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GEOTECHNICAL, GEOPHYSICAL INVESTIGATIONS AND SEISMIC RESPONSE ANALYSIS OF THE UNDERGROUND TOMBS IN MUSTAFA KAMIL NECROPOLIS, ALEXANDRIA, EGYPT

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ABSTRACT

The paper presents the geotechnical, geophysical investigations and the numerical static and seismic analysis of selected underground monuments in Alexandria, Egypt i.e. the underground tombs in Mustafa Kamil Necropolis. The analysis of the static stability and the behavior of complex monuments of this kind under seismic loading, are the key factors for the efficient restoration and retrofitting of these underground monumental structures.

In the present paper, we present in a first phase a comprehensible geotechnical survey undertaken in this site, comprising geophysical ambient noise measurements (microtremors), as well as field and short – long-term laboratory experiments and tests, in order to define the physical, mechanical and dynamic properties of the soils and soft rock materials. In the second stage, we present the main results of the detailed static and seismic numerical analysis of these underground monumental structures (Catacombs) using the code, PLAXIS b.v with different seismic scenarios corresponding to the seismotectonic features of Alexandria. Advanced soil-rock elastoplastic modeling has been used through out the different phases of the numerical finite element analysis.

The aim of the analysis is twofold: (a) to investigate the safety margins of the existing monuments, under their present conditions, against environmental (i.e. weathering) and extreme seismic loads and (b) to investigate the potential improvement of their global behavior applying specific retrofitting techniques.

KEYWORDS: Necropolis of Mustafa Kamil, Alexandria underground monuments, geotechnical problems, geotechnical investigations, microtremors, creep tests, stability and seismic analysis of underground structures

1. INTRODUCTION

Alexandria, a place of great historical and religious interest is located in eastern part of the Mediterranean Basin (Northern Egypt). Numerous Catacombs, Necropolis and Cemeteries for Greek-Roman erected in Greek-Roman and Christian era has been found. They represent actually a large complex of an underground Necropolis. The aim of the present study is the investigation and documentation of the existing stability conditions of the geological formations at a site of Mustafa Kamil Necropolis in order to define the instability problems to interpret the pathology and to propose the best retrofitting procedure.

Mustafa Kamil Necropolis site has four tombs have been excavated into limestone bedrock. Tombs No.1 and No. 2 are completely excavated in intact Calcarenitic bedrock, while tombs No.3 and No.4 are partially excavated and in a direct contact with the sub-aerial processes. Tombs 3 and 4 are completely deteriorated. With the time blocks, falling has occurred from the ceiling and the wall. In most of these two tombs (tomb 1, and 2) and the processes are irreversible. Real possibilities exist to preserve the tourist site only if appropriate enforcing intervention is realized.

The stability conditions of the historical monuments are of crucial interest, especially in regions like the Mediterranean Basin and particularly Alexandria, Egypt, where the seismotectonic and weathering regime is active and the geological structure is complex.

2. PROBLEM DESCRIPTION

The site: Mustafa Kamil Necropolis lies on the Northeast of Alexandra, not far from the so-called Stalli Bridge, on the top of the hill. The area called Mustafa Kamil pasha (the military houses and the camp of the British military in Alexandria). This Necropolis lies at about 150-200 meters from the seashore, and it is higher in topography than El-Shatbi and new bibliotheca Alexandrina area, see (Figure 1).

The structure: Its rock –cut rooms and galleries characterize the ***first tomb***. A broad stairway leads to a square court with a central altar. The court is surrounded by Doric semi –columns, all cut into the walls, and leads to ten rooms on the four sides. The plan of the ***second tomb*** consists of a stairway leading to a central courtyard. To the south stand two Doric columns at the entrance of the room, that has luculi on both sides. Another room, with two benches and luculi on both sides, is accessible. It was probably used for prayer. At the end is a small room, in front of which a limestone-offering table coated with colored plaster in imitation of alabaster was found. See (Figures 3 and 4).

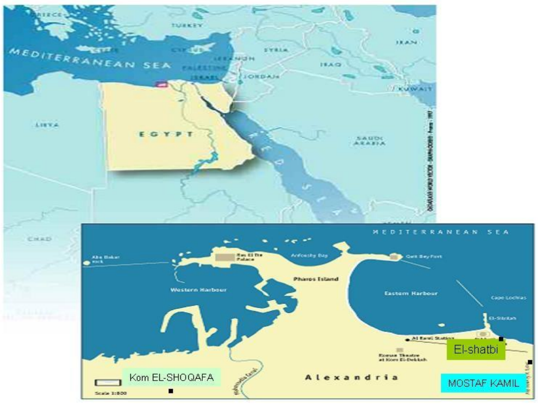


Figure 1 Location map of Alexandria, Egypt..

Figure 2 Necropolis of Mustafa Kamil in Alexandria, (general view).

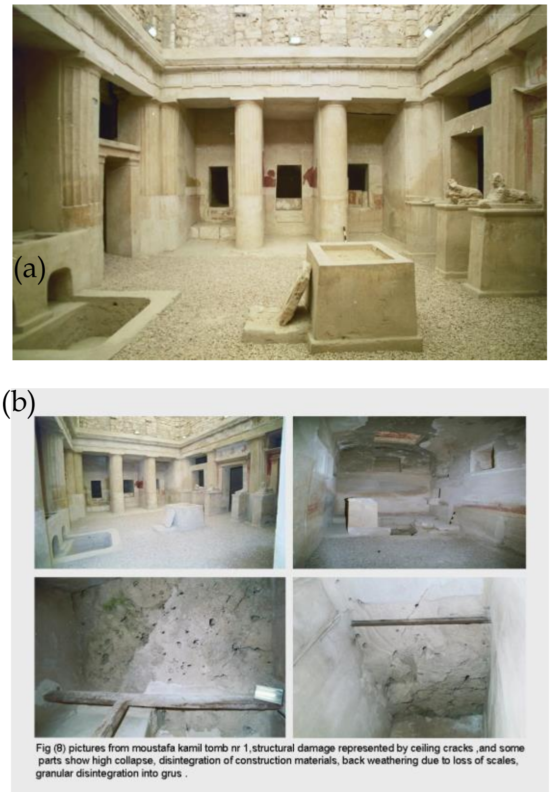


Fig (8) pictures from moustafa kamil tomb nr 1,structural damage represented by ceiling cracks ,and some parts show high collapse, disintegration of construction materials, back weathering due to loss of scales, granular disintegration into grus .

Figure 3. Necropolis of Mustafa Kamil in Alexandria, a, b (tomb_1)
Damage represented by columns buckling, ceiling cracks, and some parts show high collapse. Weathering is obvious on walls and ceilings.

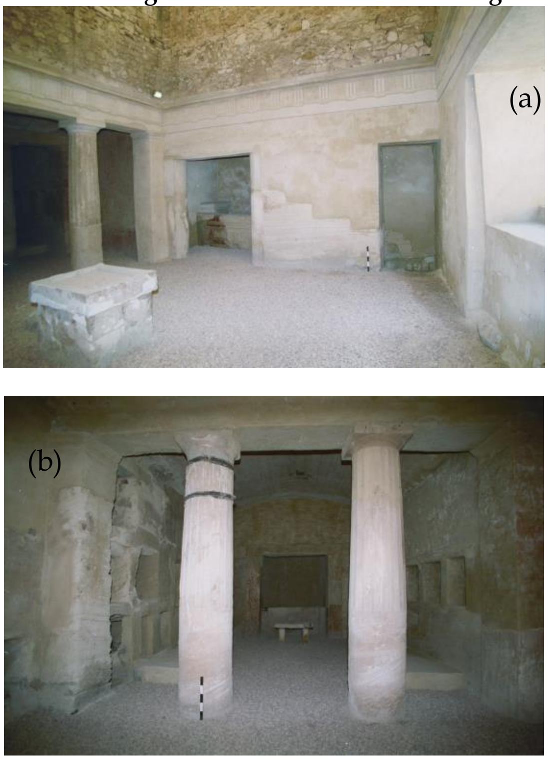


Figure 4. Necropolis of Mustafa Kamil in Alexandria, a, b (tomb_2)
Damage represented by columns buckling, ceiling cracks, and some parts show high collapse. Weathering is obvious on walls and ceilings.

Pathology and causes : Mustafa Kamil Necropolis 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, 1intense 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, columns buckling 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.

The majority of structural damage 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 far away from seashore (Catacombs of Kom EL-Shoqafa and Amod EL-Sawari or Pompey's Pillar archaeological area) (Hemeda et al. 2007).

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 damage "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.

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.

3.GEOTECHNICAL INVESTIGATIONS

The geotechnical investigation comprise four sampling geotechnical boreholes with SPT measurements carried out at the arch aeological site of Mustafa Kamil Necropolis (Figure 7) show a representative profile of Geotechnical Borehole Number_1 .

The RR=18 and RQD=15-20% for the extracted Calcarenitic rock samples.

