Response of Piles Group embedded in Sandy Soil with Cavities to Seismic Loading

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Abstract. This research is looking at the impact of cavities on the pile group foundation settlement subjected to seismic loads in the dry sandy soil of dry unit weight 16 kN/m³. The finite element software (Plaxis 3D 2020) was used to represent the way of behaving of gypseous soil under the group of piles with cavity formation. The study included the presence of a single cavity, the group of cavities, and different diameters of the cavity in different locations. The horizontal distance from the centerline of the cavity to the centerline of the pile or group of piles is defined as (X), and the vertical distance from the bottom of the pile to the cavity centerline is defined as (Y). The variations in cavity locations, numbers, and diameters were all studied. The results showed that the impact of the earthquake (El Centro) of the settlement of pile group with cavity increased the settlement when the cavity was located near the edge of piles and that when the diameter of the cavity increased, the settlement has been increased for the same vertical distance of the cavity below the group piles and under the influence of the earthquake. The effect of cavity diminishes at a horizontal distance a cavity at horizontal depth (X = 4D).

Keywords: Cavity; pile group; sandy soil; seismic load.

1. Introduction

The behavior of soils is regarded as complicated material, unlike most structural materials, to use the structures built on the soil safely, it has to be dealt with it carefully. The presence of cavities is the most well-known problem in soils. When the soils contain, the cavities are named “problematic soils,” as cavities can cause structural deterioration and even death. Cavities can be split into two parts, natural and man-made cavities. Natural cavities result from areas going dry, solids disappearing into limestone, and mostly are gypsum. In sandy soil, various sizes of cavities were ranged from 0.1 m to 3 m [1]. These cavities exist in different structures, which depend on the formation origination. Man-made cavity due to the basement (oldest) building, and natural cavity (the gypsum dissolution) due to water flowing, and with constant groundwater movement in gypseous-containing soils, the gypsum dissolves, resulting in a multitude of cavities of varying shapes under the ground surface. The literature on the stability of piled foundations under the effect of cavities is usually limited; only a few papers are available related to this appointed topic (i.e., piles and cavities) [1].

Al-Mosawe et al. [2] studied the behavior of model piles under lateral load in sandy soils that contain cavities. The number and position of the cavities have been shown to have an effect on the behavior of the pile under lateral load. Despite this, when the distance between the pile and the cavity to the diameter of the pile was more than 8, the impact of the position of the cavities in front of the pile was tiny. Al-Taie [3] investigated the conduct of laterally loaded piles in sandy soils that contain cavities. In this study, it a program of laboratory testing was done. The program of testing consisted of five groups: The first group was performed on a pile embedded in the soil without cavities. The second and the third
groups were carried out on the pile in soil that containing a single cavity located in front and in contact with the edge of the pile for the second group and in the back and in contact with the edge of the pile for the third one. The fourth group was done with a pile with the presence of two cavities, placed in front and in contact with the edge of the pile. The fifth group was carried out on the pile with the presence of three cavities, placed on the face and at varying distances from the edge of the pile. These exams are done in a free-head pile that was applied under horizontal load. The outcomes showed that the numbers and the places of cavities have a common impact on the conduct of laterally loaded piles. At X/D > 8, where X is the distance between the cavity and the pile and D is the diameter of the pile, the impact of cavities placed next to the pile is null.

Shlash et al. [1] studied the impact of laterally loaded piles in cohesive soil containing cavity in Al Najaf city, Iraq. An empirical and numerical search of the cavity that is approaching the pile reaction in sandy soils was carried out. Empirical researches were carried out to find the impact on different agents (cavity locations, vertical dead loads, and the back angle of the pile pulling elevation). The action of a side-by-side stacked pile in sandy soil with cavities is investigated. Fattah et al. [4,5] researched the impact of the existence of the cavity on the pile group in sandy soils by using experimental and analytical modeling from testing the value of settlement and group capacity of the piles with various cavity positions. Pile models had been exam in a sandbox under applied load by using a hydraulic operated winch, and by using the load cell, the load was monitored. Three strain counters were introduced into the piles to gauge the strains and then account for the load transported for all piles in the group by a strain data recorder. It was tested three sets of piles in the laboratory; a single pile, a group of piles (1×2), and a group of piles (2×2). In the first model, the cavity was simulated and positioned next to the piles at various depths below the soil surface and at various distances from the piles centerline. For each exam, the impacts of various cavity depths (Y), cavity positions (X), and cavity diameters (d) on the settlement and load of piles are investigated. It was observed that the pile load that gauged are increasing with increasing of (X/D) caused by reduction of the area affected by the existence of the cavity. It reduces the density of the soil, reduces the skin friction over the pile, and causes lowering failure load in a pile. At a range of 5.5 pile diameters and all depths, the ultimate load of the pile is unaffected by the cavity when it is placed near the pile.

