Performance of Axially Loaded Single Pile Embedded in Cohesive Soil with Cavities

Ali A. Al-Jazaairry, Tahsin T. Sabbagh

***Abstract*—**The stability of a single model pile located adjacent to a continuous cavity was studied. This paper is an attempt to understand the behaviour of axially loaded single pile embedded in clayey soil with the presences of cavities. The performance of piles located in such soils was studied analytically. A verification analysis was carried out on available studies to assess the ability of analytical model to correctly interpret the system behaviour. The study was adopted by finite element program (PLAXIS). The study included many cases; in each case, there is a critical value in which the presence of cavities has shown minimum effect on the pile performance. Figures including the load carrying capacity of pile with the affecting factors are presented. These figures provide beneficial information for pile design constructed close to underground cavities. It was concluded that the load carrying capacity of the pile is reduced by the presence of the cavity within the soil mass. This reduction varies according to the size and location of cavity.

***Keywords*—**Axial load, cavity, clay, pile, ultimate capacity.

I. INTRODUCTION

PRESENCE of cavities is one of the most common problems in soils. Structural damage might have occurred due to cavity presence and as a result, loss of life is likely to happen. In designing buildings and structures for modern industrial establishments, it is generally essential to consider the influence of underground cavities on the vicinity of a piled foundation. The underground cavities might be classified into two types; artificial and natural. Man-made cavities are due to urban installation, sewer networks creation, old conduits vault building, tunneling, digging the canals, mining, and associated activities forming underground voids in the soil mass. Natural cavities may be created because of different reasons such as extinction of some water or sea areas, also, because of the soils having dissolvable materials, mostly gypsum [1]. Consequently, the failure of structures constructed on such soils is possible to occur because of the creation of cavities before or after application of load. Cavities are a cause of challenges for design and construction. Both artificial and natural cavities must be reflected on the design and construction of pile [2].

Available literature on the behaviour of axially loaded piles embedded in cohesive soil with cavities is rare. Outcomes of previous studies on cavity presence indicated that the relation between the piles and underground cavities has important consequences on the act of piled foundation [3].

The first researchers who conducted some studies on the effect of cavities on the ultimate capacity of foundations were [4]-[6]. Reference [7] assessed analytically the performance of strip footing constructed on stiff silty clay with void. The settlement behaviour of footing built on the single void was examined by [8]. Reference [9] performed an investigation on the effect of void location and shape on the ultimate capacity of the foundation found on a single void. Reference [10] studied numerically and experimentally the behaviour of spread foundation constructed on a continuous void. The behaviour of strip foundation on two-layer soils contain cavity studied by [11] using finite element method.

Reference [12] examined the performance of a shallow foundation on covered underground tunnel in different soils analytically. A critical depth was found in which the void has insignificant influences on the load carrying capacity of the foundation. Reference [13] investigated analytically the influence of the construction impact of urban tunnels on adjacent pile using three-dimensional finite element modelling. Reference [14] examined the performance of laterally loaded piles embedded in sandy soils with cavities. It was suggested that the location and number of cavities have a combined effect on the performance of such pile.

The behaviour of a laterally loaded pile embedded into sandy soil of Al-Najaf city with the cavity has been examined experimentally and analytically by [15]. Reference [16] experimentally studied the behaviour of different shapes and sizes of foundations subjected to eccentric loading. Reference [17] examined the influence of cavity depth on the behaviour of axially loaded pile in clayey soil using finite element program (ANSYS). The influence of the cavity presence on the piled structures has been investigated experimentally and numerically by [18]. The failure mechanism and load carrying capacity of strip foundation created on two voids have been examined analytically by [1]. Moreover, [19] conducted several experimental tests on the laterally loaded pile embedded in sandy soil with presence of cavities. Moreover, axially loaded piles constructed in sandy soil and adjacent to single cavity have been investigated by [5].

