with respect to calcite matrix. The high decay rates are besides related to high porosity as well as to pore space (pore size distribution and connectivity).

Earthquake Damage to supporting rock pillars and columns inside the catacombs can lead to catastrophic failure of the entire underground structure. Rock pillars are the main load-bearing elements in the underground structural system, as shown in Fig. 2, which represents the state of the conservation of the Catacombs of Kom El-Shoqafa. (a) the in plane deformation and crack patterns in the crown zone of the 2nd level due to the geostatic loading and reduction of the strength the rock materials. (b) The intensive weathering of structural supporting rock pillar at the 3rd level due to the ground water level rising. Earthquake damage to underground structures is thus mitigated, as the confining pressure exerted by the surrounding soil can improve the level of structural integrity in the event of an earthquake. However, seismic disasters in recent decades have influenced thinking about this traditional concept, especially the recent earthquakes that damaged underground archaeological structures in Alexandria, suggesting that the potential for underground structural damage and secondary disasters is still large. [7–11].

The present research may be considered as a pilot study and an attempt to propose appropriate strengthening retrofitting intervention measures for the central supporting rock pillars and rock structures of the Catacombs using pre-stressed anchors, friction piles and injection techniques with organosilicone compounds-ester of silicic acid and polysiloxane compounds "polymers" that will be applied with injection to upgrade the mechanical strength and physical properties of these rock structures and to reduce the seismic risk of these supporting rock pillars. Provisions consolidation injection with organosilicon compounds for all the underground monumental structures are useful for the integral conservation and restoration efforts of these underground structures against the weathering and underground water activities, since the treatment include the application of stone strengthen and water repellant compounds together. Also this retrofitting technique will be more specially for designing possible retrofitting measures for these monuments during strong earthquake.

The second geotechnical provisions envisaged to limit the negative effects of the underground water due to sea level rising and heavy rain is based on the low pressure grouting of the granular soil surrounding the structures of the Catacombs to decrease its permeability and to reduce the seepage flow towards them.

These retrofitting measures provide the following benefits:

- Restores the impermeability of the structure to underground and subsurface water.
- Controls negative effects of pressure against the structure, when combined with a drainage system.
- Creates a barrier to infiltration of gases or hazardous chemicals from the surrounding soil.
- Prevents damage to the monumental structures for the long-term preservation inside the Catacombs. Special applications should be install to create a controlled environment for this pilot monument.

The conservation field frequently divides stone materials according to their main chemical nature into silicate and carbonate stones. This separation is not justified based on their susceptibility to degradation but rather on their chemical affinity with the main groups of products.

Si-based Consolidants (Si suspensions, etc.), are hypothetically more adequate for silicate stones, while most

Fig. 3 Part of the cylindrical rock specimens, who have been used in Triaxial Compression test

inorganic options (limewater, nanolime, DAP-based, etc.), or biomineralization are hypothetically more adequate for carbonate stones because of their chemical proximity. Therefore, this rough division is helpful when determining the family of products to be used in a given situation [12–16]. Si-based consolidants are theoretically more adequate for silicate stones such as sandstones or granites because of the hydroxyl-rich surfaces of the constituent minerals.

On the other hand, this widely investigated family of Consolidants has a poor affinity with carbonate stones such as marbles and limestone, something that has been discussed and studied for a long time [17–20]. These Consolidants cannot establish adequate chemical bonds with carbonate minerals, and the properties of the consolidation material can be negatively affected by forming in an antagonistic chemical environment [21, 22].

Materials and evaluation methodology

Calcarenitic rock samples (collection and characterization)

In this study, an extensive laboratory testing program using 23 core specimens have (42–44 mm^2) diameter and (91–103 mm) height, as shown in Fig. 3. Although these rocks do not show distinct layering, the cores were extracted from the structure's parts and blocks in the vertical direction, which was expected to represent the material characteristics of these units perpendicular to layering. However, a few samples were also extracted in the direction perpendicular to the bedding. Some of the specimens were broken and /or micro cracks or fissures appeared on their surfaces. However, in order to achieve reliable assessments, the number of specimens was increased as many as possible.

From the X-ray diffraction (XRD) analysis, it can be noticed that, the Catacombs of Kom El-Shoqafa is carved in the Calcarenitic rock (cemented sand); it is yellowish white massive fine to medium grained cross-bedded sandstone cemented with Calcareous cement. The construction rock material characterized as Calcarenitic rock is composed of Calcite $CaCO_3$ (47%), Quartz SiO_2 (31%), Halite NaCl (12%), Gypsum $CaSO_4$. $2H_2O$ (10%).

From the thin section examination using the transmitted plane polarized light for the rock samples collected from Catacombs of Kom El-Shoqafa, it was noticed that in the internal structure of the rock body we can observe the dominant components, which are bioclasts of gastropods, foraminifera, algae, and shell debris. The most of them are with test wall of neomorphic microspar, while the tests are internally filled with micrite and microspar. Surrounded monocrystalline Quartz grains are detected and are of variable size and iron oxides contours marking the previous existence of K-feldspar grains. Ooids and peloids are also composing this Calcarenitic rock, or cemented sand.

In view of the violent geo-environmental negative impact, such as heavy rain and the rise in ground water levels inside the archaeological Catacombs under study, in addition to the impact of geophysical action like earthquakes in the recent years, it was necessary to find effective engineering measure to protect and preserve these important archaeological underground structures. One of the engineering measures that have been proposed is to inject and strengthen these weak soft Calcarenitic rock structures with some modern silicon polymers such as synthetic Organosilicon and acrylic compounds.

Treatment application

Deterioration of the archaeological sites is one of the most serious problems that need urgent attention. Organosilicon materials have been considered to be an effective type of chemical Consolidants for heritage structures that need strengthening.

Nowadays the Organosilicon compounds like esters of silicic acid find a wide application as stone consolidating agents for historical monuments. Among these compounds the following ones are used most frequently in commercial products: tetraethoxysilane (TEOS) Wacker OH, methyltrimethoxysilane (MTMOS), a commercial product Rhodorsil 11309. In the present study some of these products were used as mixtures with the water repellent polysiloxane compounds (Tegosivin HL 100, Wacker BS 15, Wacker 280). One acrylic compounds (Eucoseal) has been used for a comparative study. Final product of their consolidating effects is a polymer network (gel). The properties of the rock samples were measured before and after the consolidation, physical properties, mechanical properties and resistance to crystallizing salts.

The Organosilicon compounds "esters of silicic acid" consist of the atoms of silicon and oxide (modified non crystalline SiO_2). Tetra functional monomers from a rigid polymer network in which distances between the single junction points are very short.

Four treatments were applied for the consolidation of Calcarenitic rock where the Catacombs are excavated. The first group included the treatment with Eucoseal, the second group included the treatment with Tegosivin HL100 + Wacker OH, the third treatment included the Wacker BS 15 + MTMOS, while the last and fourth treatment was with the Wacker 280 + Rhodorsil 11309.

Treatments were applied using the strengthening products (tetraethoxysilane (TEOS) Wacker OH, methyltrimethoxysilane (MTMOS), a commercial product Rhodorsil 11309) concentrated to 10% into white Alcohol.

The cylinder samples were pre-treated by a brush. In this stage, the treatment solutions were applied, under laboratory conditions, on sandstone samples by brushing until the surface remained wet in order to get rid of air that existed in the pores. After this, all samples were fully immersed in closed containers, as described by Pinto and Rodrigues, [23]. Finally, the samples were removed from the containers after 14 h, when they were wiped and then dried in a ventilated environmental cabinet (25 °C, 60% RH) for 10 h. This operation was cycled if samples needed an additional treatment. Three levels of concentration were chosen, 5%, 10% and 15% of mass, and were treated with 1, 3 and 5 repeats, respectively, to compare the consolidation effectiveness as a preliminary test. Samples were cured in a ventilated environmental cabinet (19 °C, 95% RH) for 7 d after treatment. The second phase of the treatment processes with water repellent polysiloxane compounds had been repeated in the same manner.

Testing procedures

The laboratory studies (experimental investigation) were performed on prepared surface and core rock specimens. The essential laboratory mechanical testing includes deformation behaviour till failure under uniaxial and Triaxial compression, also we present a complete creep rock characterization carried out during the last two years from a set of uniaxial, isotropic, and Triaxial compression creep tests which were performed at different confining pressures, The viscous behaviour was determined following a multi-step loading procedure, which emphasizes the transient creep aspect. The testing program includes also the block punch index, Brazilian tensile strength (BTS), and Acoustic wave velocity, and direct shear test on intact rock samples and completely weathered samples. The test results are used to calibrate the rock property parameters for the computer simulations. Testing program started with determination of the physical properties which include dry unit weight determinations, apparent porosity, water absorption, specific gravity, water content of the extracted rock samples.

It was necessary to develop this novel evaluation methodology to assess the effectiveness of these strengthening and water-repellent polymers and materials. The experimental study includes the mechanical testing, morphological and spectroscopic investigations of the consolidated treated samples and specimens. The macrostructure characterization program comprises the determination of flexural strength (σ_f), uniaxial compressive strength (σ_c), also the shear strength (Ʈ) of the treated samples. The elastic parameters include the Young's modulus (E) and Poison's ratio (ν) in addition to the compressive strength (σ_c) determined using the uniaxial compression test. The shear wave velocity (Vs) of the treated samples and the longitudinal prima wave velocity (Vp) measured using the Ultra sonic wave velocity.

Fig. 4 Triaxial compression test equipment. The cylindrical specimen placed inside GDS cell is loaded vertically using the compression machine. (GDS instruments limited, England)

The shear strength (Ʈ) and shear modulus of rigidity (G) and the Eodometer modulus (Eoed) in addition to the shear strength parameters determined using the triaxial compression test. The program includes also the determination of the physical properties like the absorption capacity and durability to crystallization salts. The testing program included also the shear strength parameters which are very important in the seismic response assessment, which include the friction angle (ϕ), the cohesion (c) and dilatation angle (Ψ). The laboratory tests were performed according to the testing procedures suggested by ISRM (1981) and recommended by ASTM C 568, C568M [24] in the engineering geology laboratory, civil engineering department of Aristotle University Thessaloniki, Greece.

The Triaxial compression test is a unique method for determining the shear strength parameters of intact rock. Detailed procedures for performing such laboratory tests are available as ISRM suggested methods (1981) or as ASTM D 7012-10 standards, [25]. The strength and deformation characteristics of intact rock are controlled by many factors including anisotropy, moisture content, and confining pressure. The data from this test can be used as input parameters for estimating both intact rock and rock mass strength using either the Mohr–Coulomb or Hoek–Brown failure criteria. The latter criterion is virtually the only nonlinear empirical criterion applied worldwide in tunnelling and slope excavation design. The rock material constant, mi, is a significant input parameter for the aforementioned criterion for intact rock and this can be obtained from the analysis of Triaxial test data. GDS instruments limited, England were used, as shown in Fig. 4.

An extensive series of Triaxial compression tests with local strain measurement were carried out to determine the compressive strength of rock as a function of confining pressure, and determine the shear strength envelopes (e.g. cohesion, angle of friction) on the intact rock samples. The results of multiple tests can be used to determine the rock failure envelope, failure strength parameters (e.g. cohesion, angle of friction) and brittle transition confining pressure. The air-dried core specimens were prepared in vertical direction. Preparation of totally three test sets consisting of four specimens could be possible due to sample losses during coring.

The ultrasonic velocity through the material (V, ASTM C 597, ASTM D 2845-83) [26], as a good index characteristic of the physico-mechanical behavior of the rock, a PUNDT portable ultrasonic non-destructive digital tester was used.

It is a good index characteristic not only for determining the physicomechanical behaviour but also for evaluating the weathering degree of the rocks. For this purpose a PUNDIT ultrasonic non destructive digital tester is used. Measurements are applied along the axis of the core samples and the travel time of the 54 kHz source pulse was measured (for in situ measurements a pair of small edge transducers of 500 kHz could give more reasonable results). Specific transducers of 300 kHz are used in the case of P and S wave velocity measurements. Water pump grease, covered with a specific membrane, is used as coupling media, to improve the acoustic contact between the sample and the transducers. The instrument is calibrated with aluminium standards. Thickness and travel time corrections are calculated by performing a linear regression between the actual and the measured times. Ultrasonic velocity is related to the moduli of elasticity of rocks, such as Young's modulus and Poisson's ratio. Furthermore, it is a very good index for rock quality classification and weathering determination. The ultrasonic velocity tests can also be used for the determination of the dynamic elastic moduli which express the deferability of rocks. The most common of them are the Modulus of Elasticity or Young's Modulus (E) and the Poisson's Ratio (v).

The crystallization test:

The crystallization test by total immersion was carried according to the standard DIN 5211. The weighted samples were immersed into the solution of 10% in weight sodium sulphate Na_2SO_4. Then the samples were placed in the dryer for 16 h at the room temperature. After 1 h at the laboratory temperature the samples were weighted and again immersed into the salt solution. The whole cycle was repeated several times. The weight losses occurring at each cycle were measured to original weight ratio and expressed in percent. The weight losses are considered as a measure of the stability of the stone against water-soluble salts (salt weathering). It is obvious that with increasing weight losses during the experiment the resistance of the samples against water-soluble salts decreases.