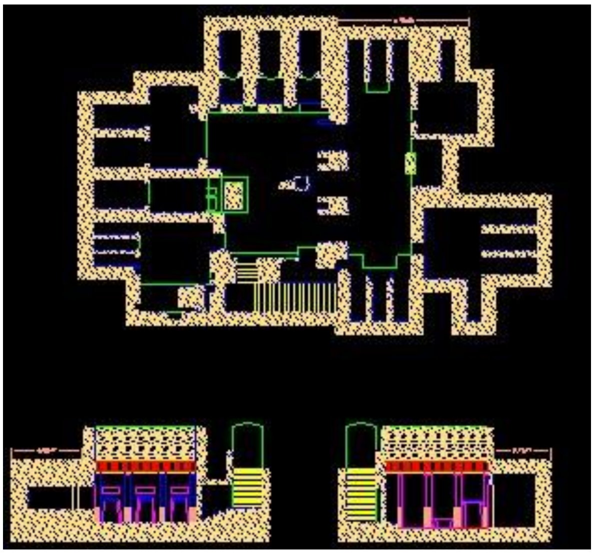


Figure 5. Plan and a typical cross section A-A/ , B-B/ of Mustafa Kamil, Tomb number_1

Figure 6. Plan and a typical cross section A-A/ of Mustafa Kamil, Tomb number_2

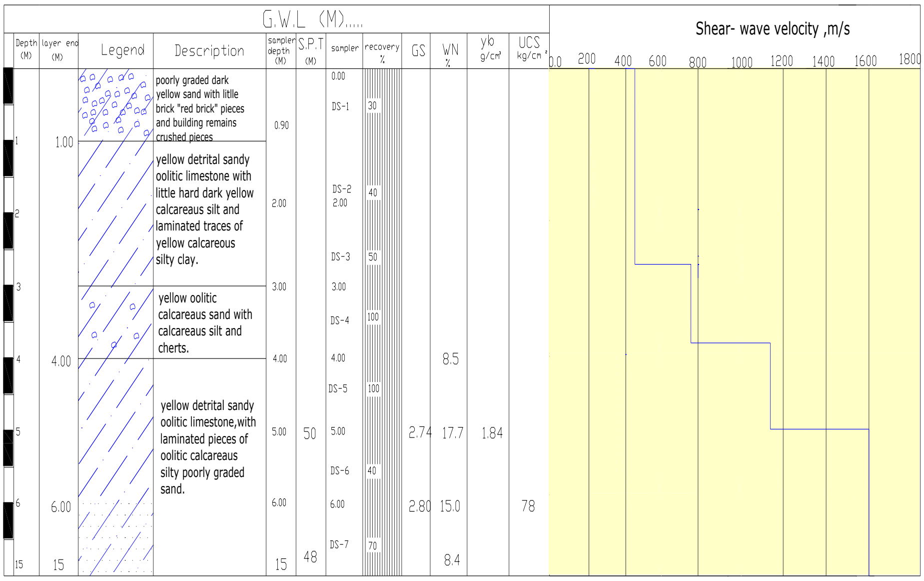
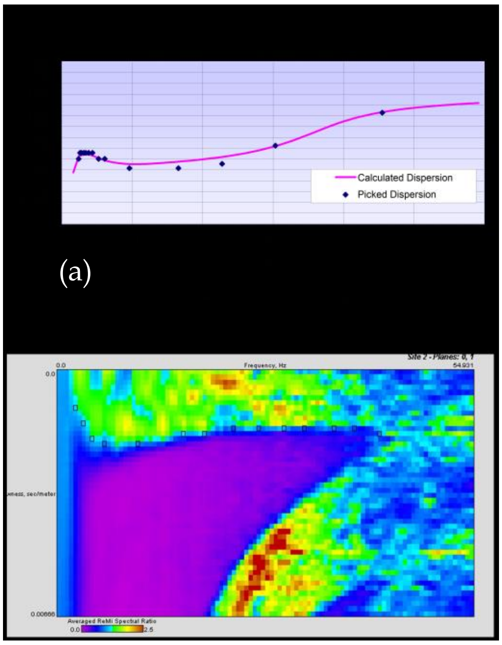


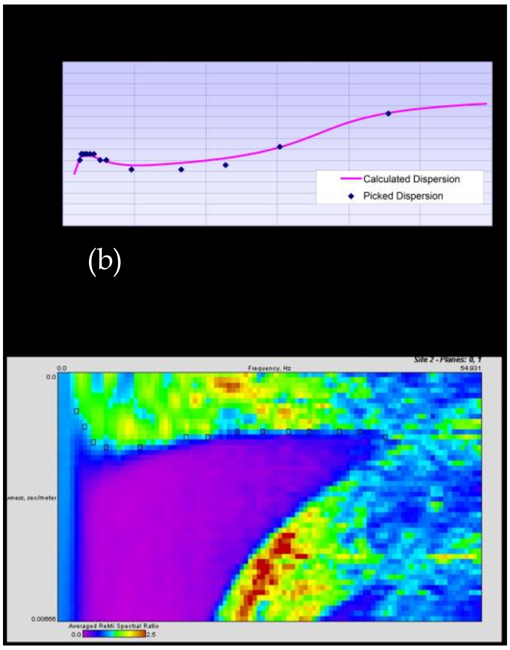
Figure 7. Geotechnical borehole 1. Mustafa Kamil Necropoli

4. GEOPHYSICAL INVESTIGATIONS

Array microtremors measurements have been carried out to define the shear velocity profile at the site. The ReMi method has been used and the estimated Vs profile is given in (Figure 8).

The obtained shear wave seismic velocities for Remi tests Remi-1 show a relatively high range of shear wave velocities ranging between 280 m/s to 1600 m/s. However it is clear that the ground conditions were the underground tombs in Mustafa Kamil Necropolis are excavated cannot be classified as real rock at least close to the surface.





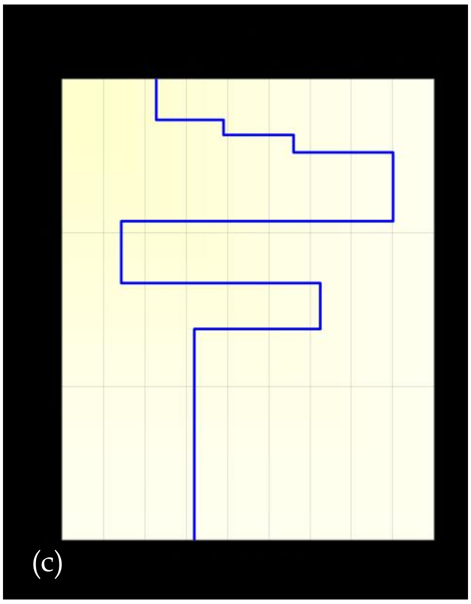


Figure 8. (a) The dispersive curve, (b) P-f image and (c) corresponding picks for Remi-1 test, Necropolis of Mustafa Kamil.

5. GEOTECHNICAL PROPERTIES OF ROCK MASS

In the framework of this study, a specific set of laboratory tests has been carried out in order to define the physical and mechanical properties of the rock where the underground tombs of Necropolis were excavated. These studies include:

- Slow Uniaxial Creep Tests.

The objective of these tests is first to a quantify the viscous parameters that govern the long-term behaviour of these underground structures and, secondly, to define the necessary parameters for the numerical modeling. Most specimens, under constant axial stress shows complete creep phase: transient, steady and tertiary creep phases. (Figure 9).

-Triaxial Creep Tests.

The objective of the triaxial creep tests is to determine visco-plastic parameters of the soft rock specimens under confinement. The time-related parameters are monitored, recorded and analyzed.

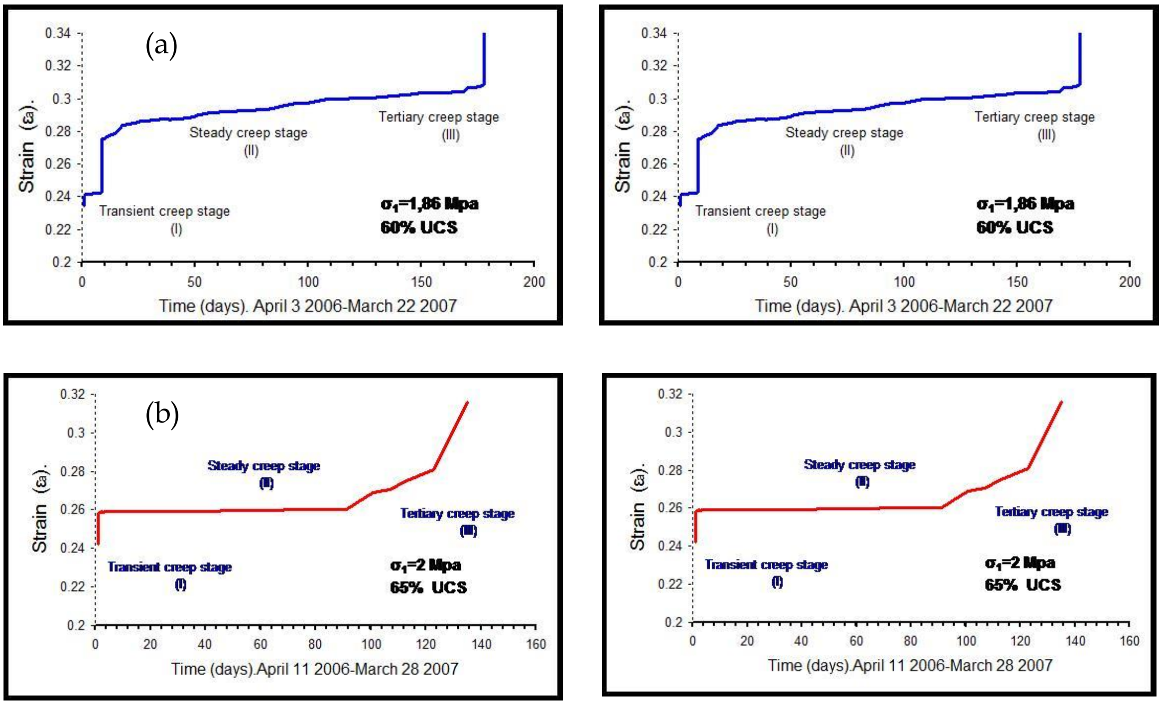


Figure 9 Mustafa Kamil Necropolis, Strain-versus-time in uniaxial creep (a) test Nr.1 and (b) No.2.

