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Three-Dimensional Stability Analysis of the Central Rotunda of the Catacombs of Kom El-Shoqafa, Alexandria, Egypt

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THREE-DIMENSIONAL STABILITY ANALYSIS OF THE CENTRAL ROTUNDA OF THE CATACOMBS OF KOM EL-SHOQAFA, ALEXANDRIA, EGYPT

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ABSTRACT

A three-dimensional numerical model has been proposed of the central Rotunda of the catacombs of Kom El-Shoqafa with its six supporting rock pillars, excavated in sandy oolitic limestone deposit. The model was based on a 3D realistic simulation of the problem geometry. The required input for the analysis (strength and deformability of the rock materials) was derived from laboratory tests and empirical assessments. The rock mass in general is normally widely jointed (> 1 m). In the analysis it is considered as an un-jointed homogeneous medium with low strength. Where 2D analysis fails to model properly the column behaviour, we use 3D modeling to evaluate the stress state in the supporting rock pillars of the excavated Rotunda, taking into account their 3D arrangement.. The results of the numerical analysis on the central supporting Rotunda show that some surface subsidence was induced during excavation of the catacombs. In particular, the displacement developed at the surface above the Rotunda reaches a maximum of 3 mm. This numerical result corroborates the observed displacements in the underground structures and the surface subsidence. The first part of this paper presents a comprehensive geotechnical survey undertaken in the archaeological site, comprising geophysical ambient noise measurements along with field and short- and long-term laboratory experiments, in order to define the physical, mechanical and dynamic properties of the soils and soft rock materials. The second part presents the main results of the detailed 3D numerical analysis of these underground monuments, using an advanced soil-rock elastoplastic modeling

INTRODUCTION

This study presents the numerical 3D static FEM analysis of selected underground monuments in Alexandria, Egypt i.e. the Catacombs of Kom El-Shoqafa (Figure 1). The analysis of the stability and behavior of such complex monuments under static loading is the key factor for their efficient restoration and retrofitting.

In this stage, we present the main results of the detailed static 3D numerical analysis of these underground monumental structures (catacombs, tombs, and cemeteries). Advanced soil-rock elastoplastic modeling has been used throughout the different phases of the numerical finite element analysis. The aim of the analysis is to investigate the safety margins of the existing monuments in their present condition against unfavorable environmental (i.e. weathering and high underground water table) and geotechnical conditions.

The paper presents a comprehensive study of underground monument safety analysis. It comprises failure analysis, and a thorough investigation of the effects of weathering and underground water on differential settlement. Commercial package FLAC3D (ITASCA, 2008) was used for calculating stresses and settlements. It is a finite element program developed for geotechnical engineering design and research and has been recently used in the analysis of geo-structures. It is especially intended for numerical static and dynamic analysis of geotechnical and underground structures. The Mohr–Coulomb model is used both for static loading and consolidation analysis. The geometry of the model is selected sufficiently large so that the boundaries do not influence the results. The code has a convenient procedure for automatic load stepping, called Load Advancement, which we made use here.

COMPUTING STRESSES IN THE SUPPORTING ROCK PILLARS

It is demonstrated that stresses of significant magnitude and ambiguous distribution are to be expected in the pillars. Multiple openings and excavations are designed on the basis of the average stress in the pillar given by equation 1, based on the tributary area theory (Figure 2).

$$\overline{\sigma}_v = \frac{A_t}{A_p} \cdot \sigma_v \qquad (1)$$

where:

A_t is the area supported by the pillar,

A_p is the area of the pillar, and

σ_v is the vertical stress at the level of the roof of the excavation (catacombs).

To evaluate the degree of safety of a pillar, the above average pillar stress (σ_v) are compared with the pillar strength (σ_p). The latter is not simply equal to the unconfined compressive strength of the material comprising the pillar (q_u), because shape and size effects introduce significant deviations from the breaking strength of unconfined compressive cylinders.

The strength in compression for rectangular pillars of square cross-section can be estimated as follows:

$$\sigma_p = \left(0.875 + 0.25 \cdot \frac{W}{H}\right) \cdot \left(\frac{h}{h_{crit}}\right) \cdot q_u{}^{1/2} \qquad (2)$$

where:

σ_p is the strength of the pillar,

W and H are the width and height of the pillar respectively,

q_u is the UCS, σ_c strength of the pillar material on cylinders with height (h) equal to twice the diameter, and

h_{crit} is the minimum height of the cubical specimen of pillar material such that an increase in the specimen dimension will produce no further reduction in strength (Bandis, 2008).

