Geotechnical Modelling of The Climate Change Impact on World Heritage Properties in Alexandria, Egypt

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Research Article

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Abstract

Alexandria is one of the Mediterranean UNESCO World Heritage sites at risk from coastal flooding and erosion due to sea-level rise.

The city's position on the Mediterranean coast means it is especially vulnerable to rising sea levels. Alexandria is one of UNESCO sites in Egypt at risk from flooding. All the archaeological sites in the northern coast of Egypt are also said to be at risk from coastal erosion. The flood risk in Alexandria is expected to reach a tipping point by 2050.

This research presents the numerical analysis of geotechnical and structural damage mechanism of Catacombs of Kom El-Shoqafa and El-Shatbi Necropolis, the sites have the lowest topography in Alexandria induced by the sea level rise and heavy rain due to the Climate Change, based on Finite Element PLAXIS Code. The purpose of the study was to investigate the behavior fully-saturated soft rock/ hard soil subjected to ground water intrusions.

The main objective of this study is to very accurately record and analyze geotechnical problems and induced structural failure mechanisms that have been observed and accounted for in field, experimental and Numerical studies. The land area is also vulnerable to coastal flooding. It is widely expected that the numerical analysis of such geotechnical problems will contribute to the preservation of cultural heritage. The present research presents an attempt and experimental study to design a PLAXIS 2D FE model to simulate hard soil/hard rock problems, distortion and stress analysis of the complex structure of the catacombs. Plastic modeling or Mohr - Coulomb model was used in advanced soils during various stages of numerical analysis. Results are recorded and discussed regarding stress and volumetric behavior of soil / rocks. Groundwater infiltration into pores or fissures of rock and soil has a great influence on the engineering mechanical properties of rocks and soils.

1. Introduction

The coastal city of Alexandria in Egypt, which has survived invasions, fires and earthquakes since it was founded by Alexander the Great more than 2,000 years ago, now faces a new threat of climate change.

Sea level rise threatens to inundate archaeological sites, prompting authorities to erect concrete barriers in the sea to break the tide. A severe storm in 2015 flooded large parts of the city, killing at least six people and the collapse of about twenty homes, see Figure (1).

Alexandria, the country's second largest city, is surrounded on three sides by the Mediterranean and backed by a lake, making it uniquely vulnerable to sea level rise caused by global warming and melting polar ice caps.

In the late 1940's and 1950's, it was a haven for writers and artists who attracted wealthy Egyptian and foreign tourists for its beauty and charm. Today, more than 60 kilometers (40 miles) of the waterfront makes it a prime summer destination for Egyptians, but many of its most famous beaches are already showing signs of erosion.

The United Nations' Intergovernmental Panel on Climate Change has warned that global sea levels could rise by 0.28 to 0.98 meters (1–3 feet) by 2100, with "serious repercussions for coastal cities, deltas and low-lying countries."

Experts acknowledge that regional differences in sea level rise and its impacts remain poorly understood. But in Alexandria, a port city of more than 5 million people and about 40% of Egypt's industrial capacity, there are already signs of change.

The Egyptian Ministry of Water Resources and Irrigation says that the sea level rose at an average rate of 1.8 mm per year until 1993. Over the next two decades, the water level rose to 2.1 mm per year, and since 2012 it reached 3.2 mm per year, which is enough to threaten building foundations.

The land on which Alexandria is built, along with the surrounding Nile Delta, is sinking at roughly the same rate, in part due to upstream dams that prevent the regeneration of silt and the extraction of natural gas. This is expected to exacerbate the effects of sea level rise, with potentially dire consequences.

A 2018 study predicted that as many as 734 square kilometers (more than 283 square miles) of the Nile Delta could be submerged by 2050 and 2,660 square kilometers (more than 1,020 square miles) by the end of the century, affecting 5.7 million people .

In El-Max neighborhood, hundreds of people were forced to leave their homes after severe floods in 2015. The Ministry of Housing built nine housing complexes to house them after the area was declared unsafe.

The archeological sites in the city are those that have survived its turbulent history are truly threatened.

The Pharos Lighthouse, once among the tallest buildings ever built and one of the Seven Wonders of the Ancient World, was hit by an earthquake in the 14th century. The famous Library of Alexandria was completely burned down when Julius Caesar set fire to a hostile fleet in 48 BC.

But Citadel of Qaitbay, a medieval fortress built on the ruins of the lighthouse at the end of a narrow peninsula jutting out into the sea, still looms over the sprawling central port of the city, on the other side of the modern Library of Alexandria, a research center has opened. In 2002.

The castle is particularly vulnerable. Increasingly strong waves and currents pushed to the foundations, forcing authorities to install a long series of concrete sea barriers visible from the downtown waterfront, known as the Corniche.

Inland sites are also at risk, including the Catacombs of Kom al-Shuqafa and the Cemetery of Shatby, the sites have the lowest terrain, dating back to the second century AD with architectural styles inspired by ancient Egypt. The catacombs and other sites such as the Shatby cemetery were flooded in 2015, as shown in Figs. 2 and 3).

Prophet Daniel Street in the city center is one of the oldest streets in the world, and today it passes in front of a mosque, synagogue and St. Mark's Church, the seat of the Coptic Christian Patriarchate.

We realize that this street, which has survived for hundreds of years, could be underwater in the years to come, in our lives.

"Every year the waves are stronger than they were in the previous year. The winters are harsher and the summers are hotter."

Groundwater infiltration into pores or fissures of rock and soil has a great influence on the engineering mechanical properties of rocks and soil. For example, groundwater intrusion will deform rock and soil seepage, which will directly affect the stability and integrity of structures inside, buildings and foundations; The change of groundwater level will alter the effective stress field in soil / rocks, resulting in soil recovery or stabilization; Changing the groundwater level will also change the soil moisture content, which will also change the mechanical properties of the soil and cause the bearing capacity of the soil.

Rising groundwater levels due to sea level rise and heavy rains will inevitably lead to a decrease in the carrying capacity of sandy soils as catacombs are excavated. The bearing capacity of sandy soils under water saturation conditions is less than that of unsaturated soils, and the average reduction range is 26 – 25%, [1–2].

This study provides a comprehensive analysis of the safety of underground antiquities. The safety analysis not only includes failure analysis but the effect of groundwater level rise around underground structures on the differential settlement has been thoroughly investigated.

Since about 1975, a series of industrial and agricultural changes have led to a remarkable increase in the groundwater level in the city of Alexandria, especially Lake Mariout (400 meters from the catacombs), which is the main source of this groundwater inside the catacombs along with the heavy rains in the winter. The ice surface gradually reaches a height higher than the height of many underground "catacombs" monuments. As a result, some intense water leakage occurred at various locations within these underground structures.

The rise in groundwater levels can be in dramatic places due to subterranean development and this reduces the bearing capacity of rocks. The rise or fall of the water level may have dire consequences for the stability (structural effect) in terms of flooding of the subsurface parts. In some cases, changes in the groundwater level have had significant impacts on stability.

After the groundwater level decreased in 1995, the second level of the catacombs was opened to visitors but the lowest level is still submerged with some groundwater so far.

All the underground ruins (catacombs) in Alexandria suffer from a common problem: water leakage. Over time, the infiltration may lead to increased humidity to excessive levels within the void created by the structure. This moisture and water seepage within the structure will cause cracking and peeling of rock surface layers and the formation of salt blooms and sub-fluorescences that can be dangerous to wall paint layers. The interaction of moisture with carbon dioxide may further degrade, resulting in the potential leakage of unwanted gases or dangerous chemicals from the surrounding soil.

The analysis of the integrity of surface and subterranean excavations in the Shore cemetery not only includes failure analysis but also the effect of high water level around underground structures on the differential settlement was investigated.