Finite element assessment (FEA)

PLAXIS is an easy-to-use, finite element software application that helps with the analysis of subsurface environments for geo-engineering problems like our present analysis of geotechnical problems of underground monumental structures (Catacombs of Kom El-Shoqafa).

Also PLAXIS code offers extensive modeling features to model structures and the interaction between the structures and the bearing soil.

In the present study macro geotechnical and structural modeling done by importing the CAD data to PLAXIS 2D where PLAXIS 2D provides a large choice of structural elements: Anchors, Beams and embedded beams, Plates, Geogrids, and Interfaces.

Plates in PLAXIS are also offered in both 2D and 3D modeling environments and are formulated based on the Mindlin-Reissner theory. Equilibrium equations of the plate introduce: In-plane normal forces (2 components), Bending and twisting moments (2+1 components respectively), and Transverse shear forces (2 components).

Plates have been used for a large variety of masonry structures, including building floors and walls.

By introducing an interface along a line (or a surface in 3D), node pairs are created at the interface between the soil and the structure (one node belonging to the structure and the other one belonging to the soil).

Structural elements use normal forces, shear forces, and moments as primary variables to enforce equilibrium. As such, these structural elements are directly computed by the calculation kernel and reported into the post-processing environment (PLAXIS Output). This is convenient from a structural engineering point of view for the design and dimensioning of cross sections and elements thicknesses.

The accuracy of the structural element response is primarily related to its slenderness ratio. The idealization of its kinematics in a given direction (s) requires some structural dimensions (thickness for plates) to be small compared to other dimensions, enabling the simplification of their geometrical representation (to a surface for plates).

With regard to the improved performance of these rock structures after they were strengthened and treated, especially in their resistance to the effects of geostatic loading and strong seismic events, it was necessary to perform numerical Finite Element Method (FEM) analysis and create numerical FEM models using PLAXIS 2D code before and after consolidation and treatment. The results demonstrated an improvement in the mechanical properties of the samples treated with synthetic organosilicone and acrylic compounds as well as a significant improvement in their performance and resistance to strong earthquakes.

Numerical modeling of the Catacombs of Kom el-Shoqafa and the mechanical analysis were performed using the PLAXIS 2D code [26] at the Department of Civil Engineering (Geotechnical Division), Aristotle University of Thessaloniki, Greece.

The entire numerical model is built from 4-node tetrahedral linear volumetric finite elements with one integration point and three degrees of freedom in each node of the C3D4 type [27]. The total number of finite elements in all analysis cases is approximately 3.5 million elements. The density of the FE network was determined in a parametric study based on the convergence analysis of the crack shape. The numerical model is loaded solely by its own weight. The nonlinear geometric analysis was performed using an explicit dynamic procedure [28], as it is computationally efficient for analyzing large models with relatively short dynamic response times and for analyzing highly intermittent events or processes. In the proposed numerical solution (quasi-static technique), the load is applied smoothly; Therefore, slow deformation leads to a low strain rate. This type of analysis allows the use of a consistent large deformation theory. Due to the above, the proposed analysis method is very effective for studying the damage and deterioration of underground archaeological structures. Thanks to this approach, the propagation of gradually occurring damage (e.g. cracks, crushing) can be closely followed under an increasing load value, regardless of the type of load. Obviously, the PLAXIS package offers several other ways to perform dynamic analysis of nonlinear problems, such as implicit dynamic analysis [29–32].

This study presents typical damages of underground archaeological structures by FEM analysis using the PLAXIS 2D code for the seismic response of the Kom el Shoqafa catacombs in Alexandria, Egypt before and after the treatment applications with synthetic Organosilicone and acrylic compounds MTMOS + Wacker BS 15 mixture.

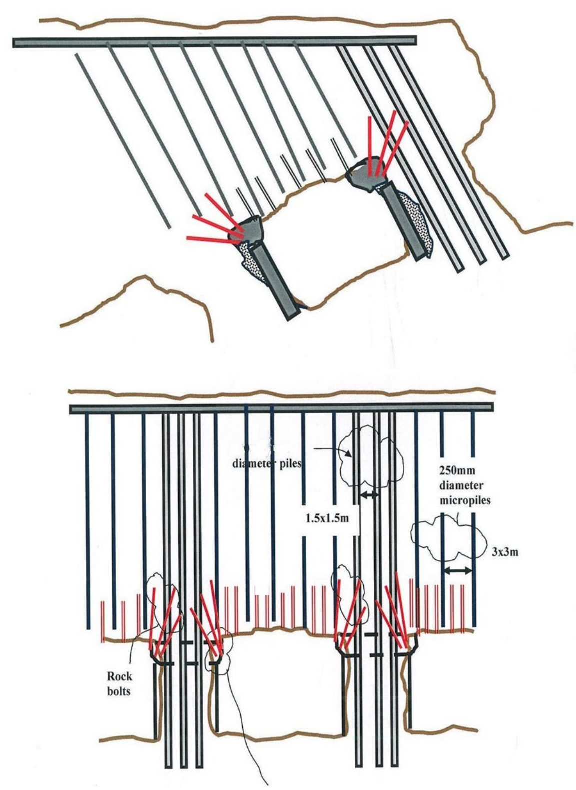


Fig. 5 Possible permanent Stabilizing Configurations for the crown zones, Rotunda in the 2nd level and the main pillar in the 3rd level in Catacombs of Kom El-Shoqafa

Possible stabilization—support configurations for the catacombs

Principles:

- The scheme should provide a strong, so-called "robust" solution which accommodates all potential uncertainties.
- The scheme development must address overall stability first and superficial instabilities (rockfall issues).
- Except for the public access areas the natural appearance of the Catacombs should be retained. This in turn indicates that the visual impact of any remedial stabilization measures should be minimal.

For an overall assessment the following requirements emerge.

Pre-support scheme-crown zones

Rock mass zones above the Rotunda and the roof of the second level of the Catacombs (the royal tomb) are needed to be stabilized prior to removal the gravel backfill:

- Pre-supporting of the lower zone of the roof is fundamental to safety against roof slabbing by controlling bending of the rock layers, including the lower beds of the upper zone of the roof.
- Pre-supporting the upper zone of this level will enhance the overall Catacombs stability, minimize long-term loading onto the lower zone and provide safety against a worst case major collapse.

Two options are considered suitable for these objectives, as shown in Fig. 5:

Table 1 Possible permanent Stabilizing Configurations and seismic intervention retrofitting measures for the crown zones, Rotunda in the 2nd level and the main pillar in the 3rd level in Catacombs of Kom El-Shoqafa

(I) Pre-support scheme-Crown zones	
Option1: Pre-stressed anchors (Rock bolts)	**Option 2: Concrete friction piles**
System is envisaged to be installed from surface and will be connected with a buried grid of reinforced concrete beams	System is envisaged to be installed from surface and will be connected with a buried grid of reinforced concrete beams
Pre-stressed anchors (Rock bolts) are a suitable option as long as the rock mass is not in a disturbed state such that pre-stressing could not be achieved due to internal deformations. Beyond the suspension effect (which could also be achieved by a passive system) the important advantage is the minimization of future delamination as a result of the increased shear resistance along the bedding	**Concrete friction piles** (typical of 100–250 mm diameter with reinforcement bars) would act against sagging, whilst in the process of construction open bedding planes would be grouted
(II) Pre-support scheme-supporting pillars of Rotunda in the second level Small diameter friction piles (typical of 50–100 mm diameter with reinforcement bars) could be used to upgrade the strength of the pillars of the Rotunda in the second level, as shown in Fig. 5	
(III) Pre-support scheme-supporting the main Pillar in the third level	
Option1: Concrete friction piles	**Option 2: Buttressing and dowelling in combination with a dedicated beam-column support system**
This could be pre-supported by reinforced concrete friction piles of large diameter than the above (typical of 200–250 mm diameter with reinforcement bars). This option is considered more appropriate for this main pillar, where construction difficulties in term of boring are minimal	Another proposal for this pillar is by buttressing and dowelling in combination with a dedicated beam-column support system as follows: - Reinforced concrete beams embracing horizontally the pillar at haunch level will provide the heading of vertical reinforce concrete columns distributed parametrically according to sectional pillar geometry - The heading beams, typically 170 × 100 mm in section are envisaged to be embedded in haunch replacing the disturbed haunch material - The columns of anticipated cross Sect. 70 × 70 mm will be structurally reinforced and embedded in the dental concrete against waisting, for buttressing, etc. because of height; they may have to be interlinked via diagonal struts to be installed in holes through the pillars. The columns will be founded in sockets of sound rock
(IV) Innovative Seismic Intervention Retrofitting Measures Innovative seismic retrofitting of the examined Catacombs, based on the strengthening of the resistant structure, also firstly hypothesized. The strengthening can be achieved also by a current intervention consisting in grouting concrete plates on the faces of the rock pillars. The plates are reinforced with steel net and connected with transversal bars disposed in holes filled with mortar. In addition, the pillars could be reinforced adequately by the steel jacket method, or one of the other innovative measures such as metal (aluminum and steel) shear panel, base isolation with horizontal diaphragm, shape memory alloy braces, steel buckling restrained braces (BRB) frames, SMA, C-FRP, etc	

- Option1: Pre-stressed anchors (Rock bolts)
- Option 2: Concrete friction piles

Both systems are envisaged to be installed from surface and will be connected with a buried grid of reinforced concrete beams.

Pre-support scheme-supporting pillars *of* rotunda in the second level

Small diameter friction piles (typical of 50–100 mm diameter with reinforcement bars) could be used to upgrade the strength of the pillars of the Rotunda in the second level, as shown in Fig. 5.

Pre-support scheme- supporting the main pillar in the third level

Two options are considered suitable for these objectives:

- Option1: Concrete friction piles
- Option 2: Buttressing and dowelling in combination with a dedicated beam-column support system

Table 1 summarizes the possible permanent Stabilizing Configurations and seismic intervention retrofitting measures for the crown zones, Rotunda in the 2nd level and the main pillar in the 3rd level in Catacombs of Kom El-Shoqafa.

Innovative seismic intervention retrofitting measures of the catacombs

Innovative seismic retrofitting of the examined Catacombs, based on the strengthening of the resistant structure, also firstly hypothesized. The strengthening can be achieved also by a current intervention consisting in grouting concrete plates on the faces of the rock pillars. The plates are reinforced with steel net and connected with transversal bars disposed in holes filled with mortar. In addition, the pillars could be reinforced adequately by the steel jacket method, or one of the other innovative measures such as metal (aluminum and steel) shear panel, base isolation with horizontal diaphragm, shape memory alloy braces, steel buckling restrained braces (BRB) frames, SMA, C-FRP, etc.

Results and discussion

Experimental study (testing procedures)

Four treatments were applied for the consolidation of extracted Calcarenitic rock specimens where the Catacombs are excavated, the first group included the treatment with Eucoseal, the second group included the treatment with Tegosivin HL100 + TEOS or Wacker OH, the third treatment included the Wacker BS 15 + MTMOS, while the last and fourth treatment was with the Wacker 280 + Rhodorsil 11309. Table 2 summarizes the results of the consolidation processes and treatment applications, It is observed that the samples

Table 2 Rock properties before and after reinforcement with synthetic organosilicone and acrylic compounds (polymers)

Parameters	Unit	Untreated Rock	Eucoseal (Acrylic)	Tegosivin HL 100 + Wacker OH (TEOS)	Wacker BS 15 + MTMOS	Wacker 280 + Rhodorsil 11309
Rock unit weight above phreatic level	$\gamma_{unsat\ kN/m^3}$	18	20.3	19.1	21.4	19.5
Rock unit weight below phreatic level	$\gamma_{sat\ kN/m^3}$	22	22.4	22.1	23.2	21.7
Young's modulus	E_{ref} kN/m^2	2.270E + 06	3.365E + 06	3.000E + 06	4.290E + 06	2.650E + 06
Shear modulus	G_{ref} kN/m^2	8.867E + 05	1.277E + 06	1.181E + 06	1.681E + 06	1.035E + 06
Oedometer modulus	E_{oed} kN/m^2	2.902E + 06	4.180E + 06	3.749E + 06	5.336E + 06	3.388E + 06
Poisson's ratio	$\nu_{(nu)}$	0.28	0.28	0.27	0.28	0.28
Cohesion	C_{ref} kN/m^2	500	–	650	800	–
Friction angle	φ^O	35	–	36	39	–
Shear wave velocity	Vs m/s	715	785	778	877	721
Longitudinal wave velocity	Vp m/s	1293	1421	1387	1563	1305
Uniaxial compressive strength	UCS kN/m^2	2400	4800	4300	6200	3500
Bending strength	Bending strength σy kN/m^2	560	1540	1220	3970	800
Shear strength	T_f kN/m^2	400	–	700	750	–

