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# Effect of Twin Cavities on the Axially Loaded Pile in Clay

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***Abstract*****—**Presence of cavities in soil predictably induces ground deformation and changes in soil stress, which might influence adjacent existing pile foundations, though the effect of twin cavities on a nearby pile needs to be understood. This research is an attempt to identify the behaviour of piles subjected to axial load and embedded in cavitied clayey soil. A series of finite element modelling were conducted to investigate the performance of piled foundation located in such soils. The validity of the numerical simulation was evaluated by comparing it with available field test and alternative analytical model. The study involved many parameters such as twin cavities size, depth, spacing between cavities, and eccentricity of cavities from the pile axis on the pile performance subjected to axial load. The study involved many cases; in each case, a critical value has been found in which cavities' presence has shown minimum impact on the behaviour of pile. Load-displacement relationships of the affecting parameters on the pile behaviour were presented to provide helpful information for designing piled foundation situated near twin underground cavities. It was concluded that the presence of the cavities within the soil mass reduces the ultimate capacity of pile. This reduction differs according to the size and location of the cavity.

***Keywords*****—**Axial load, clay, finite element, pile, twin cavities, ultimate capacity.

## I. Introduction

THE underground cavities may occur near foundations as natural cavities or artificial cavities. Natural cavities occur throughout different causes such as the chemicals actions in soils contain dissolvable materials mostly gypsum, thawing of subsurface ice lenses, and extinction of some water areas. Man-made cavities might happen as a result of tunnelling or mining activities [1]. Accordingly, the failure of structures built on such soils is likely to occur due to the formation of cavities. One of the challenges in designing and constructing foundations is the presence of cavities. It is normally essential to consider both natural and artificial cavities in the design and construction of piles for modern industrial establishments [2]. Therefore, it necessitates a technique for estimating the performance of piled foundation constructed in such soils.

Published researches on the performance of axially loaded piles embedded in clayey soil with cavities are merely few, despite the significance of the problem of pile stability above cavities. Although several investigations have been adopted to study the influence of cavities on piles, the effect of only one cavity is frequently considered.

The first studies which have been conducted on the subject of cavities and bearing capacity of foundations were [3]-[5]. The behaviour of strip foundation placed on stiff silty clay with void was assessed analytically by [6]. Reference [7] examined the performance of footing built on the single void. Reference [8] adopted a study on the influence of void shape and location on the load carrying capacity of the foundation constructed on single void. Numerical and experimental studies on the performance of spread foundation built on a continuous void have been conducted by [1].

Reference [9] assessed analytically the behaviour of a shallow foundation constructed on shielded underground tunnel in various soils. The authors found a critical depth in which the void has no effect on the ultimate capacity of foundations. Reference [10] examined numerically the impact of the construction effect of urban tunnels on nearby pile using finite element software. Reference [11] studied the effect of tunnelling generated soil movements on existing piles by performing many tests using 3D finite element software. Their results showed that for the single floating pile condition, produced bending moments are normally insignificant beyond a pile horizontal distance from tunnel center larger than double tunnel diameter. Reference [12] assessed the behaviour of single pile embedded in sandy soils with cavities and subjected to a lateral load. They recommended that the number and location of cavities have a mutual influence on the behaviour of such pile. Reference [13] adopted experimental and analytical investigation on the effect of cavity presence on the adjacent piled foundation embedded into sand of Al-Najaf city. Reference [14] used finite element software (ANSYS) to examine the effect of cavity depth on the performance of single pile subjected to axial load and embedded in clayey soil. Reference [15] conducted experimental tests and numerical analysis on the effect of cavities on the piled foundation found in sandy soil. Reference [15] stated that the reduction ratio in pile settlement was about 60%-70% compared to the no cavity condition. Reference [16] adopted a series of 3D centrifuge model tests to study thoroughly interaction between twin tunnel formation and an existing single pile. The authors investigated the effect of each tunnel depth comparative to the pile by creating twin tunnels either near the toe of the pile or close to the middle of the pile. The displacement of the pile is affected by the depth of the twin tunnels comparative to the pile. General losses of load carrying capacity of pile are recorded between 20% and 36% due to the excavation of twin tunnels close to the at the middle of pile length and pile toe, respectively. Reference [17] carried