Analysis of water samples collected from El Shatibi cemetery indicates that the water that floods all the cemetery grounds is sea water and sewage water from surrounding buildings. The rise in groundwater levels can be in dramatic places due to subterranean development and this reduces the bearing capacity of rocks. The rise or fall of the water level may have dire consequences for the stability (structural effect) in terms of flooding of the subsurface parts. In some cases, changes in the groundwater level have had significant impacts on stability.

Surface and underground excavations at El Shatbi suffer from a common problem of water leakage. Over time, the infiltration may lead to increased humidity to excessive levels within the void created by the structure. This moisture and water seepage within the structure will cause cracking and peeling of rock surface layers and the formation of salt blooms and sub-fluorescences that can be dangerous to wall paint layers. The interaction of moisture with carbon dioxide may further degrade, resulting in the potential leakage of unwanted gases or dangerous chemicals from the surrounding soil.

2. Research Methodolgy

To determine the magnitude of stresses, analyze the deformation and settlement of the hard soil/ soft rock due to the ground water intrusion, where the catacombs are excavated, analytical models of geotechnical engineering are presented in detail. Geotechnical numerical modeling of complex soil/ structure problems requires advanced two and three-dimensional advanced soil models. PLAXIS 2D (PLAXIS v.b 2018) [3] was used to calculate the soil strength and bearing capacity reduction due to the impact of coastal flooding and erosion due to sea-level rise. PLAXIS 2D is a program produced and inquired about the geotechnical construction plan and recently used as part of the structural and geotechnical survey. The Mohr - Coulomb model is used for both static dynamic analyses. The code has a handy methodology for a programmed assembly engine, called Load Advancement, which we used here.

Foundational models are the bedrock not only for understanding the mechanical behavior of soils but also for implementing numerical predictions by means of the FE method, [4–6].

3. Study Areas

The Kom al-Shoqafa cemeteries are located in the western cemetery of Alexandria. The facility was used as a burial chamber from the 2nd to the 4th centuries, before it was rediscovered in 1900 when a donkey accidentally fell into the entrance entrance and consists of three levels cut through sandstone limestone, and the third level is now completely underwater. The catacombs contain a central pillar of six columns that opens from the vestibule. To the left is a funeral banquet hall where friends and family gather on stone couches covered in pillows, at the time of the burial and also for future memorial visits.

El-Shatibi Cemetery is located in the old eastern quarter of Alexandria, overlooking the Mediterranean Sea. The Cemetery of El-Shatibi, which was rediscovered by chance in 1893. The oldest cemetery in the city, may have served as a resting place for the deceased since the fourth. Century BC. These rock tombs are the oldest example of Alexandrian-style burials. Today, the graves of El Shatibi are located above the ground and exposed to the elements. But in its infancy, it was burial vaults. To reach them, visitors must descend several steps that lead to the main burial site.

4. Pluvial Flood Hazard In Alexandria

Climate change should lead to more extreme rainfall events in Alexandria and increase the risk of copious food. However, on November 4, 2015, Alexandria and some other nearby coastal cities experienced unexpected torrential rains of up to 227 mm felt in 12 hours, which is more aggressive than the record of the 100-year return period, causing severe flooding (see Fig. 1).). This event has been described as the worst flooding in the city over the past few decades in terms of the number of people affected and the economic losses, [7].

Alexandria suffers from various urban problems that increase exposure to the expected risks. The degradation of drainage systems and their declining capacity are the main problems (African Development Bank 2015). The capacity of the sewage system in the city is about 1.6 million m3 / day, [8] which is sufficient to drain the average precipitation of 26 mm / day (World Bank 2011). There are other factors that exacerbate the severity of floods in Alexandria, such as high population density (1600 / km2), urban expansion, and lack of vegetation areas, which increases water accumulation [9] and inequality in the distribution of services.

5. State Of Preservation

The archaeological site in Alexandria exhibits complex geotechnical conditions. The geotechnical problems of this site are related to the stability of soft rocks. The mass and the action of groundwater, rocks can be considered as weak rocks consisting of low strength, sound materials (solid material), and weak in the sense that due to structural weakness (shear zones, faults), the mass of rocks behaves in a weak manner. Either way, these rocks pose special problems for engineering. Stability problems occur, in the first case, where the stress at the site and the stress created is greater than the intrinsic rock strength. In the second case, the problems are related to the weakness of the trend, [10–12].

We can see in the rock mass, almost vertical incisions are developed in which open joints, fractures and fissures intersect. This is then subjected to weathering and erosion processes. Weak areas were developed on the rock mass as favorable conditions were created to separate the rock masses causing large-scale downfall of the rocks. Surface fossils tend to be less stable because pressures at the site are lower, rocks are affected by weathering as shown in table (1) the engineering properties of the rock masses where the catacombs are excavated now are less than the ASTM standard. requirements, and water is a more active factor. The transverse stress of continuous flow around a carefully drilled underground hole tends to hold the blocks in place in the wall and ceiling, while little or no surface traction acts on the faces of the blocks on the surface where the transverse stress is usually small.

The surface excavations at the al-Shati cemetery also include weathered rocks whose strength may be much lower than that of intact rocks and which will contain many of the more important faults. Some of the weaker rocks will continue to be degraded by disturbances during construction and subsequently under the influence of water and chemical reactions in warm and humid climates.

In general, the rock mass presents the phenomena of change and decomposition of visible materials above all in anomalous levels and in relation to the phases of interruption. One of the factors that have contributed to the modification of the properties of the mass and that it continues to function, the primary factor is water in all its forms, it exerts pressures determined by its free presence in the interruption and pressure in the pores of the filler material. From the interruptions themselves; Such problems increase in conditions of thermal change.

The presence of conduction stages, of different orientations, determines the subdivision of the rock mass into prismatic bodies of variable size In some cases this discontinuation stage is filled with materials with weak mechanical strength which produce deformation processes that tend to persist with increasing the phenomenon of decompression between the crack walls and reducing the internal bonds of rocks.

In such geotectonic conditions, erosion phenomena are included due to the effect of wind currents and actions of moisture / salts, the effect of meteoric waters, which chemically attack the calcareous components of the rocks and the consequent degradation of the mechanical property of the rock itself.

These sites represent intense weathering indicative of the scaling of the rock surface. Breakdown of building materials, an intense rock meal. The moist rock surfaces in particular can be observed for the semi-protected parts of excavation and severe weathering in the form of honeycomb, white salt bloom and yellowish-brown staining of iron in many parts. Structural damage is represented by cracking of ceilings, decay of the surface of the rocks, partial collapse of some parts of roofs and walls, peeling of rocks in particular in the ceiling of narrow entrances and tunnels, severe erosion in the deepest parts, and warping. In some parts, deep erosion in the lower levels of these tunnels and collective waste of their roofs and the walls of their corridors. Cracks of irregular shape. Some parts show severe breakdown, [13, 14].

The two processes working in earnest in these locations are groundwater and salt weathering in the field of diagnostic and laboratory indications, and humidification and drying associated with dielectric heating that is prevalent in semi-arid regions and sometimes in arid regions.

The rise in groundwater level can be in dramatic places due to subterranean development, the rise or fall of the water level may have disastrous consequences for the stability (structural effect) in terms of flooding of the subterranean parts. Landslides and other geological hazards, land subsidence or non-structural impacts that accompany material degradation through physical (temperature and moisture expansion) and chemical (air pollution, etc.) erosion. As a result of the modification of the groundwater system, several failures were observed in the structure of the grave.