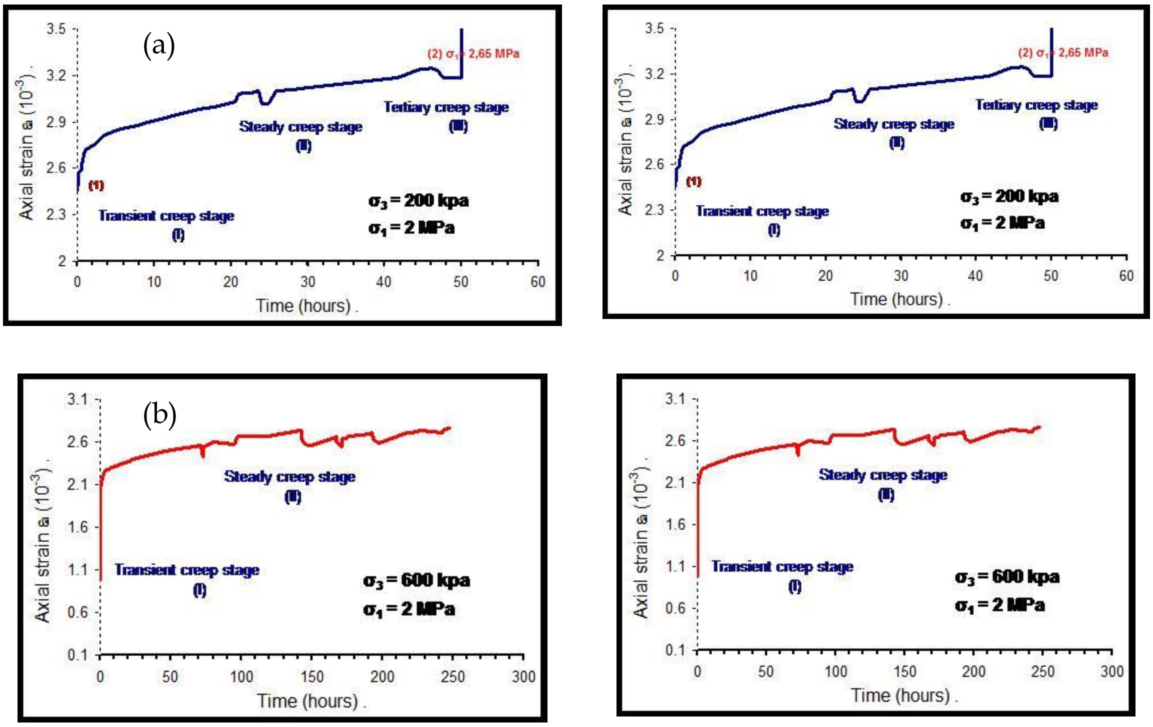


Figure 10 Mustafa Kamil Necropolis, Strain-versus-time during in triaxial creep test (a) No.1 and (b) No 2.

The axial strain-time curves are given in (Figures 10). From the results, it is proved that there is an instantaneous transient creep state under constant axial load and confining pressure followed by a steady creep phase. Post-test deformation increases rapidly at the beginning to the first few hours of the test and then tends to remain constant. No specimen failed after at the end of the test duration.Crack propagation (in the brittle field) and pore collapse (at higher stress conditions) are therefore the dominant deformation mechanisms for the Alexandria surface rock as it has been also demonstrated by (Aversa, 1998).

-Direct Shear Tests for Rock Joints.

The results of direct shear tests performed on rock samples are presented in (Figure 11). Also direct shear test has been carried out on some weathered rock samples.

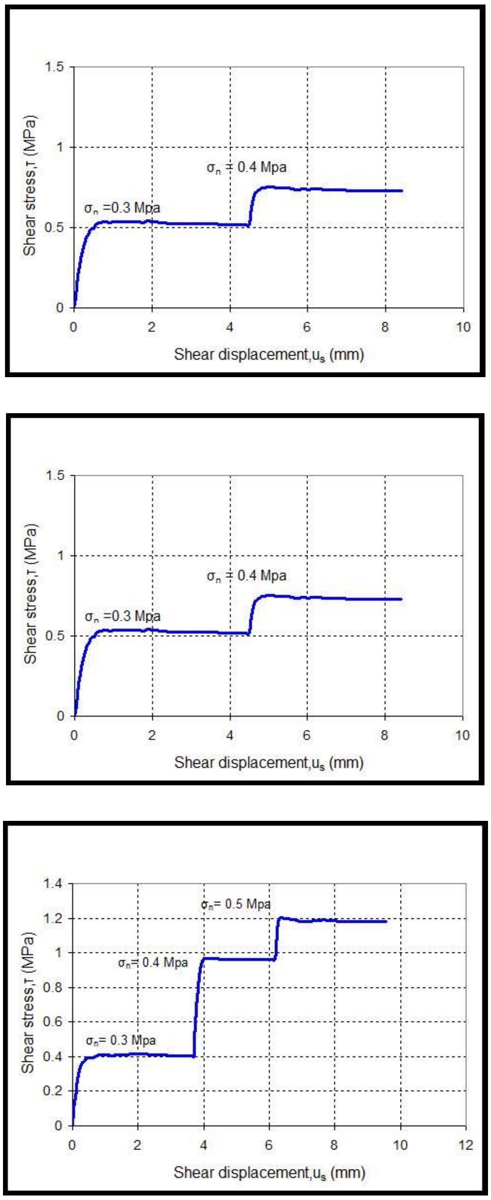


Figure 11 Direct shear test for rock joints.

-Triaxial Compressive Strength.

(Figure 12), presents the results of isotropic compression test performed on undistributed samples. It is found that the Calcarenitic rock samples have the following mechanical and elastic properties: c = 400 KN/m^2, φ = 31°, E = 300 to 410 MPa, v =0.28-0.29, Shear modulus G =160.2 MPa, Bulk modulus K=310.6 Mpa.

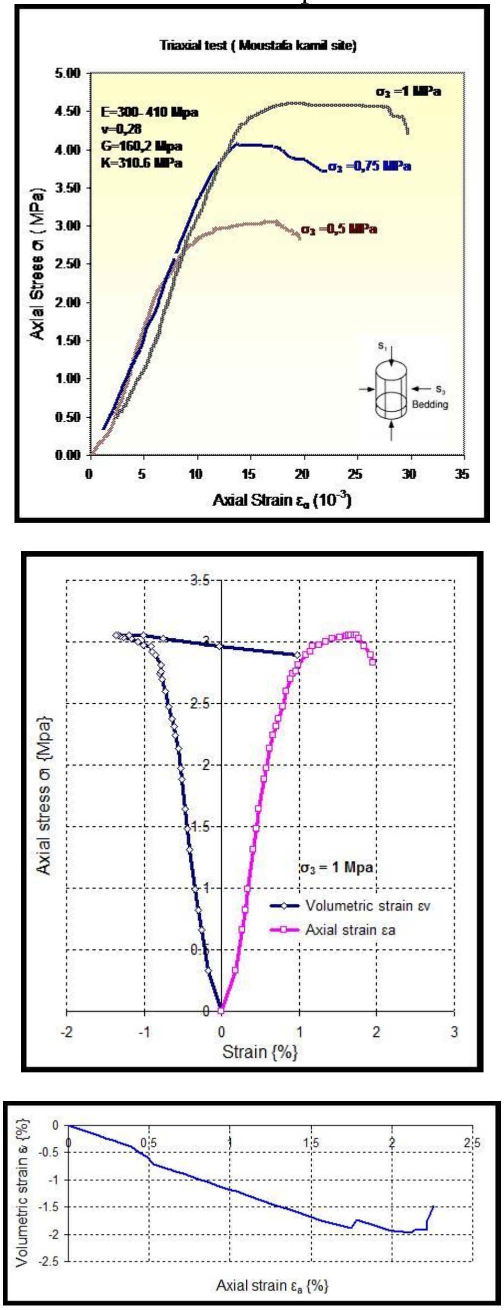


Figure 12. Results from triaxial test at different confining pressures.

6. SEISMIC ANALYSIS OF A TYPICAL CROSS SECTION

The Necropolis of Mustafa Kamil has been studied for specific seismic scenarios using the finite element code [Plaxis V8].A typical cross section from each tomb is used in this study (see Figures 5,6),The material properties (physical, mechanical and dynamic) used through out the following analysis have been defined in the previous sections.

Preliminary static FE analysis.

In the initial static analysis, the excavation is modeled by assuming non-linear soil / rock behavior and the Mohr coulomb failure criterion. The following parameters are used $\varphi = 31^{o}$ c $=400$ kN/m^2, E=2.730E+06 KN/m^2 v = 0.28, Vs= 784, 49 m/sec for the Calcarenitic rock material and $\varphi = 00^{o}$ C $=713$ kN/m^2, E =1.200E+07 KN/m^2, v = 0.20,Vs= 1492 m/sec for the modern concrete ceiling. The results from the preliminary static analysis indicate that the ground displacements were very small (of the order of few millimeters) and some piers are under relatively high compression stresses. (See Figures 13 and 14) where the calculated peak effective principal stress was $-1.02*10^{3}$ KN/m^2 in the case of tomb_2).