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out several numerical analyses and centrifuge model tests to assess the influence of construction sequence of twin tunnels on pile in dry sand. They investigated the system including tunnelling close to the toe of pile followed by tunnelling close to the middle of the pile shaft, and the system including tunnelling close to the middle of pile shaft followed by tunnelling close to the pile tip. Because of various tunnelling orders, the losses of load carrying capacity of pile were 29% for the system including tunnelling close to the toe of pile followed by tunnelling close to the middle of the pile shaft, and 40% for the system including tunnelling close to the middle of pile shaft followed by tunnelling close to the pile tip. The tunnelling sequences had a small influence on the recorded displacement of pile head, settlements of soil surface, and additional pile bending moments. Reference [18] presented a helpful study for predicting the effects produced by tunnelling on existing piles using a PGROUPN computer software for analysing pile-group which is a non-linear boundary element analysis. Reference [19] utilised a finite element software (PLAXIS) to inspect load carrying capacity and failure mechanism of strip foundation situated on soil with twin voids. They proposed that a critical distance between voids and a critical depth of them occur, where there was no influence of voids on the ultimate capacity of foundation. However, [20] 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 [21].

In the available literature, the effect twin cavities size, depth, spacing, and eccentricity on the behaviour of single pile subjected to axial load embedded in clay have not been assessed yet. Therefore, this paper concentrated on the performance of the pile-twin cavities system for different identical cavities diameter, depth, spacing, and eccentric distance to the pile centreline. It is important to mention that the study is limited to single pile subjected to central vertical load and embedded in clay with a uniform twin cavities.

## II. Bearing Capacity of Piles

The mechanical properties of soil, the water conditions in the soil, original stresses, foundation installation method, and physical characteristics of the foundation are the main factors on which the bearing capacity of foundation depends [22]. However, [22] and [23] stated the failure zone nearby the pile tip. It is believed that the failure zone is normally shear failure style and the rupture surfaces change to a certain zone over the pile base. The failure load was defined according to load-displacement curves. For comparison purposes, the failure criterion, suggested by Terzaghi, which is commonly accepted by engineers, has been adopted in this paper. Terzaghi's method can be described as a displacement generated by the load, which is equal to 10 percent of the pile width or diameter. Nevertheless, some more criteria for defining the failure load of piled foundations have been stated.

## III. Numerical Analysis

The pile-soil-twin cavity system was modelled by utilising the finite element program PLAXIS 2D. Mohr-Coulomb failure criterion has been considered to simulate the behaviour of soil numerically. This paper was normally concentrated on ultimate capacity of piles. Thus, the pile model was treated as an elastic-perfectly plastic model according to [24]. The twin cavities were characterised through idealising a hole taken out from the soil mass without lining. To describe the original condition of the soil, it was presumed that there was no cavity presence in the soil mass. Consequently, in the cavity forming stage, the stresses were restarted in the system. Following this stage, the displacements of the nodes were set to zero, and the pile was loaded. These steps are quite representing the experimental tests as well as the in site cases. Fig. 1 revealed the schematic figure mesh organisation considered in the current numerical analyses.

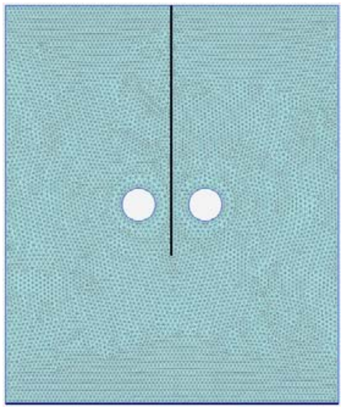

Fig. 1 The finite element mesh in PLAXIS 2D in present study

## IV. Software Verification

A comparison was adopted between the PLAXIS program results and alternative numerical results and field measurements for the purpose of assessing the validity of the current approach. Some field tests have been conducted by [25] to study the performance of a vertically bored pile in cemented sand. The length of pile, the pile's modulus of elasticity, pile width, unit weight, and Poisson's ratio were stated to be equal to 2.25 m, 20000000 kN/m$^2$, 0.1016 m, 23 kN/m$^3$, and 0.2, respectively. The soil properties are as follow: cohesion is 20 kN/m$^2$, modulus of elasticity is 25000 kN/m$^2$, unit weight is 18.5 kN/m$^3$, friction angle equals 35°, and Poisson's ratio is 0.37. Reference [14] simulated the full-scale pile test of [25] by finite element program ANSYS. Fig. 2 revealed the comparison between the results of the present study and the results of [25] and [14]. Back analysis of the field results as well as the other finite element results showed encouraging agreement between the current finite element results and the recorded results, proving the accuracy and capability of numerical modelling. Therefore, the numerical modelling indicates the ability of the method to generate acceptable predictions of the ultimate capacity of pile located in clay with the presence of cavities for many conditions of practical significance.

