Evaluation of Foundation on Soil with Cavities: A Case Study from the UAE

Reem Sabouni
Civil Engineering Department, Abu Dhabi University, Abu Dhabi, United Arab Emirates
Email: reem.sabouni@adu.ac.ae

Eng. Muhanad Airan
Civil Engineering Department, ALHOSN University, Abu Dhabi, United Arab Emirates
Email: maairan01@students.alhosnu.ae

***Abstract*—Abu Dhabi, the capital of United Arab Emirates (UAE), is one of the most rapidly developing cities during the last two decades. One of the major problems facing this rapid development is the presence of sub surface cavities and sinkholes in different areas of Abu Dhabi, which causes many engineering and geotechnical problems. The main objective of this research is to evaluate different foundation options for a case study from the UAE with foundation on soil with cavities. The evaluation will be carried out through a finite element numerical investigation using Plaxis 3D to model the four proposed foundation options for the selected case study. The foundation options evaluated are the raft foundation and the pile foundation first with no cavity treatment and then with cavity treatment. Based on the numerical investigation results, the pile foundation with grouted cavities option is recommended to be used as the foundation of the studied structure.**

***Index Terms*—Soil Cavity, Numerical Modeling, Plaxis 3D, Raft Foundation, Pile Foundation**

I. Introduction

Ground cavities are geologic features that result from water erosion in soluble rocks over time due to seasonal ground variation and/or ground water flow and the associated seepage forces. These cavities represent a serious geotechnical hazard for civil construction and urban development [1]. The procedure of cavity creation, extension and spread is hard to anticipate in light of the fact that it is driven by a blend of different scenarios depending on local geological conditions such as the dissolution rate of rock, flow of groundwater, amount of fine material within rock layers, presence of loose, uncontrolled fill over the rock and the leakage of underground utilities. In United Arab Emirates (UAE), Abu Dhabi most cavities occur in mudstone or gypsum, or at an interface between these two rock types [2].

For the past few years, UAE has been experiencing significant growth of urbanization outside the city center of Abu Dhabi, due to the population explosion that happened in a short period of time. This is accompanied with the discovery of cavities in Shakhbout City, Zayed City, Al Falah and the regions around Abu Dhabi International Airport which is located a few kilometers far from the city center as shown in Fig.1 [3, 4].

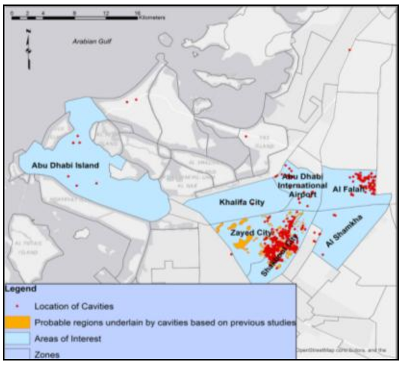

Figure 1. Cavity distribution in Abu Dhabi City [3].

The majority of cavities in Abu Dhabi (67%) were detected in Shakbout area where the risk posed by the presence of cavities is considered real, as villas and roads have been heavily damaged due to ground collapse and sinkhole formation. Fig. 2 shows two examples of damaged structures in Abu Dhabi due to presence of underground cavities.

a)

b)

Figure 2. Damaged structures in Abu Dhabi due to presence of underground cavities: a) Fence of a villa and b) Asphalt road.

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The surface layers in this region are classified as fill that consists of very loose-to-very dense silty sand underlain by deep interlayer formations of very weak to moderately strong gypsum and mudstone [3].

II. The Case Study

A structure with cavity problems was picked to study different foundation options through a numerical investigation using the finite element method. The results of this investigation are used to choose the most efficient foundation. The studied structure is an indoor multipurpose sports hall of a private school located in Shakhbout City in Abu Dhabi (See Fig. 3). By using Plaxis 3D, four foundations options are studied in this investigation which are raft foundation with no cavity treatment, raft foundation with grouted cavities, pile foundation with no cavity treatment and pile foundation with grouted cavities. The four options are assessed, compared and then a recommendation for the foundation is made.

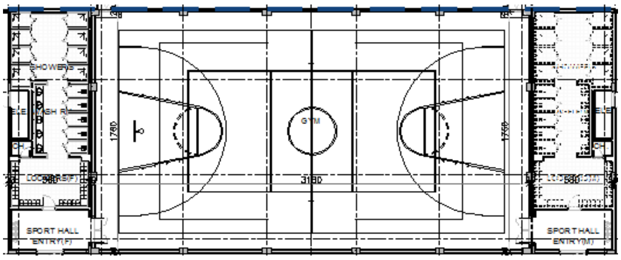

Figure 3. Multipurpose sports hall ($817m^2$) [5].

