Behavior of passive single pipe pile in sandy soil

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Abstract
This research focuses on studying the effects of soil movement on the behavior of an existing pile driven in sandy soil. A physical model has been manufactured to investigate the effect of construction of an embankment adjacent to free head single pile driven in sand of dry unit weight of 13.5 kN/m³. The model pile of diameter (D) of 10 mm are tested under two conditions of loading: loaded axially and without load. The model piles are instrumented with strain gauges along the embedded length to measure strains resulting from the soil movement. The embankment loads are applied at distances of 2.5, 5, and 10D from the edge of the pile. The results obtained from the model pile are: the lateral and vertical displacements at soil surface, the rotation at soil surface, bending moment profiles, pile deflection profiles, pile rotation profiles and shear force profiles. Some of these results are measured experimentally and others are calculated theoretically based on the measured strains. Based on the results of tests, it was found that the maximum soil reaction increased axially loaded piles by 43, 19, and 43%, when the embankment is at distances 2.5, 5, and 10D, respectively. The flexible pile provides more resistance to soil movement pressure and increasing the distance between the embankment and pile reduces the effects of embankment. The behavior of axially loaded pile is different than that of the pile without axial loading.

Keywords:
Passive pile, sandy soil, soil movement, embankment, numerical modeling.

1. Introduction
The laterally loaded piles are mainly divided into active and passive piles depending on the type of loads transmitted to the piles. Active piles are subjected to a direct horizontal load at the head of the pile. On the other hand, passive piles are loaded by the movement of the surrounding soil. Piles supporting the bridge abutments may be subjected to axial and lateral loads, which result from the soil movement [1]. Importantly, passive piles are often subjected to lateral soil movements and axial loads, simultaneously. Most of the piles are designed to support direct loads (active piles), but in many cases, the piles are not designed to carry indirect loads (passive piles) resulting from the weight of soil and surcharge on the soil surface, which causes deformation and movement of soil surrounding the existing piles [2].

Ti et al. [3] presented a general overview on the state-of-the-art researches dealing with the behavior of passive piles. This literature can be divided into four topics: effects of horizontal soil movement on piles, embankment supported by piles, slope stabilized by piles, and effects of excavation on nearby piles. The concluding remarks indicated that passive piles in open excavation may indeed prove to be one of the recent and significant research themes and this field will have invaluable contribution to the industry of deep foundation. Guo and Qin [4] developed an experimental physical model to study the effects of soil movement on the behavior of free head and vertically loaded piles in sandy soil.
maximum bending moment is almost linearly related to the driving force even for the initial movement of the frame and the extra-large for the trapezoidal movement.

Ersoy and Yildirim [5] used a large-scale shear box to investigate the behavior of piles subjected to lateral soil movement resulting from slopes. Strain gauges are used to measure the deformation and moments developed along the embedded length of piles. The results of tests were compared with those found in literature to contribute in understanding the behavior of passive piles. Shlash et al. [6] conducted series of laboratory physical model tests to measure the response of pile in loose sandy soil under different rates of lateral soil movements. The results obtained from PLAXIS 3D 2013 software well agreed with those measured experimentally under different rates of lateral soil movements, where increasing the rate of soil movement from 5 to 20 mm/min will lead to an increase in the maximum horizontal displacement. Ren et al. [7] conducted large geotechnical centrifuge model tests to simulate the behavior of sheet-pile wharfs with load-relief platform in homogeneous fine sand. The main results are the distribution of lateral pile-soil pressure and distinguishing of the pile’s passive part from active part.

Karkush and Kareem [8, 9] studied the behavior of passive piles in clayey soil contaminated with two ratios of medium fuel oil (MFO). The results of tests showed that an increase in the percentage of MFO in soil sample causes an increase in the influence of nearby embankment load on the behaviour of passive piles. In addition, an increase in the spacing between the edge of pile cap and embankment reduces the effects of embankment surcharge on the behaviour of piles. This research studies the behavior of a single flexible pile embedded in sandy soil and subjected to the lateral soil movement. The lateral soil movement is simulated by the construction of a nearby embankment to an existing pile at three spacing from the edge of the pile. The piles considered in this study under axial loading and without loading. The measured data are the vertical and lateral displacement of pile and the strains along the embedded depth of pile. The measured strains are used to calculate the bending moment, deflection, rotation, shear force, and soil reactions.