6. Numerical Analysis Results And Discussion

6.1 Catacombs of Kom El- Shoqafa

Figure (4) presents the deformed finite element mesh and boundary conditions used for the numerical analyses of the soft rock excavations of Catacombs of Kom El-Shoqafa in underground water conditions (the underground water level is 3.9 to 4.5 meters below the first floor of the Catacombs, the real state, a typical cross section_1).

The results from the preliminary static analysis indicate that the peak total displacements for the Catacombs complex is 2 mm in underground water conditions, while it was 1.13 mm in the initial dry conditions (initial model). Figures (5a) Peak horizontal displacements Ux = $374.33*10^{-6}$ m. (Fig. 5b) Peak vertical displacements Uy = $2.00*10^{-3}$ m inside the Catacombs. Static analysis of the underground water conditions. Figure 6a) Peak Total displacement = $1.13 *10^{-3}$ in the initial model, (Fig. 5b) While it is $2.00*10^{-3}$ in underground water conditions.

Some supporting rock piers are under relatively high compression stresses where the calculated peak effective principal compressive stresses are – $1.42*10^3$ KN/m^2 for the pier_1. (Fig. 7a) Vertical peak effective compressive stresses = -1.42*103 KN/m2 in the initial model, (Fig. 7b) The same value in the underground water conditions. Static analysis. The effective compressive stresses on the top of rock piers increased obviously after rising of underground water level (see Figs. 8, 9). (Fig. 8) Effective compressive stresses distribution through the supporting rock piers_1 (a) Initial model. (b) In underground water conditions. Static analysis.

(Fig. 9) Effective compressive stresses distribution through the supporting rock piers_2 (a) Initial model. (b) In underground water conditions. Static analysis. The effective compressive stresses on the top of rock piers increased obviously after raising of underground water level.

The total strains (Peak principal strain= $-67.11*10^{-3}$ % in underground water conditions, while it was = $-66.99*10^{-3}$ % in the initial model, (Fig. 10) presents the total strains. (Peak principal strain = – $67.11*10^{-3}$ %), with underground water, while it was – $66.89 *10^{-3}$ %. in the initial model. Static analysis. (Fig. 11) Vertical strains (Eps-yy). Peak vertical strain, peak Eps-yy = – $52.26*10^{-3}$ %, and the peak horizontal strain = – $31.99*10^{-3}$ %, underground water conditions while it was – $31.99*10^{-3}$ % in the initial model. Static analysis. (Fig. 12) Extreme active pore pressure – 458.69 kN/m^2. (Fig. 13) Evaluation of a global safety factor of the construction processes.

6.2 El-Shatbi Necropolis

Figure (14) presents the deformed finite element mesh and boundary conditions used for the numerical analyses of the soft rock excavations of El-Shatbi Necropolis in underground water conditions (the underground water level is 60 cm above the original ground level of the main tomb, the real state, and a typical cross section_1). Figure .14. (a) Deformed mesh and boundary conditions. (b) Plastic points distribution. Static analysis. Underground water conditions.

The results from the preliminary static analysis indicate that the peak total displacements for El-Shatbi complex in underground water conditions is = $660.38*10^{-6}$ m, while it was $86.64*10^{-6}$ m in the initial dry conditions (initial model). Figure. 15. (a) Peak horizontal displacements Ux =-49.07 *10 – 6 m. (b) Peak vertical displacements Uy = 660.18*10 – 6 m inside the excavations. Static analysis underground water conditions. Figure .16. (a) Peak Total displacement = 86.64 *10 – 6 m in the initial model, (b) while it is 660.38 *10 – 6 m in underground water conditions.

The peak total compressive stresses in the underground water conditions = -686.82 kN/m^2, while it was = -612.92 kN/m^2 in the initial model, see figures (17), Figure .17. (a) Peak total compressive stresses =-612.92 KN/m2 in the initial model, (b) while it is – 686.82 KN/m2 in the underground water conditions, Static analysis. Also the peak active pore pressure = -298.49 kN/m^2 in the underground water conditions. The Peak principal strain = $-9.98*10^{-3}$ % in underground water conditions, while it was = – $0.01 *10^{-3}$ % in the initial model. Figure .18. Peak active pore pressure = – 298.49 kN/m^2. Figure .19. Evaluation of a global safety factor of the construction processes.

When the phreatic level raised, the bearing capacity of the soil/rock decreases with the rise of the groundwater level, resulting in additional settlement. When the water level rises by **1 m inside the Catacombs of Kom El-Shoqafa**, the cumulative settlement is **2 mm**. Therefore, people must pay enough attention to it and take corresponding measures to control the rise of groundwater level and ensure the safety of the archaeological sites in Alexandria.

7. The Mitigation Strategies

Countries with a large number of World Heritage sites at risk should put in place adaptation measures at the national level; The Egyptian government is working to develop a strategy for adaptation to climate change, which will include potential scenarios in the years 2050 and 2100. While the Ministry of Environment and Energy bears full responsibility for the strategy, the Ministry of Culture is involved in drafting cultural heritage impact assessments. The Ministry of Culture says managing climate change risks will be an integral part of the management plan.

Climate change is one of the risks among a number of challenges facing World Heritage sites. This threat must be viewed in the broader context of preserving these sites.

The potential impacts of climate change range from physical, social and cultural aspects. In terms of natural heritage, the vast majority of biomes may be negatively affected by the impacts of climate change.

The impacts of climate change affect many and are likely to affect many World Heritage properties, both natural and cultural, in the coming years.

This study represents the first part of forecasting and managing the impacts of climate change on the world heritage of Alexandria.

The mitigation strategy may begin with a review of the nature and magnitude of the risks to World Heritage properties arising in particular from climate change;

Therefore, the main objective of the mitigation strategy is to review the main issues to be taken into account when preparing to implement preventive and / or corrective management responses to deal with the negative impacts of climate change.

Conservation is managing change, and climate change is one of the most important global challenges facing society and the environment today. Actions to be taken to preserve the 3D heritage:

Preventive measures: monitoring, reporting and mitigating the effects of climate change through environmentally sound choices and decisions at a range of levels: individual, community, institutional and corporate.

Corrective actions: Adaptation to the realities of climate change through global and regional strategies and local management plans.

Knowledge sharing: Including best practices, research, outreach, public and policy support, education and training, capacity building, networks, etc.

It is imperative to implement appropriate management responses to address the threats that climate change poses to their natural and cultural properties inscribed on the World Heritage List.

The Egyptian government, which is struggling to rebuild the economy after the turmoil that followed the Arab Spring in 2011, has allocated more than $ 120 million for barriers and other protection measures along the beach. Without these barriers, parts of the Corniche and buildings near the shore would be damaged, at an estimated cost of approximately $ 25 billion, see Figure (20).

As a result of the bad environmental situation around the archaeological area of Kom al-Shuqafa, it became necessary to choose some suitable places to dig some trenches to collect groundwater from the study area in Kom al-Shuqafa. In fact, because the groundwater level has become a great danger to the temples area after the construction of the new arches of Kom al-Shuqafa, it is necessary to work on drainage networks covered with a layer of sponge to draw underground water or dig trenches at certain distances from the temple to withdraw the wastewater slowly to avoid cracking the walls of the temple. The methodology includes a GIS technology phase to identify the possible possible sites based on external influence factors such as roads, DEM, archaeological area, cultivation.

8. Conclusion

Floods cannot always be prevented and this definitely applies to the Alexandria flood in October 2015 should be more prepared for floods as this type of event is likely to occur more frequently due to climate change. The observed consecutive individual storm events are events of low likelihood and the persistence and clustering of these large rainstorm events was exceptional. The October 2015 storm led to floods in Alexandria of historic proportions, such as the Kom al-Shaqfa cemeteries and the Shatibi necropolis. The risk of these rainwater cluster events cannot be properly managed using conventional methods as they are not designed to bypass or fail.