The investigated site is at Shakhbout City, Abu Dhabi. The strata characteristic of this area is dominated by Aeolian dune sand, Sabkha and evaporates deposits of Holocene to Pleistocene age. The dune sand deposits typically comprise fine-grained silty calcareous sand, which is commonly mobile layer. Although variable, the degree of cementation generally increases with depth, such that the variable cemented sand grades to predominantly calcareous sandstone. Very silty, gypsiferous Sabkha and evaporate layers commonly occur within the Aeolian sand deposits. Sabkha layers, where present, tend to occur from the surface of shallow depth [5].

The soil properties were found from interpretation of the results of both the geotechnical and the geophysical investigation. The geotechnical investigation presented the information on three boreholes drilled down to a depth of 30 m below the existing ground surface at the location of the sports hall. The findings of the drilled boreholes indicate that the materials encountered at the site were generally consistent with the general geology of the area. Moreover, a partial disappear of gypsum layer was encountered in one of the boreholes from -11.5 m to -12 m which indicate a presence of a cavity at this region. This borehole was selected to be used in Plaxis 3D in order to represent the soil layers with their sequence in addition to the groundwater level which is equal to 4.9 m below the ground surface. The soil layers from top to bottom are: silty sand, sand, gypsum, and mudstone as shown in Fig. 5 [5].

To verify the geophysical surveys results for a consistent interpretation of the geological conditions, the result of the three geotechnical boreholes were used for calibration purposes. The positions of geophysical lines and geotechnical boreholes are shown in Fig. 4. The low average shear wave velocity to 30 m depth (Vs30 = 400-600m/s) locations detected along the executed multichannel analysis of surface waves (MASW) lines are associated with adverse strata (cavities or weak zones). Only Cavity (1) which has an area of 53 m^2 has been verified by BH-2 that encountered a cavity and loss of circulation water at 11.5 to 12 m depth. On the other hand, cavities (2) and (3) with areas 42 m^2 and 138 m^2, respectively have not been captured by the geotechnical boreholes - due to the fact that the locations of the boreholes were fare from the cavities- but were captured in the geophysical test. Both cavities (2) and (3) were found by the geophysical test to be located at a depth of 12 to12.5 m [6].

The study performed by R. Sabouni, 2015 [7] indicated that the cavity will have a large influence on the foundation deflection and capacity if it is located within a depth of less than one times the width of the foundation. This case study was chosen to carry out this research due to the fact that all three cavities – as shown by the geotechnical and geophysical tests - are located within a depth of less than one time the width of the proposed foundation.

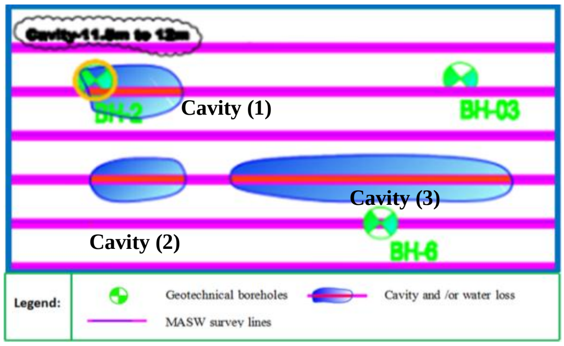

Figure 4. Location of cavities and /or water loss [6].

III. Numerical Modeling

A. Soil Modeling

The three boreholes from the geotechnical report for the sports hall showed comparable water table level and soil layer types, thicknesses and properties, but different locations of cavities. That is why only one borehole was used in the Plaxis 3D model as shown in Fig, 5. In the Plaxis 3D models the cavities were not indicated in the boreholes as they do not extend along the whole layer’s surface. The cavities were defined by clusters (an area that is fully enclosed by geometry lines) to model their extension in the horizontal plane (x-y directions) and by work planes (horizontal layers with different y-coordinates) to model their depths [8]. The cavities are represented in rectangular clusters for simplification as shown in Fig 6. The clusters that encounter the cavities are deactivated between the plans that contain the cavities when the analysis is performed. The locations of the modeled cavities are as shown in Fig.6. Cavity (1) is located at a depth of 11.5m to 12m and cavities (2) and (3) are located at a depth of 12m to 12.5m.