2. Soil sampling and materials used

2.1 Soil Sampling and Model Pile Properties

The disturbed soil sample was obtained from the bed of Tigris River at the north of Baghdad city. The soil sample can be classified according to the unified soil classification system as river sand (SP-SM). The physical and mechanical properties of soil sample are listed in table 1, the tests were measured according to the ASTM and BS specifications [10, 11]. An aluminium closed end pipe piles are used in the experimental study. The piles have annular cross-sectional area with total length of 500 mm. The slenderness ratio (L/D) of all model piles is equal to 50 and the embedded depth of pile is 420 mm, where the model pile behaves as flexible pile according to the flexibility factor \( K_R \) [12]. The engineering properties of model pile material are given in table 2. The model piles were instrumented with strain gauges on the two vertical lines of the front and rear sides of pile with respect to the location of embankment. Four pairs of strain gauges were installed on the outer surface of the piles with a spacing of 120 mm apart. In order to protect from damage during the installation of pile, the strain gauges were sealed with epoxy resin of 1 mm thickness. The wires of strain gauges were wrapped and fixed on the outer surface of the pile using glue and tapes.

| Property   | Value | Property       | Value |
|------------|-------|----------------|-------|
| Gs         | 2.67  | \( \gamma_{d_{min}} \) (kN/m\(^3\)) | 11.87 |
| Cu         | 2.934 | \( \gamma_{d_{max}} \) (kN/m\(^3\)) | 15.14 |
| Cc         | 1.188 | \( \gamma_{d} \) (kN/m\(^3\)) at Dr = 56% | 13.5  |
| Fines (%)  | 9.8   | \( \phi \) (º) at Dr = 56% | 35º   |
Table 2. Properties of model pile.

| Property                          | Value          |
|-----------------------------------|----------------|
| Outer diameter of pile (D)        | 10 mm          |
| Wall thickness of pile            | 1 mm           |
| Length of pile (L)                | 500 mm         |
| Weight of pile                    | 42 gm          |
| Density of pile material          | 2.97 gm/cm³    |
| Modulus of elasticity (Ep)        | 69.871 GPa     |

Figure 1. Locations of strain gauges on the tested model pile.

2.2 Physical Model

The physical model consists of steel container of internal dimensions of (800×800×800 mm) and loading frame with hydraulic jack used for inserting the model pile into the soil and applying the embankment load on the soil surface. The maximum load capacity of hydraulic jack is about 10 tons. Also, a load cell was fixed on the base plate of embankment load to measure the load generated by the hydraulic jack. The bedding soil poured into the steel container has a dry unit weight of 13.5 kN/m³ and dropped from a height of 240 mm. The raining technique is used for preparing the bedding soil in the steel container where a specific cone is filled with sand and poured into the steel container freely in a homogenous way. When the sand rises in the container with a certain thickness, the cone should be raised with distance equal to the thickness of sand layer that developed in the container to maintain constant dropping height to achieve the desired density. After completing the final layer, the top surface was scraped and leveled to get a flat surface, then the model pile is driven into the soil. Prior to the driving process, the pile was pushed into the soil bed, by hand, to an approximate depth of 100 mm. The pile verticality was checked and adjusted during the test, if necessary. Then, the pile was left standing and the verticality of pile was checked and adjusted by leveler. More care was given to make sure that the line joining the center lines of each pair of strain gauges coincides with the center line of embankment load. The schematic diagram of physical model is shown in figure 2.
3. Procedure of testing

The model pile was loaded to 200% of the working load, where the applied load is divided into eight equal increments. The working load of the model pile is calculated by dividing the predicted ultimate carrying capacity of pile by a factor of safety equal to 2. The procedure recommended by the American Standard (ASTM D1143) was followed during the loading tests. The pile head was located at 80 mm above the sand surface and 420 mm as embedded length. This method of load application had no restriction on the head of pile; hence, the piles are simulated as free head pile condition. The adopted failure criterion is that proposed by Terzaghi [13], where the failure load is defined as the load required to cause a settlement corresponding to 10% of the footing or pile width/diameter.

