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Numerical Modeling of Limestone Rock Mass Loaded to Failure above Underground Karstic Cavities using FLAC2D Software : A case study of Al Kharj Region - Saudi Arabia

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Abstract— The stability and potential building hazard arising from karstic cavities within the shallow limestone rock mass are a special feature of the urban environment in the city of Al Kharj (located in the south of Al Riyadh, Saudi Arabia). Numerical modeling analyses using FLAC2D , have been applied to determine the behavior of the rock mass layers above these randomly underground voids usually continuously under complex solicitation (water pressure, loading from new building at the surface and pre-existing voids). The modeling has been validated by using the geotechnical characteristics of shallow limestone which have taken based on the bibliography; initial strength parameters of the limestone were derived from laboratory testing also in the bibliography. These computer modeling analyses have been combined with the field observations and geotechnical testing. This paper describes the modeling FLAC2D being applied, the manner in which the results are used by Civil Engineers to design a type of a new building foundations above these underground voids. More field tests will be recommended as geophysical investigation in order to make a mapping allows to geo-referencing these shallow underground voids within the urban area.

Index Terms— Limestone, underground voids, FLAC2D, Stability, Risk prevention of failure.

2 Introduction

Al Kharj valley being located in the central region of Saudi Arabia in the south of Al Riyadh around 50 km, temperature variations in the last years with high winds give rise to unexpected heavy rains. In addition, in the recent years, the south of Al Riyadh (Al Kharj) is exposed to seasonal floods for example the flood during 2003 which inundates the downstream area of Al Kharj valley by a great quantity of water and many difficulties have been indexed in the vicinity of urban areas closed the valley. In fact, Municipality of Al Kharj attached a great importance to fight against the unexpected underground voids in the future. It is a question to explain the behavior of these voids by numerical modeling under the buildings in Al Kharj city based on the geospatial data from satellite images. Since flooding is the most frequent natural disaster, the Municipality has been focusing its attention to Karst Hazard Mapping (KHM) as one of the priority tasks to be accomplished in order to avoid the failure and collapse damage closed the urban area at the downstream valley of Al Kharj.

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The study using models in the case of underground voids, requires to admit hypothesis taking into account the ground complexity and to simplify it. In fact, we often work with two dimensions (plan deformation hypothesis (Hoek & Brown, 1980). To explain how the compression, tensile and shear stresses due to the loading on the surface can be induced up surface, a numerical continuous model has been proposed applying the finite difference method (Fast Lagrangian Analysis Continua (Itesca, 2005). This method is based on the numerical calculations adapted for rock mass (Piguet, 1990). In order to understand the phenomenon of karst in the sallow rock mass layers, we need to highlight the effect of natural (geological) and industrial (mining) processes that help to develop these underground horizontally and vertically. Among these phenomena we can evoke the following : 1 - Differential compacting (settling) : this uneven settling can cause cracks in the floor, walls and foundation of the structure, perhaps dramatically weakening the integrity the structure of building (Khaldaoui et al., 2011). 2 - Subsurface erosion (piping) : in areas where there has been a significant alteration in groundwater levels, either through displacement of natural rainfall, over-pumping of groundwater or pipe leakages, the soft sedimentary basement layer in karst areas can become eroded. This erosion can create large subsurface cavities, diminishing the structural support for a foundations of building (Fox & Wilson, 2010). 3 - Collapse sinkholes : a form when the basement rock supporting the soil above it becomes completely dissolved by water. The

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soil then sits on a subsurface air bubble. Progressive erosion, the weight of absorbed water or the construction of a building above the affected area can cause the bridge of soil above the bubble to collapse completely. These can be minor, foundation damaging subsidence or enormous pits large enough to swallow a small town entirely (Hatzor et al., 2010). 4 - Hazards of karst topography : land where water soluble carbonate bedrock has resulted in the formation of sinkholes, caves and underground water flow can be said to be showing karst topography. The most common bedrocks involved in karst formation are limestone and dolostone (Epting et al., 2009).

Study area : The study area is Al Kharj region in the south of Al Riyadh. This region is located in the western hill slopes of Al Kharj and can be reached Al Hota area in direction of Wadi Al Douasser about 100 km, which receives most of the south-west monsoon rainfall making the Wadi network basin vulnerable for frequent floods. Al Kharj valley watershed sets cover about 5,000 km^2 and major land-use covers are soil and weaken shallow rocks mainly sand, silty sand, gravel and limestone as a bed rock substratum types affected by underground voids "karsts". Geographically the basin lies between the 663341 m and 750964 m E, and 2618055 m and 2693852 m N referring to W.G.S.-84 (World Geodetic System 1984) coordinate system and flows from a height of about 650 m above S.A.L.S. (Saudi Arabia Leveling System) (Fig. 1 & Fig. 2). The photos (Photo 1 & Photo 2) show the underground voids "Karsts" at shallow depth under the built zones.