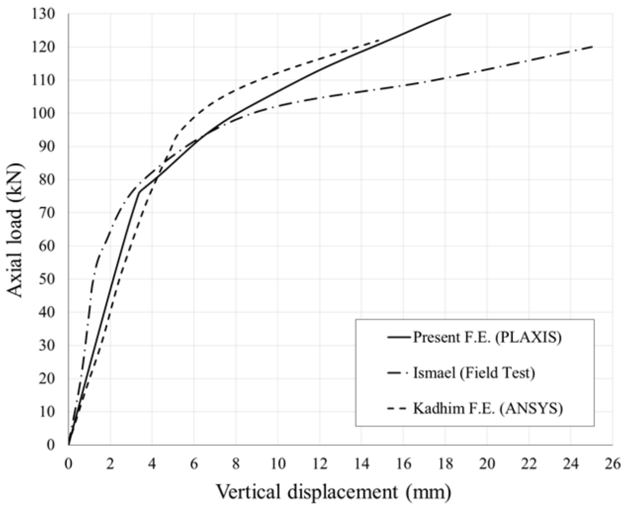


Fig. 2 Comparison between present finite element results and results of [25] and [14]

## V. Parametric Study

The parametric study of this paper was adopted to assess the influence of twin cavities on the behaviour of single pile embedded in clayey soil and subjected to axial load. The effects of cavity size, spacing between adjacent cavities, cavity depth, and eccentricity of twin cavities with regard to the axis of pile have been studied in this section. The soil mechanical properties considered in this investigation are as follow: unit weight $\gamma$ = 16.5 kN/m$^3$, cohesion $c$ = 100 kN/m$^2$, modulus of elasticity $E$ = 20000 kN/m$^2$, friction angle $\phi$ = 8°, and Poisson's ratio $\upsilon$ = 0.4. While, the properties of pile are unit weight = 23 kN/m$^3$, modulus of elasticity $E$ = 25000000 kN/m$^2$, Poisson's ratio = 0.2, pile diameter and length are 0.5 m and 7.5 m respectively.

The geometry of pile embedded in soil with two identical circular cavities is shown in Fig. 3. The geometrical parameters involved in this study are pile length ($L$), pile diameter ($b$), cavity diameter ($D$), depth of cavity centre from the soil surface ($Z$), horizontal distance between twin cavities ($H$), horizontal distance of $H/2$ to the centre of the pile ($X$). It has been assumed that the applied load in percent of total load ($P$). Thus, the percent of applied load for no cavity condition tends to 100%. Following are the dimensionless parameters that have been prepared to facilitate fair comparisons among the different numerical tests.

- ($s/b$): pile settlement to pile diameter.
- ($D/b$): cavity diameter to pile diameter, $D/b$ = 1, 2, 3, and 4.
- ($H/b$): horizontal distance between twin cavities to pile diameter, $H/b$ = 2, 3, 4, and 5.
- ($Z/L$): twin cavities depth from the ground surface to pile length, $Z/L$ = 0.6, 0.8, 1, and 1.2.
- ($X/b$): twin cavities eccentricity distance from pile centreline to pile diameter, $X/b$ = 0, 0.5, and 1.

The soil-pile-twin cavities system was numerically simulated by means of the finite element program (PLAXIS) which presents flexible features to investigate the performance of such system.

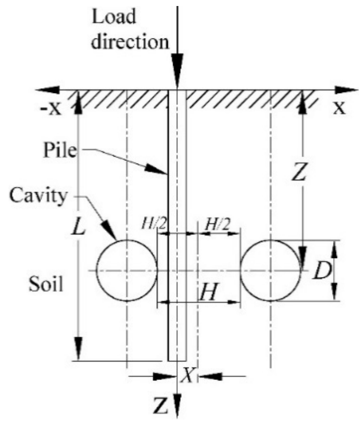


Fig. 3 Pile adjacent to twin cavities geometry

### A. Cavity Size Effect

The influence of variation in the cavity diameters on the load-displacement relationship of a single pile embedded in cavitied soil has been presented in Fig. 4. It is to be mentioned that the twin cavities depth, horizontal distance between twin cavities, and twin cavities eccentricity, i.e. $Z$, $H$, and $X$ were kept unchanged. It has been remarked that by expanding the cavity diameter, the load carrying capacity of pile reduces, while the distance between cavities edges was constant. Additionally, the load-displacement characteristics of pile tend to the without cavity condition as the cavities diameter decreases.