The previous studies did not deal with the effect of dynamic loads on the group piles with cavities, as studies lack that, despite the importance of this topic and the risk of earthquakes on buildings that are based on soils containing cavities. So, the main objectives of this paper are to evaluate the conduct of the vertically loaded pile group in dry sandy soil with a cavity under seismic load and to determine the effect of the presence of the cavity at various depths and locations on the response of the pile. The aim of the analysis is to see how different factors like cavity width, cavity location, different values of cavity diameter, and the number of cavities affect pile bearing capacity and settlement.

2. Seismic waves

Earthquakes generate elastic waves when one of a large solid piece of hard material slides against another, the break between the two large solid materials being called a ‘fault’. Seismic (elastic) waves are transmitted through the body in all directions from the focus. If the equilibrium of a solid body like the earth is disturbed due to fault motion resulting from an earthquake. Earthquakes radiate waves with periods between ten seconds to several minutes. Rocks conduct like elastic solids at these frequencies. The ground motion after an earthquake quite compels because the elastic solids allow a variety of wave types [6]. Piles are often used in weak soil conditions, resulting in low allowable contact pressures and high settlement of the mat-type base. In order to pass axial loads into the underlying soil, the piles use an end bearing, a frictional side adhesion, or a combination of both. The soil pressure bearing on the side of the pile cap or on the side of the piles was used to resist transverse loads. [7].

Ben [8] identified the failure of the pile foundation in five models: Pile head bending failure, soil layer interface bending failure, pile cap failure, excessive horizontal displacement, and excessive pile or tensile displacement. The seismic load caused large displacements and strains in the soil. With increasing strain, the soil's shear modulus degrades, and stiffness (material) increases. The stiffness of piles should be determined for strain impact. Many researchers have previously proposed elastic solutions for determining the response of piles subjected to dynamic loads in varying modes of vibration.
By using group interaction factors, the rigidity of the pile group is estimated on the single piles. If applicable, pile cap support is also included. The response of the individual pile or pile group was based on structural dynamics ideals.

Finn [11] studied the behavior of models that were performed on the pile group in a geotechnical centrifuge of 2.5 m arm length in disaster prevention research institutes on liquefiable and non-liquefied ground. The research aimed at obtaining an overview of the impact on the behavior of the soil-pile system of differences in fundamental conditions such as individual and collective pile conditions and static or dynamic conditions. Model test results showed that (1) larger soil-pile system residues were replaced for the same level of inertia during dynamic loading, and (2) group pile effects were observed in liquefied soil. Fattah et al. [12] The experiments were carried out using the pile embedment depth (L/d) ratio and the rotating system running occurrence. In both exams, the pressure along the pile's length and the vertical vibration capacity of the pile cap is calculated. It was discovered that the axial strain along the pile is frequency dependent, so it was increased when the frequency of activity and vibration was increased. The capacity of oscillation of the head of the pile also depended on the hesitation, it was increased when the operating hesitation increased.

3. Numerical modeling

The powerful analytical, numerical technique, and high-speed computer, make it simple to perform the behavior of non-linear soil in the study. A very effective solution approach in geotechnical engineering is the Finite Element Method (FEM). It's become a much more effective technique to solve the issues of geotechnics. In this current research, the finite element software (Plaxis 3D 2020) is used to perform the conduct of gypseous soil below group pile containing cavity. The program was improved, especially for stability, foundation projects, and analysis deformation. During this research, the Mohr-Coulomb standard was adopted to state the conduct of the soil, as it was a recognized model that was applied as a first approach to the conduct of soil. The model is a bilinear model defined by five input parameters: the elasticity modulus (E), the Poisson's ratio (ν), the angle of internal friction (ϕ'), the cohesion (c'), and the dilatancy angle (ψ'). Before reaching failure, the elastic parameters control the settlement, while the shear strength parameters (ϕ' and c') control the failure conditions, and the dilatancy angle (ψ') controls the irreversible volume change due to shearing for related not to the flow rule conditions [13].

3.1 Footing material modeling

The model of this study has dimensions of (30×60) m and 20 m thickness. The footing was presumed to be a linear elastic body, and the physical characteristics were set to ideal concrete values in order to make the footing completely rigid, with a material modulus of Ec = 26 GPa, unit weight of c = 24 kN/m3, and a Poisson's ratio of ν = 0.25. The geometrical arrangement of the situation is shown in Figure 1.