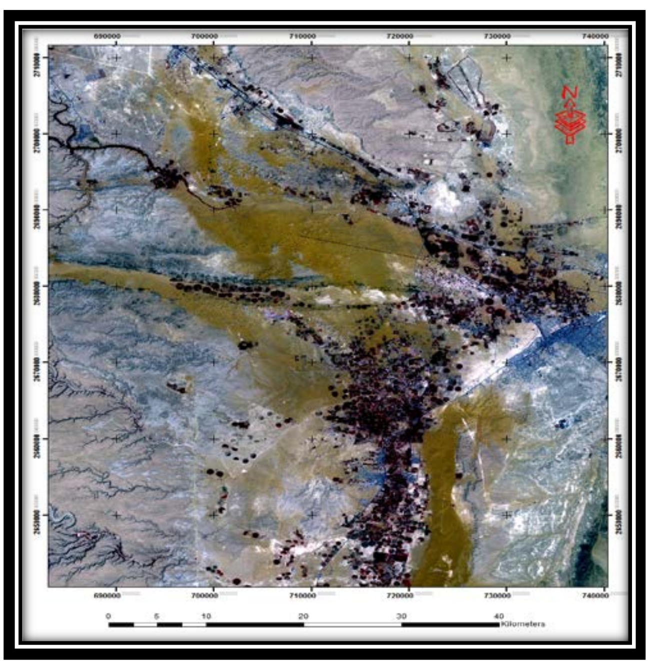

Fig. 1. Al Kharj region.

(LandSat7 Image from RSI-KACST*, 2014).

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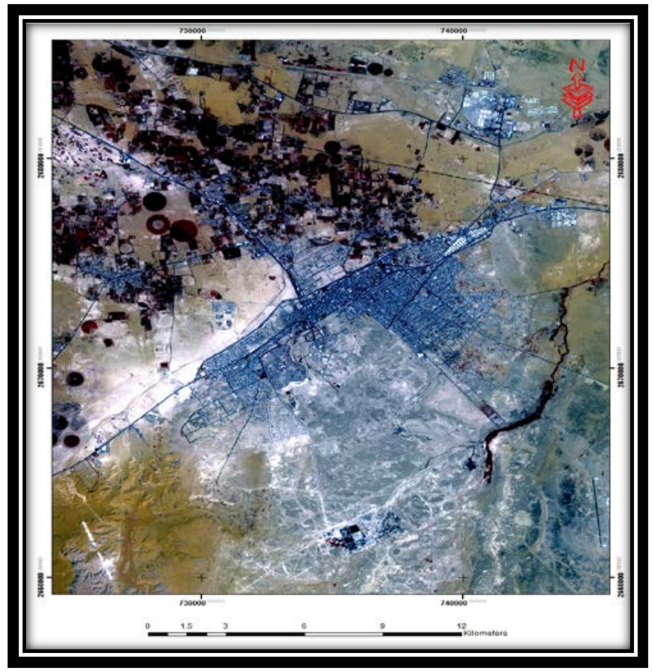

Fig. 2. Enlarged view of study area.

(LandSat7 Image from RSI-KACST*, 2014).

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Photo. 1. Underground void below heavy building (SAU*, 2010).

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These underground voids can reach the surface according the many successive collapses according to the seepage water through the cracks and faults network and the mechanical behavior linked to natural stresses (Kheder,

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1996).

Photo 2. Underground voids below heavy building (SAU*, 2010).

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2 MATERIELS AND METHODS

The finite differences method represents the oldest of the numerical techniques used to solve differential equations (Itasca, 2005). As for the resolution technique used to solve the set of algebraic equations set up, the finite differences method can not build a global stiffness matrix of the system, but to make local resolution stepper on an element and its near neighbors, the equations considered independent insofar as the calculation steps (time step) is sufficiently small so that the consequence of a result could not physically spread from one element to another during the computation step (Itasca, 2005). This process is called explicit resolution. To detail the principle, say that the finite difference method invokes the equation of movement to calculate velocities and displacements from stresses and forces (Fig. 3). From velocities, the deformation rate is calculated and new stresses are deduced. This set of operations is performed on a cycle (one step), in which the variables are assumed constant (one computed velocities, they remain constant during a cycle until they are computed again). This is to validate this hypothesis consistently than the time step must be chosen small enough so that a change of magnitude elsewhere in the system "did not have time" to spread its effects until the element considered (Itasca, 2005). The main advantage of the finite difference method on other numerical methods (Finite Element Method (FEM) for example) lies in the simplicity it presents to the introduction of laws of nonlinear behavior, and thus allow, without effort significant programming to model large displacements. FlAC2D is the software using the finite differences method that we used. The general calculation sequence embodied in FLAC2D software is illustrated in Fig. 4. This procedure first invokes the equations of motion to derive new velocities and displacements from stresses and forces. Then, strain rates are derived from velocities, and new stresses from strain rates (Fig. 3).