One of the first short-term and inexpensive mitigation measures could be using precipitation forecasting in modeling rainwater.

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Tables

Table .1. Short-term laboratory tests carried out on calcarenitic, ooloitic intraclastic, and sandy oolitic limestones under investigation.

Type of Rock	γ_d Mg/cm^3	(GS)	η %	Uniaxial compression test				Triaxial compression test						Direc Shea test c rock
				σ_{ucs} MPa	Failure Strain E_f (%)	E Young's Modulus (MPa)	ν [-] Poisson's ratio	φ [o]	C KN/m^2	E Young's Modulus (MPa)	ν [-] Poisson's ratio	{G} Shear modulus (MPa)	{K} Bulk modulus (MPa)	φ [o]
Intact Calcarenite rock (pure Limestone). *Moustafa kamil necropoli\ ssite.*	1.62	2.74	36	3.55		68	0.28	31º	400	410	0.28	160	311	
	1.75	2.80	28	3.45		106	0.30			340	0.28	133	258	
	1.77	2.79	19	2.30		78	0.24			300	0.30	117	227	56 0
	1.65	2.67	28	3.40		106	0.30							
	1.65	2.84	27	3.45		80	0.28							
Sandy oolitic limestone. *Catacomb of komEl-shoqafa.*	1.69	2.66	32	2.6		74	0.24	36º	500	360	0.29	141	273	
	1.70	2.78	31	2.74		102	0.28			345	0.26	135	261	
	1.68	2.49	21	2.7		74	0.28			270	0.26	105	205	50 0
	1.65	2.80	40	2.6		74	0.24							
	1.68	2.74	31	2.74		80	0.24							
Oolitic intraclastic limestone *El-shatbi necropolissite*	1.80	2.58	23	6.3		147	0.30	53º	700	445	0.28	173	353	
	1.79	2.82	23	4.7		138	0.28			440	0.28	172	333	62
	1.84	2.58	36	5.03		142	0.28			392	0.25	153	297	
	1.62	2.49	16	6.3		147	0.30			353	0.24	138	267	
	1.82	2.55	24	6.1		140	0.30			233	0.25	91	177	

Figures

Figure 1

Oct. 25, 2020, floodwater in the coastal and inside city of Alexandria.

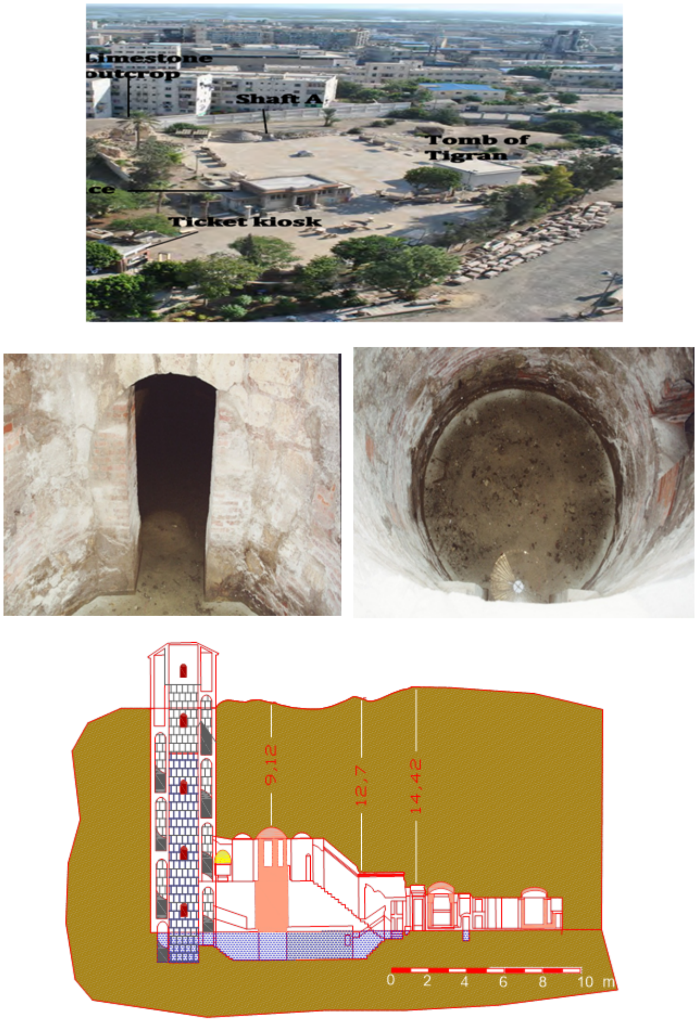
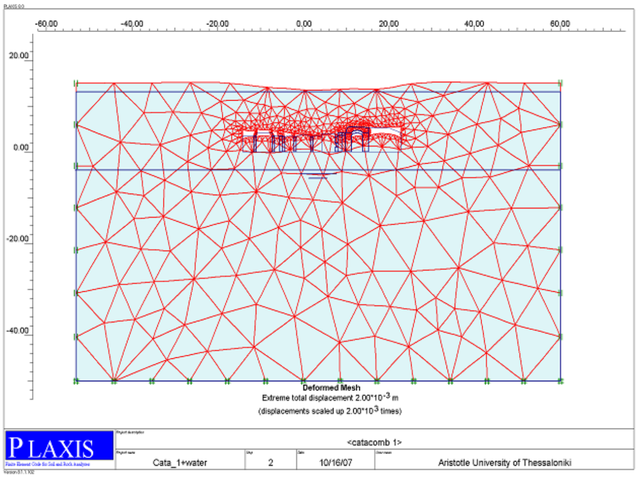


Figure 2

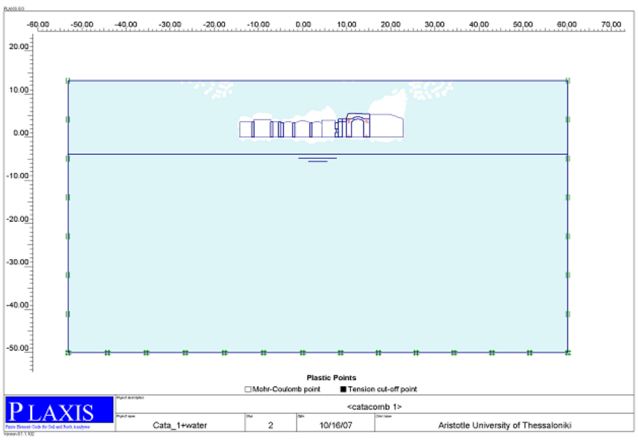
Ground water intrusion inside the Catacombs of Kom El-Shoqafa in Alexandria.

Figure 3

Sea water intrusion inside El-Shatbi Necropolis in Alexandria.