The following procedure is used to study the effect of construction an embankment nearby an axially loaded pile and pile without loading:

1) Preparing of soil bed by using raining technique.
2) Connecting the channels of strain gauges pairs on the model tested piles to the data logger.
3) Driving the first model pile (LP-loaded pile) at a distance larger than (10D) from the walls of steel container to avoid the effect of tip resistance [14], then the second model pile (UP-unloaded pile) was driven at distance larger than (15D) to eliminate any rigid boundary [15]. More attention was given to ensure that the line joining the center of the pair of strain gauges coincides with the center line of surcharged area, which was used to simulate the embankment.
4) Applying axial load on the model pile (LP) equal to the working load.
5) Installing two mechanical dial gauges for each model pile (LP and UP), which were placed horizontally to measure the horizontal displacement of model pile at two points along the upper part of model pile over the soil surface. One of them at the soil surface and the second at a distance from the soil surface.
6) Applying the surcharge load, which was used to simulate the embankment as shown in figure 2, with increments of (10, 20, 40, 40, 50 and 60 kPa) each increment maintained for 2 minutes, which is equal to 14.9 days in 100 g [16-18].

7) Recording the dial gauges readings and time of readings at the end of each loading increment. Also, the readings of strain gauges were saved at the data logger for each load increment.

4. Processing of data

The flexural stress ($\sigma_z$) is calculated from the measured bending strain ($\varepsilon_z$) by using Hooke’s Law (Equation 1), then discrete bending moment (M) is calculated from the flexural stress ($\sigma_z$) by applying the elastic flexure formula for a beam under bending (Equation 2).

$$\sigma_z = \frac{E_p}{\varepsilon_z}$$  \hspace{1cm} (1)

$$M(z) = \frac{2}{D} \sigma_z I_p = \frac{2}{D} E_p I_p \varepsilon_z$$ \hspace{1cm} (2)

Where

$\sigma_z$: is the flexural stress.

$E_p$: is the Young modulus of the pile.

$\varepsilon_z$: is the measured strain.

$M(z)$: is the bending moment.

$I_p$: is the moment of inertial of the pile.

$D$: is the outer diameter of the pile.

According to the beam theory, four parameters expressing the pile responses (displacement, rotation, shear force and soil reaction) are derived from bending moment. By differentiating the bending moment profile to the 1st and 2nd order, the shear force and the soil reaction can be obtained, respectively. The pile rotation can be obtained by integrating the bending moment profile to the 1st order. Subsequently, the pile rotation profile is integrated to obtain the pile deflection.

$$y(z) = \int \left( \int \frac{M(z)}{E_p I_p} dz \right) dz$$ \hspace{1cm} (3)

$$S(z) = \int \frac{M(z)}{I_p} dz$$ \hspace{1cm} (4)

$$T(z) = \frac{dM(z)}{dz}$$ \hspace{1cm} (5)

$$P(z) = \frac{d^2M(z)}{dz^2}$$ \hspace{1cm} (6)

Where

$z$: is the depth measured downward from the soil surface.

$M(z)$: is the bending moment as a function of depth.

$y(z)$: is the lateral displacement of pile.

$S(z)$: is the rotation of elastic curve defined by the axis of the pile in radian.

$T(z)$: is the shear force in the pile.

$P(z)$: is the soil reaction per unit length of pile.