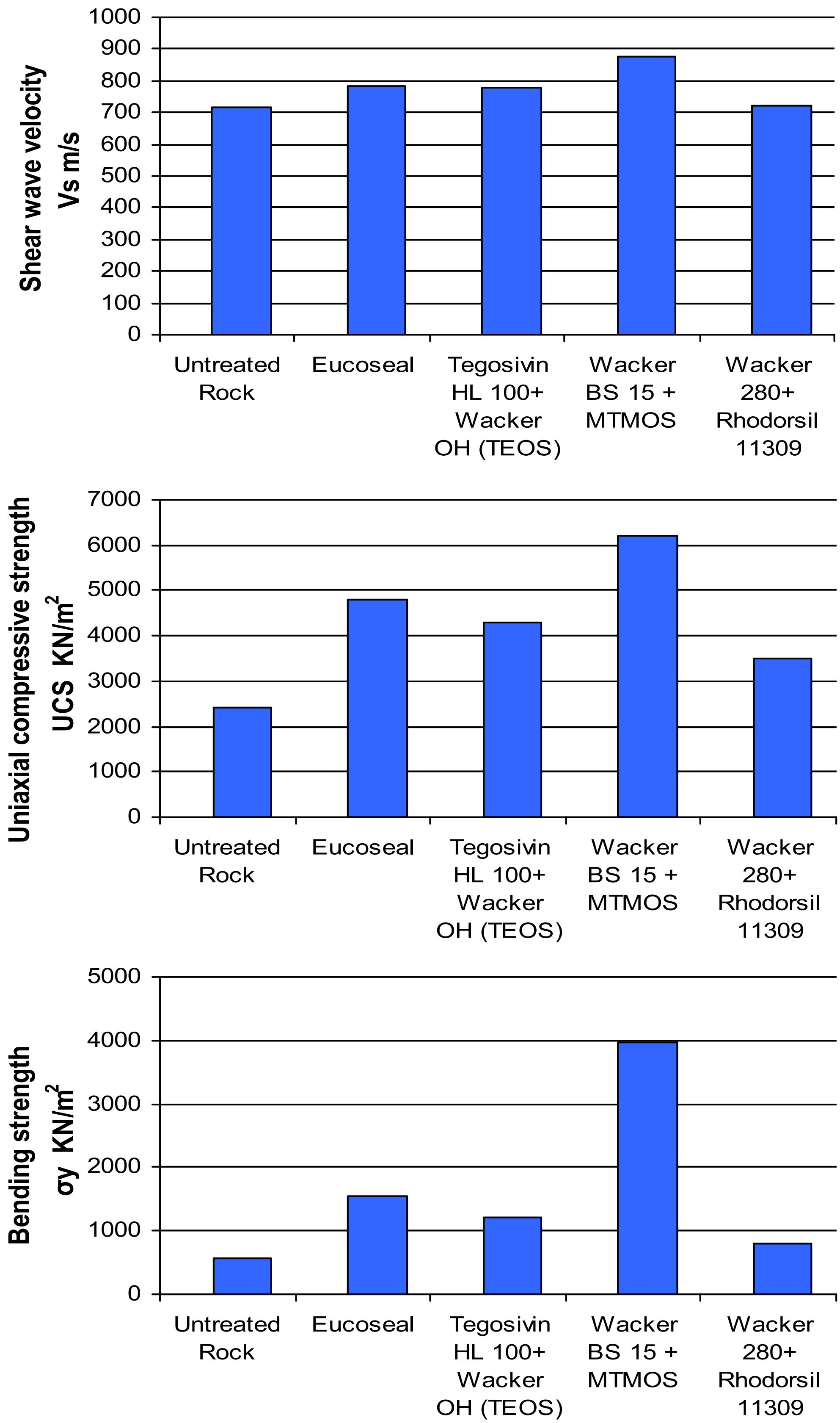


Fig. 6 Rock properties before and after reinforcement (injection) with synthetic organosilicone and acrylic compounds (polymers)

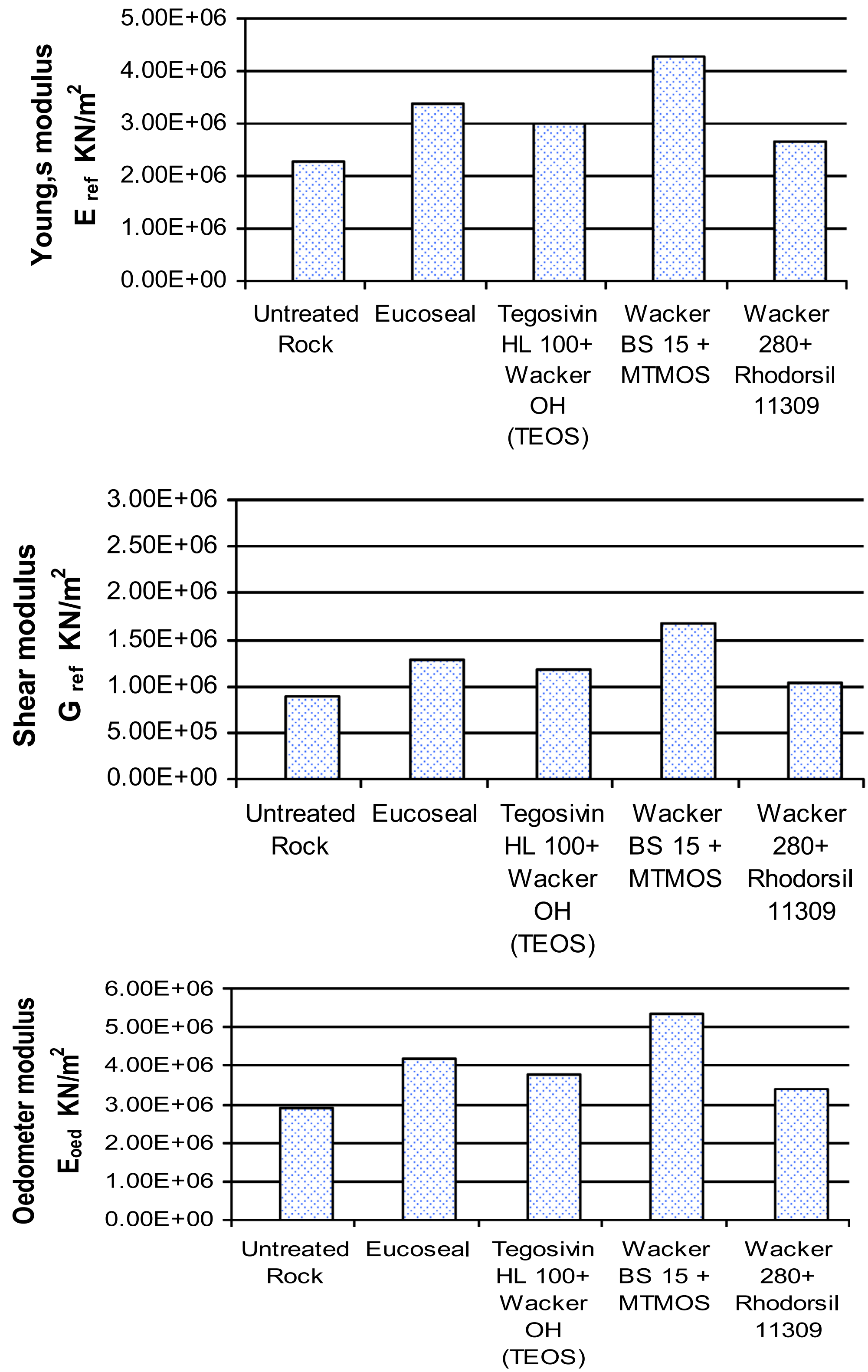


Fig. 7 Rock properties before and after reinforcement (injection) with synthetic organosilicone and acrylic compounds (polymers)

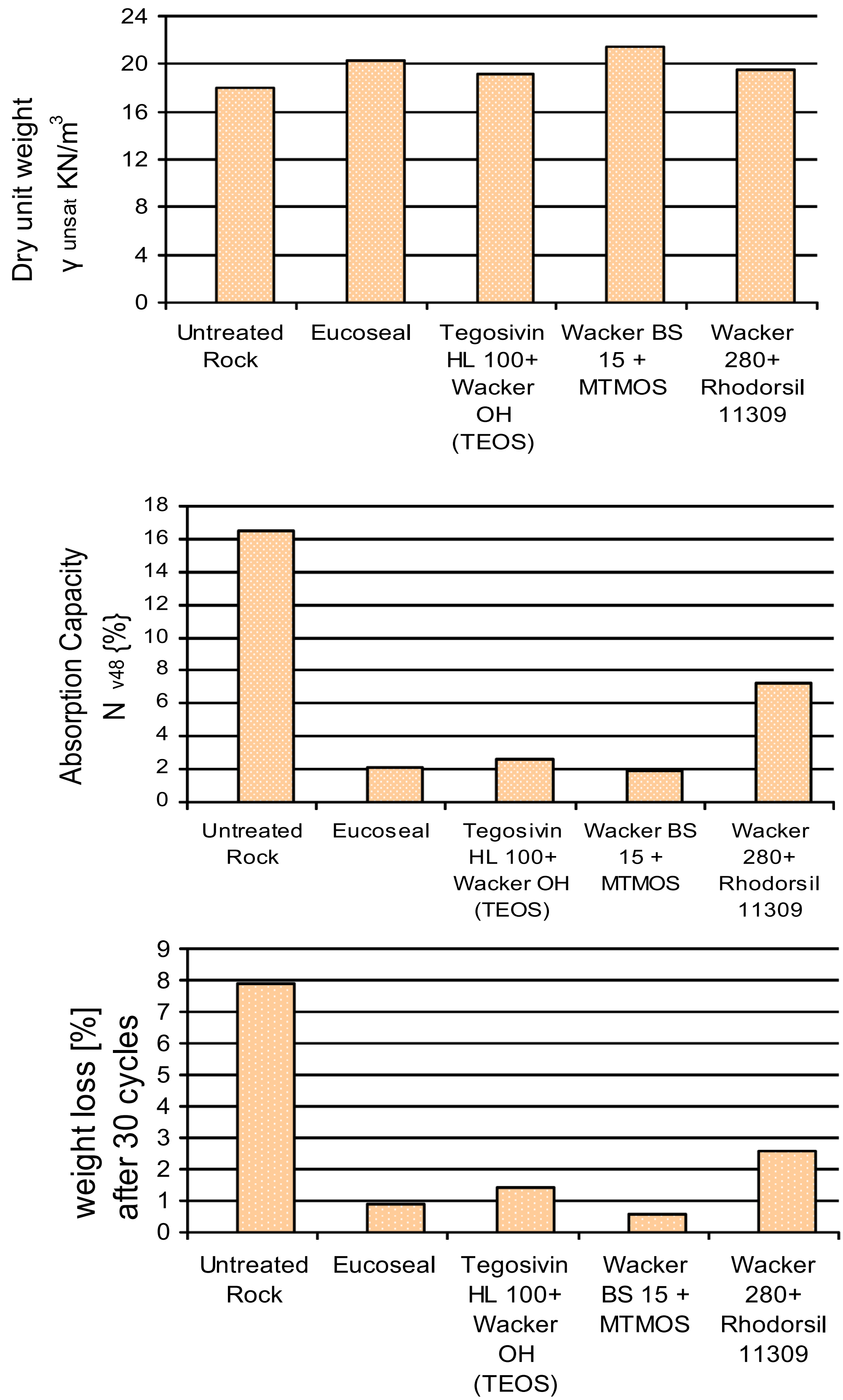


Fig. 8 Rock physical properties before and after reinforcement (injection) with synthetic organosilicone and acrylic compounds (polymers)

containing the modified binder (MTMOS + Wacher BS 15) reach higher mechanical strength parameters: where the flexural strength (σf) is = 3970 kN/m^2 and uniaxial compressive strength (σc) is = 6200 kN/m^2, also the shear strength (Ʈ) of the treated samples reached 750 kN/m^2. The elasticity of the treated samples seem to have a permanent higher character where the Young's modulus (E) is = 4.290E + 06 kN/m^2 and Poison's ratio (ν) is = 0.28. The shear wave velocity (Vs) of the treated samples is = 877 m/s and the longitudinal prima wave velocity (Vp) is = 1563 m/s. The shear modulus of rigidity (G) is = 1.790E + 06 kN/m^2 and the Eodometer modulus E_{oed} is = 5.370E + 06 kN/m^2. Also the treated samples reach lower absorption capacity = 2% and higher durability to crystallization salts than the other treated samples = 0.7%. For the shear strength parameters which are very important in the seismic response assessment, it is observed the friction angle (ϕ) is = 39°, the cohesion (c) is = 800 kN/m^2 and dilatation angle (Ψ) is = 1°. These results are represented in details in Figs. 6 and 7

While the treatment with modified binder (Wacker 280 + Rhodorsil 11309) came in the last class as it achieved a lower bending and uniaxial compressive strength, higher absorption capacity and lower durability to crystallization salts, as shown in Table 1. Based on its behavior after injection or consolidation of rock samples its elasticity doesn't seem to have a permanent character. In addition, it is obvious that the treatment with organosilicone compounds were more effective than the treatment with organic acrylic polymers (Eucoseal) and it is because of the high percent of free silica inside the structure of these rock formations.