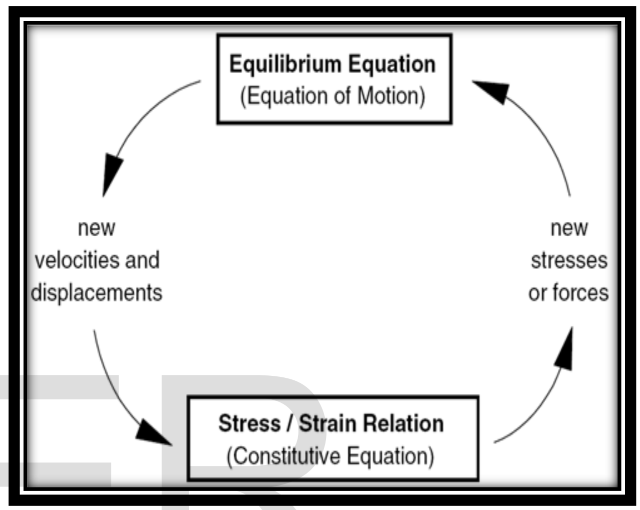

Fig. 3. Basic explicit calculation cycle in FLAC2D (Itasca, 2005).

Within this model based on finite difference method, the initial stresses estimation before making underground voids depend strongly on limit boundary conditions of the model. However, to minimize the boundary effect, the dimensions of the model must be 5 to 10 times the interest zone. In this case the width of one underground void in cross section is 1 m (Fig. 5). To take into account the symmetry of the underground voids, one half of the model has been undertaken. In the bottom of this model, the vertical displacements are nulls. On the lateral limits and for the reason of symmetry of model, the horizontal displacements are too nulls. To better explain the stresses state within the rock mass, a phase by phase simulation has been done. In a first model, we estimate the initial stresses without the underground voids (phase of materials consolidation). After that, we simulate the effect of underground voids and at the same time we cancel the displacement received at the time of consolidation and reinitialize the stresses.

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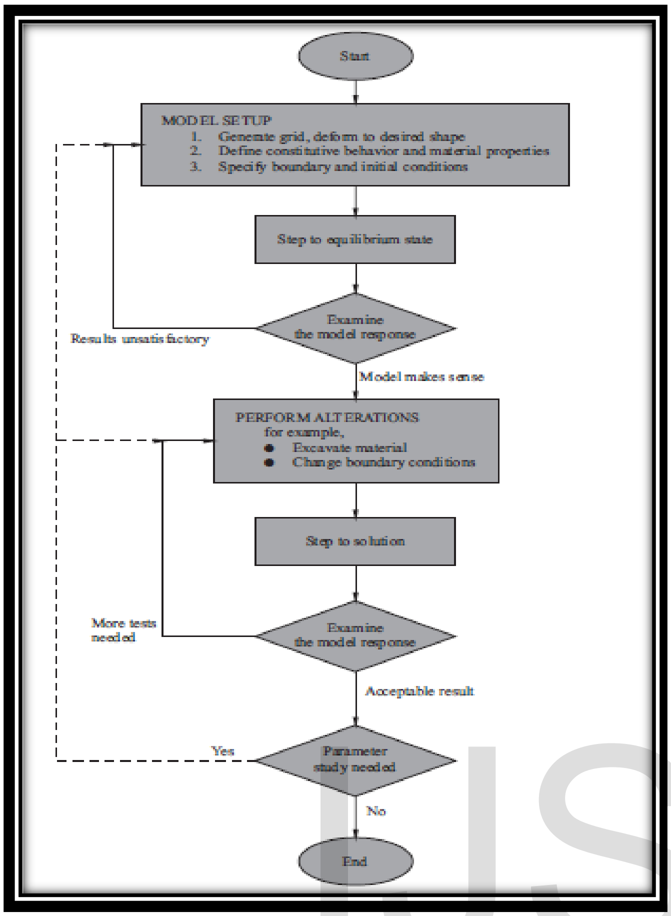

Fig. 4. General solution procedure using FLAC2D (Itasca, 2005).