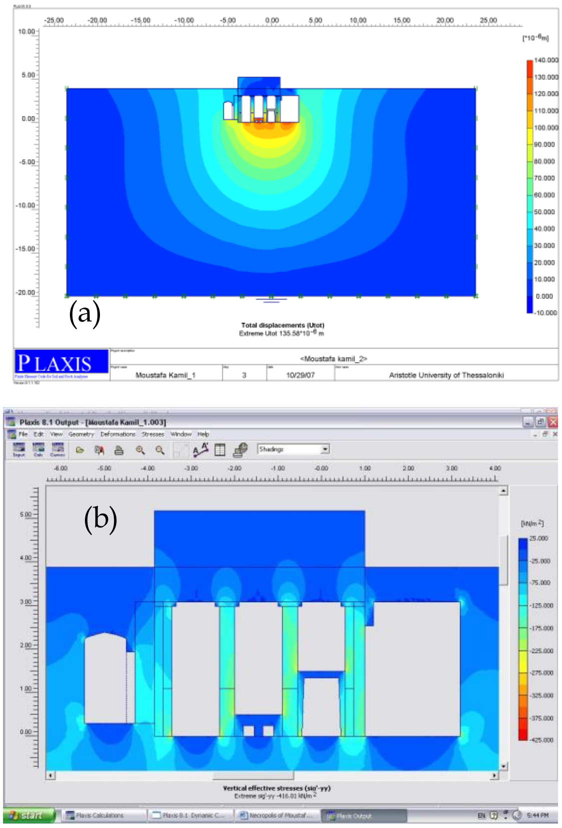


Figure 13. Static analysis (a) Peak total displacement = $135.58*10^{-6}$ m. (b) Vertical peak effective stresses (-416.01 KN/m^2), Tomb Number_1.

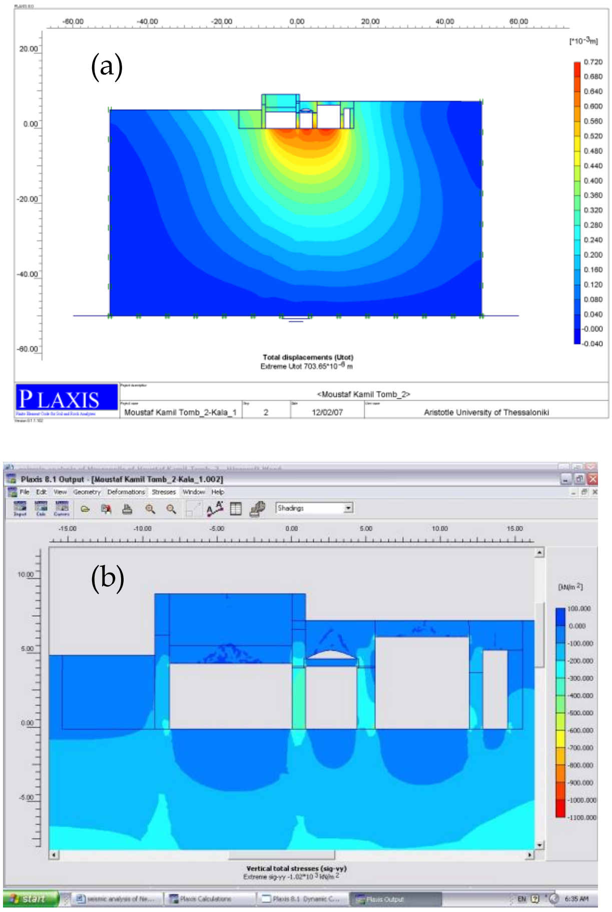


Figure 14 Static analysis (a) Peak total displacement = $703.56*10^{-6}$m. (b)Vertical peak effective stresses ($-1.02*10^{3}$ KN/m^2), Tomb Number_2.

7. SEISMIC FE ANALYSIS

Alexandria during its long history has suffered important seismic damages from near and distant sources earthquakes. As the under-water archeological remains in Abou Kir bay strongly support, the city was destroyed by either local or remote earthquakes (El-Sayed, 2004). Seismogenic zones such as the Red Sea, Gulf of Aqaba-Dead Sea Hellenic Arc, Suez-Cairo-Alexandria, Eastern-Mediterranean-Cairo-Faiyoum and the Egyptian costal area may all affect the city. However the seismic hazard of the city has not been fully defined, (Hemeda, 2008).

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 (Figure 15) of these earthquakes representing different seismotectonic settings and frequency content were scaled to three peak ground acceleration values equal to 0.08g, 0.16g and 0.24g respectively. In addition, they are used as input motions at the bedrock. They should not be considered as 3 distinctive seismic scenarios we just selected three input motions representative of the Egyptian seismotectonic context and in particular of that of Alexandria, believed to be representative of the expected ground motions. At the same time they cover in a satisfactory way the expected frequency content and amplitudes. The design acceleration in Alexandria according to the Egypt code is 0.08g. The records were retrieved from PEER and ESMD online database.

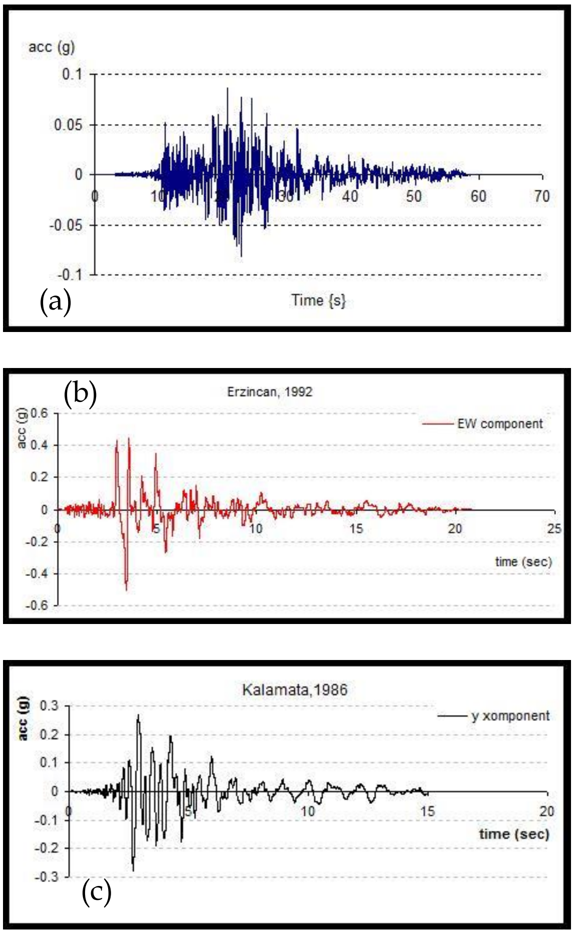


Figure 15 Seismic excitations at the bedrock for the reference ground motions (acceleration-time history, and Fourier amplitude spectrum). (a) Aqaba RQ, 1995 (b) Erzincan RQ, 1992, and (c) Kalamata RQ, 1986.

8. SEISMIC FE ANALYSIS RESULTS

Tomb Number_1

Figures 16 through 21 are summarizing the calculated displacements for the three PGA scenarios and the three design earthquakes. In case of Aqaba earthquake, it is clear that a great part of seismic energy is dissipated to the upper parts of the excavations (ground surface) even for small values of PGA. The Kalamata and Erzincan input motions give much low displacements values than for all. The maximum horizontal displacement at the top of the tomb for Aqaba earthquake at PGA= 0.24g earthquake scenario was ux = 8.01 cm, while the peak effective shear stress was 606 KN/m2. In the case of Erzincan and Kalamata, 0.24g scenarios the respective values were 422 kN/m^2 and 460 kN/m^2. The maximum horizontal displacements were 2.47 cm and 2.29 cm, respectively.

Given the value of the static strength estimated in the laboratory, the seismic analysis of Mustafa Kamil Necropolis, Tomb number_1, proved that the rock piers, which are the most vulnerable parts of the whole complex, are rather safe for PGA values lower than 0.24g in case of the Kalamata and Erzincan earthquakes and PGA =0.14 g for the Aqaba seismic scenario. (See Figures 22a,b).

Tomb Number_2

Figures 19 through 21 are summarizing the calculated displacements for the three PGA scenarios and the three design earthquakes. In case of Aqaba earthquake, it is clear that a great part of seismic energy is dissipated to the upper parts of the excavations (ground surface) even for small values of PGA = 0.08g. In addition, it is observed that the threshold PGA value for collapse of the supporting rock columns cannot be precisely defined. Collapse for column_2 is observed for a PGA around 0.08g ,on the other hand the supporting rock column_1 is rather safe for PGA values lower than 0.24g.the motion transmits fast to the upper parts of the columns and produce intense rocking and their collapse. In the cases of The Kalamata and Erzincan input motions, they give much low displacements values than for all. In the three PGA scenarios of Aqaba earthquake, the rock supporting columns collapse at dynamic time 22.450 second at the peak horizontal ground acceleration ,that arrived 1.15 m/s^2 in PGA value =0.24g giving 23cm as a maximum horizontal displacements at this time, while the peak effective shear stresses on the base of rock column_2 was 310 KN/m^2, 529 KN/m^2, and 753 KN/m^2 for PGA values 0.08g, 0.16g, and 0.24g respectively. In the cases of Erzincan and Kalamata earthquakes at PGA value 0.24g scenarios the respective values of the effective shear stresses were 395 KN/m2 and 500 KN/m^2, while the maximum horizontal displacements were 24 mm and 21.6 mm, respectively. For the maximum vertical displacement as can be seen for Aqaba earthquake at PGA=0.24 g it was 0.005m. while for Erzincan and Kalamata cases it was 0.0014 m and 0.0012m respectively.