For pillar 1 (Figure 3), with σ_v =1.74 Mpa, A_t = 0.50 m^2, and A_p = 0.25 m^2, we can derive:

$$\overline{\sigma}_v = \frac{A_t}{A_p} \cdot \sigma_v = \frac{0.50}{0.25} \cdot 1.74 = 3.48 MPa \qquad (3)$$

The strength of the pillar σ_p can be estimated from equation 2: For pillar 1 we have W=0.50m and H=3m. If we assume h_{crit} = 0.2m and h=1m, and for q_u =2.5 Mpa, we have σ_p = 5.12 MPa. The Factor of Safety is then:

$$F_s = \frac{\sigma_v}{\overline{\sigma}_v} = \frac{5.12}{3.48} = 1.47 \qquad (4)$$

The tributary theory is based on average pillar stresses and derives a stress value of 1.74 Mpa, which is generally close to the average values predicted by the 3D code.

On the other hand, the overloading of particular sections may have an overriding influence on pillar stability, particularly in terms of long-term creep effects and associated strength loss or thinning-out of the effective load bearing section.

Hoek and Bray quote Salamon and Munro’s suggestion of acceptable safety factors being greater than 1.6. Such values may be adequate for stability of this excavation (Hemeda, 2008).

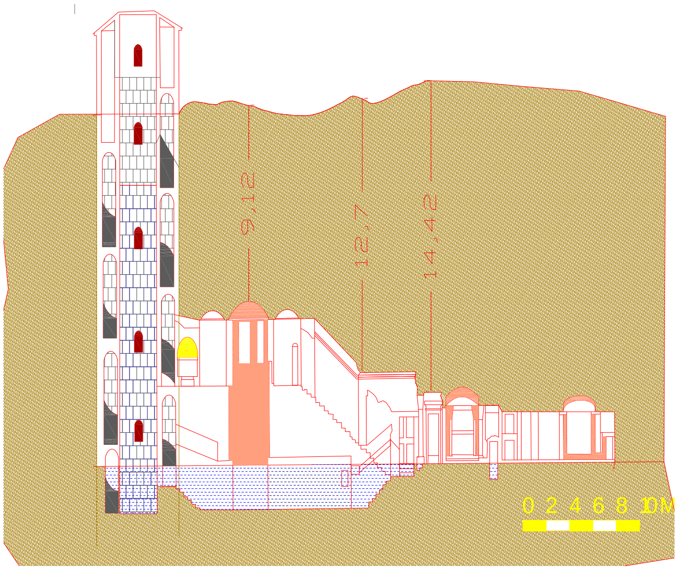


Fig. 1. Main cross-section of the Catacombs of Kom El-Shoqafa, including location of the rotunda.

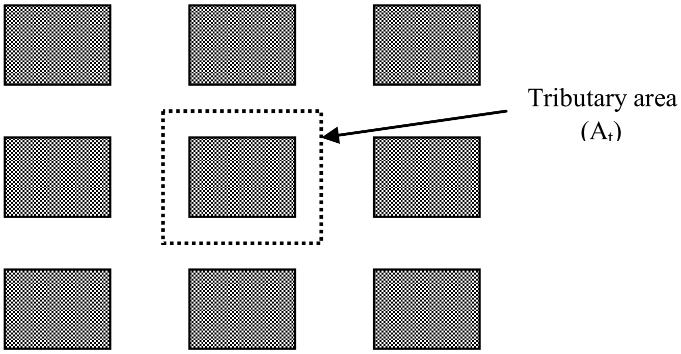


Fig. 2. Diagram of the tributary area theory.

STABILITY ANALYSIS

The rock mass where the Catacombs of Kom El-Shoqafa are excavated and constructed is composed from sandy oolitic limestone horizontally bedded. It is an unjointed, soft, weathered rock with considerably low mechanical strength and high porosity. (Hemeda et al., 2007). Considering all other factors, especially the weathering, ageing, rise of underground water level, high stresses, along with the utter lack of preservation and the specific geometry of these complexes, this low rock strength seriously affects the safety of the Catacombs both under static and seismic loading conditions. We present herein a 3D numerical analysis of the central Rotunda with its six supporting rock piers, which are located in the first floor of the catacombs, 9.12 m below the ground surface.

