Settlement of Shallow Foundations Placed on Limestone Rock Formations with Open or Closed Cavities

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Abstract**—** Limestone formation is the main formation of the subsurface strata in Riyadh region, KSA. Due to high strength of rock formation, most of the buildings are designed on shallow foundations. Limestone strata may have cavities through its formation in some places which reduces the rock strength and increases its settlement. These cavities are varied in their location depths below the foundation, and their widths or thicknesses. In our study, the settlement prediction of shallow foundations placed on rock formation which contains open or closed cavities were compared. Results showed that, spread foundations placed on limestone formation with closed cavities reduced the settlement up to ten times compared to that with open cavities. In the other hand, the settlement due to mat foundation placed on limestone formation with closed cavities reduced the settlement up to three times compared to that with open cavities. Therefore, grouting should be recommended to fill the open cavities of limestone rock formation to the significant depth below footings before placing the foundations to gain more strength with reducing the limestone settlement. Recommendation of the study are given for geotechnical investigation engineers to expect the maximum depth for cavity probing search through any project depending on the loads and widths of the shallow foundation.

Keywords- limestone; shallow; footings; settlement; cavities; grouting.

I. INTRODUCTION

The Arabian Peninsula is bisected by the Tropic of Cancer. It is well divided into various topographic units depending on geological features. These are the mountainous units, dominated by rock formations; the associated foothill alluvial fans, the dunes and the coastal plains. Figure 1 shows the generalized geological features of the Arabian Peninsula. In our study, more focus on the middle region of Saudi Arabia where karst limestone formation is the main top formation which is named as Arab formation followed by Jubaila formation as a deeper layer, [2], [6], [7], and [9]. Karst limestone foundation bedrock worldwide problems create serious construction problems and effective costs due to insufficient understanding of karst features during the design phase, [4], [6], and [8]. A full understanding of the nature of karst as well as the method of surface and subsurface detection are very important to avoid the risk of sudden collapse of constructed buildings. The geotechnical problems associated in Riyadh area as a desert region are of different nature in each of its units and in general can be summarized by the presence of cavities in its limestone formations or the presence of highly weathered layers and variability of foundation material, [3], and [10].

II. SETTLEMENT OF SHALLOW FOUNDATIONS

A. *Settlement of Foundations on intact Rock*

Reference [4] summarizes settlements of foundation on rocks are as following two different types. First, elastic settlements result from a combination of strain of the intact rock, slight closure and movement of fractures and compression of any minor clay seams (less than a few millimeters). Elastic theory can be used to calculate this type of settlement. Detailed information can be found in [1], and [4].

Second, settlements result from the movement of blocks of rock due to shearing of fracture surfaces. This occurs when foundations are sitting at the top of a steep slope and unstable blocks of rocks are formed in the face.

The stability of foundations on rock is influenced by the geologic characterization of rock blocks. The information required on structural geology consists of the orientation, length and spacing of fractures, and their surface and infilling materials.

Procedures have been developed for identifying and analyzing the stability of sliding blocks, stability of wedge blocks, stability of toppling blocks, or three-dimensional stability of rock blocks.

Where the rock mass is homogeneous and isotropic, the vertical settlement is approximated as one or more uniformly distributed loads acting on circular or rectangular areas, as in [4].

$$\Delta H = C_d\, q\, B\, (1\text{-}\nu 2) / E \qquad (1)$$

where q is the uniformly distributed bearing pressure; B is the characteristic dimension of the loaded area; C_d is a parameter which accounts for the shape of the loaded area and the position of the point for which settlement is being calculated; n is Poisson's ratio and E is Young's modulus. The Young modulus is from the estimate of empirical formula [8]. The C_d for circular and square footing bearing on uniform, elastic rock is as Table1.

TABLE I. FACTOR C_d FOR DIFFERENT FOOTING SHAPE

Shape	**Values of C_d**		
	middle	***center***	***average***
Circle	1.0	0.64	0.85
Circle (rigid)	0.79	0.79	0.79
Square	1.12	0.56	0.95
Square (rigid)	0.99	0.99	0.99

B. Detection of Presence of Cavities in Rock

In our study, as the presence of cavities in the limestone rock formation in the studied area of Riyadh region will effect on the achieved settlement below footings. The settlement values below footings will be causes defect for the super structure concrete elements. Thus, the calculation of settlement values should be calculated as the location depth and thickness of the cavities below the shallow footings. So, cavity search probing should be performed before construct the footings at the site, especially at the important projects.