Given the value of the static strength estimated in the laboratory, the seismic analysis of Mustafa Kamil Necropolis tomb_2 proved that the rock columns, which are the most vulnerable parts of the whole complex, are rather safe for PGA values lower than 0.24g in case of the Erzincan earthquake and PGA =0.16 g for the Kalamata seismic scenario. In addition, PGA values lower than 0.08g in the case of Aqaba earthquake. With cases of failure beginning to occur for higher levels of excitation. (See figures 23a, b).

For larger earthquake, which are most likely to happen in the region of Alexandria, the seismic stability of these shallow underground excavations is not satisfied and it is necessary to proceed to specific retrofitting works to upgrade their seismic performance. The maximum differential horizontal displacements of the top and the base of the rock columns are very small of the order of 1-2.mm. considering that the induced seismic ground deformations are better correlated with the intensity of damages in underground structures, the seismic design of these excavations must be based on these kinematic forces.

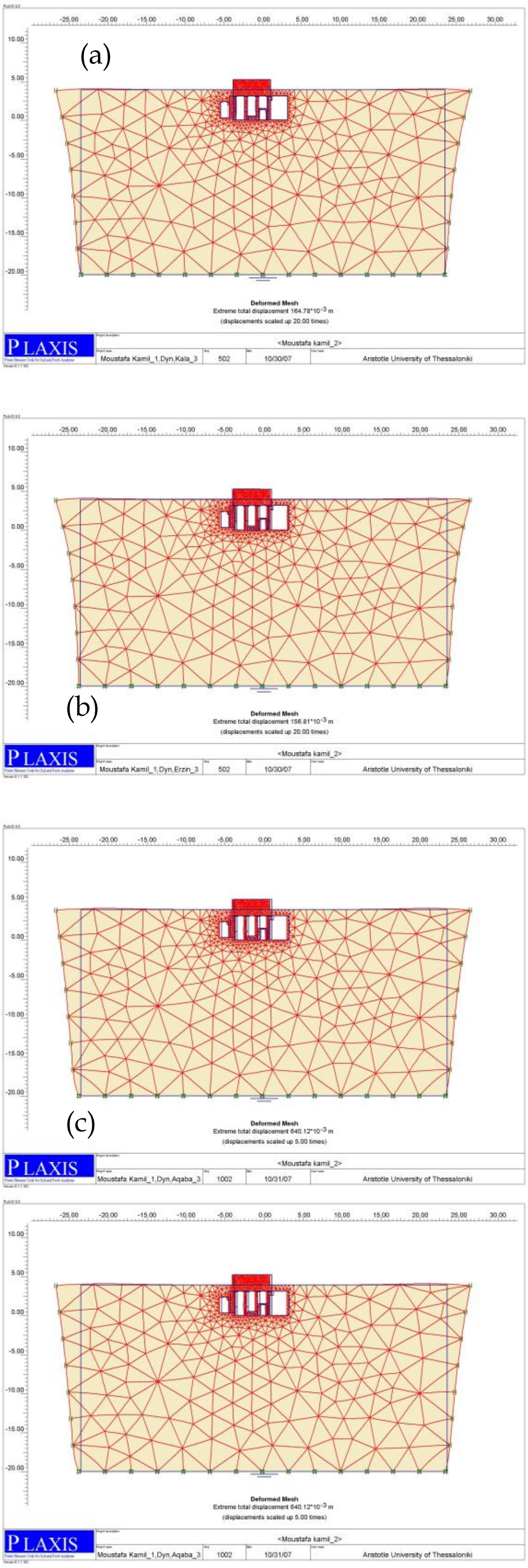
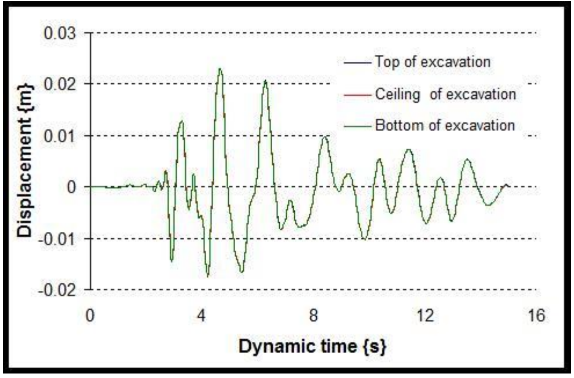
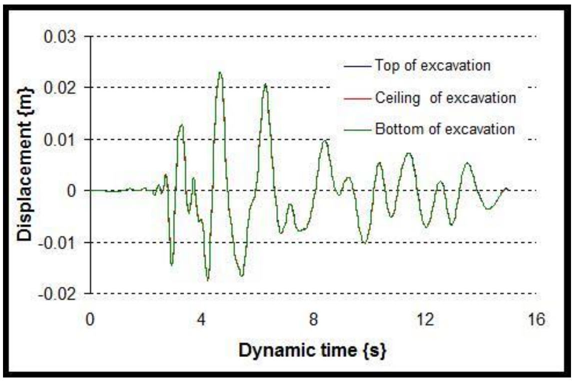
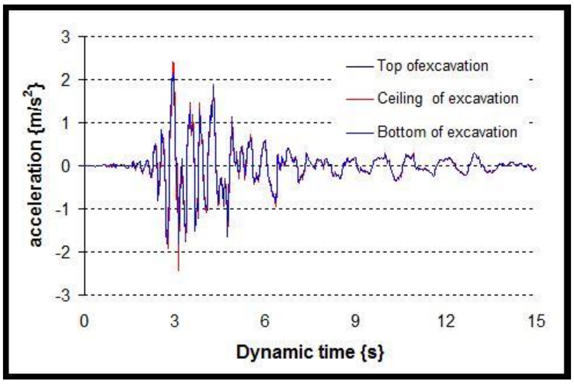


Figure. 16. Deformed mesh and peak total displacement at the final step,(a)Kalamata RQ,(b)Ertzincan RQ, (c)Aqaba RQ ,the PGA =0.24 g .Tomb No.1

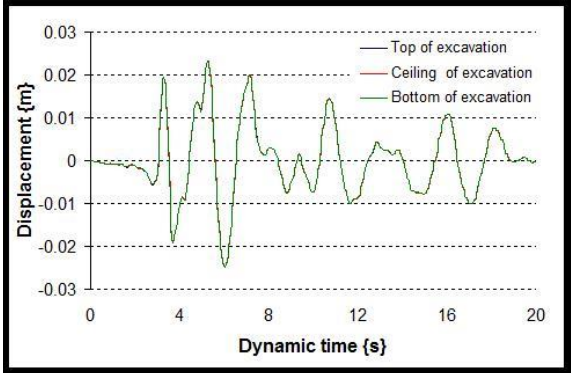
(17a)

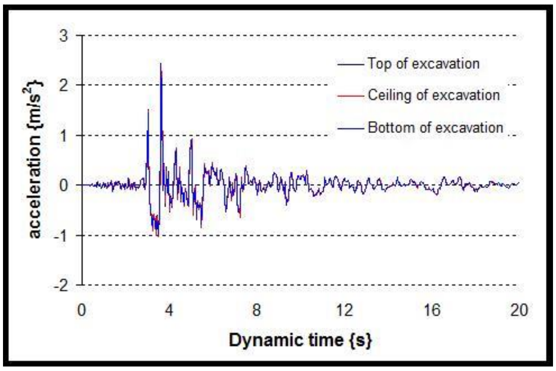




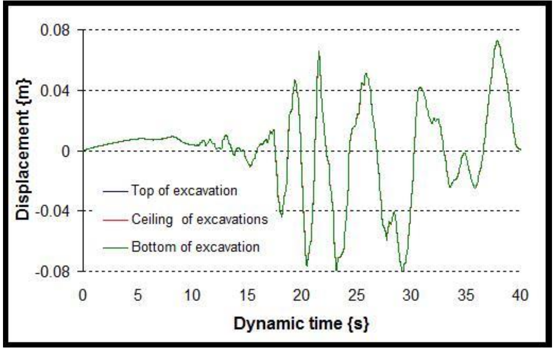


(17b)





(17c)



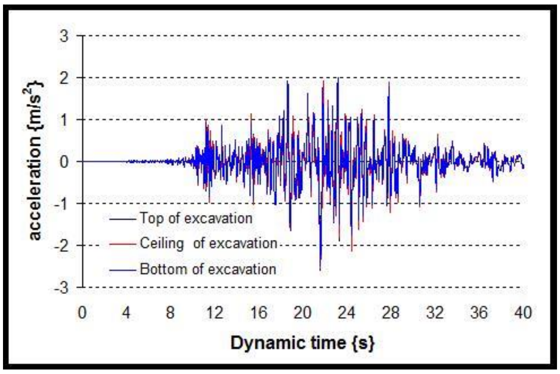
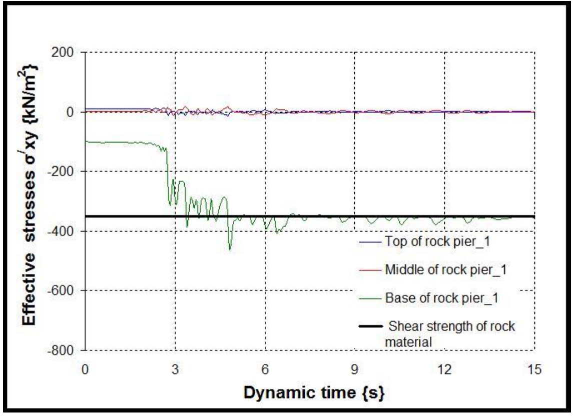
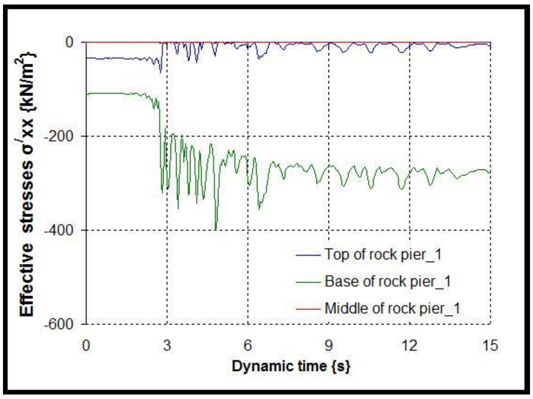


