Dynamic response of pile group model in sandy soil to lateral excitation

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Abstract

This study offers an understanding of cyclic response of piled foundations in dry and saturated sand with different relative densities. The results of dry soil reveal the mechanism of dynamic response of piles and soil subjected to dynamic horizontal shaking including the variation and distribution of acceleration, bending moment along the pile, and vertical soil pressure with time in different states of soil; and the vertical and horizontal displacements, end-bearing load, peak acceleration and the peak velocity of foundation with time. A series of 94 laboratory tests were conducted to measure the response of pile foundation when subjected to dynamic loads. Eight tests were conducted on single pile in dry soil at relative density (R.D.) 30% (loose) and 50% (medium); 66 tests on group of piles with different spacings and patterns in dry soil at relative density 30% and 50% were conducted, too. All tests were carried out under operating frequencies 0.5, 1 and 2 Hz under horizontal shaking. Twenty tests for single piles and pile group with different patterns and spacings at relative density 30% were performed in saturated sandy soil under frequencies 0.5 and 1 Hz under horizontal shaking. All tests were achieved with one embedment ratio (L/d=30). These tests were grouped in three different numbers of piles; 2 piles in row and line patterns, 3 piles and 4 piles; and three pile spacing ratios (s/d=3, 4 and 5).

The main conclusion is that the manufactured vibrating box can simulate accurately the earthquake motion induced on foundations and, especially pile groups. The values of soil pressure decrease with increasing frequency and relative density. The soil pressure shows slight change with increasing frequency, while no clear changes appeared between pile groups with different pile spacings. The pile spacing is an important indicator that affects the acceleration and time-frequency characteristics of the displacement at pile top. With the increasing of S/D, the internal forces are slightly reduced.

Keywords
Pipe, earthquake, acceleration, pressure, sand.

1. Introduction:

The design and analysis of foundation system include the relationship of a broad variety of related disciplines and sciences such as seismology, geology, soil and rock dynamics, and applied mechanics. Therefore, the foundation engineers need to pay attention for the advances and technical developments in these fields, or to be well advised in these fields in order to achieve cost-efficient and safe designs.
For shallow and deep foundations, there is still much to do in the development of procedures to evaluate seismic bearing capacity of foundation, and earthquake-induced permanent displacements in such structures. Thus, to determine foundation seismic loading for practical applications, simple and uncomplicated procedures are required, which can be derived or developed from the accessible numerical modeling to reproduce perfectly the seismic response of manufactured prototypes (Romo., 2000).

Pile foundation response during earthquakes

There are several cases of damage and failure of piles during earthquake. Events have been noted by several researches (e.g., Mizuno, 1987; Meymand, 1998). The possible reasons causing pile foundation damage have been divided into six classes. Based on the pile damage characteristics and position, Ben (2013) classified the pile foundation failure cases into five models as follows:

1. Bending (or Shearing) failure of pile head
2. Bending failure at the soil layer interface
3. Pile cap failure
4. Excessive horizontal displacement
5. Excessive pile settlement or tensile pull-out

The seismic loading induces large displacements or strains in the soil. The shear modulus of the soil degrades and damping (material) increases with increasing strain. The stiffness of piles should be determined for these strain effects. The elastic solutions for determining response of piles subjected to dynamic loads have been presented by several investigators in the past in several modes of vibrations, (Novak, 1974; Novak and El-Sharnouby, 1983; Prakash and Sharma, 1991 and Fattah et al., 2016). The stiffness of the pile group is estimated from that of the single piles by using group interaction factors. The contribution of the pile cap, if any, is also included. The response of the single pile or pile groups may then be determined using principles of structural dynamics.

The present study is focused on dynamic response of piles to lateral shaking, soil liquefaction and soil-structure interaction in order to understand the mechanism of liquefaction, settlements and to predict the lateral dynamic responses of foundations in a liquefiable soil under earthquake loading (during shakings).

The main objectives of the present study are determination of the frequency independent dynamic response of both single pile and group of piles to lateral vibration for different patterns and spacings, calculation of a velocity and acceleration - time history in addition to displacement - time history of pile groups subjected to earthquake excitation, and investigating the effect of soil confinement due to pile spacing on the load transfer in pile groups.

Testing Apparatus

The testing device (the manufactured model) is a metal structure, which consists of three main interrelated parts. All these parts have the ability to slide (slip) one against the other by means of ball bearings, which can work together giving a relative horizontal motion between them as shown in Figure 1a. As it is not needed in the current study, so the two parts have been linked by a piece of metal connected by steel screws to fix these movable sliding parts.

In the second part (slide II), a metal holder (with dimensions 800 mm wide and 400 mm long) is mounted which is also being slided by ball bearings along the longitudinal axis with a distance more than 600 mm in the two directions (sides). But in this work, the distance was limited to only 50 and 60 mm.