The results indicated that the samples containing the modified binder (MTMOS + Wacker BS 15) have a lower absorption capacity, these samples are hydrophobic than other treated samples with other Organosilcones and acrylic polymers which have lower hydrophobic properties, as shown in Fig. 8.This hydrophobic properties because of the presence of alkyl groups bound to the silicon atom. The measurements of absorption capacity under atmospheric pressure were carried out according to the standard CSN 75011055.

Even after 30 cycles of the crystallization test no weight losses were observed at the samples containing modified binder MTMOS + Wacher BS 15 and Eucoseal treatment came at the second class which are compensated for higher mechanical strength. With the increasing amount of the modified compound, the weight losses decreased. The stability of the samples against crystallizing salts corresponds to the hydrophobic properties of the samples consequently to its absorption capacity, see Fig. 7. The impact strength influenced the bending and compressive strength; the hydrophobic properties influenced the absorption capacity and the results of the crystallization test. Fig.s 9, 10, 11 represent the SEM photomicrographs of the treated sandy oolitic limestone specimens, from Catacombs of Kom El-Shoqafa, with (MTMOS + Wacker BS 15) mixture, before and after the treatment and consolidation. The uniform coating on the rock particles is well observed. The formation of a network of resin also is obvious.

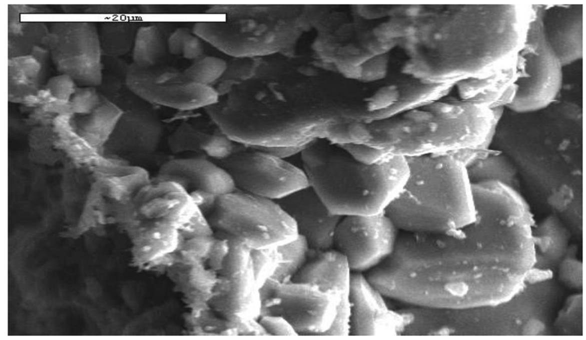


Fig. 9 SEM photomicrograph of weathered Calcrenitic limestone samples, from Catacombs of Kom El-Shoqafa before the treatment

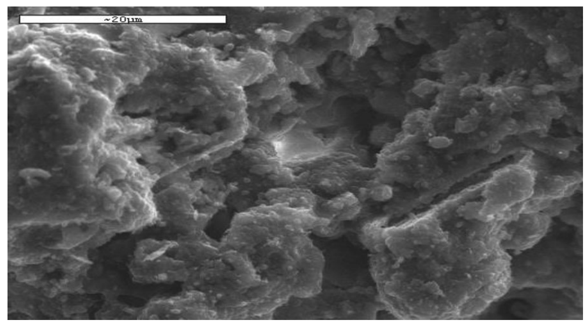


Fig. 10 SEM photomicrograph of treated sandy oolitic limestone specimen, from Catacombs of Kom El-Shoqafa, treated with MTMOS + Wacker BS 15 mixture, Note the uniform coating on the rock particles

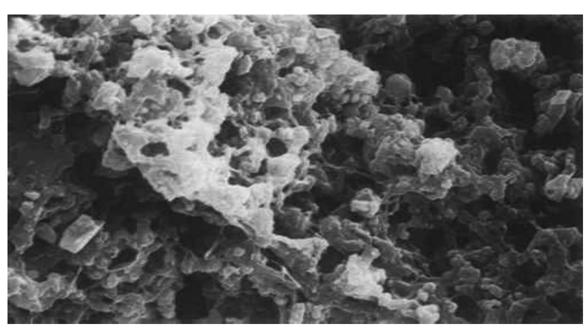


Fig. 11 SEM photomicrograph of an artificially weathered specimen, from Catacombs of Kom El-Shoqafa treated with MTMOS + Wacker BS 15 mixture. Note the formation of a network of resin

Based on these experimental results we decided to use the modified Organosilicone compound (MTMOS + Wacher BS 15) for reinforcement and consolidation of this kind of underground structures as a first step of the appropriate strengthening retrofitting measures especially to reduce the seismic risk, aging and underground water negative effects.

Hybrid composites are formed as a result of parallel reactions of polycondensation of Organisilicone monomers and polymerization of acrylic acids. Interpenetrating polymer networks are formed in these composites. The networks are held by coordination bonds between the oxygen atoms of carboxy groups of acrylic acids and silicon atoms of silicon polymers. The composites have a lamellar structure, indirectly confirming the electrostatic interaction of the silicon and organic blocks of the composites.

Numerical static FE analysis using PLAXIS 2D

Figure 12a, b represent the deformed finite element mesh and boundary conditions used for the numerical analyses of the soft Calcarenitic rock excavations of Catacombs of Kom El-Shoqafa after reinforcement of supporting rock pillars using the Organosilicon compound (polymers) MTMOS + Wacher BS 15, a typical cross section_1.

The results from the preliminary static analysis after treatment applications and reinforcement indicated that the peak total displacements for the Catacombs complex decreased from 1.13 mm to 1.00 mm, while it was = 1.13 mm in the initial model (before treatment applications) and 2.00 mm in the underground water conditions, as shown in Figs. 13 and 14 also the horizontal displacement reduced from $375.25*10^{-6}$ m to $365.26*10^{-6}$ m after the treatment application. In the initial model some supporting rock pillars are under relatively high compression stresses where the calculated peak effective principal stress was $1.42*10^3$ KN/m^2 for the rock pillar_1, as shown in Fig. 15, while it became $1.31*10^3$ KN/m^2 after the reinforcement of rock pillar_1, because of the increasing in dry unit weight and modulus of elasticity after the injection with Organosilicon polymers. For the total strains, Peak principal strain decreased to $-65.45*10^{-3}$%, while it was $= -66.99*10^{-3}$% in the initial model before treatment.

Also it was observed that, after the treatment applications with MTMOS + Wacker BS 15, the factor of safety for the supporting rock pillars increased from 1.47 to be 1.53 which is adequate for the mechanical stability of the Catacombs.

Table 3 summarizes the results of the static numerical analysis using PLAXIS 2D before and after the treatment applications.

Numerical seismic FE analysis using PLAXIS 2D

The preliminary seismic analysis of the Catacombs with three seismic scenarios of different PGA values 0.08, 0.16 and 0.24 g proved that some critical supporting parts of the Catacombs structure (i.e. supporting rock pillars and columns) are safe without any strengthening measures only for PGA values lower than 0.10 g, which is rather low considering the seismic activity and the past seismic history of the city. The seismic performance assessment of these Catacombs discovered that, the shear force caused by a possible earthquake could exceed the bearing force capacity of the sidewalls and central pillars.

Figures 16 thorough [25] are summarizing the calculated effective compressive and shear stresses and displacements for the three PGA scenarios for the three design earthquakes (Kalamat, Erzincan and Aqaba) after the treatment applications and reinforcement of supporting rock pillars inside the Catacombs complex, using the Organosilicon compound (polymers) MTMOS + Wacker BS 15.

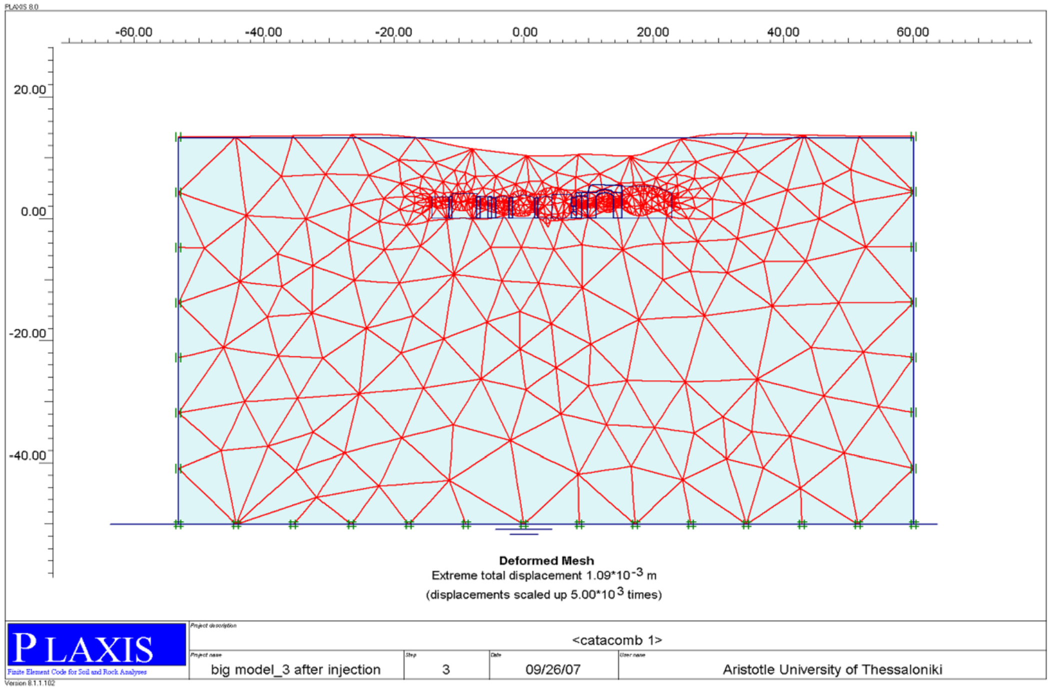
It is obvious that after the reinforcement processes, all the input motions (Aqaba, Erzincan and Kalamata earthquakes) give much lower displacements values for all the complex especially the supporting rock piers than before reinforcement (the initial model).

The maximum horizontal displacement at the top of Catacombs for Aqaba EQ at PGA = 0.24 g earthquake scenario was: Ux is 7.91 cm, while it was 7.95 cm before the reinforcement processes, and this is under peak vertical effective principal compressive stresses = -2900 kN/m^2 while it was -4190 kN/m^2 in the initial model before treatment applications.

In the cases of Erzincan and Kalamata 0.24 g scenarios the respective horizontal displacements values are 2.3 cm and 1.90 cm respectively, while it was 2.34 cm and 2.01 cm before treatment and reinforcement processes (initial model). Figure 17 represents the Acceleration—time histories. (a) Kalamata RQ, (b) Erzincan RQ, (c) Aqaba RQ. PGA = 0.24 g, after treatment and reinforcement of rock pillars.

For the maximum vertical displacement values after the treatment applications and reinforcement of rock pillar_1 it is 6.0 mm, 1.5 mm, and 2.6 mm for Aqaba, Erzincan and Kalamata earthquakes respectively at PGA = 0.24 g, while it was 6.5 mm, 2.3 mm, and 3.0 mm in the initial models before treatment applications, as shown in Fig. 18.

In addition, it was observed that the maximum differential horizontal displacements of the top and the base of the rock pillars are of the order of 2–3 mm. The reinforcement of rock pillar_1 relieved the effective stresses on the other supporting rock pillars under the static and seismic loading, considering that the induced seismic ground deformations are better correlated with the intensity of damages in underground structures.



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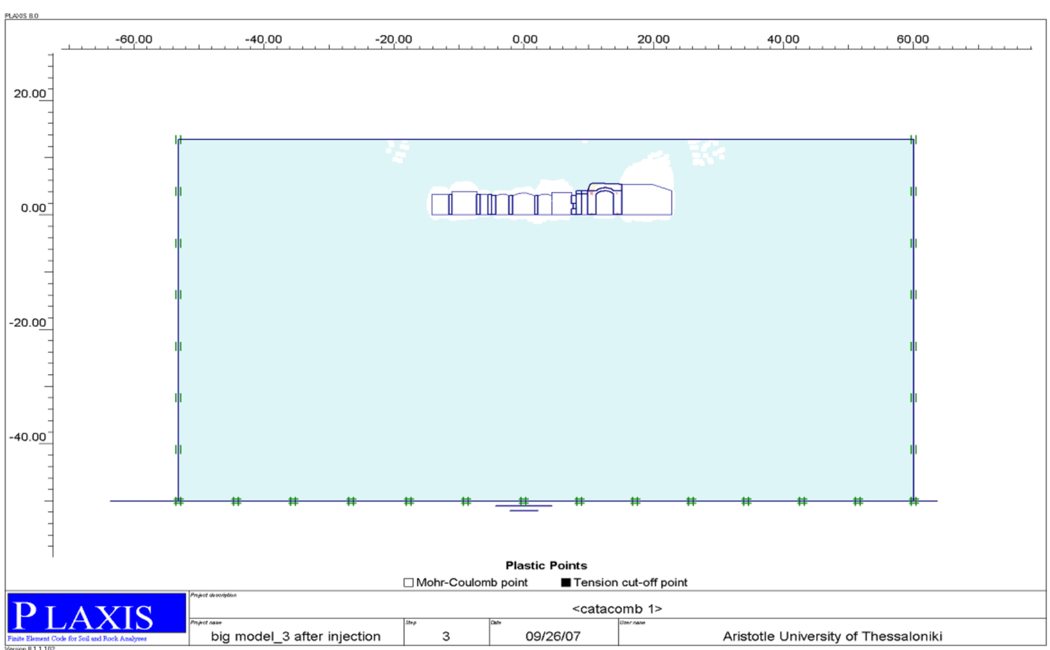