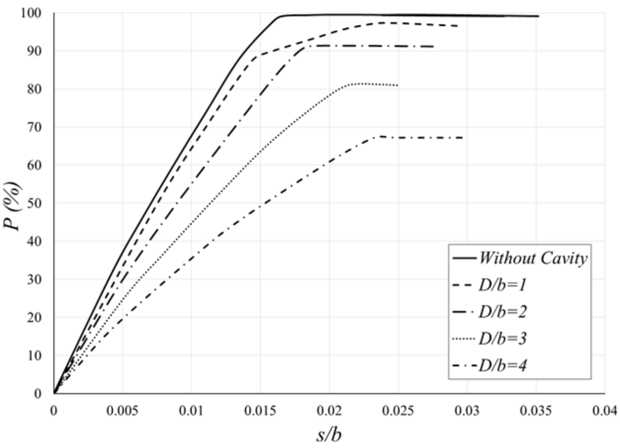


Fig. 4 Variation of load versus settlement ratio for various twin cavities sizes, $X/b$=0, $Z/L$=0.8, and $H/b$=2

### B. Effect of Spacing between Twin Cavities

Fig. 5 reveals the differences in the applied load percent of pile versus settlement ratio for various values of the spacing between twin cavities ($H$). As shown in Fig. 5, an increase in the spacing between twin cavities, the ultimate capacity increases while keeping cavity diameter, cavity depth, and twin cavities eccentricity constant. It is to state that, at the nearest twin cavities to the centreline of the pile, a shear failure is consequently imagined to occur in that zone.

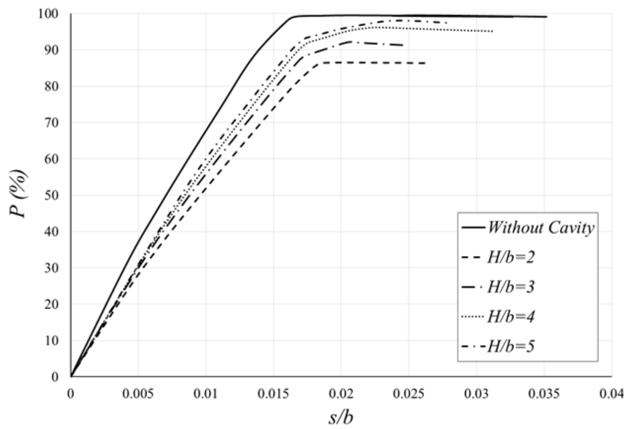


Fig. 5 Variation of load versus settlement ratio for different twin cavities spacing, *X/b*=0, *Z/L*=0.8, and *D/b*=2

### C. Cavity Depth Effect

Fig. 6 illustrates the influence of the twin cavities depth from the ground surface on the ultimate capacity of single pile at a constant cavities diameter, cavities spacing, and twin cavities eccentricity. It is realised that the reduction in the load carrying capacity is with increasing *Z/L* ratio. The explanation for this performance is because of generation the soil shear failure nearby the pile tip. The ultimate capacity is considerably influenced by the twin cavities only when these cavities are found in the critical region.

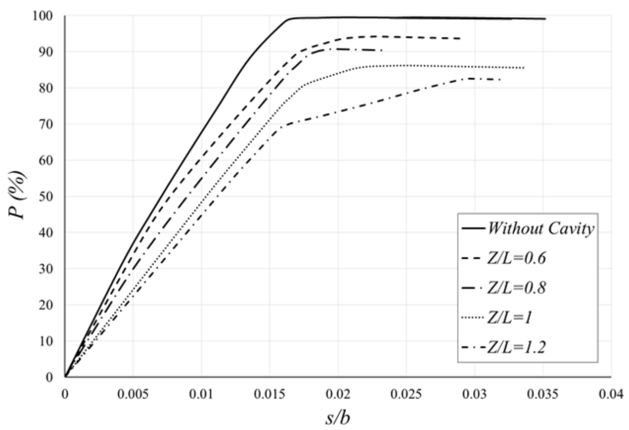


Fig. 6 Variation of load versus settlement ratio for various twin cavities depths, *X/b*=0, *D/b*=2, and *H/b*=2