The effect of size and location of the cavity on the behaviour of axially loaded pile embedded in clayey soil has been studied in this paper. Moreover, this research offers the load carrying capacity behaviour of the pile-soil-cavity system for different cavity sizes and locations. This study is limited to axially loaded pile placed on clayey soils with uniform and continuous cavities.

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II. Bearing Capacity of Piles

The bearing capacity of foundations mainly relies on the water conditions in the soil, original stresses, mechanical properties of soil, physical characteristics of the foundation, and the installation method [20]. Nevertheless, [20] and [21] proposed the failure zone around the pile base. It is thought that the failure zone is generally shear failure type and the rupture surface develops to a certain distance from the pile tip. The methods of defining the failure loads are commonly depending on load-displacement curves.

III. Numerical Analysis

The pile-soil-cavity system was simulated using the finite element program PLAXIS 2D. The behaviour of soil was simulated numerically considering Mohr-Coulomb failure criterion. Since this study normally focuses on the load carrying capacity of piles, an elastic perfect plastic behaviour of the model soil is thought to be suitable [22]. In these analyses, cavities are represented by the idealizing a hole subtracted from soil volume and assumed to have no lining. It was supposed that the soil is without cavity for describing the original condition of the soil. Therefore, the stresses were restarted in the system while cavity was formed. Consequentially, the nodes' displacements were set to zero and the load was attempted on the pile. This scenario is believed to be a simulation of real situation on site as well as experimental tests. A schematic figure of appropriate mesh organization considered in the current numerical analyses is revealed in Fig. 1.

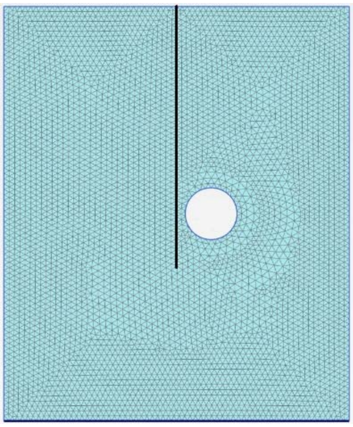

Fig. 1 Schematic finite element mesh (PLAXIS 2D) for numerical analyses in present study

IV. Verification of Finite Element Software

In order to validate the capability of the software to simulate the problem, a comparison was made between the finite element software results and other related case study results. Reference [23] carried out field tests to examine the performance of a vertical bored pile in cemented sand. The pile length, width, modulus of elasticity, Poisson's ratio, and unit weight were reported to 2.25 m, 0.1016 m, 20000000 kN/m^2, 0.2, and 23 kN/m^3 respectively. The soil modulus of elasticity is 25000 kN/m^2, Poisson's ratio is 0.37, cohesion is 20 kN/m^2, unit weight is 18.5 kN/m^3, and friction angle equals to 35°. Reference [17] simulated the test results of [23] using finite element program ANSYS. Fig. 2 illustrates the results of the present study compared with [23] and [17]. The results of the present work show a good agreement with the field and analytical results over a wide range of the curve, demonstrating the capability and accuracy of analytical modelling by PLAXIS software. Therefore, it is believed that the analytical modelling can be extended to investigate the effect of cavity presence on the pile's ultimate capacity located on such soil.

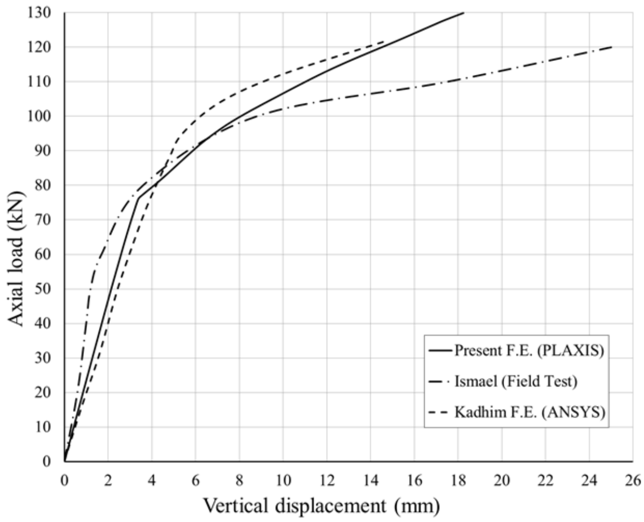

Fig. 2 Comparison between present finite element results and the results of [23] and [17]