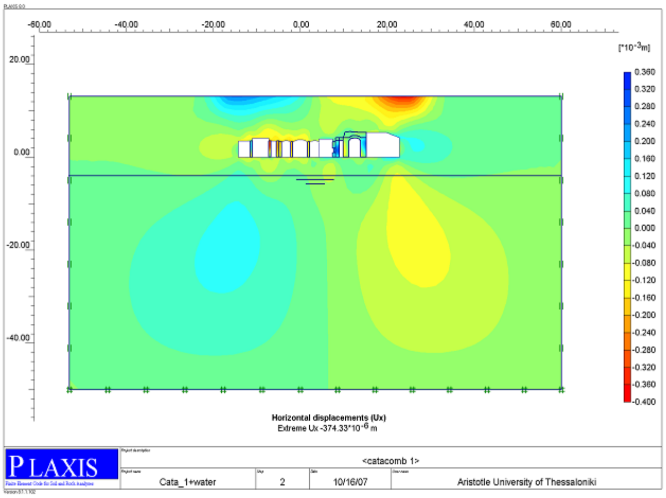
(a)



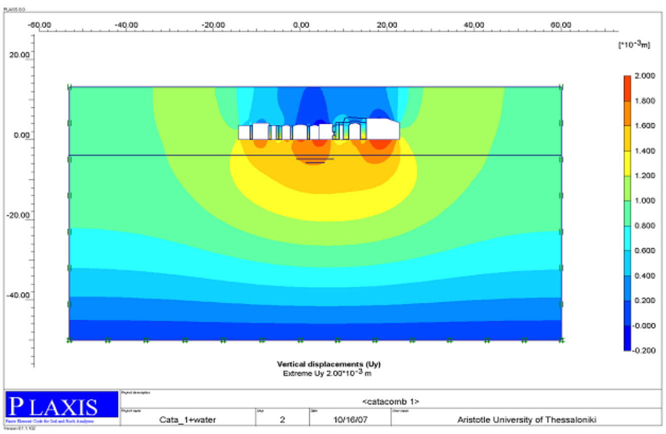
(b)

Figure 4

(a) Deformed mesh and boundary conditions. (b) Plastic points distribution. Static analysis. Underground water conditions.



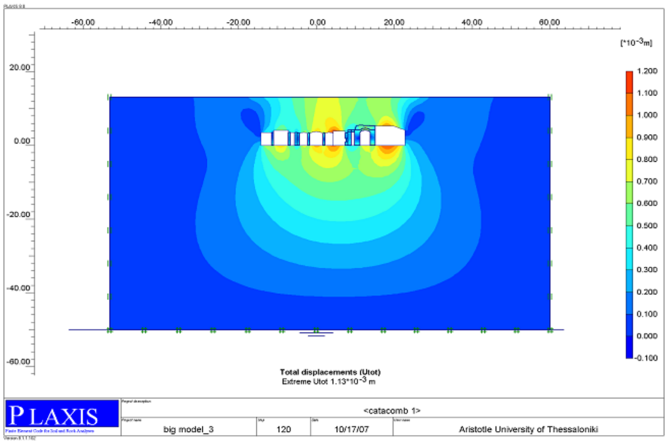
(a)



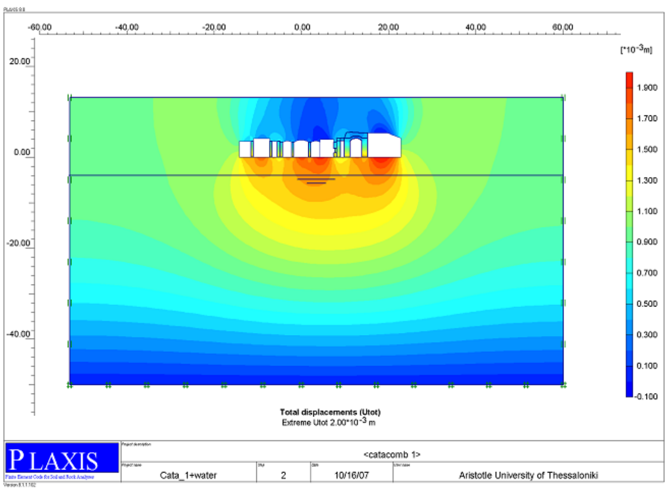
(b)

Figure 5

(a) Peak horizontal displacements Ux =374.33*10-6 m. (b) Peak vertical displacements Uy= 2.00*10-3 m inside the Catacombs. Static analysis. Underground water conditions.



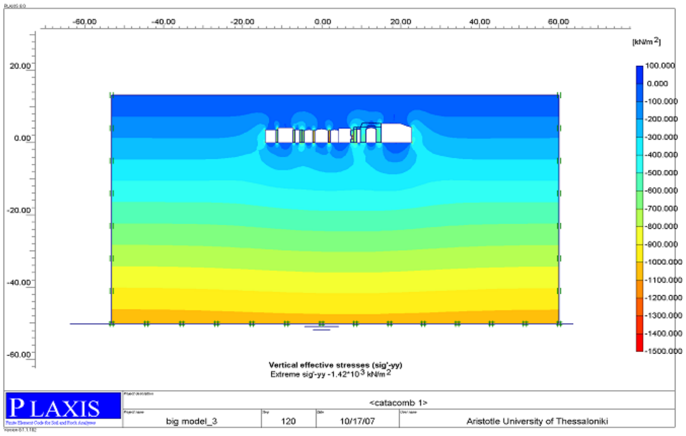
(a)



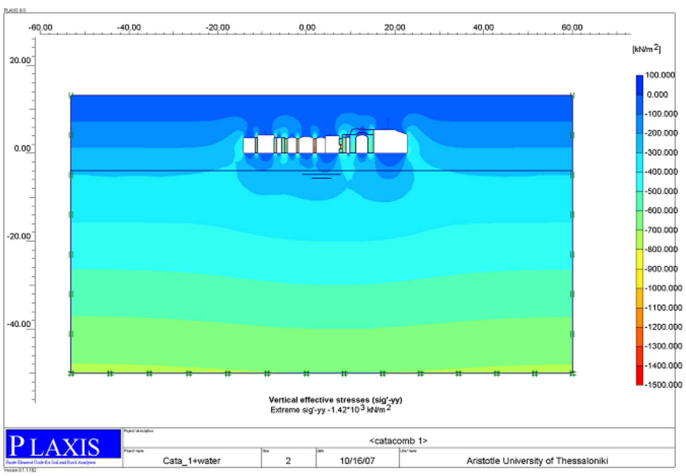
(b)

Figure 6

(a) Peak Total displacement = 1.13 *10-3 in the initial model, (b) While it is 2.00*10-3 in underground water conditions.



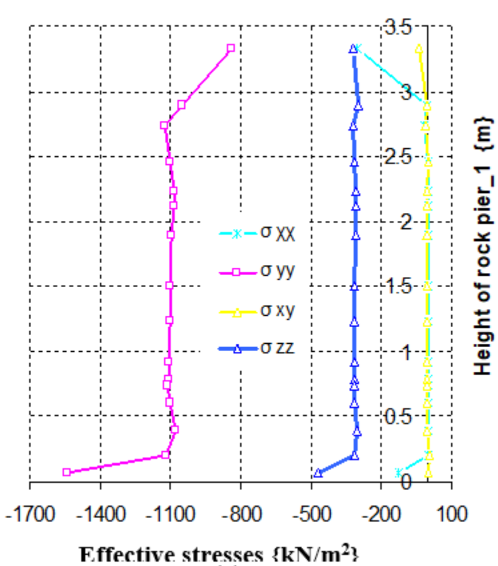
(a)



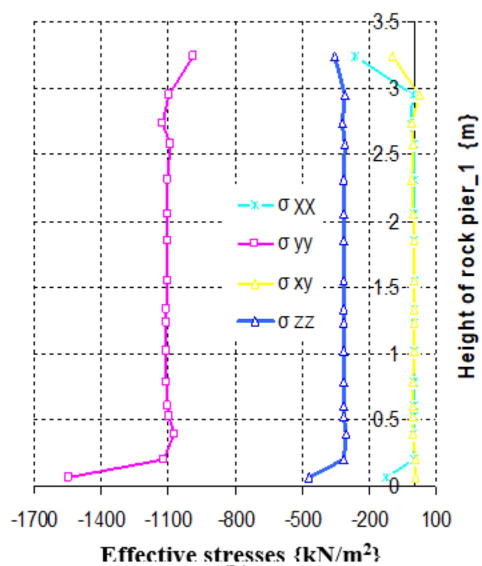
(b)

Figure 7

(a) Vertical peak effective compressive stresses = -1.42*103 kN/m2 in the initial model, (b) The same value in the underground water conditions. Static analysis.