### D. Effect of Twin Cavities Eccentricity

In the previous numerical analyses, twin underground cavities were located symmetrically in both sides of the pile centreline while in this section, the middle distance between twin cavities is positioned at one side of the pile's axis. In addition, cavities diameter, the distance between them, and the depth of twin cavities from the bed surface were remained unchanged. Fig. 7 shows the variations of applied load on the single vertical pile located close to identical cavities versus displacement for various values of cavities eccentricity. The cavities are positioned at both sides of the pile vertical axis, refer to Fig. 3. It can be recognised, from Fig. 7, that decreasing in the ultimate pile capacity with the increase in *X/b* ratio which reaches a minimum value at *X/b* = 0.5.

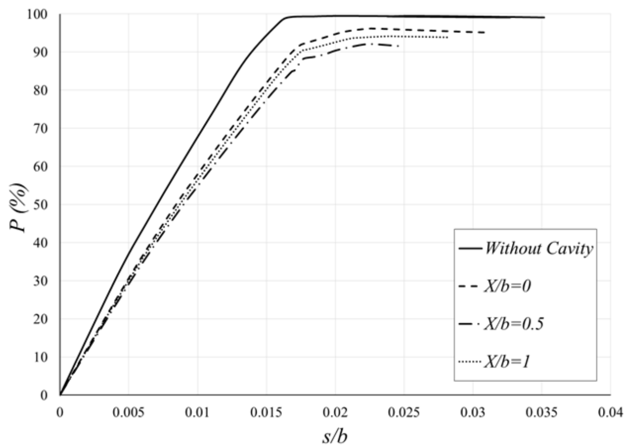


Fig. 7 Load-displacement curves of pile head for various cavity eccentricity *Z/L*=0.8, *D/b*=2, and *H/b*=4

## VI. Critical Values for Design Recommendations

For the aim of accounting the influence of all the mentioned parameters, such as *D/b*, *X/b, H/b, and Z/L*, a reduction factor (*RF*) stated as:

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

where $P$ and $P_c$ are the failure load of no cavity case and failure load of with cavity case, respectively.

The variants of the involved parameters against *RF* were studied in this section. Changing in *RF* (%) for different *D/b* is revealed in Fig. 8. The other dimensionless ratios were maintained constant. As illustrated in Fig. 8, the *RF* of axially loaded pile decreases when cavity diameter becomes greater. This performance happened due to the extension of the failure zone generated in the soil around the pile. It seems that reducing the cavity diameter by less than *D/b* = 0.5 has no influence on the load carrying capacity of the pile. Thus, the critical diameter ($D_{cr}$) of the twin cavities located nearby the pile is $D_{cr} = 0.5b$ for the stated conditions.

The relationship between *RF* and *H/b* ratio is shown in Fig. 9. It is recognisable from this figure that the ultimate capacity of single pile is improved by increasing the spacing between the twin cavities. It appears that changing in twin cavities spacing near piles will no longer affect the load carrying capacity of the pile at *H/b* = 6. Accordingly, the critical value for the spacing between the twin cavities $H_{cr}$ is 6*b* pile subjected to axial load.

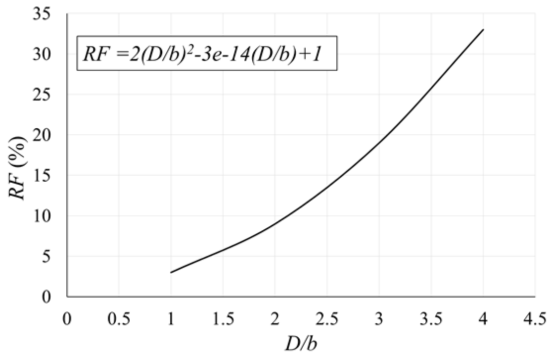


Fig. 8 Variation of *RF* versus *D/b*, (*H/b*=2, *Z/L*=0.8, and *X/b*=0)