This decentralized Cama rotates inside the bearing ball (needle bearing) which is linked by a 400 mm long connecting arm (or connecting rod) to the eccentricity installed by a pin as shown in figure 1.
As the test in this research requires obtaining the reciprocating motion at different speeds and frequencies, so an electric current controller (AC Inverter from Hyundai Company) for different rotational speed of the engine was chosen. The inverter is used to determine the type and speed of rotation. To get the required velocities in this research, the inverter has been linked to gear box (Configuration Gear Box through the shaft) to reduce the speed by around 3 folds.

![Figure 1](image1.png)

**Figure 1.** Slides and base bracket system during manufacturing of shake box.

**Steel box**

The other part of the manufactured device is the steel box, which is used for model tests. Its dimensions are (800 × 800) mm for its base and 1000 mm height, it is connected with the L- shaped steel plate by four screws M12 for installation and to prevent any movement as shown in Figure 2. A side slot 400 mm wide and 700 mm high of the steel box has been made to facilitate the process of discharging sand or soil. A steel angle has been installed at the top of the steel box to make a platform for the devices and sensors used in the test.

During tests using different velocities from slow (1 up to 14) Hz as shown in a controlled screen read out screen of inverter, the motion is slow without any strong vibrations. But, with increasing the rotational velocity, the motion is converted to be a linear speed accompanied with the appearance of a direction change problems after the cycle end for outgoing and return giving unacceptable vibrations due to the great moving mass, which generates a high momentum and high inertia:

\[
I = MV^2
\]  

(1)
where: \( M \) = moving mass; and
\[ V = \text{velocity}. \]

It is noted in the above equation that a little change of soil mass for a different model tests has a limited effect on (I) but the speed is of greatest value in increasing the value of (I), so when the velocity is increased, the linear mass starts to move quickly making it difficult to change the direction smoothly, therefore this problem has been solved by adding operating dampers to absorb the surging mass momentum at the end of the half, then give the initial speed in the opposite direction of the movement after the arrival of the CAMA to the tipping point as shown in figure 3.

It is worthy to mention that in order to make the damping value variable in correspondence to the change (increase or decrease) in the linear speed; the dampers have been connected with source of pneumatic pressure from the compressor tank added to the system. The compressor contains a regulator valve for air pressure to provide air to the dampers at different pressures according to the speeds that are selected in the tests as shown in figure 2.

**Figure 2.** Pneumatic dampers system.

### Raining technique

To obtain a homogeneous fill of sand with specific relative densities inside the steel box, sand raining technique device had been manufactured with dimensions (700×700×200) mm. The device is supplied with perforated cone holes distributed in an adequate way in correspondence to the speed of the sand falling, height of fall and the required relative density. This technique regulates the mechanism of sand fall, filling method, and the homogeneity of distribution.

### Data acquisition systems

The system of data acquisition was utilized so that all data could be scanned and recorded automatically, this system consists of the following:

1. Strain gauge data logger; 2. Pile's tip load data system; 3. LVDT data system; 4. Accelerometer data system; 5. Vibration data system

### Soil

In this work, poorly grained fine to medium dry sand taken from one of the sites middle of Baghdad city at a depth of 10 to 15 m was used to study the responses of piles subjected to dynamic actions. The soil properties are given in Table 1.

### Model piles
The model pile used has a diameter of 18 mm. The size of pile's model was chosen after reviewing the literature about the suitable pile size that could be considered representative. The ratio between the equivalent ground plane diameter of tank and the structural plane size of the test object (pile) was taken equal to 44. This equivalent diameter is large enough, so as the circumferential circle radius exceeds the extent far beyond the zone of primary compaction around the pile in sand; therefore, the effect of lateral boundaries of container is minor and could be ignored.

The pile's model used in the present study is made of smooth aluminum tube having outer diameter of 18 mm and inner diameter of 15 mm covered with plastic sleeve to protect strain gauges. Pile-embedment ratio (depth-to diameter) (L/d) used in testing single and group piles was (30). Four different arrangements of the pile groups (2×1, 1×2, triangle and 2×2) with different spacing ratios (S/d) (3, 4 and 5) are used for testing a group of piles. The mechanical properties of pile used are shown in Table 2.