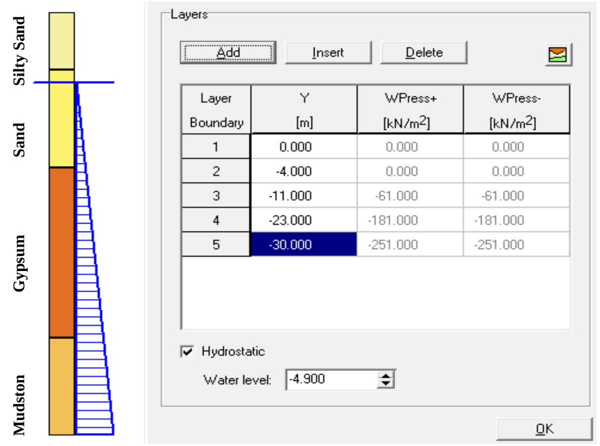

Figure 5. The soil layers of the calibrated borehole.

The soils parameters used in the Plaxis 3D model are presented in Table I. The material behavior of all modeled soil layers was assumed to be drained. The Mohr-coulomb material model was used for all the modeled soils.

TABLE I. SOIL AND GROUT PARAMETERS [5].

Parameter Name	Silty Sand	Sand	Gypsum	Mudstone	Grout
Type	Porous	Porous	Porous	Porous	Non-Porous
γ_{unsat} [kN/m^3]	18.8	24	19	18	24
γ_{sat} [kN/m^3]	19.5	27	20	20	-
E_{ref} [kN/m^2]	13000	15000	100000.	15000	2.5x10^7
v	0.3	0.3	0.3	0.3	0.2
C_{ref} [kN/m^2]	12	1	100	1.00E-03	1
φ [°]	23	32	30	25	30
ψ [°]	0	2	0	0	°

B. Foundation Modeling

Through using Plaxis 3D Foundation, one comprehensive model that contains both raft and pile foundation elements (raft, pile caps, ground beams and piles) was developed (shown in Fig. 6) to run the analysis of the four foundation options. Using the stage construction option in Plaxis 3D four foundation and soil treatment options were generated through activation and deactivation of soil layers and structural elements during the analysis stage. The first two options a raft foundation was used as the foundation system were in the first option the soil cavities were not treated and the second option the soil cavity was treated with grout injection. For the third and fourth options a pile foundation system was used once with no treatment for the soil cavities and the other with grout injection treatment for the cavity, respectively. The grout was modeled by assigning a grout material type to the deactivated cavity cluster throughout the layers that encounter the cavity. The grout properties are shown in Table I.

The raft foundation was modeled with a thickness of 65 cm and had a width and length of 19m and 45m, respectively. The pile foundation was modeled to match the pile foundation design details including the piles the pile caps and the ground beams as shown in Fig.6. The used properties of all the structural elements (Raft foundation, pile, pile caps and ground beams) in the Plaxis 3D model are summarized in Table II.

The model boundaries in the horizontal directions were taken to be twice the foundation width away from each edge of the foundation. The depth of the soil model was extended to three times the foundation width from the tip of the piles.

C. Structural Load

The applied loads on the foundation were found from the concentrated loads at the supports of the sports hall columns and are shown in the SAFE model in Fig. 7. The same loads were applied to the four studied foundation options.

TABLE II. PARAMETERS OF THE STRUCTURAL ELEMENTS [9].

Parameter Name	Raft Foundation	Pile	Pile Cap	Ground Beam
Model	Linear-elastic	Linear-elastic	Linear-elastic	Linear-elastic
γ_{unsat} [kN/m^3]	24	24	-	-
A [m^2]	-	-	-	0.78
V	0.2	0.15	0.15	0.1
d [m]	0.65	-	1.2	-
γ [kN/m^3]	24	-	24	78.5
G [kN/m^2]	1.25E+07	-	1.30E+07	-
E_{ref} [kN/m^2]	3.00E+07	2.92E+07	3.00E+07	3.00E+07
I_2 [m^4]	-	-	-	1.31E-04
I_3 [m^4]	-	-	-	1.37E-03
I [m^4]	-	-	-	0