V. Parametric Study

A parametric study was carried out, in this section, to examine the influence of cavities' size and location on the load carrying capacity of the axially loaded piles embedded in clayey soil. The physical properties of soil used in this study are as: modulus of elasticity E = 20000 kN/m^2, cohesion c = 100 kN/m^2, friction angle ϕ = 8°, unit weight γ = 16.5 kN/m^3, and Poisson's ratio υ = 0.4. However, the pile properties are as follows: Modulus of elasticity E = 25000000 kN/m^2, unit weight = 23 kN/m^3, Poisson's ratio = 0.2, pile length and diameter are 7.5 m and 0.5 m respectively.

Fig. 3 shows the geometry of pile embedded in soil with circular cavity and the parameters such as pile diameter (b), pile length (L), cavity diameter (D), depth of cavity centre from the ground surface (Z), and the horizontal distance of cavity centreline to the pile's centre (X). The applied load has been defined in percent of total load (P). Therefore, the percent of applied load for without cavity condition tends to 100. To facilitate a fair comparisons between the different analytical tests, the following dimensionless parameters are presented:

- (s/b): pile settlement to pile diameter.
- (D/b): cavity diameter to pile diameter, D/b = 1, 2, 3, and 4.

- (*X/b*): cavity horizontal distance from pile centerline to pile diameter, *X/b* = 1.5, 2, 2.5, and 3.
- (*Z/L*): cavity depth from the soil surface to pile length, *Z/B* = 0.4, 0.8, 1, and 1.2.

The analytical simulations were carried out by means of the finite element software (PLAXIS) which offers flexible features for investigating the performance of Soil-Pile-Cavity system problems.

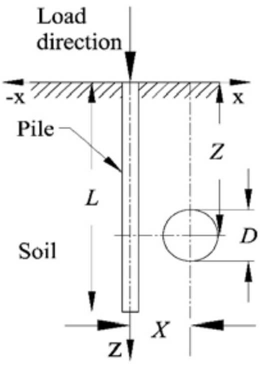

Fig. 3 Geometry of pile on cavitied soil with details of parameters.

A. Effect of Cavity Size

Fig. 4 illustrates the load-displacement variants as dimensionless ratios of a single pile embedded in cavitied soil with various cavity diameters. It is to be noted that the centres of cavities are located at the same depth from the ground surface, and the horizontal distance between cavity centre and pile centreline was unchanged, i.e. *Z* and *X* are constant. It has been noticed that by increasing the cavity diameter, the ultimate capacity of pile decreases.

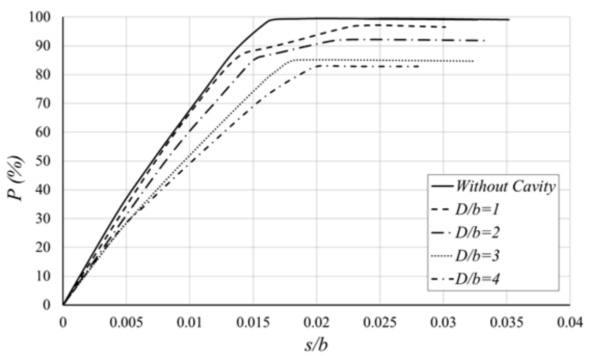

Fig. 4 Variation of load versus settlement ratio for various cavity sizes, *X/b*=2, *Z/L*=0.8.

B. Effect of Cavity Position from Pile Centerline

The differences of the applied load percent of pile versus displacement ratio for variant values of cavity horizontal distance from pile centerline is revealed in Fig. 5. As shown in this figure, while the horizontal distance of cavity from the pile centerline increases, the load carrying capacity improves. It is to mention that the closest cavity to the pile's centerline, a shear failure is therefore expected to establish in that zone.