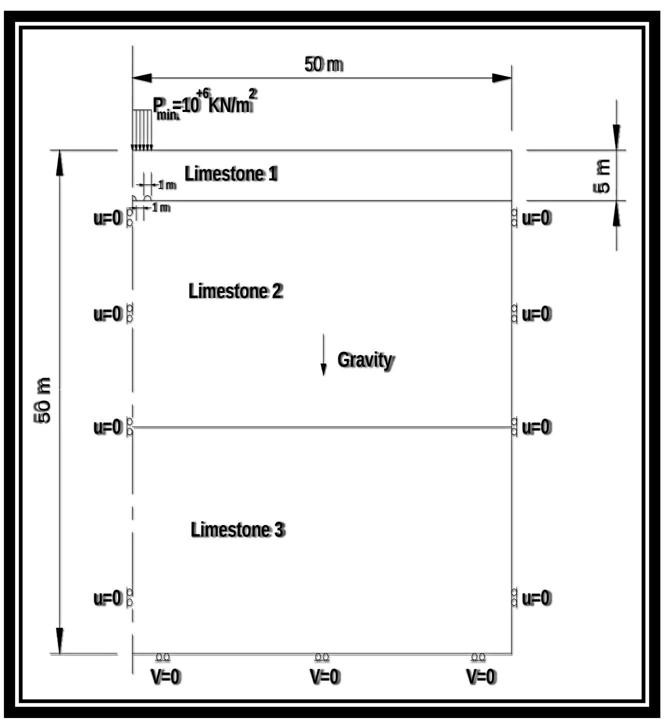

Fig. 5. 2D model and boundary conditions.

This method of calculation phase allows to predict areas of the model with exaggerated stresses (Kheder, 1996). Table 1 shows a reference geotechnical characteristics of materials and shallow layers introduced within the model (Goodman, 1989).

Table 1 : Reference geotechnical characteristics of shallow rock mass layers.

Layers	**γ[1] (kN/m³)**	**C[2] (MPa)**	**φ[3] (°)**	**R_c[4] (MPa)**	**R_t[5] (MPa)**
Limestone1	20	0.30	35	5.0	0.50
Limestone2	25	0.50	35	10.0	1.00
Limestone3	25	0.50	35	15.0	1.50

[1]: Unit weight; [2]: Cohesion; [3]: Friction angle; [4]: Compressive strength; [5]: Tensile strength.

The present 2D model will be performed four underground voids (two voids by symmetry) below a static loading ($P_{min}=10^8$ KN/m²) on three layers of limestone rock mass. Based on the deformation plane hypothesis, the appropriate boundary conditions are presented on the Fig. 5. (Goodman, 1989). The dimensions of these underground voids are assumed 1 m and having a circular form (Photo 1 & Photo 2). Before applying the static load, the first phase is to build the model by applying a gravity load. Due to the symmetry of the model, the DFM grid is done only for the half of the structure. Horizontally and vertically, the size of the elements gradually decrease towards the area of interest which is localized at the base of the first layer of limestone. For this model we assume that the vertical displacements are zero in the bottom of it and on the each lateral side the horizontal displacements are also zero. Using successive calculations, we found that for 50 m by 50 m as dimension of this model (25 times the dimension of the underground void vertically and horizontally) the fields of stresses, displacements and strains are converging. That is to say if these dimensions are increased, the results do not change much (Fig. 9).

3 Results and Discussions

In order to understand the behavior of these underground voids, we focus around these voids vertically and horizontally. In this sense, we look at the main and shear stresses variation within the roof and pillar between the voids. Three phases have been performed in this model (Fig. 6, Fig. 7 & Fig. 8). The first phase initializes the consolidation before opening the underground voids. The second phase introduces the first underground void in the model after consolidation and the third one creates the second underground void. The main stresses around the interest zone have been estimated within the model where

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we see increasing the tensile and compression stresses around the underground voids (Fig. 9). A details concerning the magnitude of main and shear stresses have been indicated around these underground voids (Fig. 10, Fig. 11, Fig.12 & Fig.13). After opening the first underground void, horizontally the main stress in compression has became around 1000 kN/m² and an important shear stress increasing especially within the pillar between the underground voids 400 kN/m². Above this underground void tensile tresses have been developed, about 200 kN/m² (Fig. 14). After opening the second underground void, also horizontally the main stress in compression has became around 1200 kN/m² and more an important shear stress increasing especially within the pillar between the underground voids reaching 1200 kN/m² near the first void and 1100 kN/m² around the second one. Around these underground voids tensile tresses are reached more than 400 kN/m² on the first underground void (Fig. 15). After opening the first underground void, vertically in the roof at the level of the first pillar, the main stress in compression has became around 3000 kN/m² and an important shear stress increasing especially within the pillar reaching about 1000 kN/m² (Fig. 16). After opening the second underground void, vertically in the roof at the level of the second pillar, the main stress in compression has became around 5000 kN/m² and an important shear stress increasing especially within the pillar reaching about 2000 kN/m² (Fig. 17). After opening the first underground void, vertically within the first pillar, the main stress in compression has became more than 1500 kN/m² and the shear stress can reach about 400 kN/m² (Fig. 18). After opening the second underground void, vertically within the second pillar, the main stress in compression has became around 2700 kN/m² and an important shear stress reachs 500 kN/m² (Fig. 19). To compare the stresses before and after opening underground voids, we observe a minimum value of shear stresses around 25 kN/m² under the uniform loading involved by the building at the surface after the consolidation phase and before opening the first underground void. Before opening the second underground void the shear stress can reach 400 kN/m² and an important shear stress increasing especially within the pillar between the underground voids. After opening the second underground void the shear stress becomes around 1200 kN/m² and an important shear stress increasing especially within the pillar between the underground voids (Fig. 20). The interaction between the static loading surface and the degradation (water infiltration from the surface and the stresses redistribution around the underground voids and so on…) due to the time around the underground voids allow to classify the interest zone around the underground voids in two zones : 1 – the first one above the underground voids where a tensile stress can be propagated toward the surface. 2 – the second under static