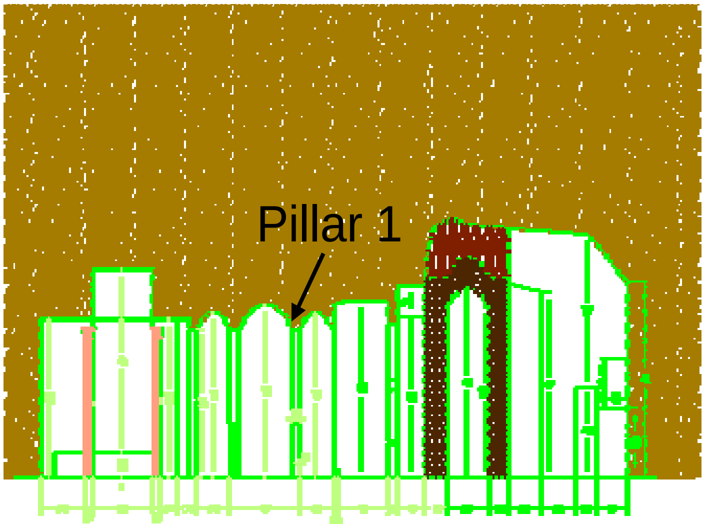


Fig. 3. Main cross-section of the Catacombs of Kom El-Shoqafa, including location of the rotunda pillars.