(a)



(b)

Figure 8

Effective compressive stresses distribution through the supporting rock piers_1 (a) Initial model. (b) In underground water conditions. Static analysis.

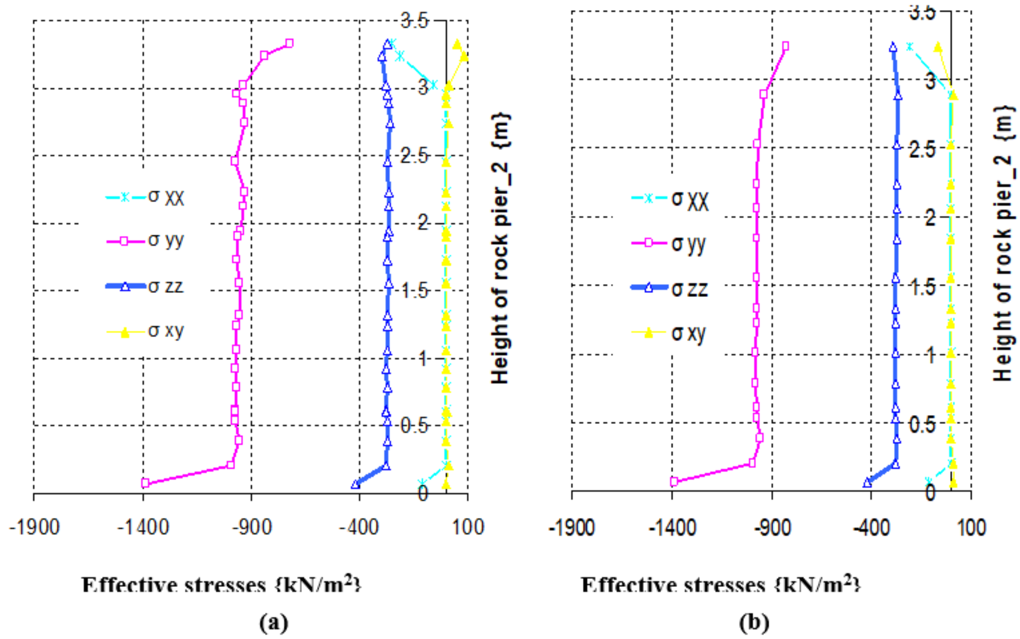


Figure 9

Effective compressive stresses distribution through the supporting rock piers_2 (a) Initial model. (b) In underground water conditions. Static analysis. The effective compressive stresses on the top of rock piers increased obviously after raising of underground water level.

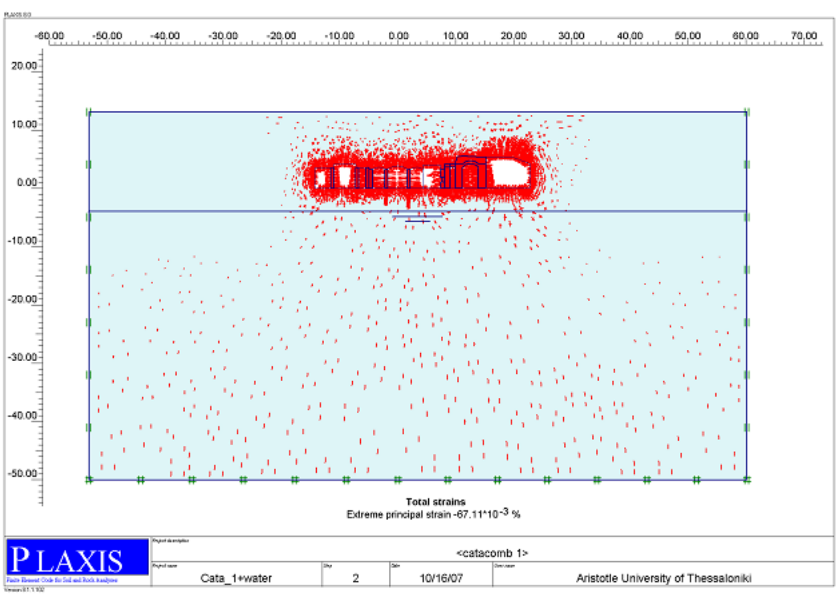


Figure 10

Total strains. (Peak principal strain = - 67.11*10-3 %), with underground water, while it was -66. 89 *10-3 %. in the initial model. Static analysis.

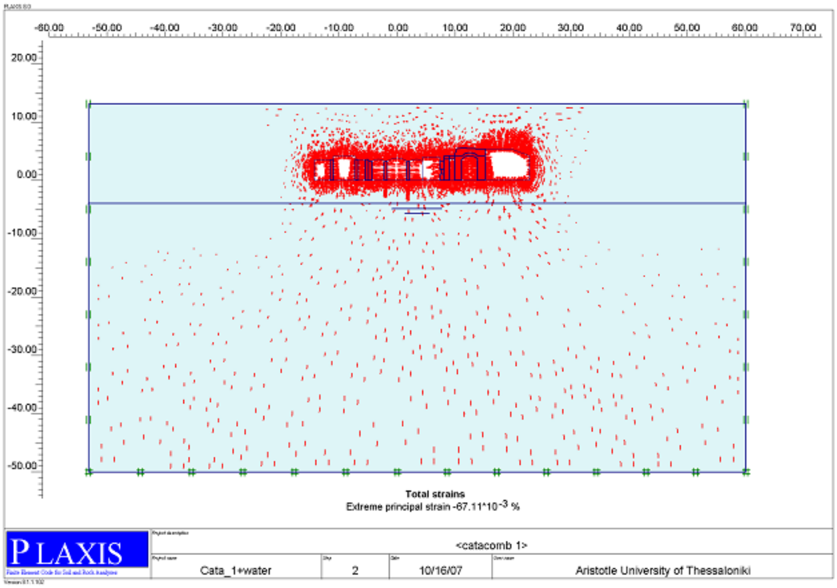


Figure 11

Vertical strains (Eps-yy). Peak vertical strain, peak Eps-yy = - 52.26*10-3 %, and the peak horizontal strain = - 31.99*10-3 %, underground water conditions while it was -31.99*10-3 % in the initial model. Static analysis.

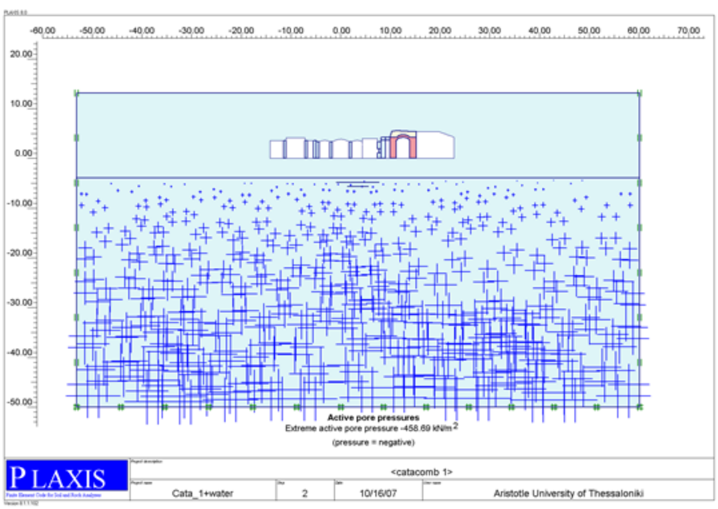


Figure 12

Extreme active pore pressure - 458.69 kN/m2.