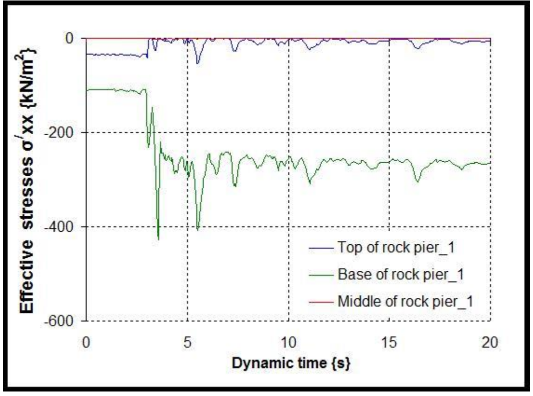
Figure 17 Computed displacement and acceleration time histories for (a) Kalamata RQ,(b)Erzincan RQ, (c)Aqaba RQ .input motions PGA= 0.24g . Tomb No.1

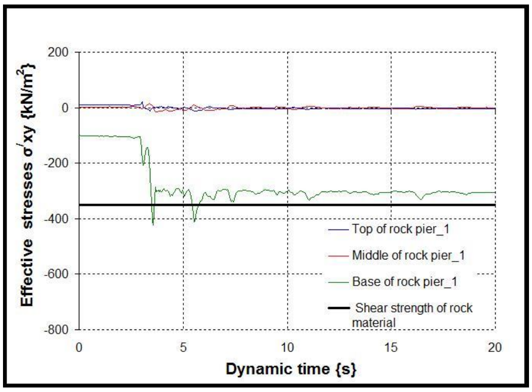
(18a)



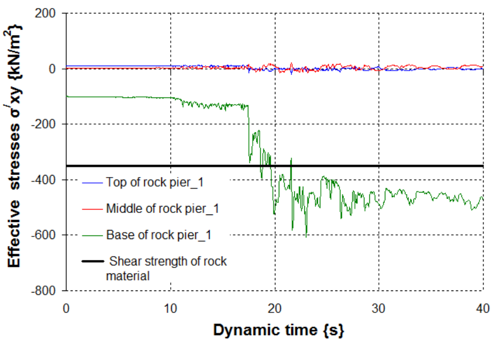


(18b)





(18c)



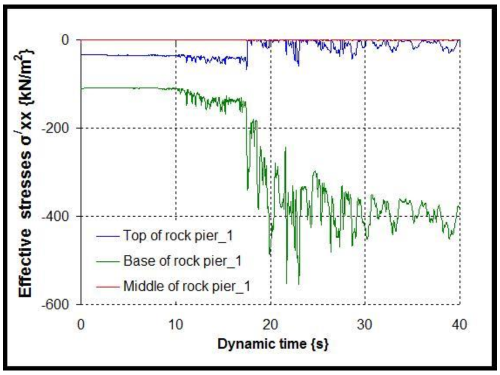
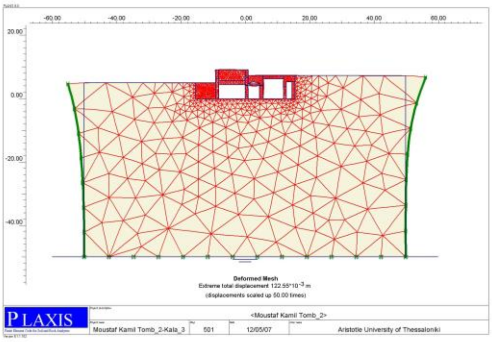
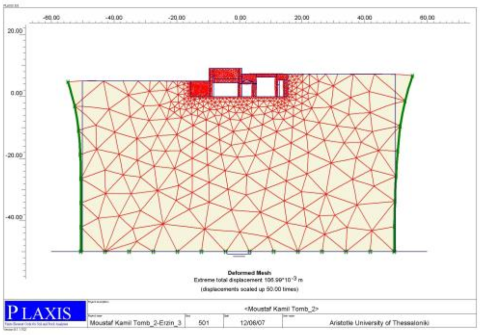


Figure 18 Effective shear stresses σ/xy and effective horizontal stresses σ/xx - time histories for the most critical Rock Pier No.1 (see figure 3) (a) Kalamata RQ,(b)Erzincan RQ,(c)Aqaba RQ. The PGA value =0.24g. Tomb No.1

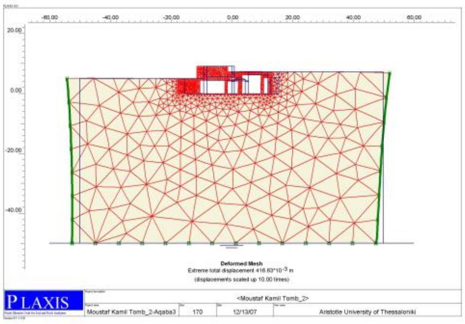
(19a)



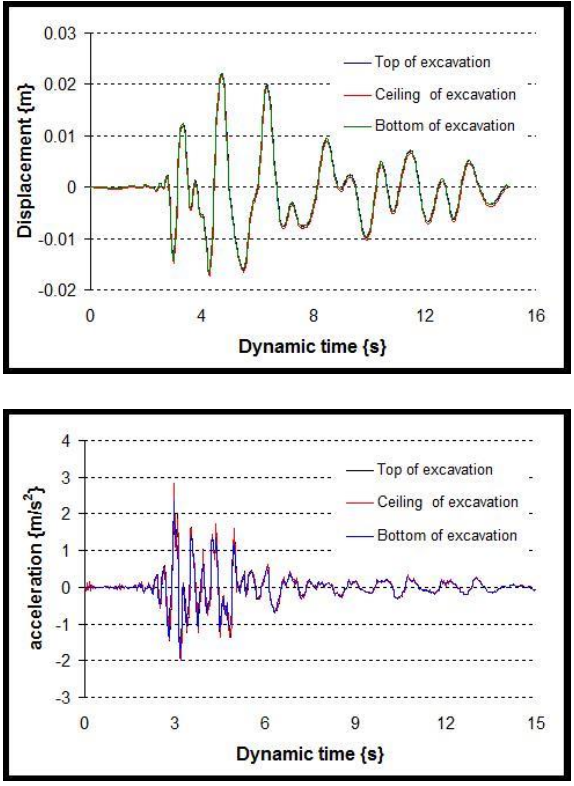
(19b)



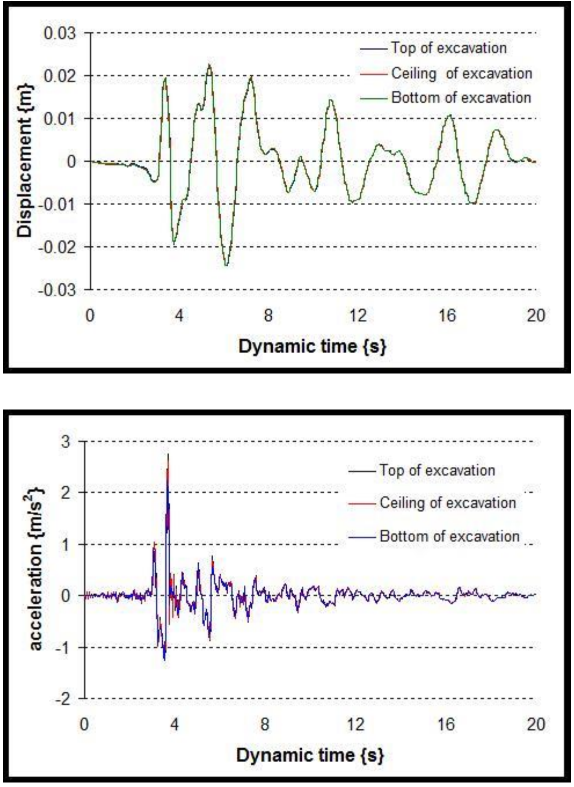
(19c)



(20a)



(20b)



(20c)