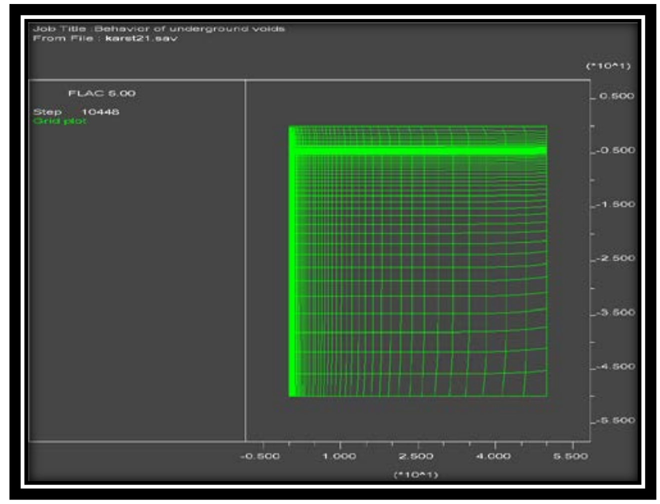

Fig. 6. Whole grid model before opening underground voids.

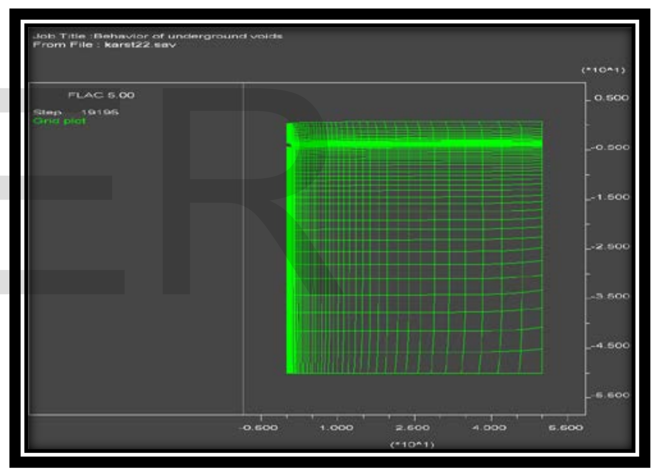

Fig. 7. Whole grid model after opening one underground void.

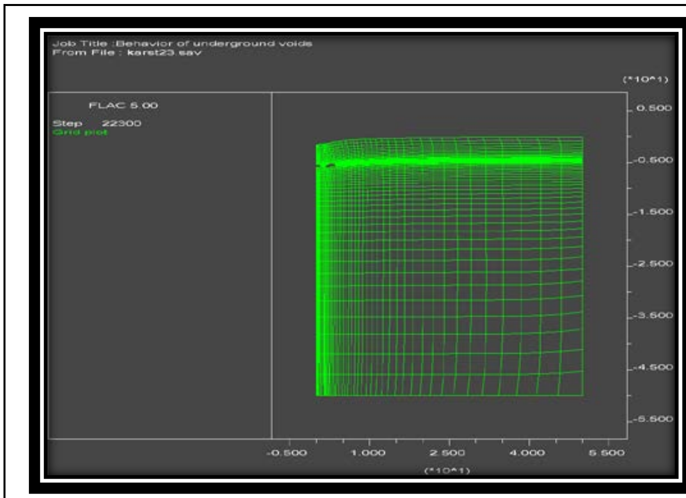

Fig. 8. Whole grid model after opening two underground voids.

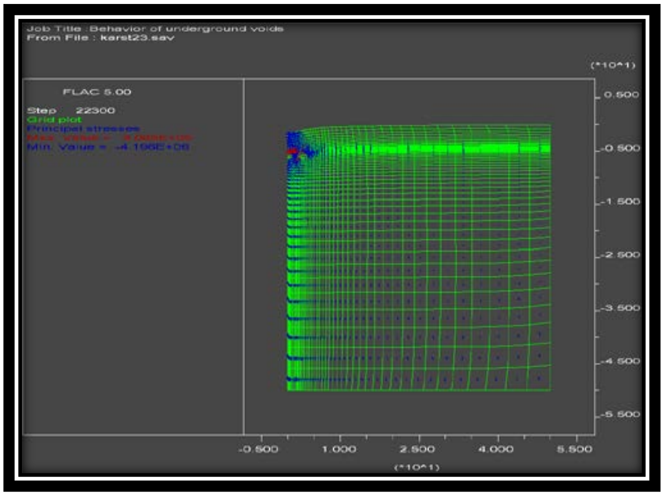

Fig. 9. Main stresses after opening two underground voids.