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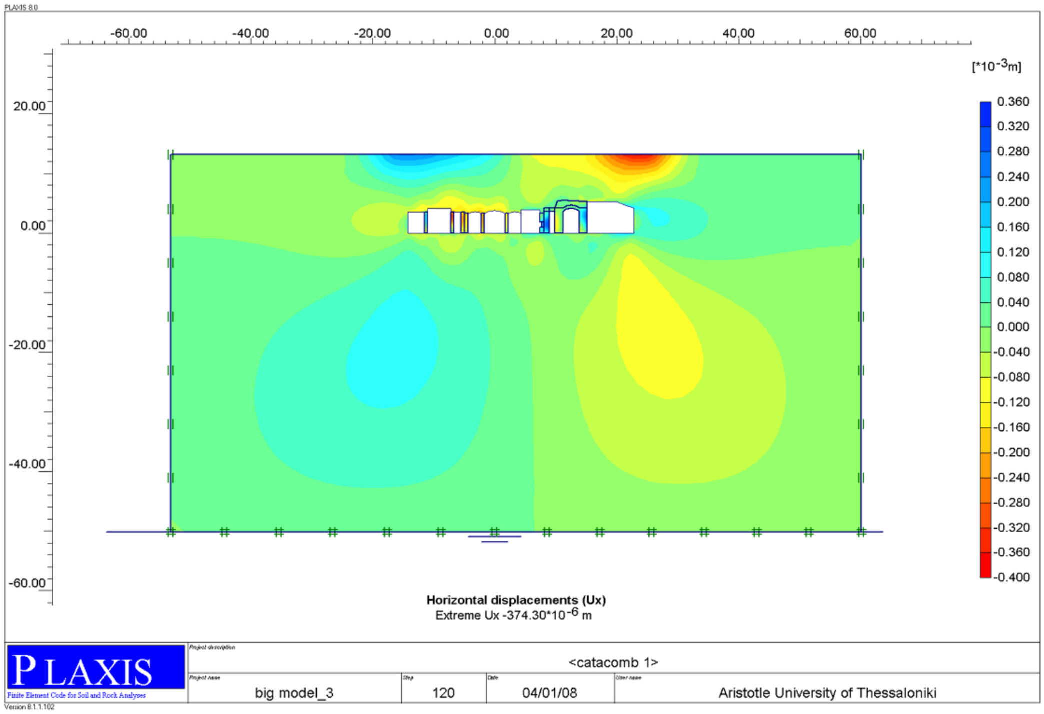
Fig. 12 **a** Deformed mesh and boundary conditions. **b** Plastic points distribution through the Catacombs. Static analysis. After reinforcement of supporting rock pier_1



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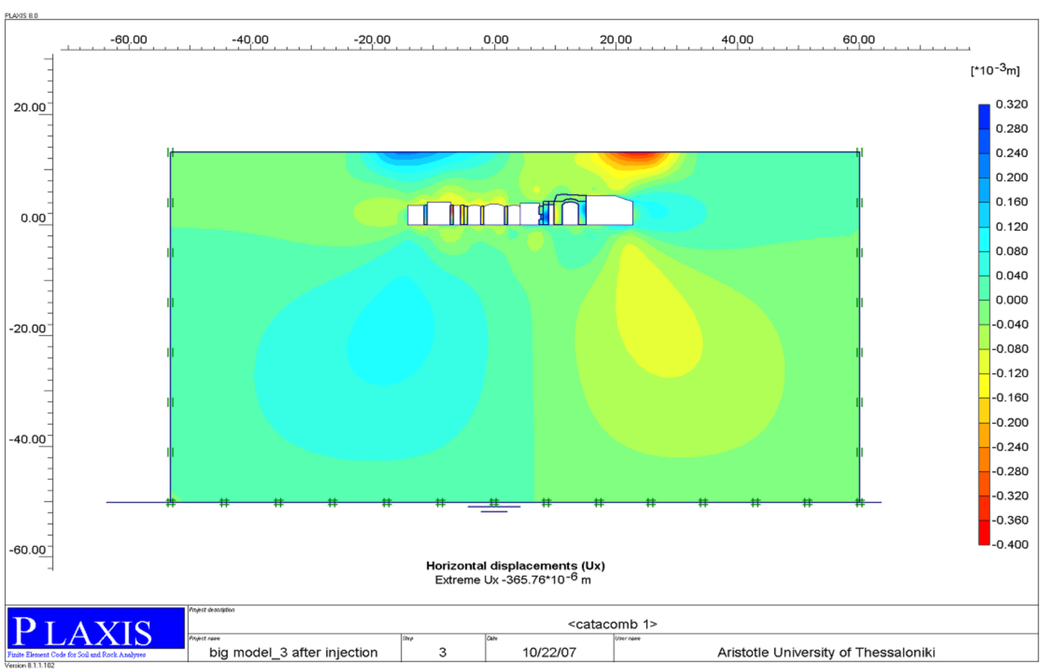

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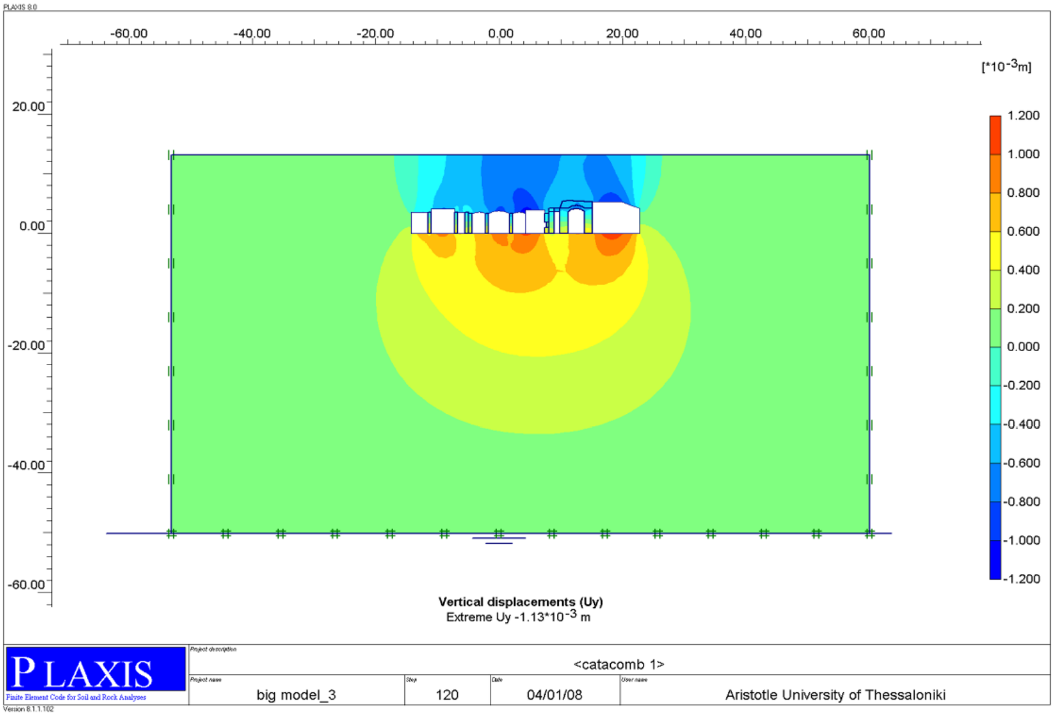
Fig. 13 Horizontal displacements **a** Peak horizontal displacements Ux = 75.85*10^{-6} m in the initial model. **b** Peak horizontal displacementsUx = 365.76*10^{-6} m after reinforcement of rock pier_1



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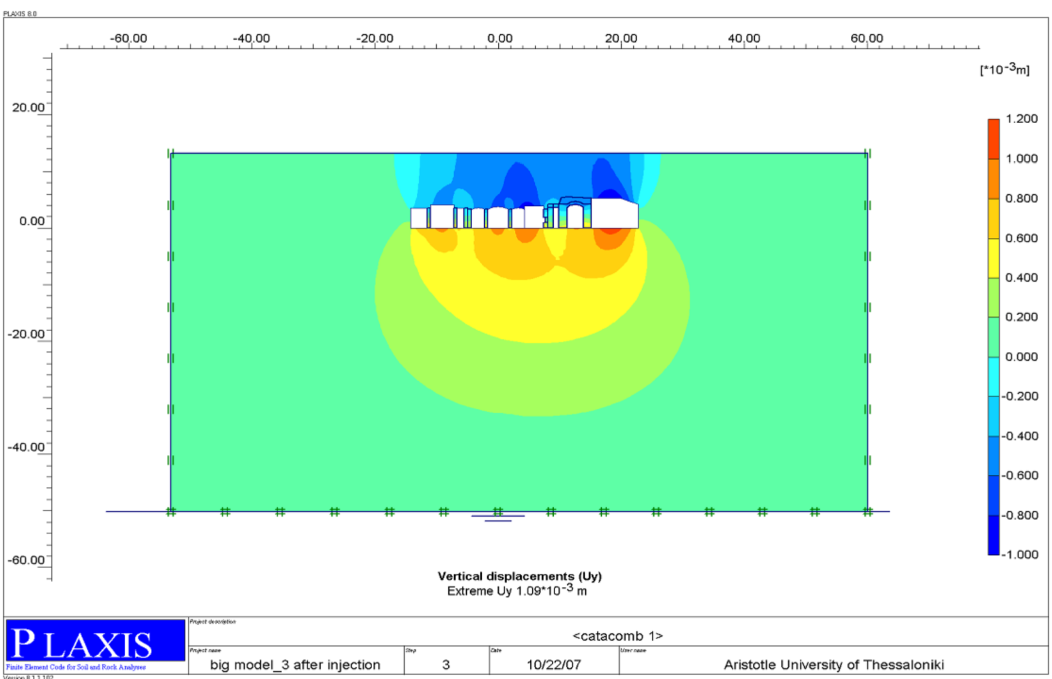


(b)

Fig. 14 Vertical displacements **a** Peak vertical displacements Uy = 1.13*10^{-3} m In the initial model. **b** Peak vertical displacements Uy 1.00*10^{-3} m after reinforcement of rock pier_1

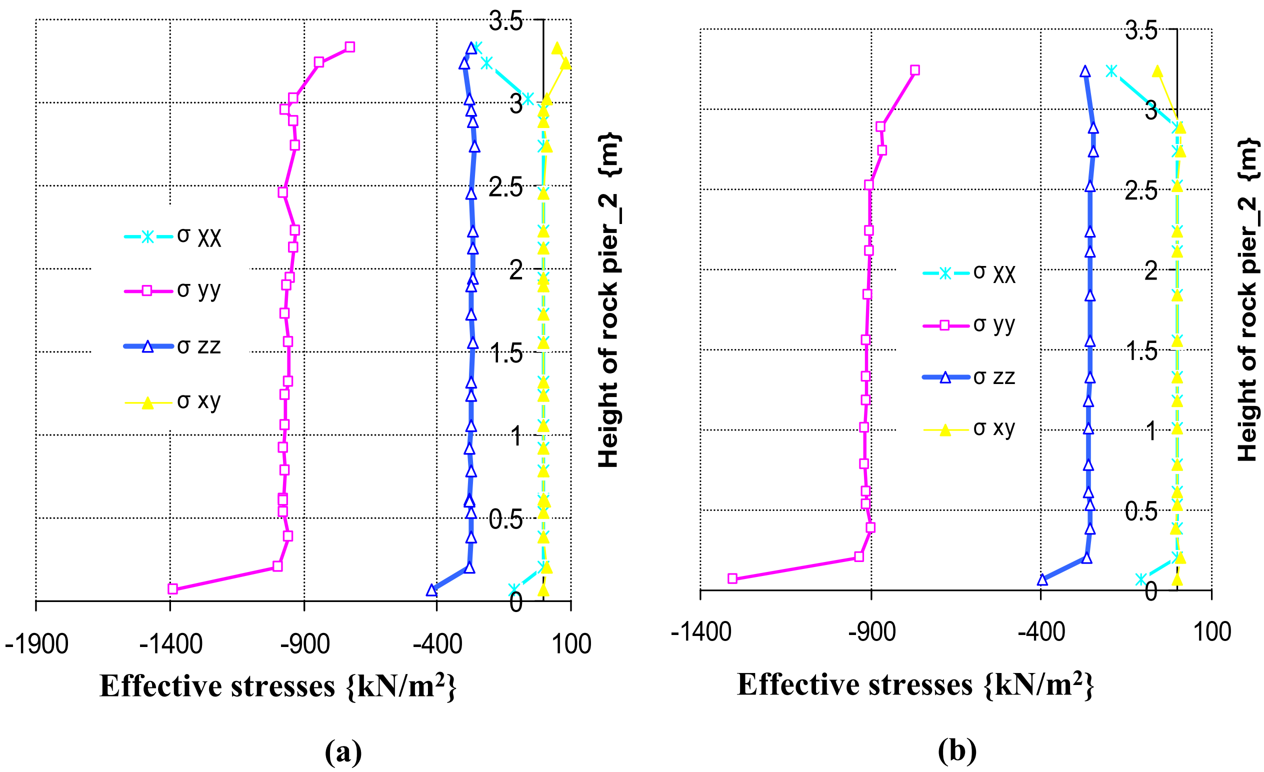


Fig. 15 Effective compressive stresses distribution through the supporting rock piers_2 (**a**) Initial model. **b** After reinforcement of rock pier_1. Static analysis

Table 3 The results of the static numerical analysis using PLAXIS 2D before and after the treatment applications

Parameter	Before treatment application	After treatment application
Total displacement U (mm)	1.13	1.00
Horizontal displacement Ux (mm)	0.375.25	0.365.26
Peak effective principal compressive stresses on pillars (kN/m^2)	1.42*10^3	1.31*10^3
Total strain (%)	– 66.99*10^{-3}	– 65.45*10^{-3}
Factor of safety (Fs)	1.47	1.53

Figure 19 represents the calculated 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 reinforcement of rock pillar_1.