![Figure 1. Geometrical arrangement of the situation.](image)
3.2 Model piles
The model of the pile used in the present study constructed of concrete with the properties given in Table 1.

| Diameter (D), m | Length (L), m | No. of piles | Area of cap, m² | Thickness of the cap (t), m | Spacing between the piles (center to center) (s), m |
|-----------------|--------------|--------------|----------------|---------------------------|-----------------------------------|
| 0.6             | 12           | 4            | 25             | 0.5                       | 1.2                               |

Table 1. Mechanical properties of concrete pile used.

![Figure 2. Model pile group.](image)

3.3 Modeling of Soil
The soil properties used can be seen in Table 2. The soil was represented as an elastic-ideal plastic material by using the Mohr-Coulomb failure standard. The tensile strength (σ≤) was measured as one-half of the adhesive strength [14]. The cavity was represented by using sphere injunction in the finite element software (Plaxis 3D foundation 2020) and using volume element.

| Soil properties                  | Values  |
|----------------------------------|---------|
| Gypsum content, χ (%)            | 20%     |
| Apparent cohesion, c (kN/m²)     | 9       |
| Angle of internal friction, φ (°) | 19      |
| Modulus of elasticity, E (kN/m²) | 20000   |
| Poisson’s ratio ν                 | 0.25    |

Table 2. Soil properties [14].

4. Numerical modeling of the problem
In this study, PLAXIS 3D has been used in the numerical modeling of the problem. Numerical modeling of this problem has been utilized by using the finite element software PLAXIS-3D, a rectangular region (60 * 30) m is performed in the numerical model analysis. The analysis involved static and dynamic stages. The boundary conditions for the static analysis stage have been applied similar to previous studies where the bottom of the mesh has been fixed against the movement in all directions to consider the influence of the rock layer, and the left- and right-hand sides of the model have been allowed to move only in the vertical direction. Moreover, the viscous boundaries (X max. and X min. as viscose and the other directions Y, Z as fixed) have been considered in the dynamic analysis stage to eliminate the effect of the wave reflected back to the finite element model during the time-history finite element analysis[15], [16]. These viscous boundaries have been added to the right and left sides of the model boundaries.
The depth of the numerical model has been considered to be equal to 20 m because the location of the rock layer has been assumed to be at a depth of 20 m from the natural ground surface. The length of the model has been considered equal to 60 m, and the width of the model has been considered to be equal to 30 m. This length has been chosen based on parametric analyses performed to investigate the effect of the finite element model length. The parametric analyses have been done by simulating different model lengths and selecting the length, after which there is no effect of the finite element model extend on results of the analysis. It is important to know that the results have been obtained by using the Mohr-Coulomb model and for sandy soil with a relative density of 45%.

The mesh size was also chosen after conducting a mesh convergence study to ensure that the results obtained were independent of the mesh size. In this study, the seismic loading is adopted according to the El-Centro earthquake with a peak acceleration of 0.35g was used to simulate the response of the foundation, as shown in Figure 3. The earthquake was simulated as a specified acceleration used at the bottom of the finite element model (where the location of the rock layer); this process is common in simulating the influence of the earthquake in the analysis of the finite [17,18]. The linear elastic model has been employed to emulate the reaction of the pile foundation; the $E$ and $v$ values of the concrete foundation was considered to be equal to 30,000,000 kPa and 0.2, consecutively similar to a previous study [19]. A static surface load was applied on the piles cap in the static phase to simulate the pressure applied from the residential building; the value of the load was considered equal to 200 kPa based on the study of Maheshunri and Viladkar [20].

5. Results and discussion
This study highlights the influence of the cavity on pile group from studying several parameters.

The following different parameters are used in this study:

1) Cavity position (X): the horizontal space from centerline of the cavity to the centerline of the pile or pile group, $X=D=0.6$ m, $X=2D=1.2$ m, $X=3D=1.8$ m, and $X=4D=2.4$ m, $X=5D=3$ m, and $X=6D=3.6$ m

2) Cavity depth (Y): the vertical space from the bottom of the pile to the cavity centerline, $Y=D=0.6$ m, $Y=2D=1.2$ m, $Y=3D=1.8$ m, $Y=4D=2.4$ m, and $Y=5D=3$ m.

3) Cavity diameter (d): three values of (d) are used in the study, $d=0.8$ m, $d=0.5$ m and $d=0.3$ m.

![Figure 3. Acceleration-time record for El-Centro earthquake.](image-url)
5.1 Settlement of pile group without cavity
The settlement was calculated at node A, shown in Figure 2. The results presented in Figure 4 show that the impact of the seismic load caused the settlement of pile group without a cavity. The maximum settlement reaches 0.54 cm. under the effect of El-Centro earthquake. It can be seen that the settlement increases rapidly at a short time then reaches a steady state after about 12 seconds.