C. Effect of Cavity Depth

Fig. 6 shows the effect of the depth of cavity centreline on the load carrying capacity of piled foundation at a constant cavity diameter and cavity horizontal distance. It is found that decreasing in the load carrying capacity with the increase in *Z/L* ratio which reaches a minimum value at *Z/L* = 1. The reason for this behaviour is due to formation the soil shear failure around the pile base.

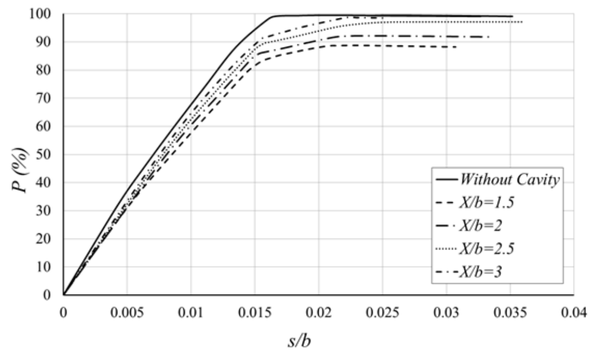

Fig. 5 Variation of load versus settlement ratio for various cavity horizontal distances, *D/b*=2, *Z/L*=0.8.

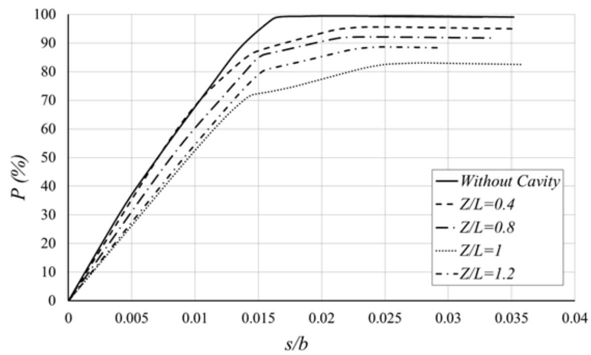

Fig. 6 Variation of load versus settlement ratio for various cavity depths, *D/b*=2, *X/b*=2.

VI. Critical Values for Design Recommendations

In the purpose of accounting the effect of all the involved parameters in this study, such as *D/b*, *X/b*, and *Z/L*, a Reduction Factor (*RF*) has been presented as follow:

$$Reduction\ Factor = \frac{P - P_c}{P}$$

where P and P_c are the failure load of without cavity condition and failure load of with cavity condition, respectively.

The variations of the above parameters versus the reduction factor have been investigated in this section. Variation of the *RF* (%) for different *D/b* is illustrated in Fig. 7. It should be noticed that other dimensionless parameters are kept unchanged. As shown in Fig. 7, the *RF* of the pile subjected to axial load decreases with an increase in the diameter of the cavity. This behaviour occurred because of the expansion in the size of failure mechanism created in the soil close to pile. This has produced a failure before increasing the load carrying capacity of the pile. It appears that decreasing the cavity diameter less than D/b = 0.4 has no influence on the load carrying capacity of pile. Therefore, the critical diameter (D_{cr}) of the cavity found near the pile is D_{cr} = 0.4b for the above conditions.

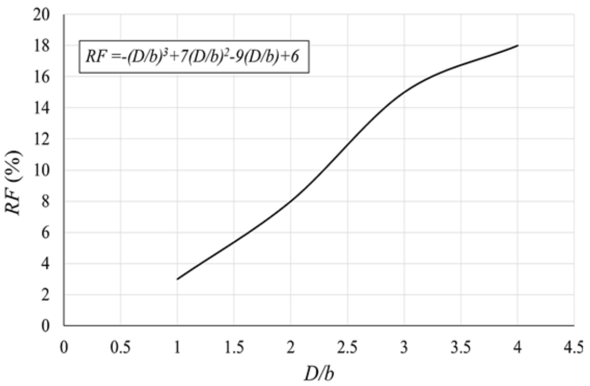

Fig. 7 Variation of reduction factor for various D/b, (X/b=2, Z/L=0.8).