Figure 20 represents the effective vertical compressive stresses σ/YY—time histories for the most critical rock Pillar _1 (the right side of rotunda). (a) Kalamata RQ (b) Erzincan (c) Aqaba RQ. The PGA value = 0.24 g, after treatment application and reinforcement of rock pillar_1.

Figure 21 represents the effective shear stresses σ/XY—time histories for the most critical rock Pillar_1. (a) Kalamata RQ (b) Erzincan (c) Aqaba RQ. The PGA value = 0.24 g, after treatment application of rock pillars_1.

Figure 22 represents the vertical displacement—time histories for rock pillar_1 after treatment application and reinforcement. (a) Kalamata RQ, (b) Erzincan RQ, (c) Aqaba RQ. PGA = 0.24 g.

Figure 23 represents the vertical displacement—time histories for the top of rock pillar_1. Before and after treatment applications. (a) Kalamata RQ, (b) Erzincan RQ, (c) Aqaba RQ. PGA = 0.24 g.

Given the value of the static strength estimated in the laboratory after consolidation processes, the UCS of the rock material = 6.2 MPa and the shear

(See figure on next page.)

Fig. 16 Deformed mesh and peak total displacement, the final step, **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. The PGA = 0.24 g. After reinforcement of rock pier_1

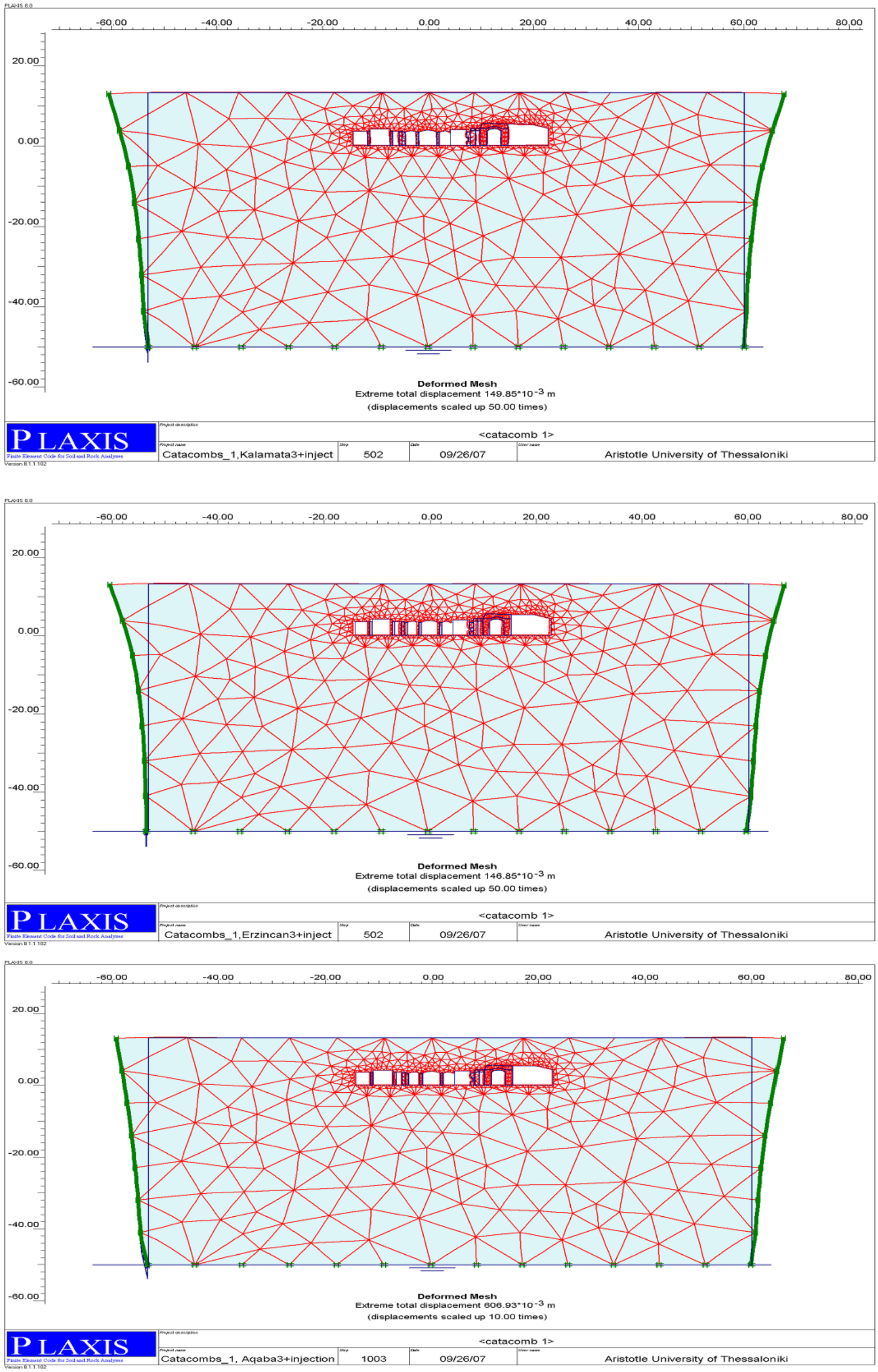


Fig. 16 (See legend on previous page.)

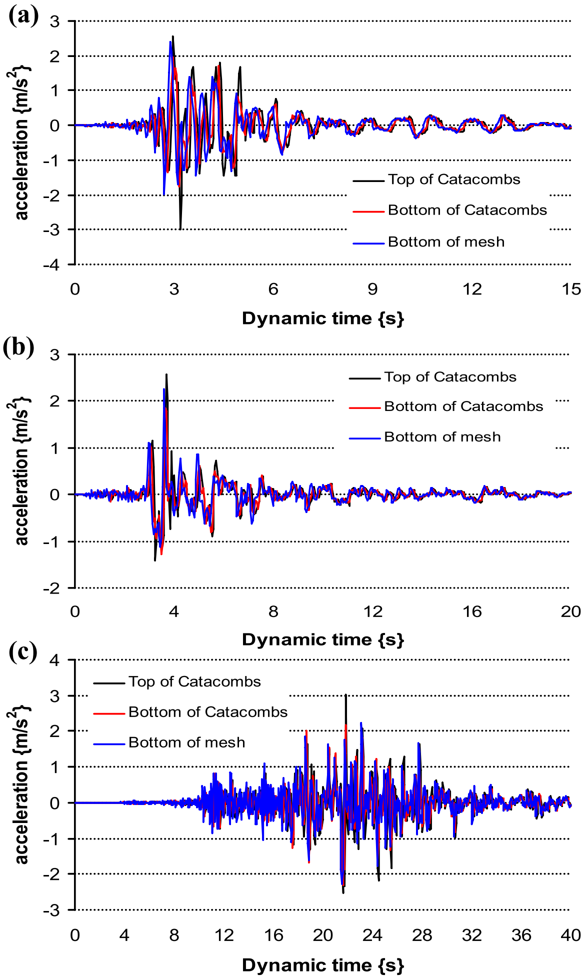


Fig. 17 Acceleration—time histories. **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. PGA = 0.24 g. After reinforcement of pier_1

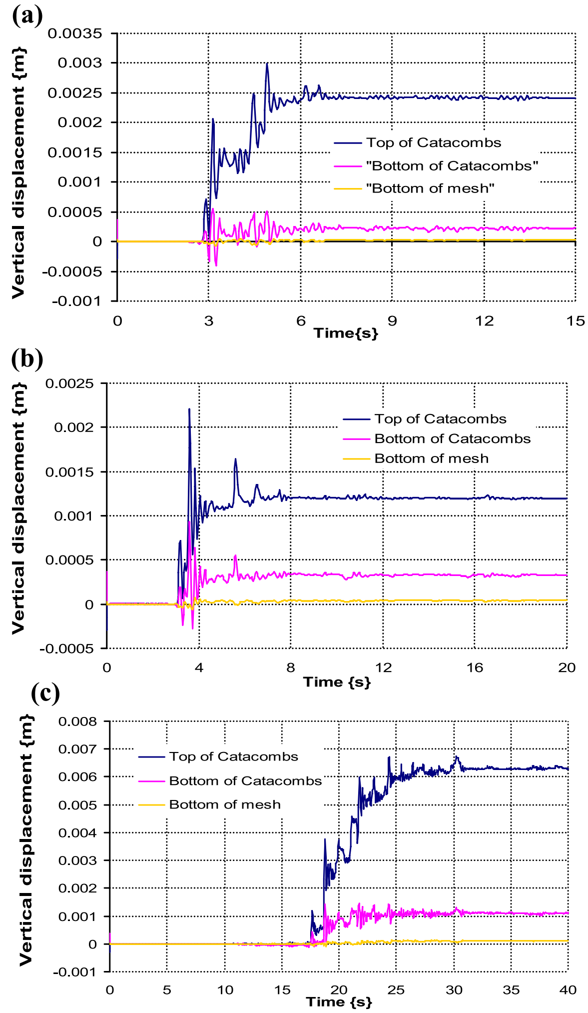


Fig. 18 Vertical displacement—time histories. **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. PGA = 0.24 g. After reinforcement of rock pier_1

strength = 0.750 MPa, the seismic analysis of the Catacombs complex after reinforcement of rock pillar_1 proved that the rock pillarss, which are the most vulnerable parts of the whole complex, are now rather safe for PGA values lower than 0.24 g seismic scenario in cases of the Kalamata, Erzincan, and Aqaba earthquakes, as shown in Figs. 24, 25. For large earthquakes more than PGA = 0.24 g, which are most likely to happen in the region, the seismic stability of the Catacombs is not satisfied even their seismic performance is upgraded after treatment and reinforcement, and it is necessary to proceed for more effective seismic isolation method to protect the catacombs against strong earthquakes.

The numerical analysis using the PLAXIS 2D indicated the efficiency of the pre-stressed anchors and concrete friction piles (with the mentioned specifications in section three) in the permanent stabilization of the underground heritage sites like Catacombs of Kom El-Shoqafa in Alexandria which suffers the negative impact of climate change in recent years.

Table 4 summarizes the results of the seismic numerical analysis using PLAXIS 2D before and after the treatment applications.