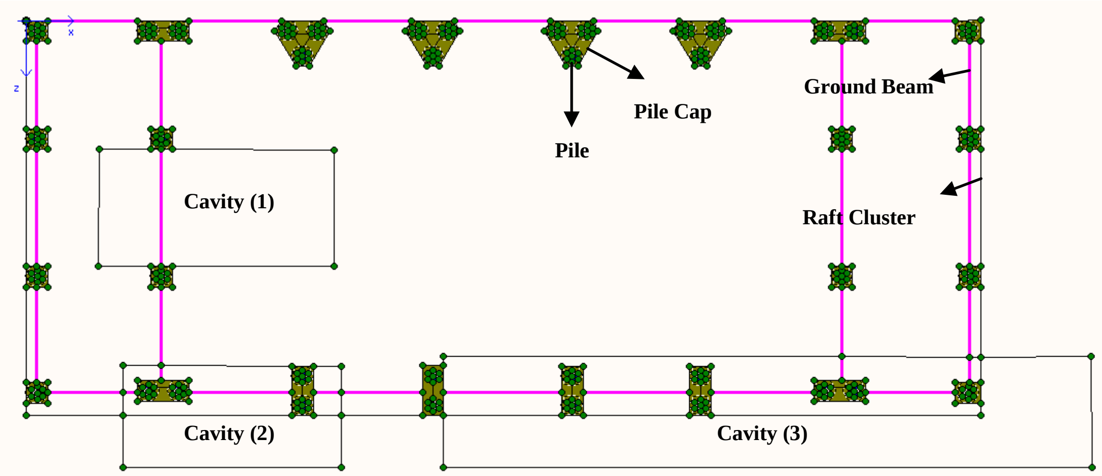

Figure 6. Top view of a comprehensive model.

Figure 7. Concentrated load values in KN from the SAFE model.

IV. Results and Discussion

The aim of this research is to study different foundations options available for structures on cavities to select the most efficient and safe foundation based on the results of the extreme total displacement of the studded foundation options.

A. Raft Foundation with No Cavity Treatment

In raft foundation phases all the loads applied equally distributed with a value of -140.700 KN/m^2 at work plan y = -1.95 m (the surface of the raft foundation). As shown in Fig. 8, the resulted extreme total displacement is equal to 34.6 cm which is very high and can cause severe damages to the structure.

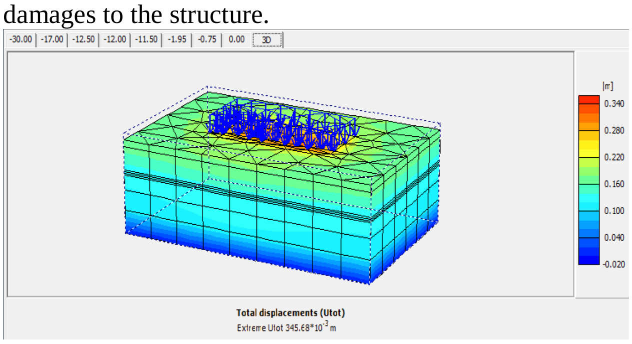

Figure 8. Shading of total displacement.

B. Raft Foundation with Cavity Treatment

In the raft foundation with cavities that were treated with grout injection (Fig. 9), the extreme total displacement is equal to 28.3 cm. In this option the total displacement has slightly reduced due to filling the three cavities with grout as shown in the figure below.

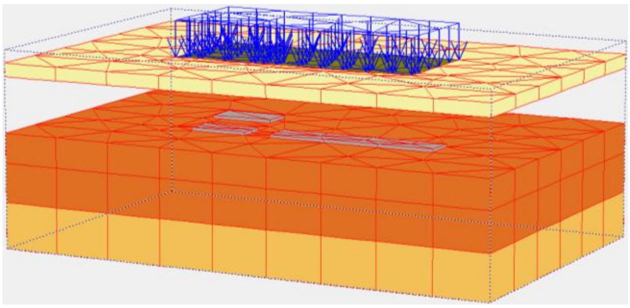

Figure 9. View of the raft foundation with grout (some soil layers were removed to show the grouted cavities in gray color).

C. Pile Foundation with No Cavity Treatment

In the case of pile foundation with no cavity treatment, the extreme total displacement is 30.24 cm as shown in the Fig. 10. The current option shows larger settlement than the raft foundation with cavity treatment; this is due to the heavy weight of the pile foundation compared to the raft foundation. The load of the structure has been applied directly at the top of the piles to avoid any failure in the structural elements that might affect the result of the study.