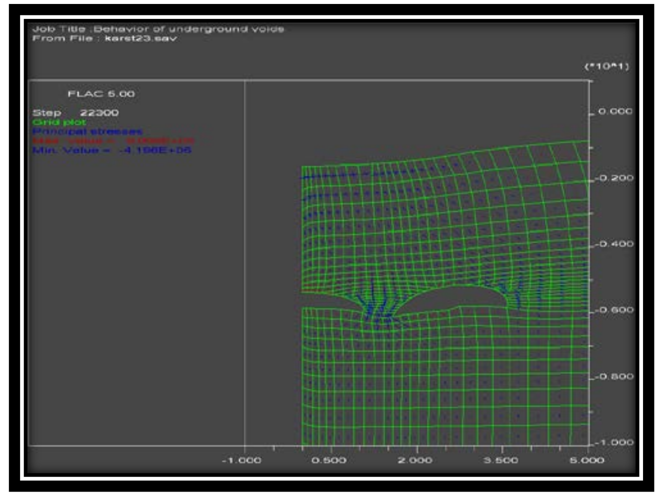

Fig. 12. Zoom grid model with main stresses after opening voids.

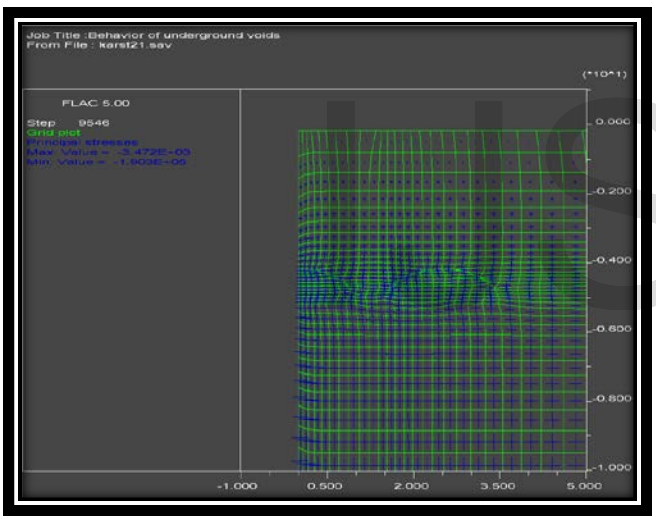

Fig. 10. Zoom model with main stresses before opening underground voids.

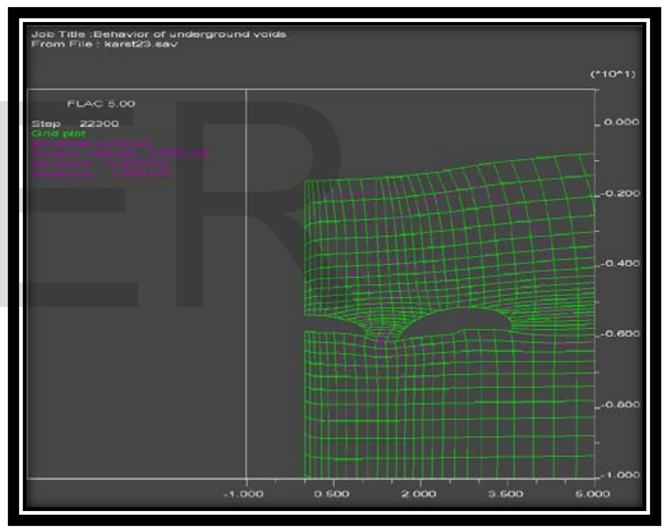

Fig. 13. Zoom grid model with shear stresses contours after opening underground voids.

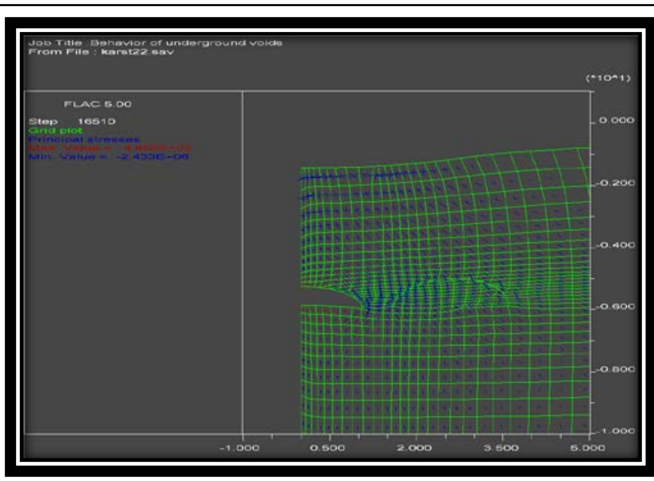

Fig. 11. Zoom grid model with main stresses after opening one underground void.