Conculsions

The rock Formation, into which the Roman Catacombs of Kom El-Shoqafa are excavated or constructed, is a horizontally bedded, unjointed Calcarenitic rock Formation. These rock structures are highly weathered with considerably low mechanical strength, and high porosity due to the negative impact of climate change. Considering all other affecting factors specially the weathering, underground water and the specific geometry of these complexes, this low rock strength affects seriously the safety

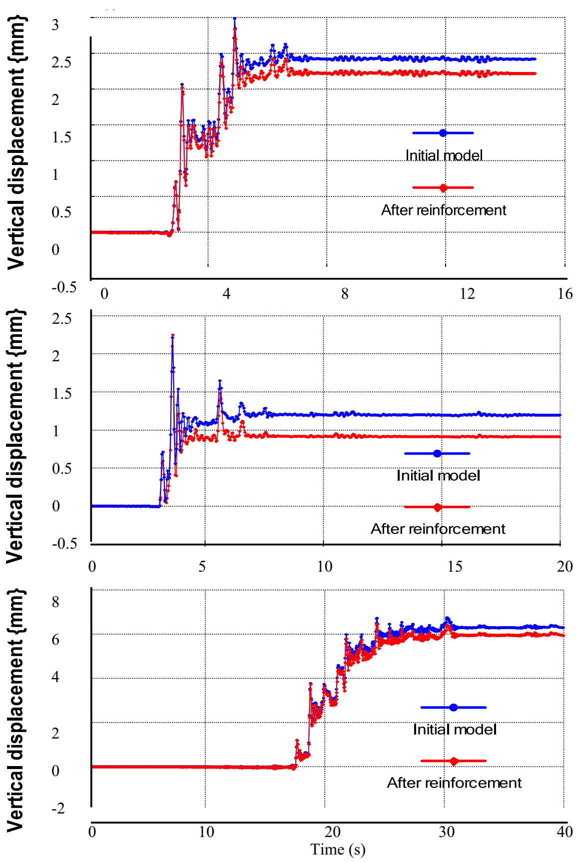


Fig. 19 Vertical displacement—time histories on the top of Catacombs (**a**) Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. PGA = 0.24 g. Before and after reinforcement of rock pier_1

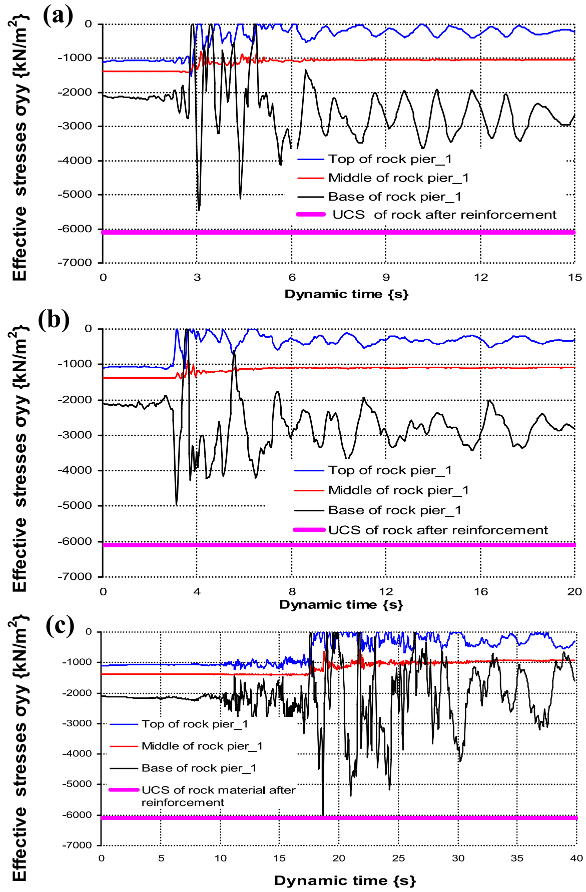


Fig. 20 Effective vertical compressive stresses σ/YY—time histories for the most critical rock Pier _1 (the right side of rotunda). **a** Kalamata RQ **b** Erzincan **c** Aqaba RQ. The PGA value = 0.24 g. After reinforcement of rock pier_1

of these unique Catacombs under the static and seismic loading conditions.

These outstanding underground monumental structures (Catacombs of Alexandria) need considerable strengthening measures and specific stabilizing configurations to improve their global behavior against the negative impact of salt weathering, underground water activities, and other geo-environmental hazards.

Based on the experimental results, the modified Organosilicone compounds (MTMOS + Wacher BS 15) was recommended for the treatment and consolidation of the most critical supporting rock pillars and sidewalls inside the Catacombs of Kom El-Shoqafa as a first step of the appropriate strengthening retrofitting measures especially to reduce the negative impact of climate change on this kind of underground structures, also to upgrade the global seismic behaviour of the whole complex of the Catacombs against strong earthquakes, where the supporting rock pillars are the most critical parts in the complex.

Here we present the main results of the experimental (testing procedures) and numerical analyses (static and seismic analysis) of this complex before and after the intervention (treatment applications) for the rock pillars and sidewalls, to detect the effectiveness of these new injection methods and stabilizing configurations (Prestressed anchors and friction piles) in preservation of underground heritage sites.

In general, it can be emphasized that the extreme climate events and gradual climate change are affecting all kinds of culture Heritage in particular the underground culture heritage in the coastal cities of the Mediterranean and all over the world.

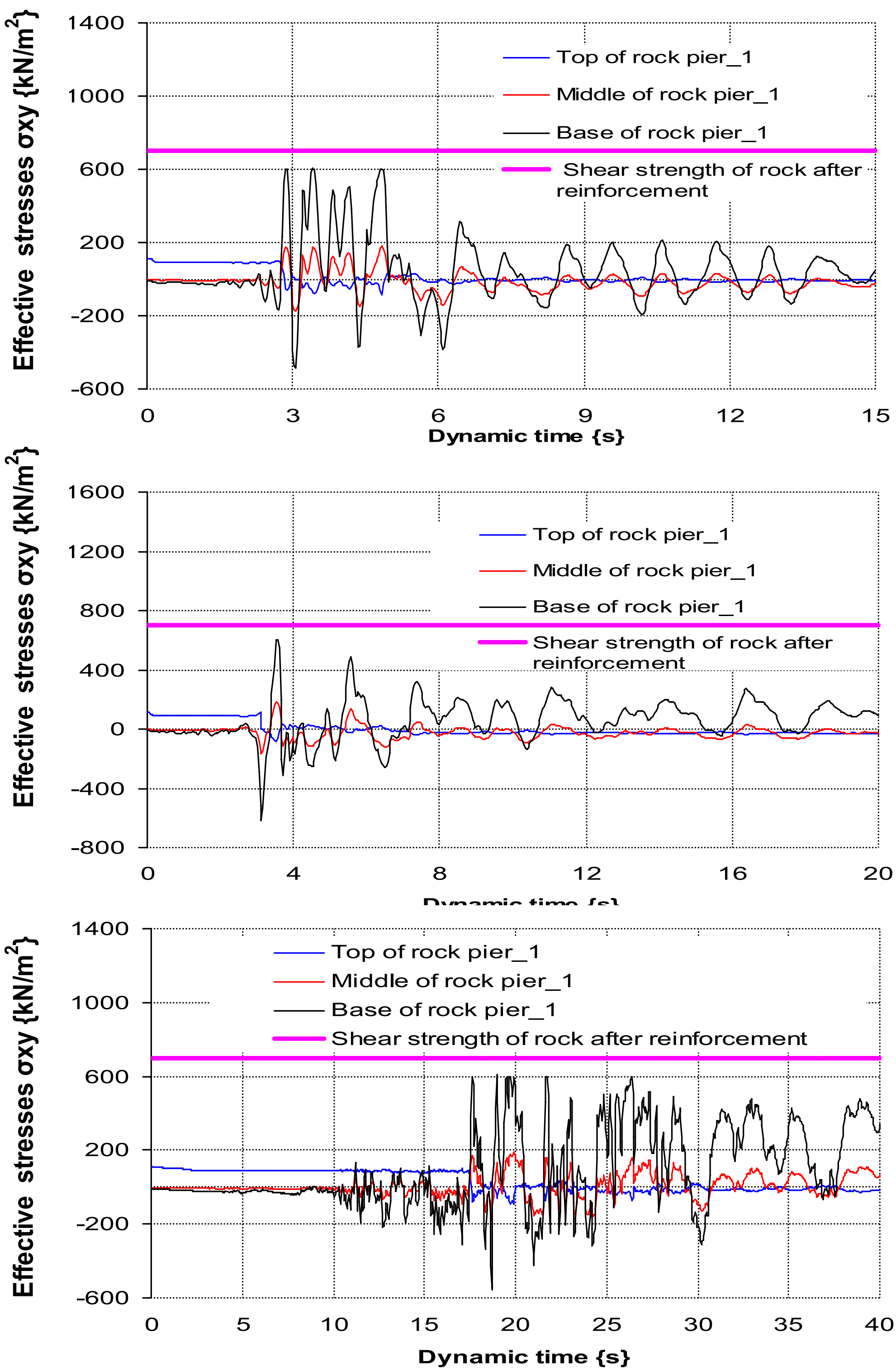


Fig. 21 Effective shear stresses $\sigma/_{XY}$—time histories for the most critical rock Pier _1. **a** Kalamata RQ **b** Erzincan **c** Aqaba RQ. The PGA value = 0.24 g. After reinforcement of rock pier_1

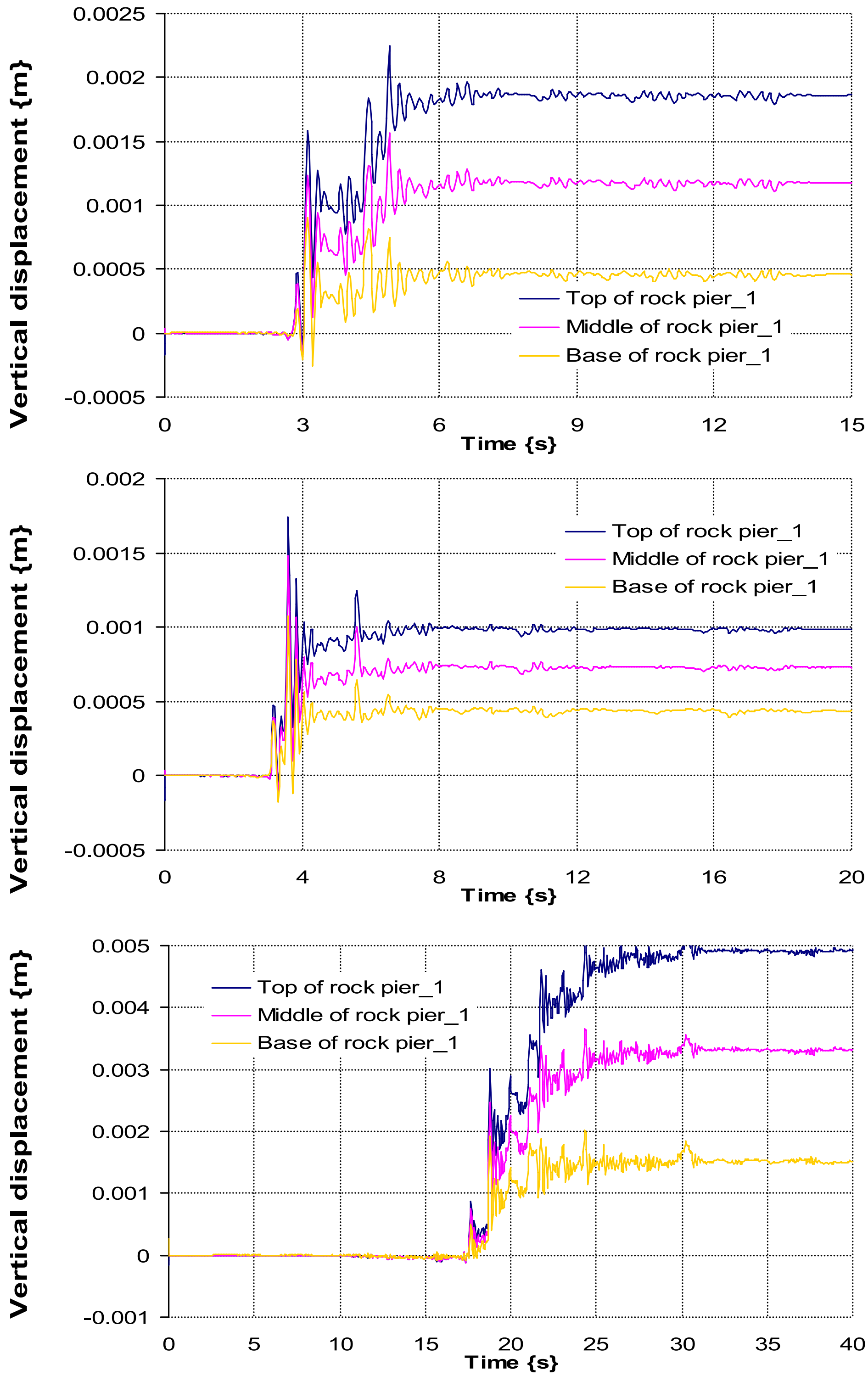


Fig. 22 Vertical displacement—time histories for rock pier_1 after reinforcement. **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. PGA = 0.24 g