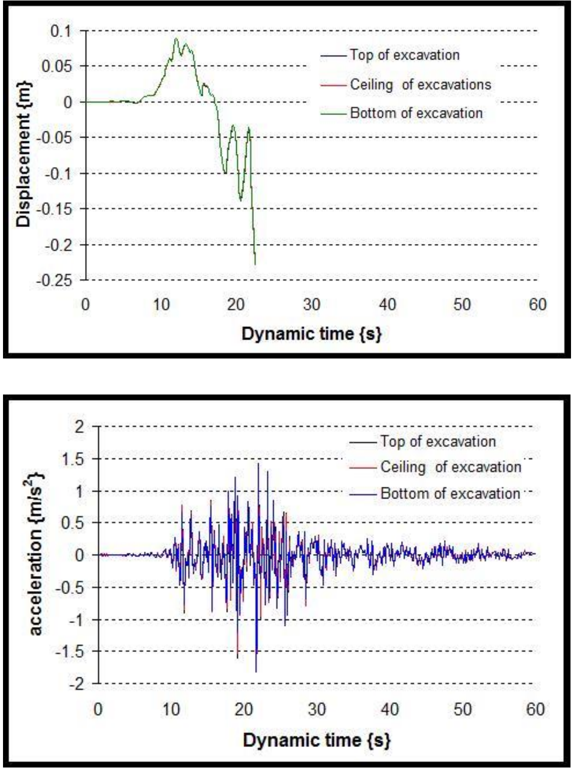
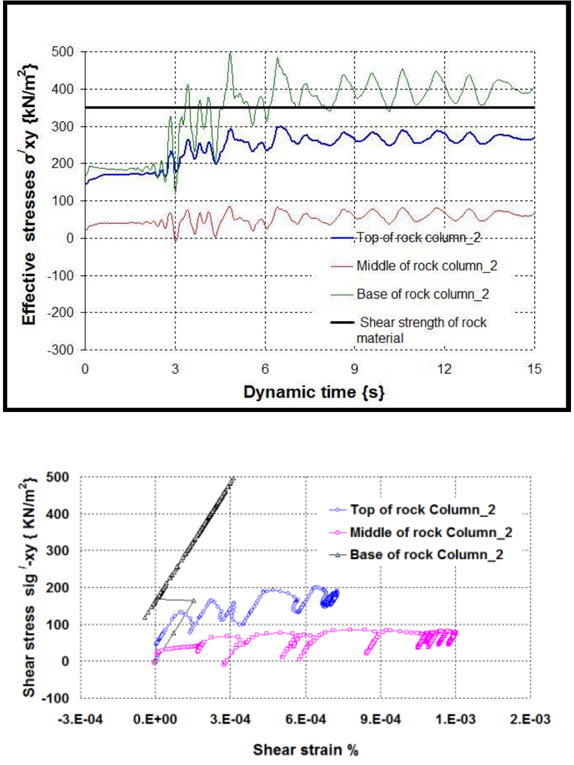
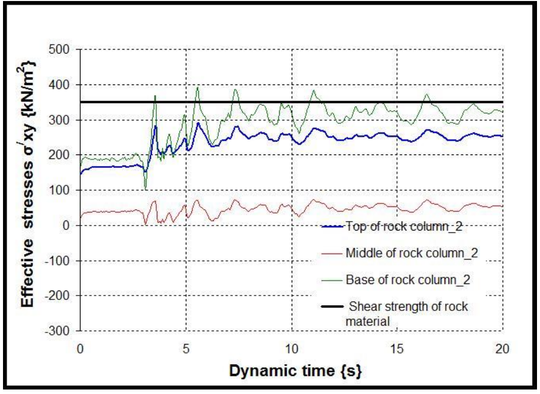


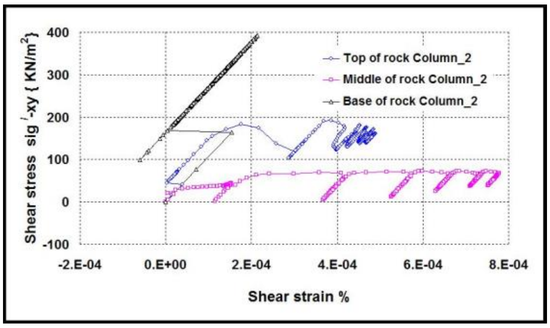
Figure 20 Computed displacement and acceleration time histories for (a) Kalamata RQ, (b) Erzincan RQ, (c)Aqaba RQ input motions PGA= 0.24g . Tomb No.2

(21a)

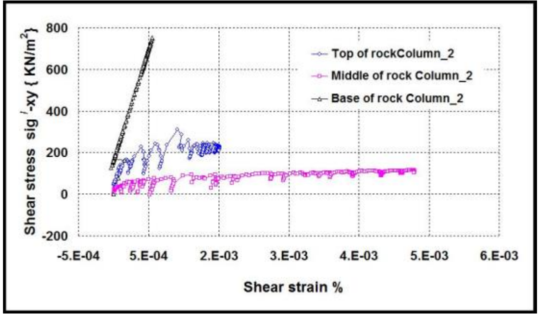


(21b)





(21c)



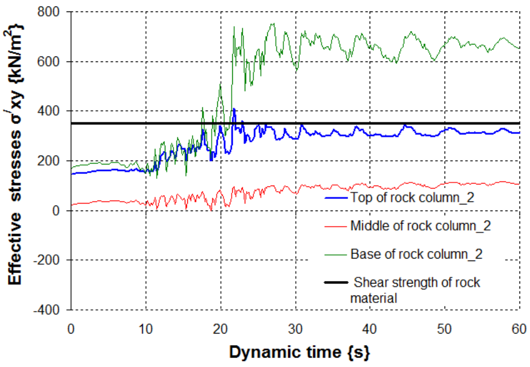
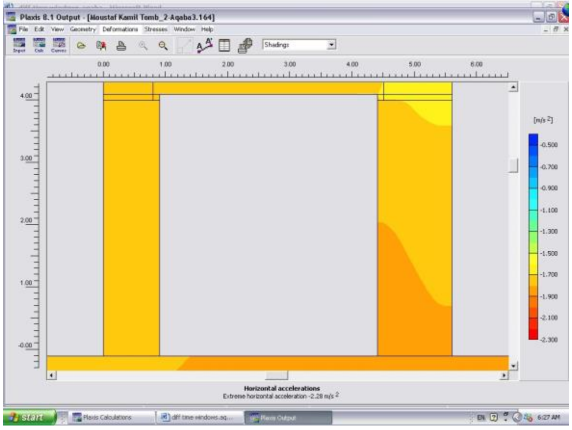


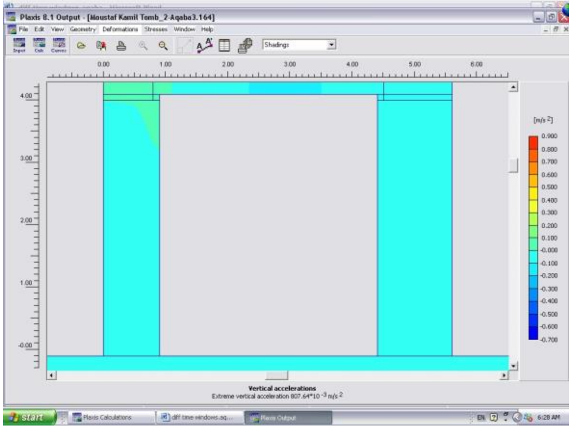
Figure 21 Effective shear stresses σ'xy - time histories, Effective shear stresses σ'xy-shear strain γxy for the most critical Rock Column No.2 (see figure 4) (a) Kalamata RQ, (b)Erzincan RQ,(c)Aqaba RQ. The PGA value =0.24g Tomb No.2.

(22a)


Plaxis 8.1 Output - [Moustaf Kamil Tomb_2-Aqaba3.164]

Horizontal accelerations
Extreme horizontal acceleration -2.28 m/s²

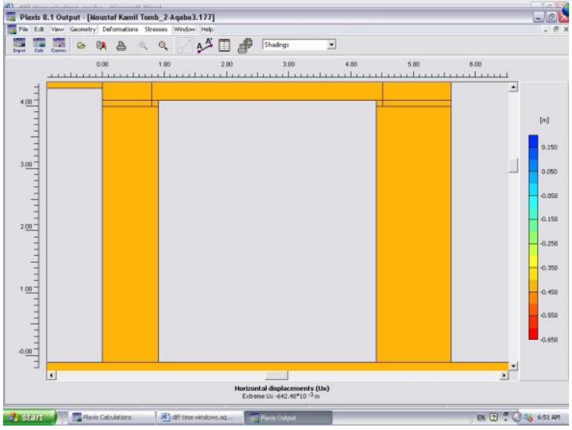
(22b)


Plaxis 8.1 Output - [Moustaf Kamil Tomb_2-Aqaba3.164]

Vertical accelerations
Extreme vertical acceleration 807.64*10⁻³ m/s²

Figure 22 (a) Horizontal acceleration (b) Vertical acceleration for rock column_1 and _2.at dynamic time 21.6 second. Aqaba earthquake. PGA =0.24g

(23a)


Plaxis 8.1 Output - [Moustaf Kamil Tomb_2-Aqaba3.177]

Horizontal displacements (Ux)
Extreme Ux -642.48*10⁻³ m

(23b)