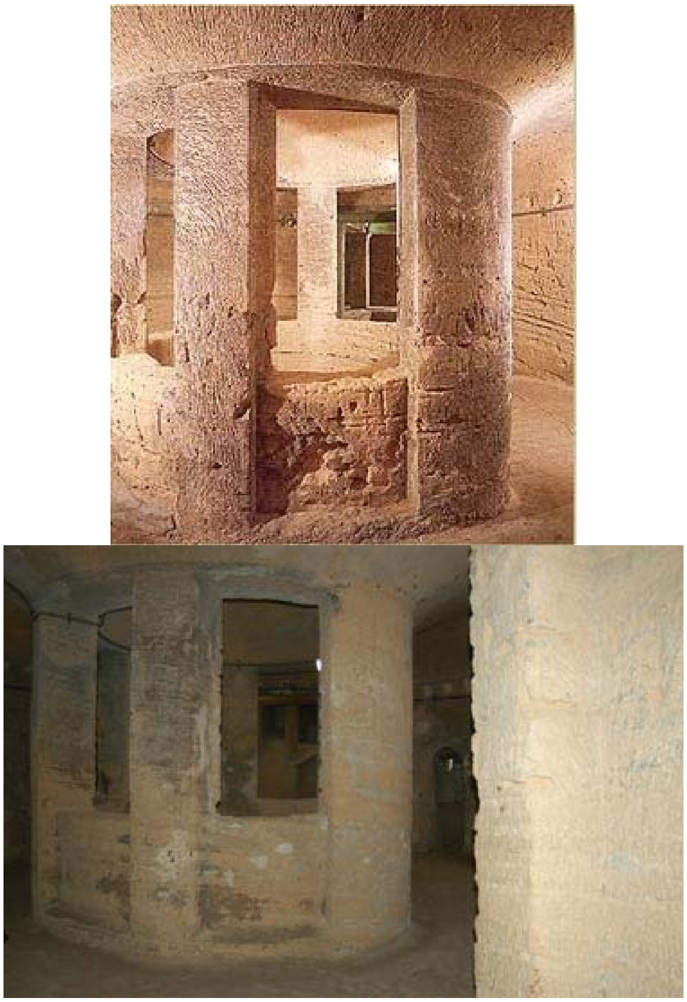


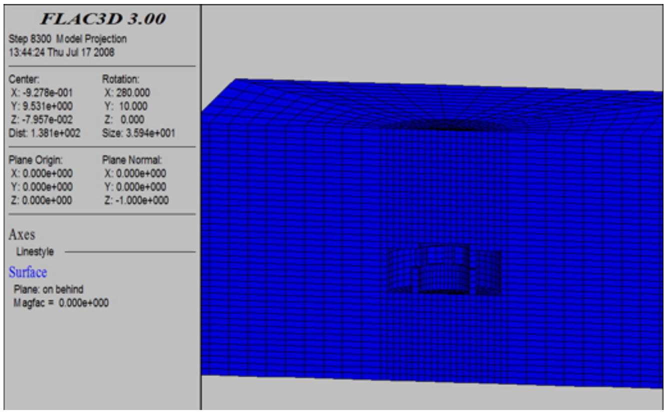
Fig. 4. The Rotunda of the Catacombs of Kom El-Shoqaf (present state).

CODE USED

FLAC3D is a numerical code for advanced geotechnical analysis of soil, rock and structural support in three dimensions. The code utilizes an explicit finite difference formulation that can model complex behaviors not readily suited to FEM codes, such as: problems that consist of several stages, large displacements and strains, non-linear material behavior and unstable systems (even cases of yield/failure over large areas, or total collapse). The proposed 3D analysis can yield more precise results on ground movement and displacement of the underground monument excavation, as well as effective stresses on the supporting rock columns and piers, which are the most vulnerable parts in these underground monuments.

MODEL GEOMETRY

The 3-D meshes cover the 9 m in width (w) for the excavated rotunda region and the excavation region around the rotunda and 40 m from the intact rock within which the Rotunda and whole catacombs are excavated. The height (h) of 3-D model is about 20 m (Figure 5). In addition, the length from the roof of Rotunda to ground surface is 3.80 m. In addition, the geological characteristics are considered in modeling as filling of dirty grey crushed stones, crushed bricks filling of dirty yellow crushed calcareous. cemented sand, some med/coarse calcareous (0-4 m depth), Filling of dirty yellow med/coarse calcareous sand, trace pieces of calcareous cemented sand, trace fine crushed bricks (4-10m depth), Filling of dirty, grey pieces of crushed calcareous Stone crushed bricks (10-12 m depth), Yellow med/coarse calcareous sand trace pebbles of calcareous cemented sand, trace very fine crushed shells (12-25 m depth), and sandy oolitic rock (beneath 25 m depth). Material properties of rock and other construction material were used in the stability analysis of Catacombs of Kom El-Shoqafa summarized in Table 1, where the static young's modulus (E) 360 MPa, Bulk modulus (K) 273 MPa, Shear modulus (G) 141 MPa, Poisson's ratio (ν) 0.28, Cohesion (c) 500 kPa, Friction angle (Φ) 35°, Dilatancy (Ψ) 1°, Gravity 10, and Unit weight (γ) 21 kN/m^3.



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FLAC3D 3.00
Step 8300  Model Projection
13:44:24 Thu Jul 17 2008

Center:                Rotation:
 X: -9.278e-001         X: 280.000
 Y: 9.531e+000          Y:  10.000
 Z: -7.957e-002         Z:   0.000
Dist: 1.381e+002       Size: 3.594e+001

Plane Origin:          Plane Normal:
 X: 0.000e+000          X: 0.000e+000
 Y: 0.000e+000          Y: 0.000e+000
 Z: 0.000e+000          Z: -1.000e+000

Axes
  Linestyle
Surface
  Plane: on behind
  Magfac =  0.000e+000
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Fig. 5. Geometry, the excavated Rotunda and the excavated regions.

In order to improve the quality of the results from the numerical simulation, the sufficient site investigation should be performed (Pitilakis et al, 2009b). In the present case study we performed several types of geotechnical and geophysical field & in-situ tests, such as SPT tests, ambient noise measurements, geotechnical boreholes with integral sampling Lugeon tests, borehole deformation tests and laboratory testing on soils and rocks.