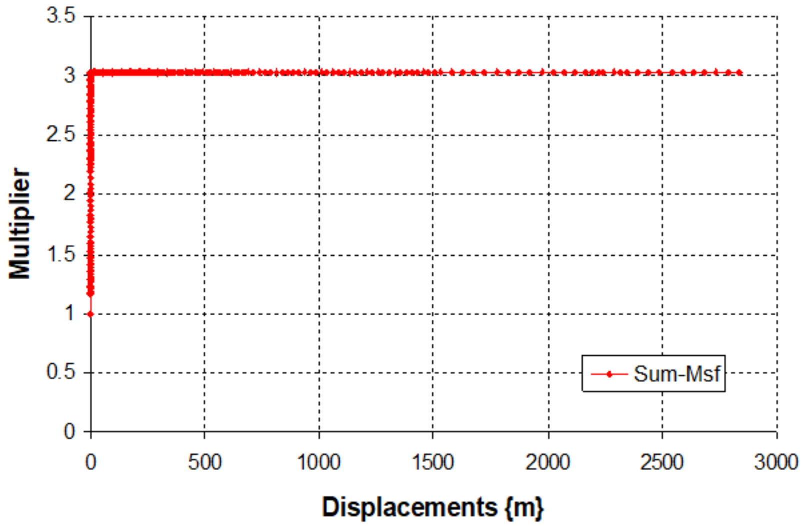


Figure 13

Evaluation of a global safety factor of the construction processes.

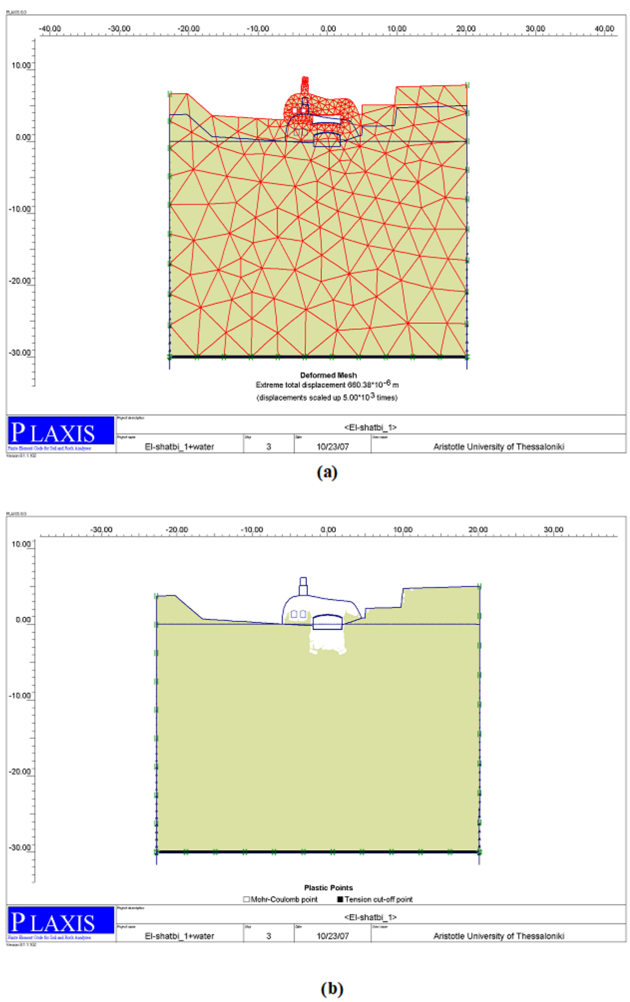
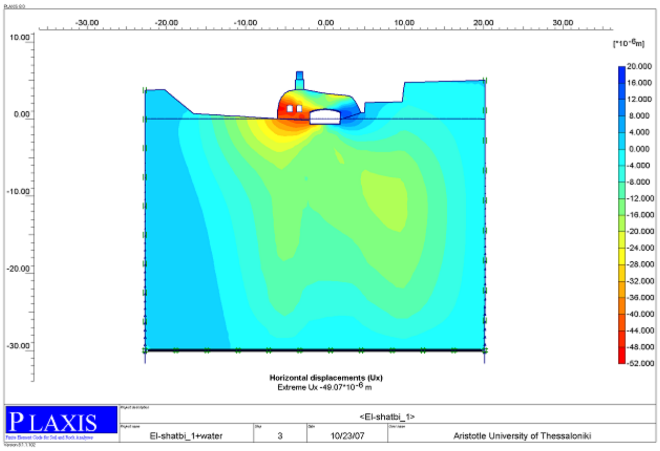
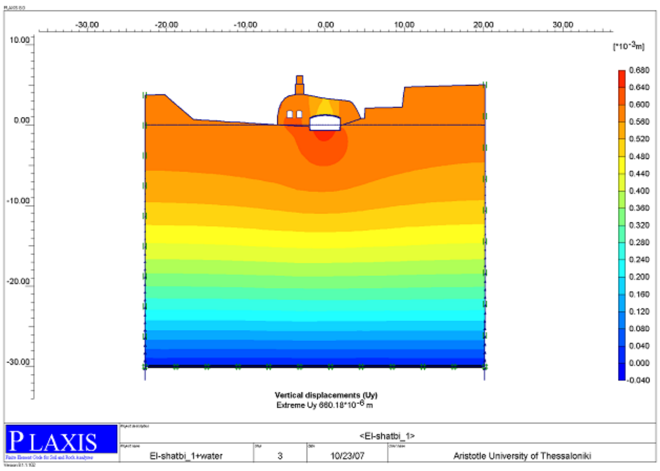


Figure 14

(a) Deformed mesh and boundary conditions. (b) Plastic points distribution. Static analysis. Underground water conditions.



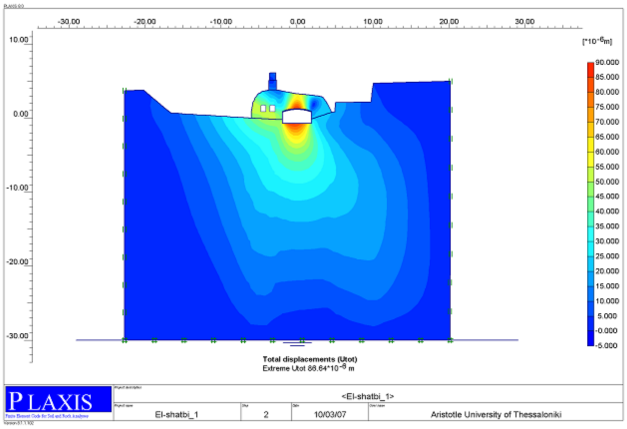
(a)



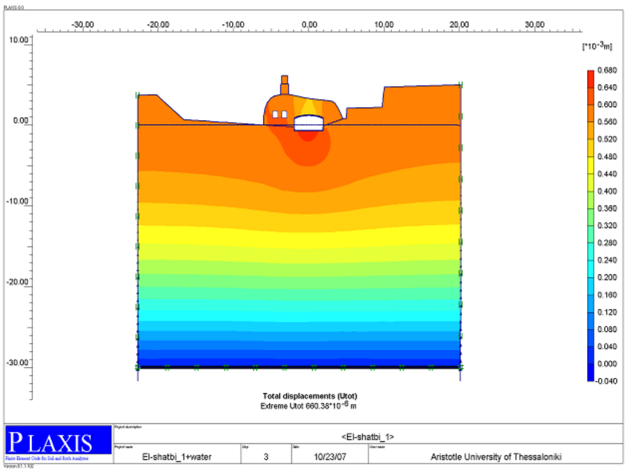
(b)

Figure 15

(a) Peak horizontal displacements Ux =-49.07 *10-6 m. (b) Peak vertical displacements Uy= 660.18*10-6 m inside the excavations. Static analysis. Underground water conditions.