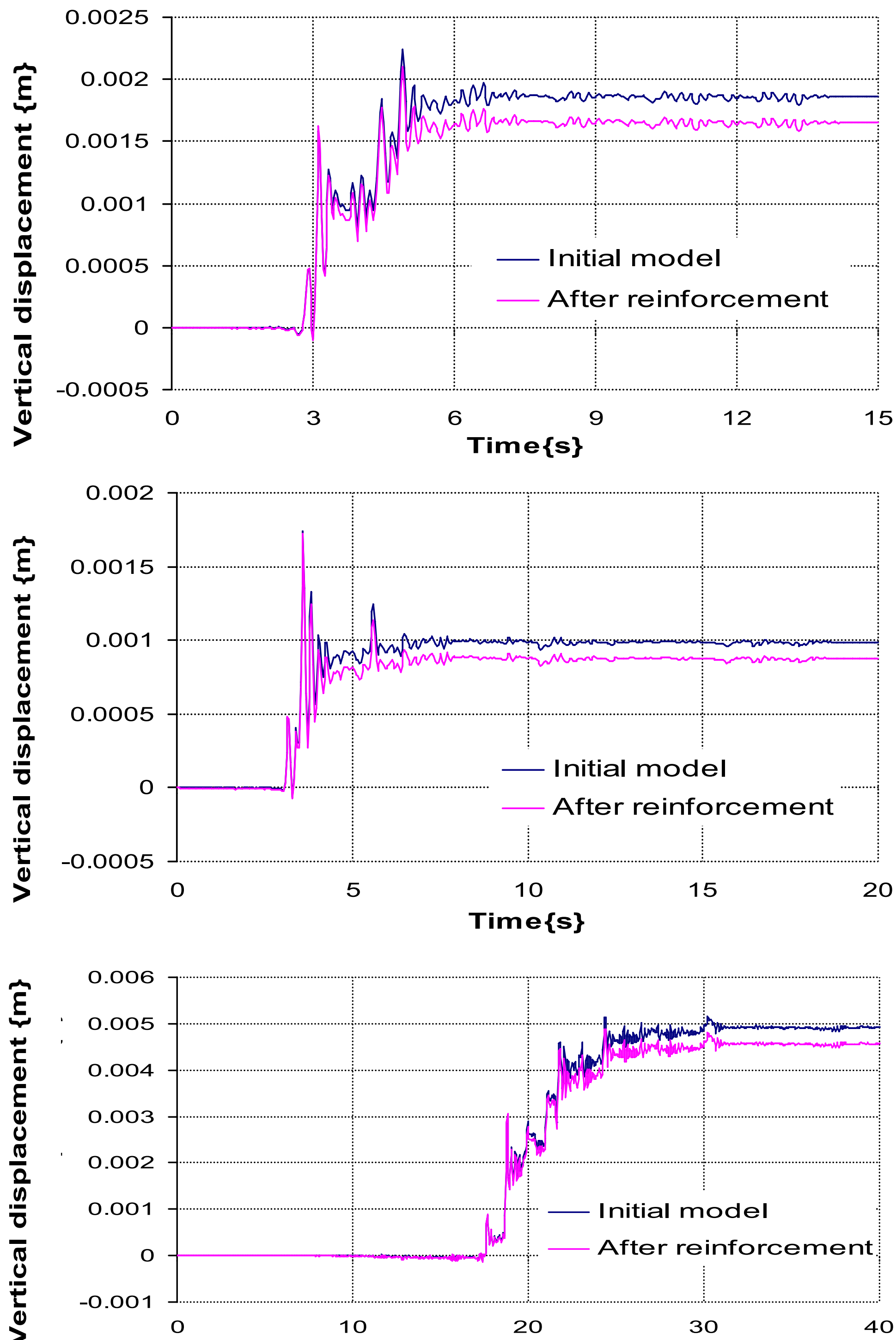
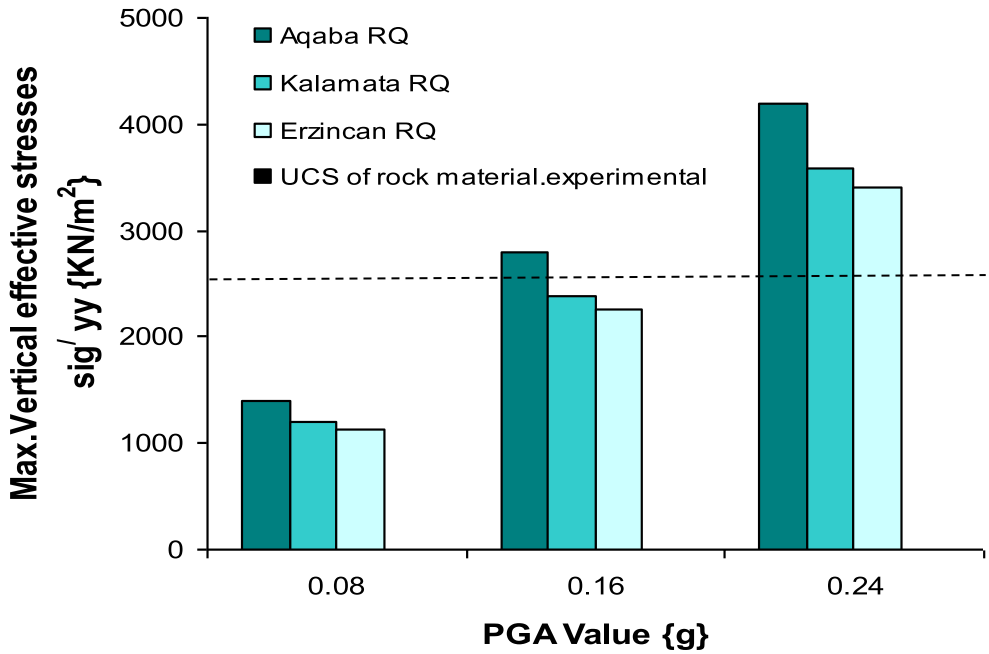


Fig. 23 Vertical displacement—time histories for the top of rock pier_1. Before and after reinforcement. **a** Kalamata RQ, **b** Erzincan RQ, **c** Aqaba RQ. PGA = 0.24 g



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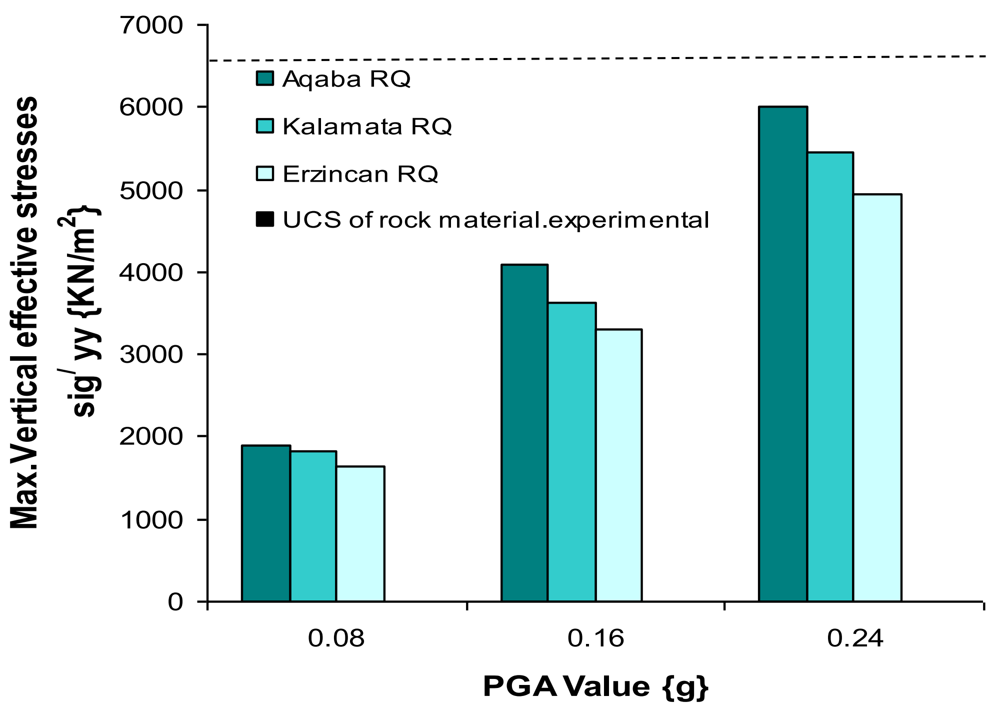

(b)

Fig. 24 Maximum vertical effective stresses sig/yy on the base of rock pier_1, for Aqaba, Erzincan, and Kalamata earthquakes, scaled to several values of PGA. **a** Initial model **b** After reinforcement of rock pier _1

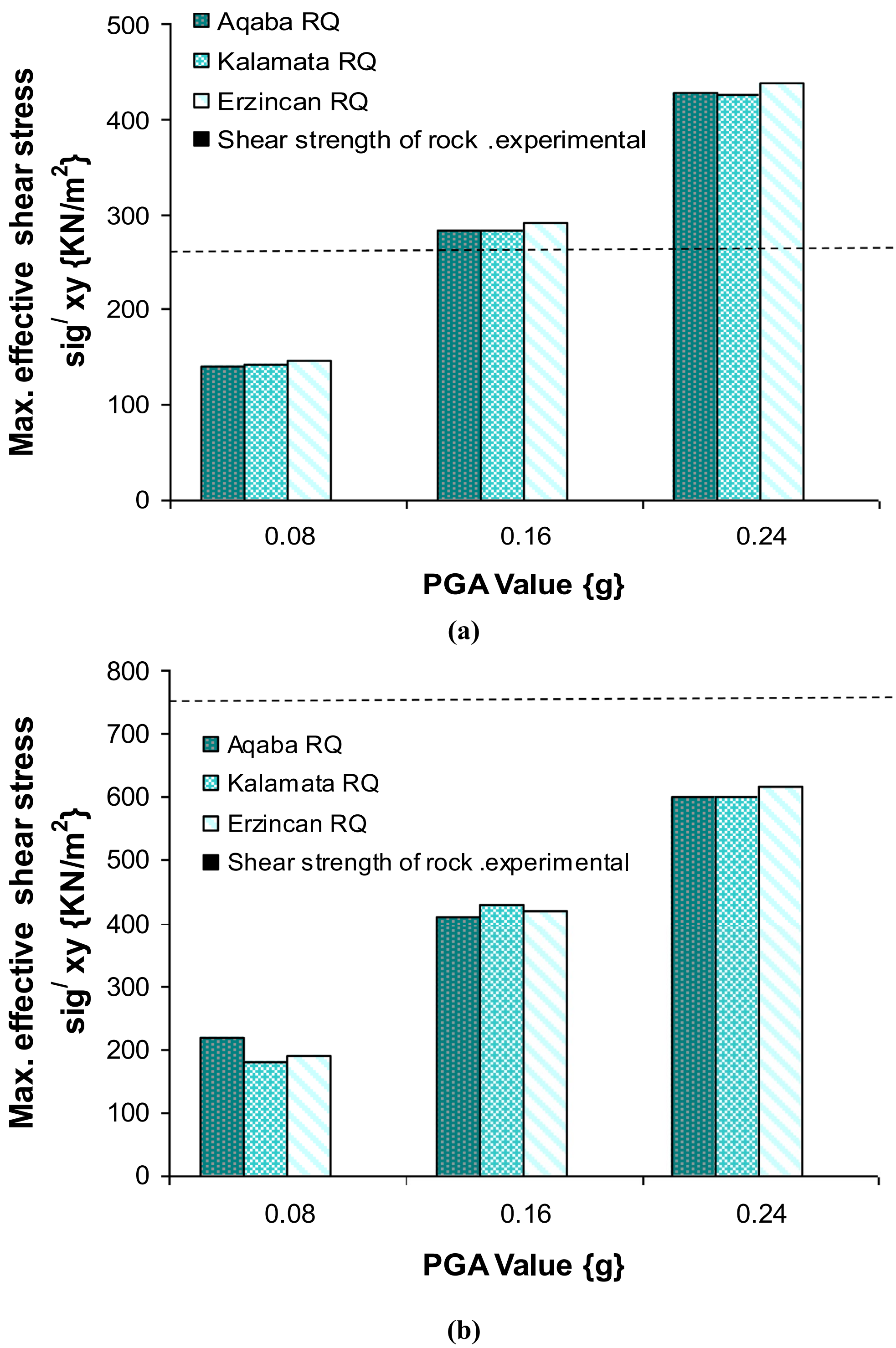

Fig. 25 Maximum effective shear stresses sig./xy on the base of rock pier_1, for Aqaba, Erzincan, and Kalamata earthquakes, scaled to several values of PGA. **a** Initial model **b** After reinforcement of rock pier _1

Table 4 The results of the seismic numerical analysis using PLAXIS 2D before and after the treatment applications

Parameter	Before treatment application	After treatment application
Max horizontal displacement Ux (mm) Aqaba EQ PGA = 0.24	79.5	79.1
Max horizontal displacement Ux (mm) Erzincan EQ PGA = 0.24	23.5	23
Max horizontal displacement Ux (mm) Kalamata EQ PGA = 0.24	20	19
Max vertical displacement Uy (mm) Aqaba EQ PGA = 0.24	6.5	6
Max vertical displacement Uy (mm) Erzincan EQ PGA = 0.24	3	2.5
Max vertical displacement Uy (mm) Kalamata EQ PGA = 0.24	2.3	1.5
Peak effective principal compressive stresses (kN/m^2) Aqaba EQ PGA = 0.24	− 4190	− 2900

There are still many gaps in understanding and knowledge about climate change impact on Culture Heritage. The big challenges for the conservators are the relevant and reliable data are missing. Also it is difficult to collect the information. Unfortunately many national adaptation plans do not consider culture heritage. Lack of awareness about urgency to adapt exists on all levels push us for more future studies and research regarding the impact of climate change and mitigation strategies to protect our culture and natural heritage in particular in the coastal cities.

Future studies should consider the broader impact of climate change on archaeological sites, particularly in vulnerable areas like the northern Nile Delta. Advanced remote sensing methods and modern satellite data analysis, as demonstrated by Hagage et al. [33] in their study of archaeological landscapes in the northeastern Nile Delta, could provide valuable insights into these impacts. Additionally, the risks posed by urban sprawl to buried heritage sites, as explored by Hagage et al. [34] in their analysis of Akhmim city, should be taken into account when developing conservation strategies for underground structures like the Catacombs of Kom El-Shoqafa.

Author contributions
The Author wrote the main manuscript text and prepared all figures. also the author reviewed the manuscript.

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Declarations

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Competing Interests
The authors declare no competing interests.

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