Parameter	Symbol [Unit]	Rock material	Brick (adobe)
Unit weight above phreatic level	γ_{unsat} [kN/m^3]	18	17
Unit weight below phreatic level	γ_{sat} [kN/m^3]	22	20
Young's modulus	E_{ref} [kN/m^2]	2.27E6	1.35E6
Shear modulus	G_{ref} [kN/m^2]	8.867E5	5.4E5
Oedometer modulus	E_{oed} [kN/m^2]	2.902E6	1.62E6
Poisson's ratio	ν [.]	0.28	0.25
Cohesion	c_{ref} [kN/m^2]	500	450
Friction angle	φ [°]	35	31
Shear wave velocity	V_s [m/s]	715	558
Bending strength	σ_y [kN/m^2]	560	200
Shear strength	T_f [kN/m^2]	364	-
Dilatancy	Ψ [°]	1	0

Table 1. Material properties of rock and other construction materials used in the analysis.

ANALYSIS RESULTS

Results of the numerical analysis of the central supporting rotunda as originally designed shows that some surface subsidence was induced during excavation of the catacombs (Figures 6 - 18). The displacement developed at the surface, right above the excavated rotunda, reached a maximum value of about 3 mm. This numerical result corroborates the displacement and surface subsidence observed at the underground structures. The results of the 3D static analysis indicate that the ground displacements above the rotunda are small (of the order of 2.7 mm), while the maximum horizontal displacement remains below 1.0 mm. The evaluation of the stress state in the pillars indicates that some supporting rock pillars are under relatively high compression stresses. The maximum compressive effective principal vertical stress calculated is -1.74 MPa. A lower magnitude has been computed applying a 2D analysis with PLAXIS, where the computed maximum compressive stress has a value of -1.42 MPa. The maximum compressive effective principal horizontal stress is -1.12 MPa. The computed factor of safety for the supporting rock pillars is equal to 1.47.

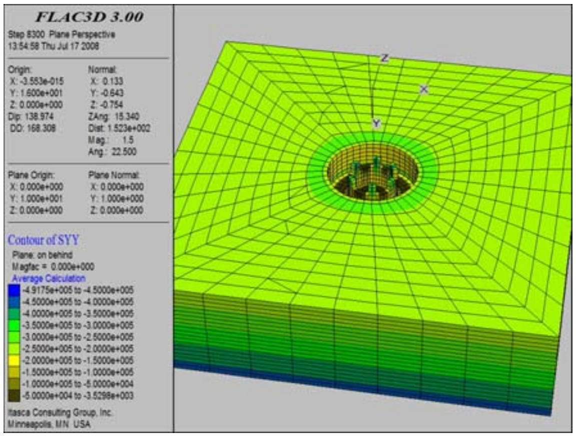

Fig. 6. Contour of vertical effective compressive stresses σ_{yy} through the rotunda.

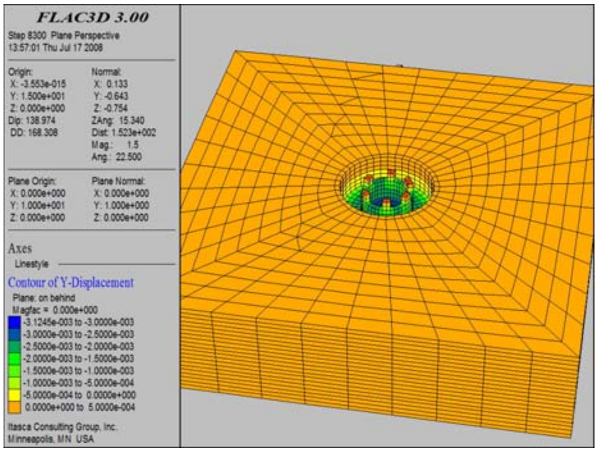

Fig. 7. Vertical displacements U_{yy} in the rotunda.

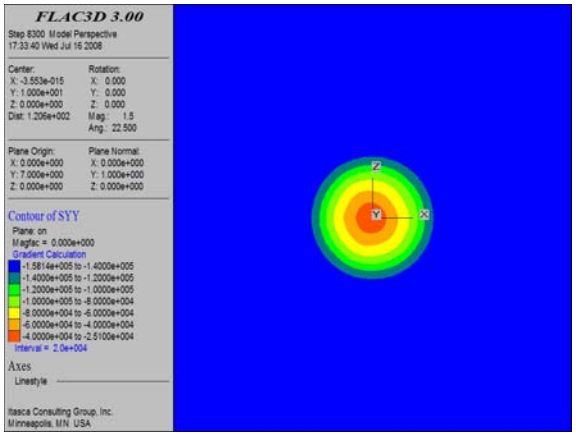

Fig. 8. Horizontal cross-section showing contours of vertical compressive stresses σ_{yy} above the rotunda, 7 meters below the ground surface.