In order to obtain the pile response, the bending moments were then subjected to extensive analysis and data processing. One approach involved fitting the profile to a best-fit polynomial curve, which ranged from the 4th to 7th order, to obtain a continuous distribution of the bending moment profile along the pile length [16, 19-21]. Numerical integration with the trapezoidal rule was used, in the current study,
to integrate the bending moment profile, and so to derive the pile rotation and the pile deflection profiles. Once the pile rotation profile was obtained, it was further integrated to derive the pile deflection. The integration constants, which consisted of the pile rotation ($S_E$) and the pile deflection ($y_E$), at the soil surface, were measured directly from the displacement measured by the dial gauges mounted at the pile head.

\[ S_i = \sum_{i=0}^{n} \frac{M_i + M_{i+1}}{2} \Delta z - S_0 \]  
\[ y_i = \sum_{i=0}^{n} \frac{S_i + S_{i+1}}{2} - \Delta z - n \Delta z S_0 + y_0 \]  

In order for the finite difference method to be applied easily to the pile, the strain gauges were spaced at equal lengths ($\Delta z$) as shown in figure (1). The strain measurement, in terms of bending moment, was measured at each point of the pile. The bending moment was plotted against depth ($z$) at the final increment of surcharge load. Consequently, the shear force ($T_i$) could be obtained by differentiating the bending moment ($M_i$). This differentiation was achieved by using the 1\textsuperscript{st} order finite differentiation.

\[ T_i = \frac{1}{2} \frac{M_i - M_{i+1}}{\Delta z} \]  

The soil reaction could be obtained by the 2\textsuperscript{nd} order finite differentiation, as noted by Levachev et al. [21], this method offered a more reliable value for soil reaction and exact results when compared to the usual finite difference method.

\[ P_i = \frac{1}{7} \frac{2M_{i-2} - M_{i-1} - 2M_{i-1} - 2M_{i} + M_{i+1} + 2M_{i+2}}{\Delta z^2} \]  

5. Results and discussion

The results obtained from the vertical loading tests and the tests of simulated embankment nearby axially loaded pile are presented and discussed in this section. Two parameters had been studied in this section: the axial load applied on top of model pile and the distance between the edge of the embankment and model pile. The load-settlement curve for model pile is shown in figure 3. The predicted ultimate carrying capacity of the pile is 60.7 N and the measured value of ultimate carrying capacity obtained from loading test is 50 N.

![Figure 3. Load-settlement curve of model pile.](image_url)
The effect of axial load application does not appear on the model piles because it acts as a relatively flexible pile according to the flexibility factor $K_R$, which is defined as follows [12]:

$$K_R = \frac{E_p l_p}{E_s L_e} < 10^{-5}$$  \hspace{1cm} (11)

Where:

- $E_p$: Young’s modulus of the pile.
- $I_p$: the moment of inertia of the pile section.
- $E_s$: the secant modulus of the soil elasticity.
- $L_e$: the embedded length of pile.

The results of model pile displacement at soil surface showed a decrease in the maximum displacement by (32–42) % and (24–40) % for LP and UP as shown in Figure 4, respectively. This range of decrease was noticed with an increase in the distance between the pile and the constructed embankment from 2.5D to 10D. The embankment applies vertical load on the surface of soil, which causes densification of soil under the embankment and soil moves away from the source of loading due to the weak structure of sandy soil used in this work. The movement of soil will apply pressure on the front side of the pile and the value of such pressure decreases with an increase in the distance between the embankment and the pile.

![Figure 4](image_url)

**Figure 4.** Displacement at soil surface of piles.

The rotations at soil surface of LP and UP at different distances between the embankment and the edge of pile are shown in Figure 5. The rotation at soil surface of LP was increased by (28–48) % with an increase in the distance between the embankment and the edge of the pile from 2.5D to 10D. This behavior is resulting from the application of axial load and relative flexibility due to the long-embedded length of pile. The rotation at soil surface of UP was decreased by 48% by increasing the distance from 5D to 10D because the pile was not restrained with axial load, while the rotation increased by 97% with an increase in the distance from 2.5D to 5D because the pile moved away from its original location.
The bending moment profiles of LP are shown in Figure 6. For 2.5D, the bending moment profile of the pile shows that 240 mm of the embedded length subjected to soil movement pressure, while the rest of embedded length, 180 mm, which is equal 43% of the total embedded length acts to resist the pressure of soil movement by soil reaction. The percentage of length that is subjected to soil reaction to the total embedded length increases with an increase in the distance is about 86% due to the reduction in soil movement, which is limited at shallow depth at distance 5D. At distance 10D, the percentage decreases to 71% due to the flexibility of the pile. The unloaded piles, showed the same behavior of loaded piles, but the percentages increased more than that of loaded piles because the piles are not restrained with the axial load application. The bending moment profiles with positive sign when the distance equal to 2.5D that means the pile bent by soil movement pressure, except UP where the maximum bending moment is negative because the pile is bent under soil reaction.
Figure 6. Bending moment profiles of piles.