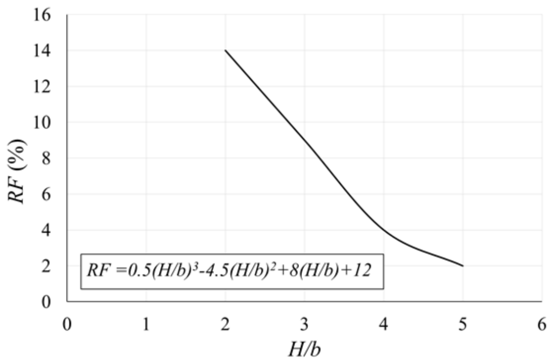


Fig. 9 Variation of *RF* % for different *H/b*, (*D/b*=2, *Z/L*=0.8, and *X/b*=0)

Fig. 10 shows the variation of *RF* versus *Z/L* and stipulates that the impact of twin cavities on the ultimate capacity of the pile vanishes and the *RF* approaches that of no cavity case at *Z/L* = 0.3. Therefore, the influence of twin cavities' presence on the load carrying capacity of pile disappears at critical depth $Z_{cr} = 0.3L$.

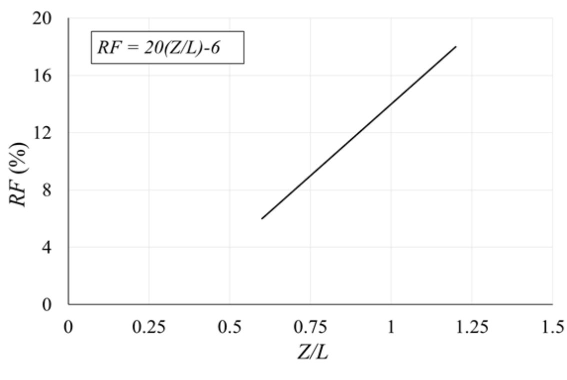


Fig. 10 Variation of *RF* for various *Z/L*, (*D/b*=2, *H/b*=2, and *X/b*=0)

The impact of the twin cavities eccentricity on the *RF* of the axially loaded pile is revealed in Fig. 11. It is obvious that the pile behaviour weakens with the increase in *X/b* ratio and it reaches the minimum at *X/b* = 0.5. After this limit, it can be recognised that, by increasing the eccentricity ratio, the ultimate capacity of pile is improving.

It is important to mention that the critical values and equations presented here are appropriate for the proposed geometry of pile and cavities as well as materials' properties. The figures introduced before offering helpful data for the design of piles embedded in clay with twin cavities at least within the analysed conditions.

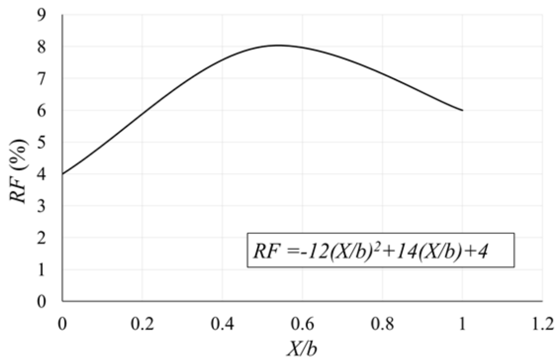


Fig. 11 Differences in *RF* for various *X/b*, (*D/b*=2, *Z/L*=0.8, and *H/b*=4)

## VII. Summary and Conclusion

Finite element analyses have been adopted to reveal the effect of the presence of twin cavities on the performance of axially loaded pile embedded in clay. Conducting some inclusive verification on published field test and numerical study assessed the accuracy of the numerical modelling. Subsequently, the parametric study was accomplished to inspect the influence of including parameters, such as twin cavities size, spacing, depth, and eccentricity from the pile axis on the pile performance subjected to axial load. The numerical results were guided to the following conclusions.

1. Presence of twin cavities near piles produces a reduction in the load carrying capacity of pile according to cavities size and location.
2. Increasing cavities diameter leads to a noticeable decrease in the ultimate capacity of the pile.
3. It is to mention that the pile ultimate capacity develops with the increase of the *H/b* ratio.
4. Based on the numerical results, reducing the twin cavities size by less than $D_{cr} = 0.5b$, the ultimate capacity of the pile remained constant when the *H/b* = 2, *X/b* = 0, and *Z/L* = 0.8.
5. When $Z_{cr}$ less than 0.3*b*, the pile load-displacement response is similar to that of no cavity condition.
6. The spacing between twin cavities has no effect on pile behaviour when $H_{cr}$ is more than 6*b* at *D/b* = 2, *X/b* = 0, and *Z/L* = 0.8.

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