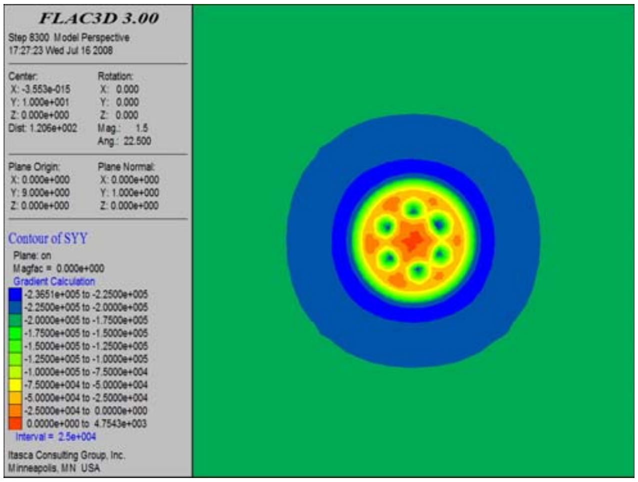

Fig. 9. Contours of vertical compressive stresses σ_{yy} *above the rock pillars of rotunda, 9 meters below the ground surface.*

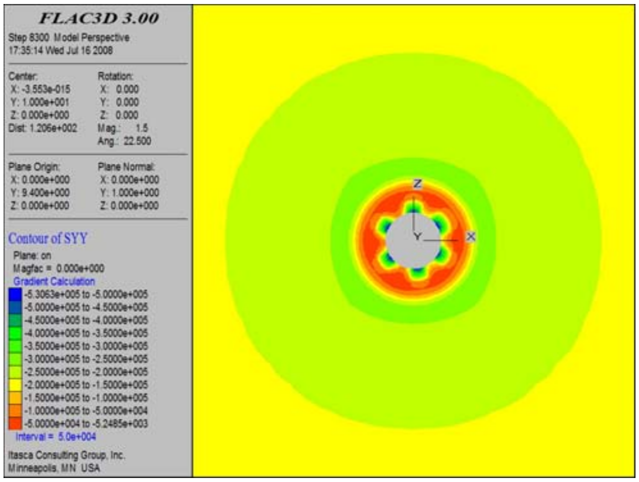

Fig. 10. Contours of vertical compressive stresses σ_{yy} *above the rock pillars of rotunda, 9.4 meters below the ground surface.*

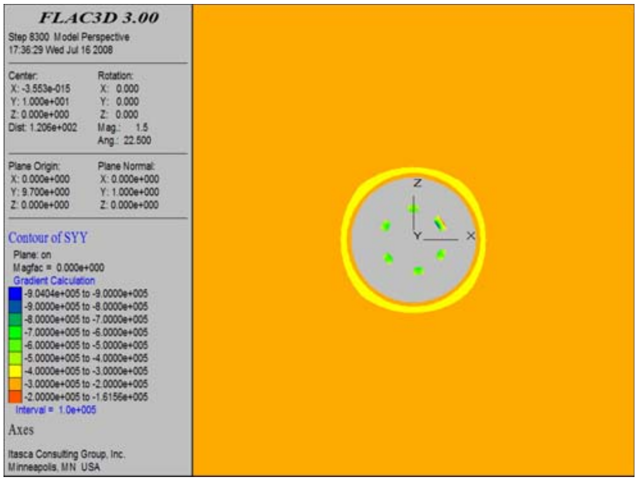

Fig. 11. Contours of vertical compressive stresses σ_{yy} *above the rock pillars of the rotunda, 9.7 meters below the ground surface.*