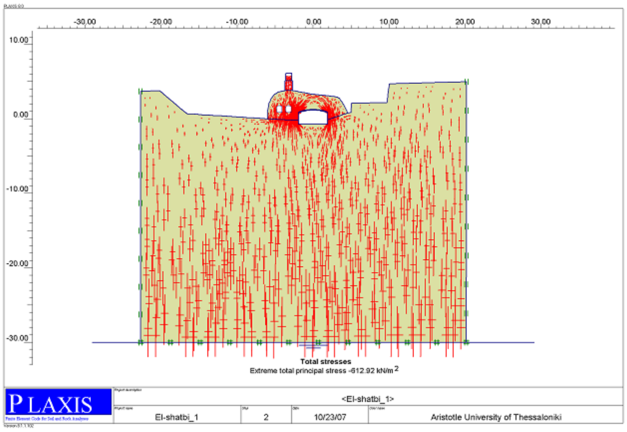
(a)



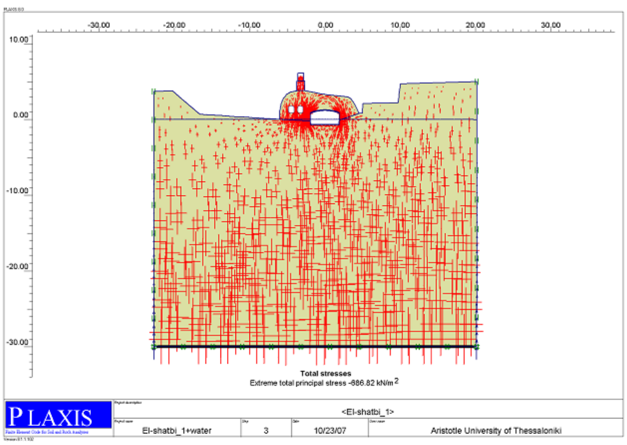
(b)

Figure 16

(a) Peak Total displacement = 86.64 *10-6 m in the initial model, (b) while it is 660.38 *10-6 m in underground water conditions.



(a)



(b)

Figure 17

(a) Peak total compressive stresses =-612.92 KN/m2 in the initial model, (b) while it is - 686.82 KN/m2 in the underground water conditions. Static analysis.

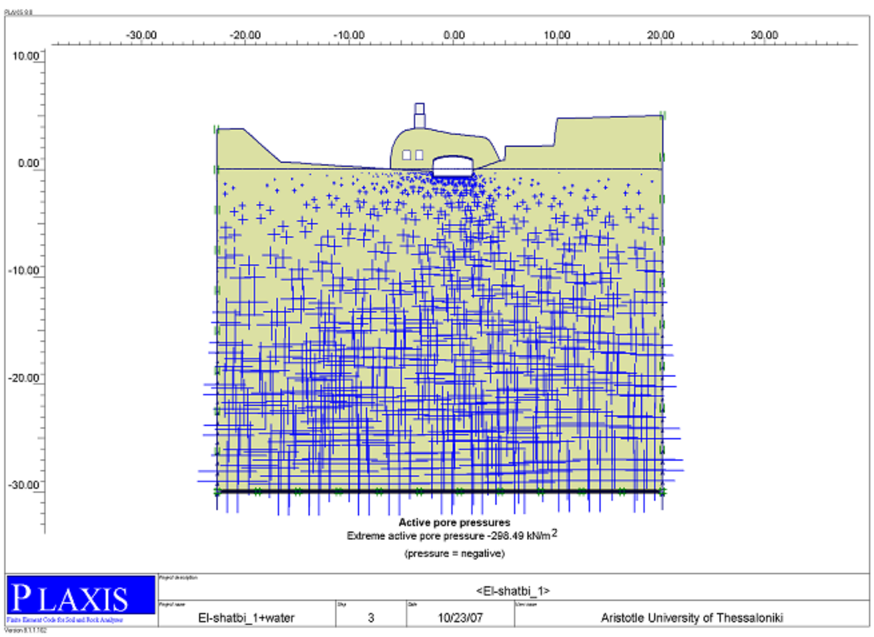


Figure 18

Peak active pore pressure = - 298.49 kN/m2

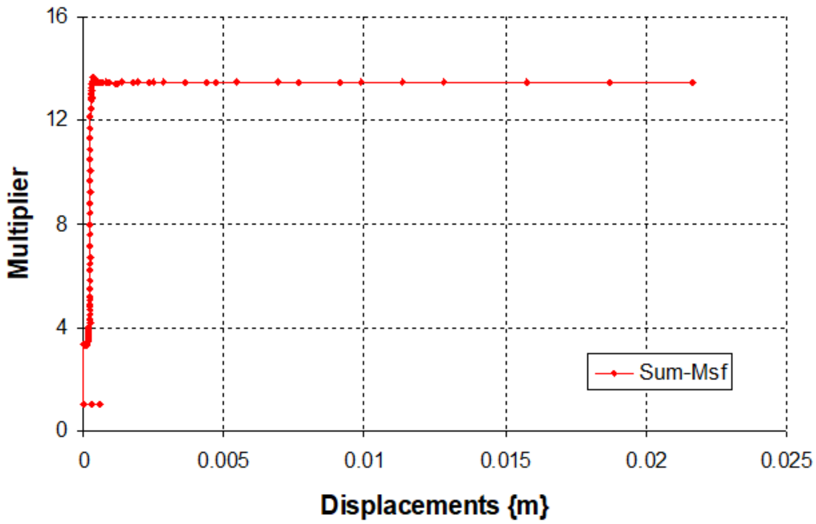


Figure 19

Evaluation of a global safety factor of the construction processes.

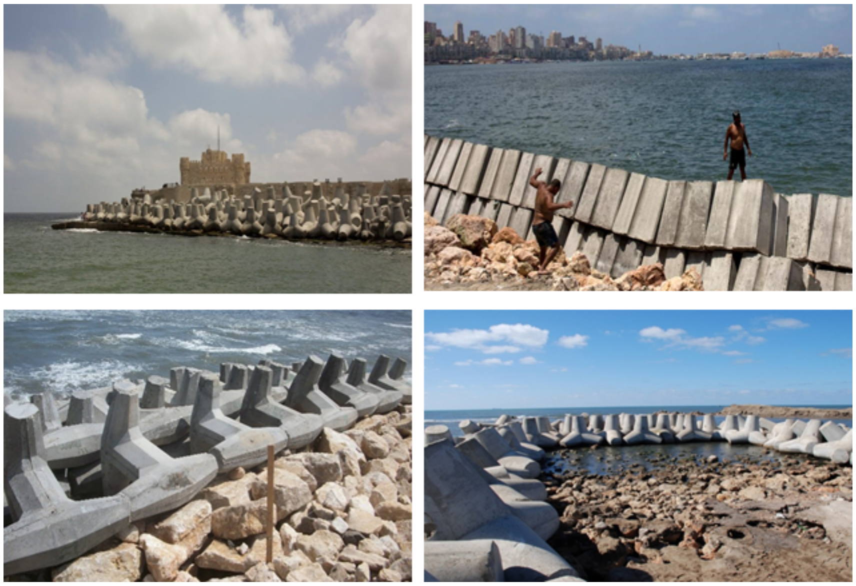


Figure 20

A cement barrier placed as reinforcement against rising water levels near the citadel. b. The barriers and other protective measures along the shore of Alexandria. In this August 8, 2019, photo, workers prepare to place cement blocks to reinforce the sea wall against rising water levels on the corniche in Alexandria, Egypt.