![Figure 4. Time-settlement curve of pile group (2x2) in sandy soil without a cavity, L=12 m, D=0.6 m.](image)

5.2 Impact of the cavity location on the displacement of pile group
The study found that the influence of earthquake (El-Centro) on the settlement of pile group with the presence of cavity was increased the settlement if the cavity is setting near to the edge of piles. Figures 5 and 6 show the influence of alteration the cavity location on the displacement of pile group (2x2) in dry sandy soil with the cavity of diameter (d = 0.5 m) at different vertical and horizontal depths. It can be observed that the cavity at a vertical depth (Y = D) = 0.6 m led to an increase in the ratio of settlement by 40 times than without cavity, and the cavity at vertical depth (Y = 2D, Y = 3D, Y = 4D, Y = 5D) led to an increase in the ratio of settlement by (20 times, 4 times, 3 times, 2 times), respectively, while the cavity at vertical depth (Y = 6D) =3.6 m led to a value of settlement which is the same as that of the case without a cavity.

![Figure 5. Time-settlement curve of pile group (2x2) in sandy soil with a cavity of diameter (d = 0.5 m) at different vertical depths.](image)
It is also noticed that the cavity at a horizontal depth \((X = D) = 0.6\) m led to an increase in the ratio of settlement by 46 times more than without cavity, and the cavity at horizontal depth \((X = 2D, X = 3D)\) led to an increase in the ratio of settlement by (6 times, 4 times) respectively, while a cavity at horizontal depth \((X = 4D) = 2.4\) m led to return the value of the settlement to the same of that without a cavity.

![Figure 6](image)

**Figure 6.** Time-settlement curve of pile group \((2 \times 2)\) in sandy soil with a cavity of diameter \((d = 0.5\) m) at different horizontal depths.

### 5.3 Impact of number of cavities on settlement of pile group

In this study, the model consists of two groups of cavities: group one was performed on a group of piles embedded in dry sandy soil under the effect of dynamic load and contained 4 cavities: one cavity under the piles with vertical distance \(Y = 3D = 1.8\) m and three of cavities located with variable distance near the face of the pile. The second group was performed on group piles embedded in dry sandy soil under the effect of dynamic load contains 5 cavities: where located all under the piles with the same vertical distance \(Y = 3D = 1.8\) m. The results are presented in Figure 7. It is noticed that the increase of the number of cavities affects the settlement by increasing the amount of settlement than it was in one cavity with the same distance in the vertical direction \(Y = 3D = 1.8\) m.

![Figure 7](image)

**Figure 7.** Time-settlement curve of pile group \((2 \times 2)\) in sandy soil with numbers of cavities of diameter \((d = 0.5\) m) at different locations.

### 5.4 Effect of the diameter of the cavity on the settlement of pile group

In this study, three different diameters of the cavity \((d) = 0.3, 0.5,\) and 0.8 m were used. It was found that when the diameter increases, the settlement was increased for the same vertical distance of the cavity below the group piles and under the influence of the earthquake, as illustrated in Figures 8 to 13.
Figure 8. Time-settlement curve of pile group (2×2) in sandy soil with a cavity of diameter (d = 0.3 m) at different vertical depths.

Figure 9. Time-settlement curve of pile group (2×2) in sandy soil with a cavity of diameter (d = 0.3 m) at different horizontal depths.

Figure 10. Time-settlement curve of pile group (2×2) in sandy soil with a cavity of diameter (d = 0.5 m) at different vertical depths.

Figure 11. Time-settlement curve of pile group (2×2) in sandy soil with a cavity of diameter (d = 0.5 m) at different horizontal depths.
Figure 12. Time-settlement curve of pile group (2×2) in sandy soil with a cavity of diameter (d = 0.8 m) at different vertical depths.

Figure 13. Time-settlement curve of pile group (2×2) in sandy soil with a cavity of diameter (d = 0.8 m) at different horizontal depths.

6. Conclusions
The impact of the earthquake (El Centro) on the settlement of pile group with cavity resulted in an increase in the settlement when the cavity is set near to the edge of piles. When the diameter of the cavity increased, the settlement has been increased for the same vertical distance of the cavity below the group piles and under the influence of the earthquake. The increase in the number of cavities affects the settlement by increasing the amount of settlement more than in one cavity with the same distance in the vertical direction Y = 3D =1.8 m. The effect of cavity diminishes at a horizontal distance a cavity at horizontal depth (X = 4D).

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