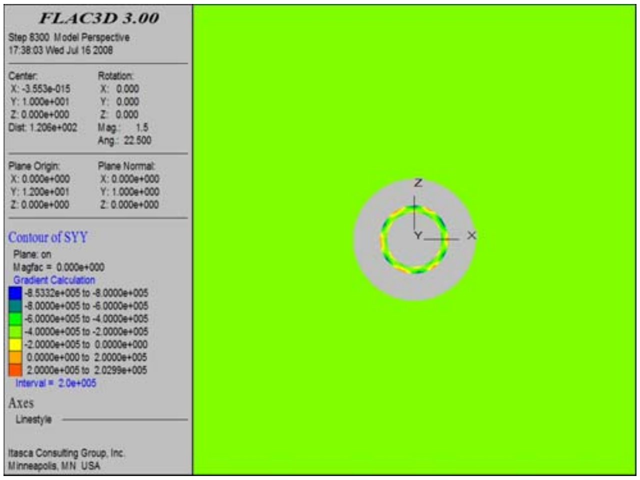

Fig. 12. Contours of vertical compressive and tensile stresses σ_{yy} *above the rotunda, 12 meters below the ground surface.*

Fig. 13. Contours of vertical compressive stresses σ_{yy} *below the rotunda, 13.5 meters below the ground surface.*

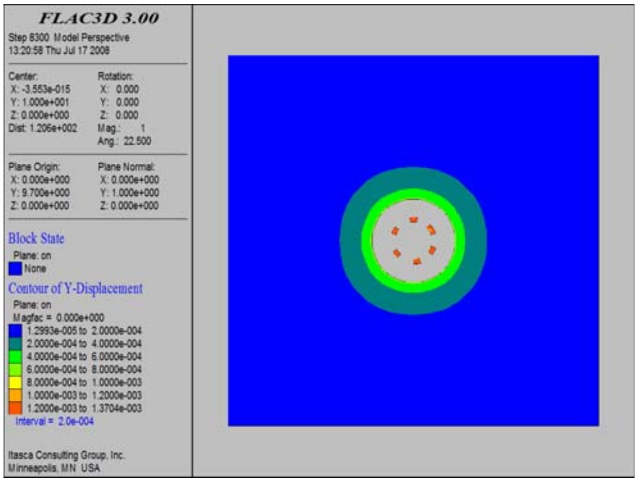

Fig. 14. Contours of vertical displacements U_{yy} *of the rock pillars of rotunda, 9.7 meters below the ground surface.*

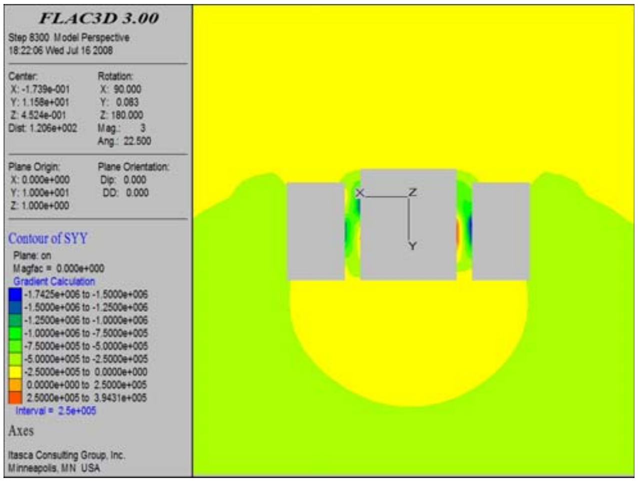

Fig. 15. Contours of vertical stresses σ_{yy} *on the rock pillars of rotunda; the maximum effective compressive stresses -1.74*103 kN/m*^{2}.

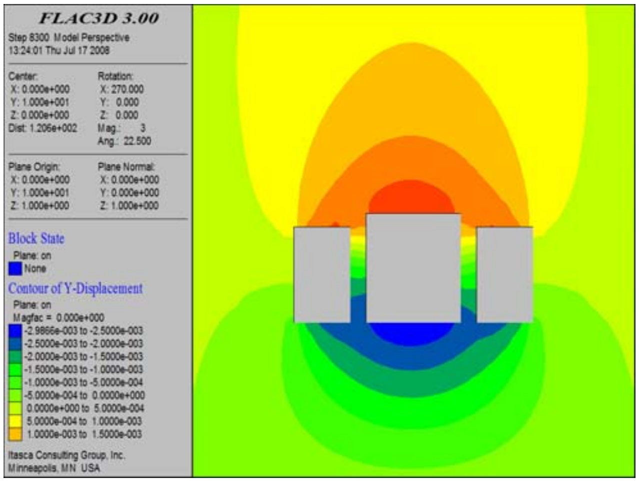

Fig. 16. Contours of vertical displacements U_{yy} *of the catacombs, the maximum vertical displacements above the rotunda is 2.6 mm.*