The cavity search probing will be performed down to a desired depth below foundation level. All the probe holes will be drilled in rock strata from the foundation level. The drilling at different locations will be carried using rock drill machines. The probe holes will be filled with sand/cement/water slurry. The method statement for cavity probing and grouting works shall be as follows: Cavity probing will be carried out by using drill percussion rigs, by means of penetrating a probe into the bearing strata through pneumatic driving. Compressed air will be used to clear the hole as the drilling advance. The time for penetration of probe through each consecutive 20cm penetration will be recorded, which indicate the resistance to bearing strata penetration. In case of occurrence of cavity/loose zones in underlying strata, the time for penetration records will be small. Generally, duration of less than 10 seconds for 20cm penetration is considered the presence of loose zone or soil filled fractures, while in case of cavity, there will be no resistance to rock penetration and it occurs all of a sudden. The probing and the record of time for consecutive 20cm penetration will be carried out down to the required investigation depth. In case of occurrence of any cavity/loose zones and in the foundation area, injection grouting will be carried out. Grout consisting of sand, cement and water in the ratio of 0.5:1.0:0.8 will be used.

In our study, different cavities of depth and thicknesses were used for prediction of settlement below the shallow footing. The presence of cavities can detect and examples of the field cavity probing search results can be drawn as shown in figures (1-a) through (1-c). It can be shown from the field tests that the cavities could be found in one, two or more depths below foundation. According to that in case of important projects and highly load footings, cavity probing will be the good method for detection of the cavities.

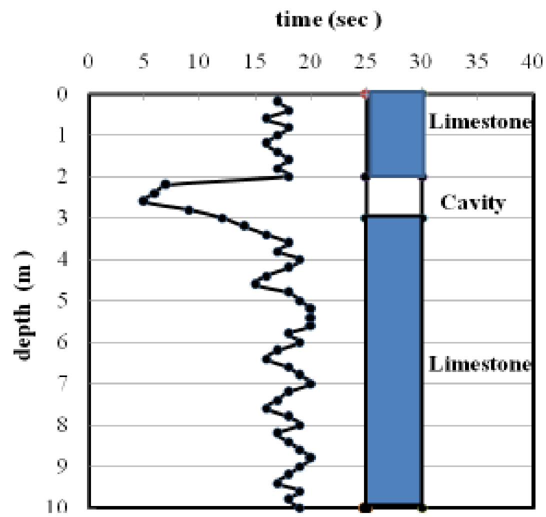

Fig. (1-a) Cavity detection in limestone rock at depth ranged from 2.0 to 3.0meters.

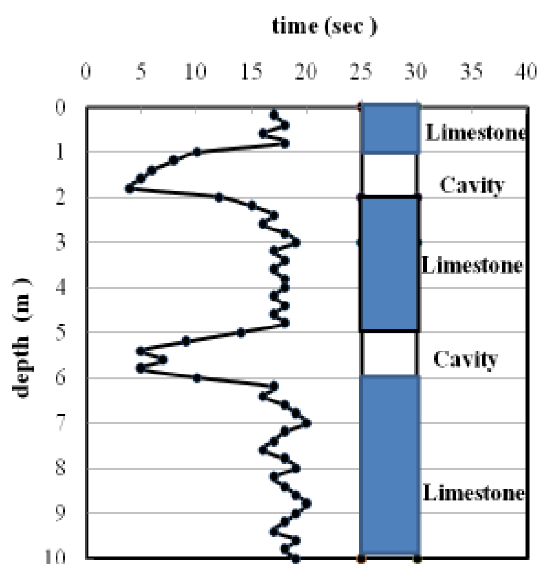

Fig.(1-b) Cavity detection in limestone rock at two depth ranged between 1.0 to 2.0 and 5.0 to 6.0 meters.

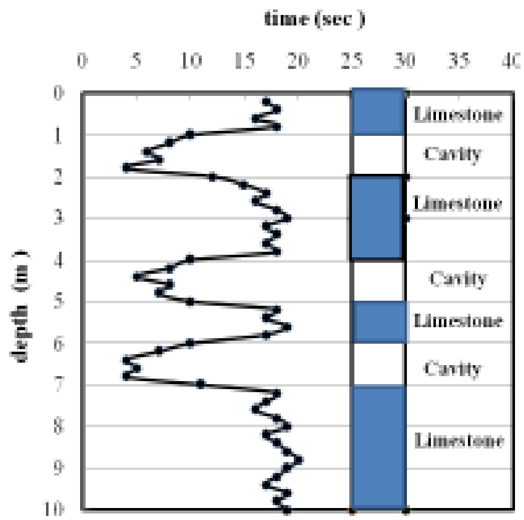

Fig. (1-c) Cavity detection in limestone rock at multi depths ranged between1.0 to 2.0, 4.0 to 5.0 and 6.0 to 7.0 meters.