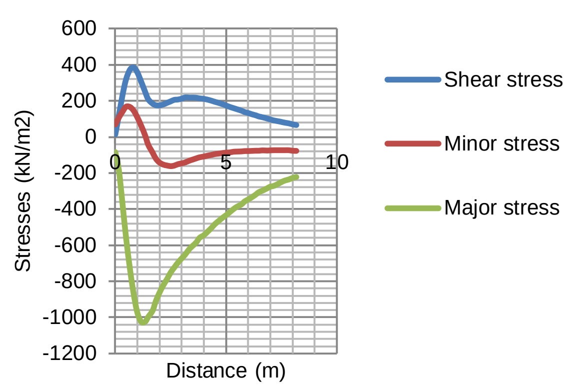

Fig. 14. Main and shear stresses after opening one underground void in the pillar (horizontally).

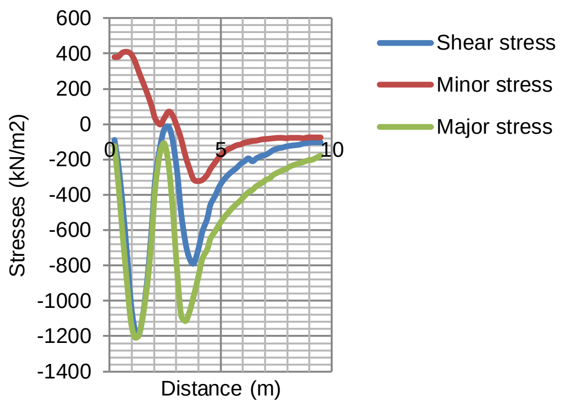

Fig. 15. Main and shear stresses after opening two underground voids in the pillars (horizontally).

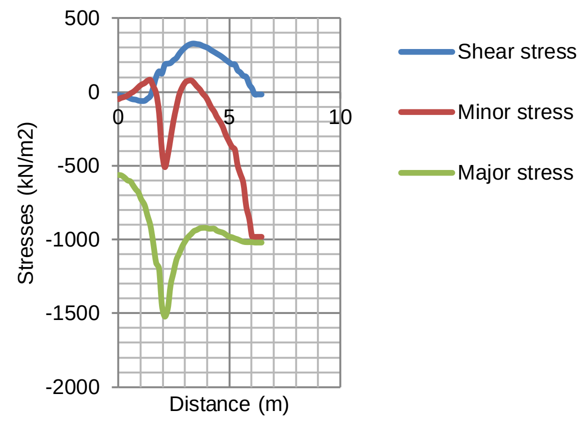

Fig. 18. Main and shear stresses after opening one underground void in the first pillar (vertically).

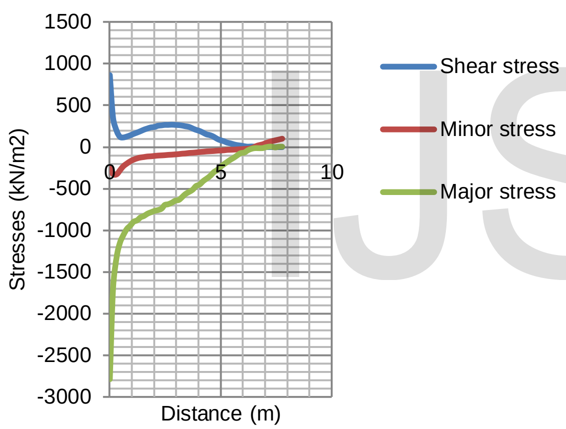

Fig. 16. Main and shear stresses after opening one underground void in the roof (first pillar vertically).

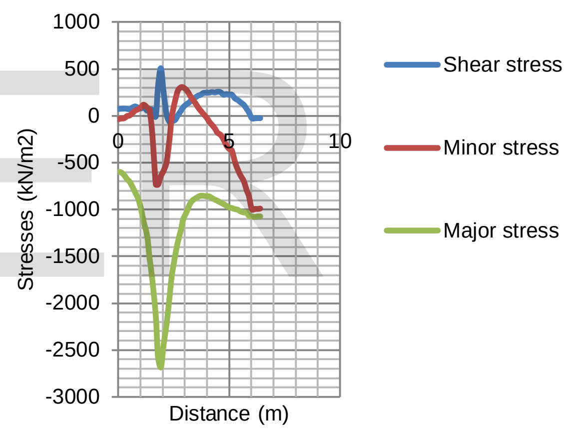

Fig. 19. Main and shear stresses after opening two underground voids in the second pillar (vertically).