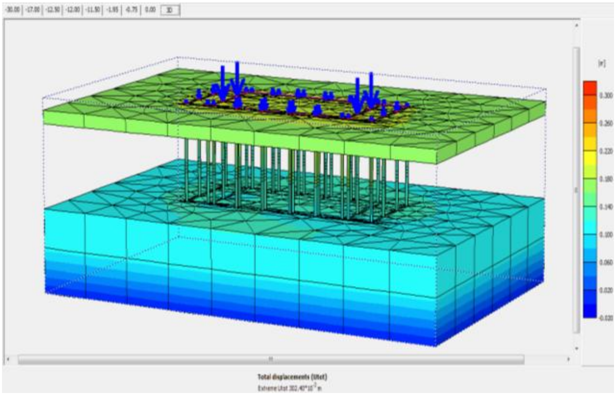

Figure 10. Shading of total displacement (some layers were removed to show the distribution of the piles within soil profile).

D. Pile Foundation with Cavity Treatment

For this option, the extreme total displacement of the pile foundation with grouted cavities was found to be 11.62 cm (see Fig.11). This option gives the best resistant to settlement compared with the previous options.

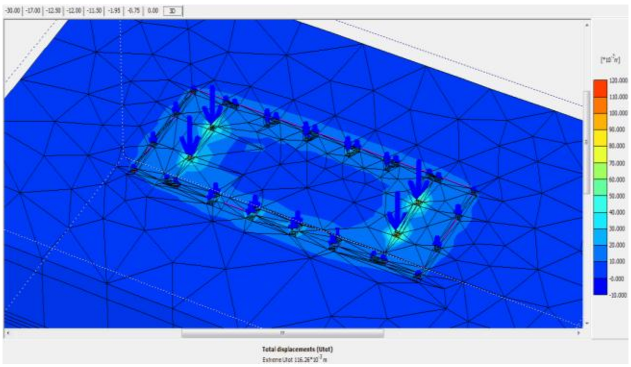

Figure 11. Shading of total displacement at soil ground level.

E. Comparison of the Options

All the four studded options showed no structural failure or soil collapse. The results of the three first options showed excessive displacements. The displacement in the fourth option was largely reduced when the grout was used with the pile foundation option. This value is still considered to be somewhat high. This can be attributed to the fact that the worst case scenario was considered in the model. Where both modeled cavities (2) and (3) where indicated in the geophysical test to be week layer and could not be verified by the geotechnical test if they are cavities or week soil so they were taken as cavities. Moreover, the settlement also can be lowered to a considerable value by using light weight concrete or by modifying the pile design.

A point that should be kept in mind when choosing a foundation option including grout treatment, is that cavities can grow and expand to form cavity networks which will make cavity grout treatment extremely expensive.

V. Conclusion

Underground cavity problems have been one of the major problems faced by geotechnical engineers when designing foundations for structures. In this paper, an indoor multipurpose sports hall resting on soil with three cavities located at a relatively shallow depth was chosen to carry out this study. This structure is located in Shakhbout City in Abu Dhabi, UAE. Four foundations options are modeled using the finite element analysis program Plaxis 3D and studied in this investigation. These options are: raft foundation with no cavity treatment, raft foundation with grouted cavities, pile foundation with no cavity treatment and pile foundation with grouted cavities. Based on the results of this study, the pile foundation with grouted cavities was recommended to be used as the foundation of this structure. This research will be extended further in the coming stage to incorporate several other case studies from a number of locations in the Abu Dhabi city that encounter the presence of sub surface cavities and sinkholes. This will be done in order to enable the researcher to come up with a more comprehensive recommendation for these areas.

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Reem Sabouni is an Associate professor at Abu Dhabi University (ADU) in United Arab Emirates (UAE) with several publications in the fields of geotechnical and structural engineering. Prior to her joining ADU Dr. Reem Sabouni held the position of Chair of the Civil Engineering Department and Director of University Laboratories at ALHOSN University in UAE. She is a member of several prominent professional engineering societies, such as the CGCE, CSCE, ASCE, ACI and is the Chair of Women Engineers in the Fib-UAE Chapter.

Dr. Reem acquired her PhD and Master degree in Civil Engineering from the University of Western Ontario in Canada. She was the first researcher in North America to conduct full scale tests on circular precast concrete manholes in a controlled laboratory environment. These tests were conducted in the Large Scale Geotechnical Testing Facility in the University of Western Ontario and in collaboration with the Ontario Concrete Pipe Association.

Dr. Reem received several Canadian awards and research scholarships, including the Industrial NSERC Scholarship, the Ontario Graduate Scholarship, the University President Scholarship, and the prestigious Milos Novak Memorial. She had also received the Excellence Award from H.H. Sheikha Fatima Bint Mubarak, for ranking first in the UAE University’s Class of 2002.