C. Settlement of Foundations on Rock with Open or Closed Cavities

Shallow footings constructed on limestone bedrock with cavities are a more important to calculate their settlements where the cavities are founded depending on its depth and thickness. In our study, settlements of footings with or without cavities are calculated. Elastic modulus for the limestone rock at Riyadh region was found to be ranged between 5GPa and 15GPA. For our study we use the average value of 10GP for settlement calculations. In case of limestone having cavities, the cavity volume used in the study as filled weathered rock or soil of an average elastic modulus of 0.3GPa. After grouting the cavities with the above mentioned sealing mix material, the elastic modulus of limestone rock formation will be recover its elastic modulus which will be reach nearly the original values or more with average value of 15GPa [4]. To calculate the settlements below shallow footing construct on rock formation with cavities through its layers, equation (1) will be used after applying the availability of cavities at one or more layers. The following modified equation for settlement calculation will be used taking into consideration, the different elastic modulus for the rock and the weathered material filled the cavities.

$$\Delta H = C_d \; B \;\; q\,(1\text{-}\nu^2) \,/\, H \sum h_i / E_i \qquad (2)$$

Where, H is the maximum depth for settlement calculation witch not less than five times the foundation width. E_i, is the modulus of elasticity for each layer of rock or cavity with its thicknesses, h_i.

III STUDY PROGRAM

In the present study, three different dimensions of shallow footings rested on limestone with or without cavities are chosen for the prediction of the settlement values. Three different footings of dimensions 2.0m × 2.0m, 4.0m× 4.0m and 20.0m× 20.0m are used in the study. Finite element numerical program was used to compare the achieved results using the mentioned equation. Figures (2-a) and (2-b) show the settlement for footing of 2.0m × 2.0m placed on rock formation with or without cavities under loading stress of 500kN/m^2 and 1000kN/m^2, respectively. The case having cavities at two different depths in the same time, two and three meters below the footing gives higher value of settlement than that having only one cavity at 2.0 meter below the footing.

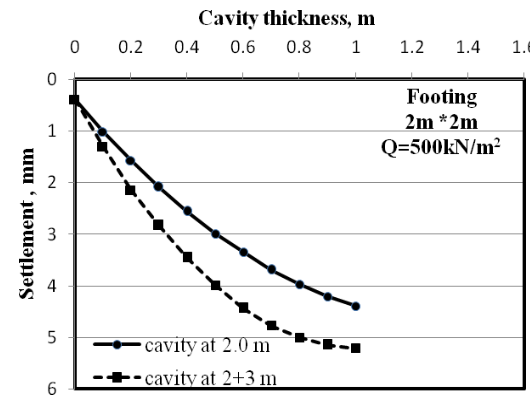

Fig.(2-a) Settlement for (2m*2m) footing placed on limestone with or without cavities due to 500kN/m^2 loading stress.

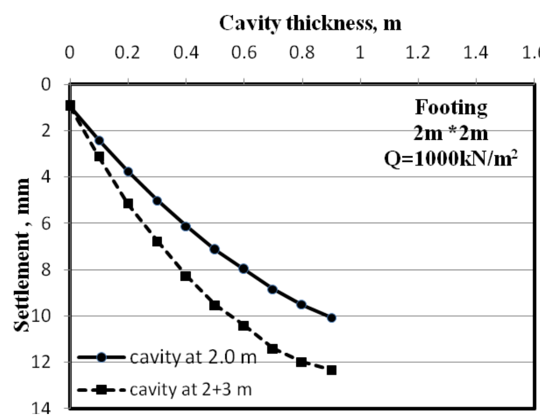

Fig.(2-b) Settlement of (2m*2m) footing placed on limestone with or without cavities due to 1000kN/m^2 loading stress.