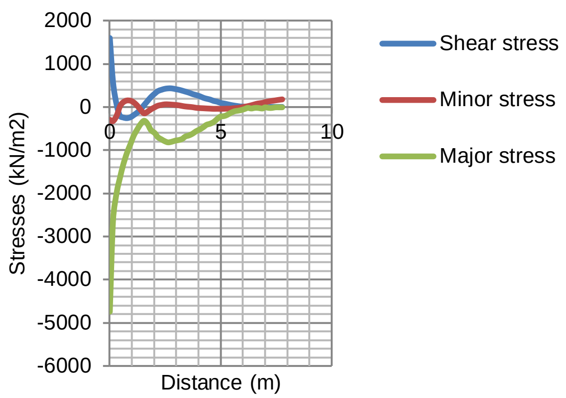

Fig. 17. Main and shear stresses after opening two underground voids in the roof (second pillar vertically).

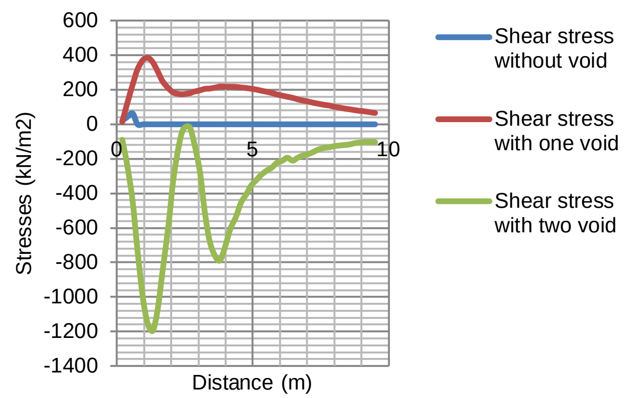

Fig. 20. Comparison of main and shear stresses before and after opening underground voids in the roof (horizontally).

loading and between the underground voids which allows to develop a zone of failure between the building and these underground voids in long term within the limestone layer 1 (Fig. 21).

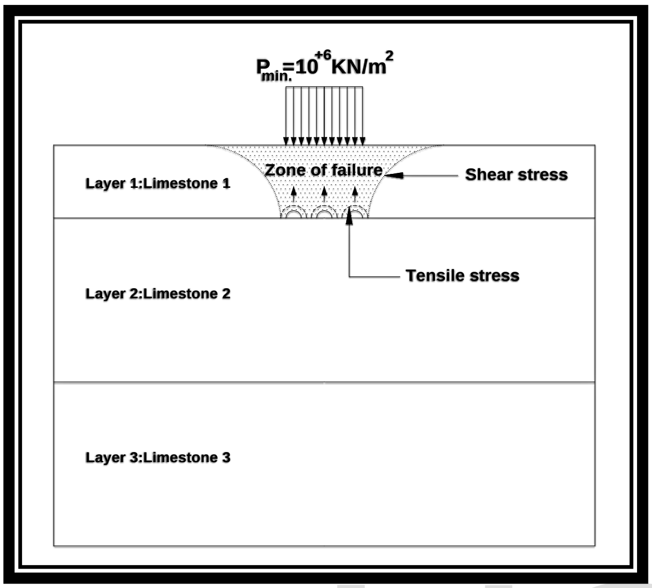

Fig. 21. Zone failure around the underground voids until the surface due to the heavy building static loading.

4 Conclusions

According to 2D modeling using FLAC 5.0, an important results have been found within the interest zone (limestone layer 1) where many underground voids have been investigated at shallow locations under heavy building. We found in term of stresses (tensile, compression and shear) different future zones of failure around these underground voids within the limestone layer1. We observe toward two main directions (horizontally and vertically) an excessive increasing of stresses : 1 – Horizontally, after opening the second underground void, the main stress in compression increases significantly and more an important shear stress increasing especially within the pillar between the underground voids. Around these underground voids tensile stresses have been developed on the first underground void. 2 – Vertically, after opening the second underground void, within the roof at the level of the second pillar, the main stress in compression reaches a maximum value (5000 kN/m^2) and an important shear stress increasing especially within the pillar reaching 2000 kN/m^2. To compare the stresses before and after opening underground voids, we observe a minimum value of shear stresses under the static loading involved by the building at the surface after the consolidation phase and before opening the first underground void. After opening the second underground void an important shear stress increasing especially within the pillar between the underground voids. In order to investigate and fill all the underground voids in the shallow layers of soil and rock mass a geophysical study will be undertaken according to the present results given. A civil engineering study will be required in order to choose the optimum methods and materials used for good stability of these shallow underground voids.

Acknowledgment

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