The deflection profiles of axially loaded piles are shown in figure 7. The maximum deflection decreased by (21–298) % in LP and by (5–180) % in UP when the distance increased from 2.5 to 10D. The maximum deflection of LP was located at the pile head due to the application of axial load will restrain the tip when the embankment is at 2.5 and 5D, while at 10D the maximum deflection located at the pile tip because the pile is rotated at shallow depth. The pile was moved through the soil due to the high soil movement pressure at distance 2.5D, thus, the maximum deflection was located at UP head, but at 5 and 10D the maximum deflection located at the pile tip as presented in figure 7. Decrease in soil movement pressure causes less rotation in flexible pile as shown in figure 8. The trend of rotation profiles varied with an increase in the distance from 2.5 to 5D and from 5 to 10D, where the maximum rotation decreased by 17%, then increased by 69% in LP, while increased by 250% then decreased by 27% in UP due to the flexibility of piles.

Figure 7. Deflection profiles of piles.
Figure 8. Rotation profiles of piles.

The shear force depends on the reduction in the maximum bending moment with an increase in the distance between the model pile and the embankment because such reduction comes from a decrease in the resistance of soil behind the pile to soil movement that means the pile subjected to more soil movement pressure. As the bending moment increased in LP and UP with an increase in the distance from 2.5 to 5D, so the shear force does not affect. When the maximum bending moment decreased by 33 and 50%, the maximum shear force also decreased by 25 and 33% for LP and UP with an increase in the distance from 5 to 10D, respectively as shown in figure 9. From the soil reaction profiles, the maximum soil reaction with negative sign defined as soil movement, while the soil reaction with positive sign defined as soil resistance or reaction. The application of axial load increases the resistance of the flexible pile, which has long embedded length to provide more resistance to soil movement pressure as shown in figure 10. The soil reaction decreased with an increase in the distance between the edge of the pile and the embankment due to the reduction of soil movement pressure. The maximum soil reaction decreased by (20–38) % in LP and by (7–46) % in UP with an increase in the distance from 2.5D to 10D.

Figure 9. Shear force profiles of piles.
6. Conclusions

Based on the results obtained from the present study, the following conclusions can be drawn:

- The application of axial load decreases the displacement at the soil surface, where UP displaced more than LP by 1, 12, and 16% at distances 2.5, 5, and 10D, respectively.
- The bending moment of the pile did not get influenced by the application of axial loading on the pile due to the high soil movement, where the maximum bending moments of LP and UP at distances 2.5 and 5D is the same values, while at 10D, the maximum moment in LP is more than in UP by 33%.
- The maximum deflection of LP is more than that of UP by 1 and 110% when the embankment is at 2.5 and 10D, respectively. While the maximum deflection of UP is more than LP by 19% at 5D.
- The maximum rotation of LP is more than that of UP by (176–51) % and the maximum rotation of LG is more than that of UG by (208–209) % when the embankment is at 2.5 and 10D, respectively. While the maximum rotation of UP is more than LP by 53%.
- The maximum displacement at soil surface decreased by (32–42) % in LP and by (24–40) % in UP with an increase in the distance from 2.5 to 10D.
- The maximum shear force decreased in both loaded and unloaded pile(s) with an increase in the distance between the embankment and edge of pile(s).
- The soil reaction decreased with an increase in the distance between the edge of the piles and the embankment due to the reduction of soil movement pressure. The maximum soil reaction decreased by (20–38) % in LP and by (7–46) % in UP.
- The application of axial load increases the soil reaction in flexible pile, which have long embedded length to provide more resistance to soil movement pressure.

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