Figure s(3-a) and (3-b) show the settlement for footing of 4.0m × 4.0m placed on rock formation with or without cavities under loading stress of 500kN/m^2 and 1000kN/m^2, respectively. The case having cavity at two meter depth below the footing gives higher value of settlement more than that having cavity at depth deeper than 2.0 meter up to 7.0 meter below the footing. The settlement due to cavity deeper than 7.0meter below the footing depth has no effect of the value compared to rock formation without cavities. It is obvious that the increase in settlements are ranged between 3 and 10 times for isolated footings on limestone with cavities compared to that without cavities. Also, the depth of insignificant of cavity depth and thickness is nearly more than two times the foundation width.

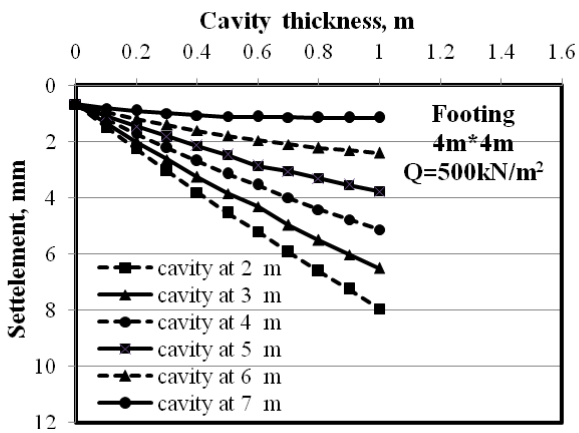

Fig.(3-a) Settlement of (4m*4m) footing placed on limestone with or without cavities due to 500kN/m^2 loading stress

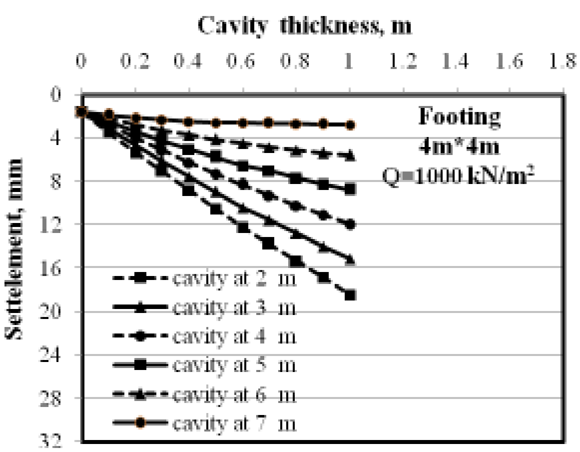

Fig.(3-b) Settlement of (4m*4m) footing placed on limestone with or without cavities due to 1000kN/m^2 loading stress

Figure s(4-a) and (4-b) show the settlement for footing of 20.0m × 20.0m placed on rock formation with or without cavities under loading stress of 500kN/m^2 and 1000kN/m^2, respectively. The case having cavity at depth less than 30 meter below the footing gives higher value of settlement compared to that having cavity at deeper depths below the footing. The settlement due to cavity deeper than 39.0meter below the footing depth has no effect of the settlement value compared to rock formation without cavities. It is obvious that the increase in settlements are ranged between 1.5 and 3 times for mat foundations on limestone with cavities compared to that without cavities. Also, the depth of insignificant of cavity depth and thickness is nearly more than two times the foundation width.

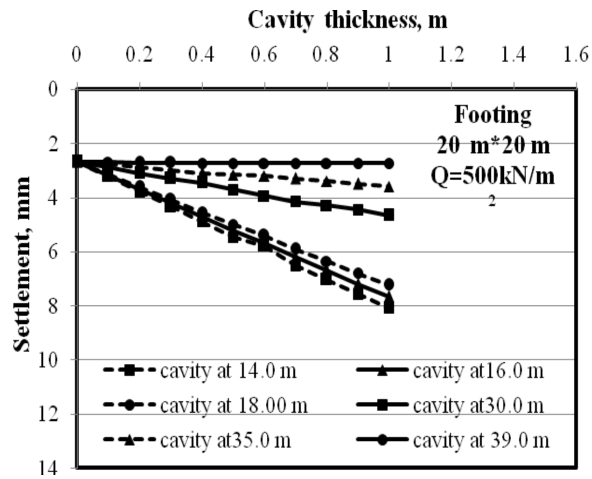

Fig.(4-a) Settlement of (20m*20m) footing placed on limestone with or without cavities due to 500kN/m^2 loading stress