The relationship between (RF) and X/b ratio is shown in Fig. 8. It is obvious from this figure that the load carrying capacity of piles is increased by increasing the horizontal distance between the cavity and pile. It seems that the change in horizontal distance of cavities near piles will no longer influence the ultimate capacity of the pile at X/b = 3.3. Therefore, the critical value for the horizontal distance between the cavity centreline and pile centreline X_{cr} is 3.3b for axially loaded pile.

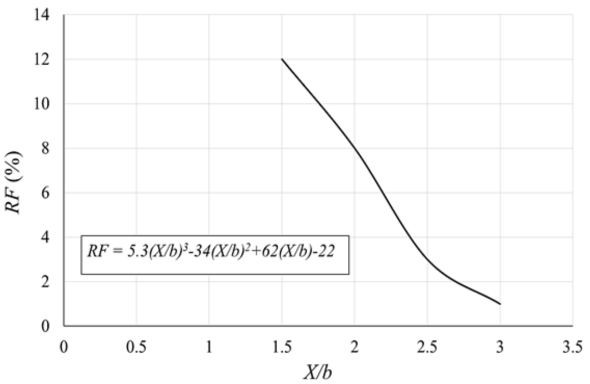

Fig. 8 Variation of RF % various X/b, (D/b=2, Z/L=0.8).

Variation of reduction factor versus Z/L is shown in Fig. 9. The figure stipulate that there are two critical values for Z/L, in which the impact of cavity on the ultimate capacity of the pile is vanished and the reduction factor approaches that of without cavity condition. The effect of cavities presence on the ultimate bearing capacity of pile disappears at about critical depth Z_{cr} = 0.2L and 1.6L.

It should be mentioned here that critical values and equations stated are applicable for the assumed pile and cavity geometry and materials properties. The figures presented earlier provide beneficial information for the design of pile embedded in clayey soil with a continuous cavity at least within the states analysed.

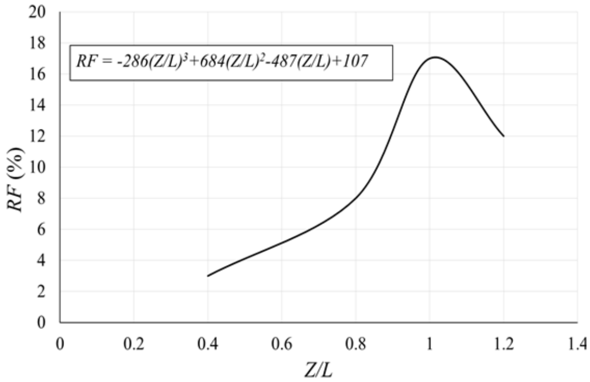

Fig. 9 Variation of reduction factor for various Z/L, (D/b=2, X/b=2).

VII. Summary and Conclusion

The effect of cavity presence on the single pile performance in clayey soil has been revealed from the results that are acquired analytically. Several inclusive verifications were adopted on existing field test as well as numerical investigation to assess the accuracy of analytical modelling. Consequently, the parametric study was carried out to estimate the effect of including parameters, such as size and location of the cavity on the pile behaviour subjected to axial load. Below are the main conclusions:

1. Cavity Presence near piles generates a reduction in the ultimate capacity depending on the location and size of the cavity.
2. The ultimate capacity of the pile decreasing noticeably with the increase in the cavity diameter.
3. Pile load carrying capacity increases with the increase of the X/b ratio.
4. Changing the cavity depth beyond Z_{cr} = 1.6L or less than 0.2L, the load carrying capacity of the pile remained constant.
5. The influence of the cavity position in the horizontal distance, at $X/b \geq 3.3$, on the behaviour of piled foundation can be neglected when the D/b = 2 and Z/L = 0.8.

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