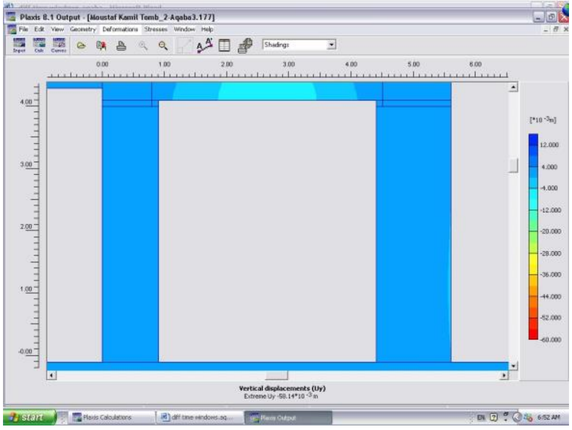
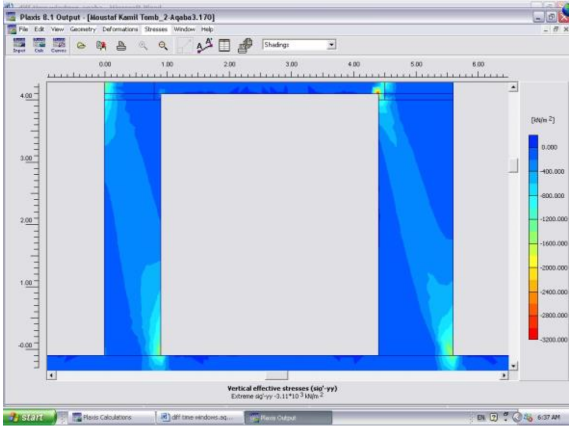


Figure 23 (a) Horizontal displacements (b) Vertical displacements for rock column_1 and _2.at dynamic time 22.45 second. Aqaba earthquake. PGA =0.24g

(24a)



(24b)

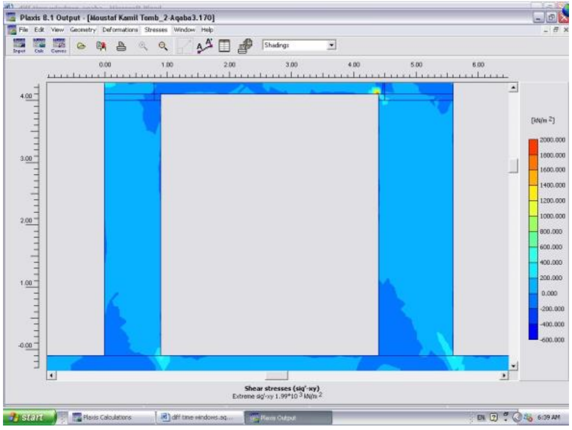
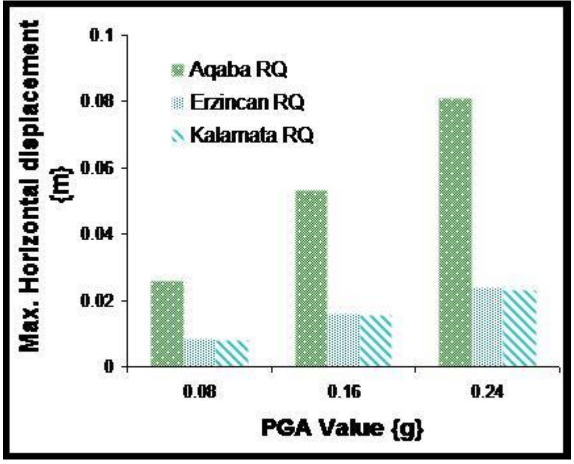


Figure 24 (a) Vertical effective stresses (b) Shear stresses for rock column_1 and _2.at dynamic time 22.45 second. Aqaba earthquake. PGA =0.24g

(25a)



(25b)

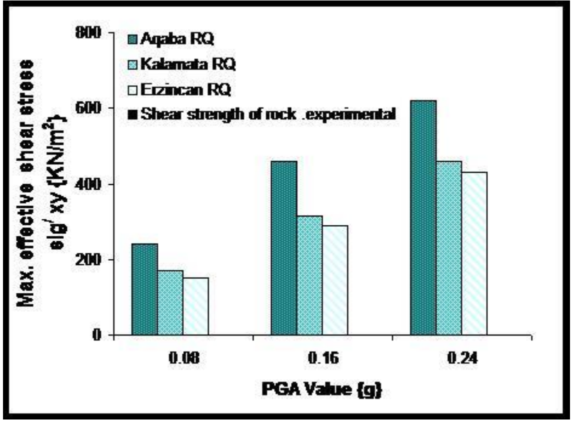
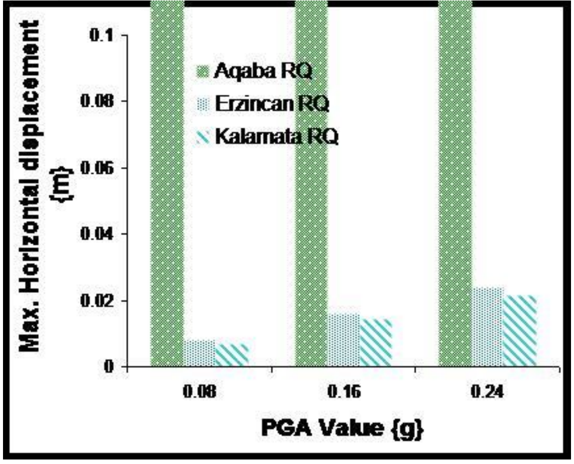


Figure 25 (a) Maximum horizontal displacements for different PGA values (b) Peak effective shear stresses at the top of the most critical rock column No.1 for different PGA values. Tomb No.1

(26a)



(26b)

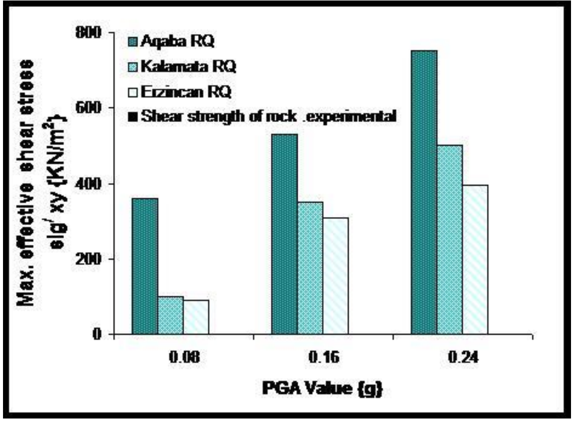


Figure 26. (a) Maximum horizontal displacements for different PGA values (b) Peak effective shear stresses at the top of the most critical rock pier No.2 for different PGA values. Tomb No.2

9. CONCLUSIONS

A summary of the present state of the underground monumental structures in Mustafa Kamil Necropolis in Alexandria, Egypt has been presented. In order to assess the pathology of the underground structures in this Necropolis a detailed laboratory and field surveys and tests have been carried out. The rock material (Calcarenitic rock) has an important intrinsic sensitivity to weathering factors especially the underground water and salt weathering effect. The infiltration of the water through the porous rock is one of the main problems of these tombs. The weathering process is linked to the textural characteristics, like poor geotechnical properties, chemical carbonated composition, presence of soluble salts in the porous system, marine climate with characteristic humidity and marine spray, underground water. The durability of the rock is moderate to low due to its high free silica content (in sand grain form). The strength of the Calcarenitic rock where the underground tombs of Necropolis of Mustafa Kamil is carved is low where the Rock Mass Rating (RR)=19 and Rock Quality Designation (RQD) =15-20%.

Considering all other affecting factors and the specific geometry of the complex this low rock strength affects seriously the safety of these underground monumental structures both under static and seismic loading conditions. The preliminary seismic analysis of these tombs with three seismic scenarios of different PGA values proved that some critical supporting parts of these structures (i.e. rock columns and piers) are safe, without any strengthening measures, only for PGA values lower than 0.07-0.08g, which is rather low considering the seismic activity and the past seismic history of the city.

The present 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.

The analysis presented herein should not be considered as the final one for the monuments. The aim is to identify some important features of the static and seismic stability of the monuments. It is believed that in the phase of the final study a more detailed analysis of the seismic hazard and the section of the input motions is deemed necessary.

REFERENCES

Aversa, S. (1991) Mechanical behaviour of soft rock: some remarks, *in 'XXI Convegno Nazionale di Geotecnica, Experimental characterization and modelling of soils and soft rocks, (ed) CUEN publisher:* Napoli, Italy.191—223

El-Fouly, A. (2002) Void investigation at Gabbari tombs, Alexandria, Egypt using ground penetrating radar technique" *Proceedings of the International Conference on the Environmental Hazards Mitigation, ICEHM2000*, Cairo University, Egypt, September, 84-90

El-Sayed.A, Korrat. Hussein. I.M, (2004) Seismicity and seismic hazard in Alexandria (Egypt) and its surrounding. *Pure Appl.Geophys*.161.1003-1019.

Girgis. G.P, (1965) Geology of the Pleistocene sediments of the Mediterranean coast west of Abou Qir" Ph. D thesis, Geology, Faculty of Science ,Cairo University, 23,24

Hemeda, S. (2008) An integrated approach for the pathology assessment and protection of underground monuments in seismic regions. Application on some Greek-Roman monuments in Alexandria, Egypt. Ph. D thesis, Civil Engineering Department, Aristotle University of Thessaloniki, Greece.

Hemeda.S, Pitilakis. K,Papayianni. I, Bandis. S, (2007) Underground monuments (Catacombs) in Alexandria, Egypt". *4th International Conference on Earthquake Geotechnical Engineering, (Springer),* Thessaloniki, Greece.

Louie. J.N, (2001) Faster, Better: "Shear-wave velocity to 100 meters depth from refraction microtremors arrays". Bulletin of the Seismological Society of America (BSSA), 347-364.

PLAXIS Manual, (2002) Finite Element Code for Soil and Rock Analysis. Published and distributed by AA Balkema Publishers, Nederland's Comput. Geotech. 32(5).326–339.