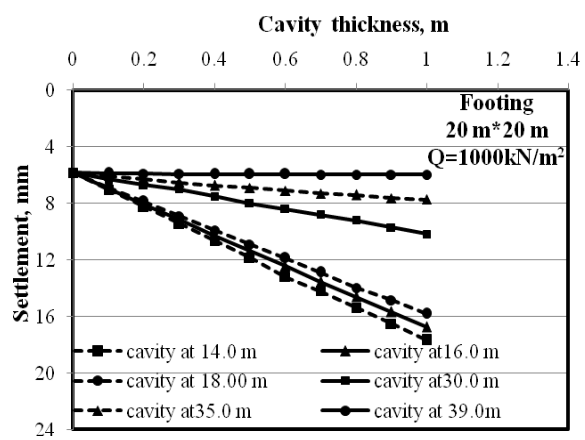

Fig.(4-b) Settlement of (20m*20m) footing placed on limestone with or without cavities due to 1000kN/m^2 loading stress

Figures (5-a) and (5-b) show the settlement calculated using the finite element method for mat foundation of 20.0m × 20.0m due to stress of 1000kN/m^2 using Settlement software program. Results achieved form the numerical analysis is nearly matching with that calculated using the mentioned model equation.

IV CONCLUSION

The settlement obtained for the spread footings placed on rock formation with cavities was higher than that without or closed openings with grouting depending on the location and the thickness of the cavity. It is clear that, the probe searching for cavities in limestone rock formation is recommended to be done by penetrating probe until reach to about two times the width of footing design, especially in case of high loading stress from superstructure. After having completed of filling the cavities by grouting, it will gain nearly the same or more than its original elastic modulus which will reduce the settlement as limestone formation without cavities.
Numerical study for settlement of footings placed on rock was matching with that predicted by the empirical equation mentioned in the study. The settlement after grouting reduces from 3 up to 10 for isolated footing, while it was reduces from 1.5 up to 3 times for mat foundations. Thus it is recommended to do probing search for cavities under shallow footings up to twice their depths, especially in case of higher loading gives higher bearing stresses on limestone rock and filling any cavities appeared from the probing search to reduce the overall total settlements of the foundations and also reduce the differential settlements consequently.

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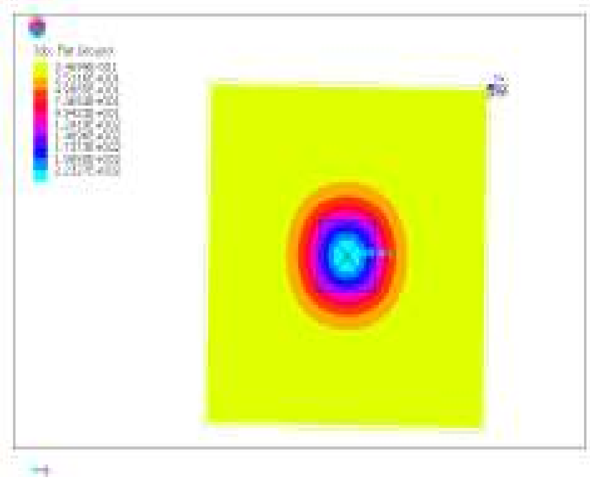

Fig.(5-a) Settlement of (20m*20m) footing placed on limestone with cavity under 1000kN/m^2 stress.

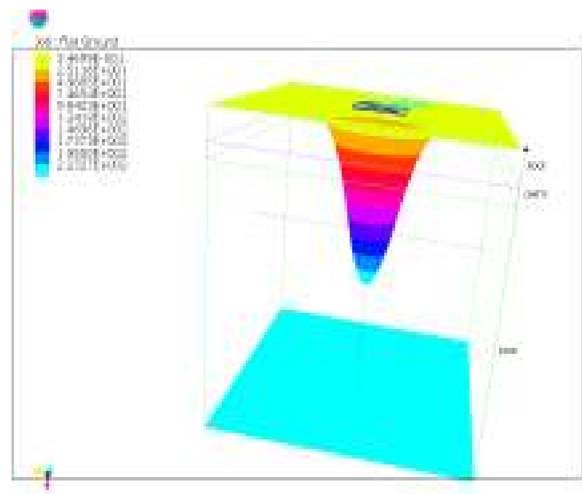

Fig.(5-b) Settlement of (20m*20m) footing placed on limestone with cavity of 1.0m thickness at 14.0meter due to 1000kN/m^2 loading stress.