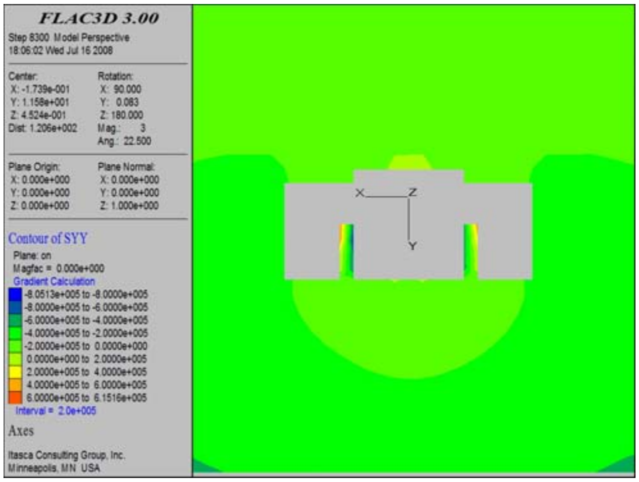

Fig. 17. Contours of vertical compressive and tensile stresses σ_{yy} *between the rock pillars of rotunda, on the windows.*

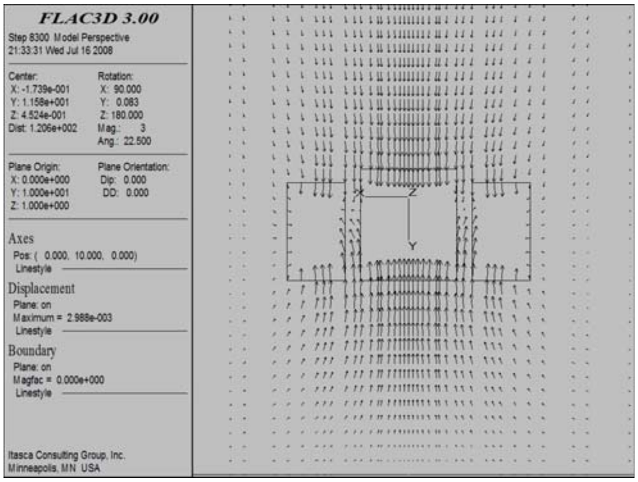

Fig. 18. Contours of vertical displacements U_{yy} *of the catacombs, the maximum vertical displacements in the domain being 3 mm. The pillars are under strong compression.*

CONCLUSIONS

2D analysis does not adequately model a complex structure's behavior under static and seismic loading. The Rotunda of the Catacombs of Kom El-Shoqafa in Alexandria- is a typical case where a 3D analysis is deemed necessary to capture the real behavior and response. The results of the numerical analysis on the central supporting rotunda show that some surface subsidence was induced during the excavation of the catacombs.

The displacements developed at the surface right above the rotunda should be about 3 mm. This numerical result corroborates the phenomena observed, namely the underground structures' displacements and surface subsidence.

The computed maximum horizontal displacement is even lower (about 1 mm). Certain supporting rock pillars are under relatively high compression stresses For example the calculated maximum compressive effective principal vertical stresses on pillar 1 is 1.74 MPa, a value 30% higher that the relative 2D PLAXIS analysis . The calculated peak effective principal compressive horizontal stress on this pillar is 1.12 Mpa, and the maximum tensile stress is 0.2 MPa. The computed factor of safety for the supporting rock pillar 1 of the Rotunda is relatively low for static loading conditions (i.e. 1.47). Such a value may not be adequate for the stability of the catacombs under static and certainly under seismic conditions. Computations also indicated that the overstress state of the rock pillars is beyond the elastic regime: σ_v=-1.74 MPa, which is larger than the 50% of the estimated unconfined strength q_u (UCS) of the in situ rock material, which is presenting several active cracks in the ceiling of the second floor where the royal tomb. The existing cracks decrease the nominal strength of the intact rock mass, due to the long-term creep effects which are associated with strength loss or thinning-out of the effective load bearing section.

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