### Table 1. Physical properties of sandy soil used for testing.

| Property                        | Value   | Standard of the test                             |
|---------------------------------|---------|--------------------------------------------------|
| **Grain size analysis**         |         |                                                  |
| Effective size, D$_{10}$ (mm)   | 0.14    | ASTM D 422 and ASTM D 2487                      |
| Mean size, D$_{50}$ (mm)        | 0.22    | ASTM D 422 and ASTM D 2487                      |
| Coefficient of uniformity, C$_u$| 1.70    | ASTM D 422 and ASTM D 2487                      |
| Coefficient of curvature, C$_c$ | 0.96    | ASTM D 422 and ASTM D 2487                      |
| Classification (USCS)*          | SP      | ASTM D 422 and ASTM D 2487                      |
| Specific gravity, Gs            | 2.69    | ASTM D 854 (2006)                               |
| **Dry unit weight**             |         |                                                  |
| Maximum, $\gamma_d$ (max.) kN/m$^3$ | 15.2   | ASTM D 4253 - (2000)                            |
| Minimum, $\gamma_d$ (min.) kN/m$^3$ | 13.2   | ASTM D 4254 - (2000)                            |
| Maximum void ratio, $e_{\text{max}}$ | 0.99   | -------------------------------------------------|
| Minimum void ratio, $e_{\text{min}}$ | 0.74   | -------------------------------------------------|
| Initial dry unit weight, $\gamma_d$ (test) | 13.74, 14.13 | -------------------------------------------------|
| **Saturated unit weight**       |         |                                                  |
| Initial $\gamma_{\text{sat}}$ (test) kN/m$^3$ | 18.14, 18.65 | -------------------------------------------------|
| Saturated water content, w$_w$ %| 32 %    | -------------------------------------------------|
| Initial relative density, R.D % | 30%, 50%| -------------------------------------------------|
| Initial void ratio, e (test)    | 0.922, 0.868 | -------------------------------------------------|
| Coefficient of permeability k ($cm/sec$ in loose state) | $2.45 \times 10^{-3}$ | ASTM D2434 - (2006) |

*USCS: Unified Soil Classification System.

**Table 2. Mechanical properties of aluminum pile used.**
Pile cap and payload
Two steel plates with dimensions of (100 × 100 × 10) mm and (150 × 150 × 10) mm were used to simulate the pile caps, Figure 3. The purpose of using steel plate rather than aluminum plate is to ensure the rigidity of the pile cap with respect to the piles. Also another steel plates were used as payloads on the pile foundation.

Models Preparation
To prepare the sand specimens, the container was fixed in its vertical position and sand was dry-rained (air-pluviation) into the container from specific heights to produce uniform beds of sand. The raining apparatus (perforated plate and diffuser) were suspended from an overhead crane girder that allowed continuous adjustment of its height to maintain a constant gap between the soil surface and the outlet. Preliminary experiments were conducted to determine the uniformity of the process and how sand density changes with raining from different heights. Results from raining the sand from different elevations over known volume molds placed on the model floor demonstrated that uniform sand density could be achieved across the width of the model. By adjusting the pluviation height, different sand densities were obtained. The trial results suggested that the distance between the rainer and top of the sand should be 550 mm and 850 mm in order to produce uniform loose sand of relative density 30-50%.

The selection of sensors of suitable size and stiffness, and the careful design of the emplacement procedure are important in obtaining reliable results of maximum reproducibility. To minimize the influence of buried instruments on the soil deformation, miniature earth pressure cells (EPCs) and miniature accelerometers were used. The active EPCs diameter to grain size ratio (D/d_{50}) is 12, which is twice the recommended minimum to ensure a continuum response between the soil and the EPC active face (Weiler and Kulhawy, 1982). Details of the instrumentation used in this work are shown in Figure 4. The EPCs were used to measure the total pressure on the soil at the target locations and for estimating the total stresses. Instrumentation records were acquired and recorded by multi data acquisition systems model.

| Embedded length (mm) | Outer diameter (mm) | Wall thickness (mm) | Bending stiffness, \( E_n \) (kN.mm²) |
|----------------------|---------------------|---------------------|-----------------------------|
| 540                  | 18                  | 1.5                 | \( 0.18 \times 10^6 \)    |

Figure 3. Steel plate used as pile cap and payloads.
To investigate the response of the soil to the application of dynamic shaking, earth pressure cells (EPCs) and accelerometers were embedded within the soil body in the locations and orientations. The instruments were concentrated in the area beneath the pile tip to a distance 50-80 mm beneath the pile tip and in the middle of pile length.

Results and Discussion

Detection the acceleration in soil bed

Two accelerometers (measuring 3-components; in X, Y and Z directions) were used to detect acceleration, one of them was inserted in the soil bed nearby the pile tip, while the other one was attached to the foundation surface to detect acceleration in the soil and foundation. The inspections were achieved for all cases of tests. Figures 5 to 7 present the responses of the single pile and group of piles with s/d=3 ratio, for different number of piles, operating frequencies and states of soil.

By examining acceleration time history in the soil bed in all these figures together, it can be seen that the acceleration amplitudes increase with frequency for both soil relative densities (loose and medium) and different pile patterns (number; single or group and different s/d ratios). For single pile, the acceleration values are increased slightly with relative density of the soil from 30% to 50%. In general, it can be stated that the acceleration values increase with relative density from loose to medium state.

For maximum acceleration recorded in the soil bed for loose and medium state, it can be seen that the rate of increasing of acceleration is between (1.5-6) % for single pile and for frequency between (0.5-2 Hz), and for group piles, it is between (1.7-8) % approximately. Mostly, the high values of acceleration are recorded with X-direction with low amplitudes for the other directions (Y and Z-directions), since the motion of the model was achieved in the x-direction only.
It is worth mentioning that the acceleration in the soil bed in the vertical direction is positive for the direction of the gravity. These results can be discussed based on the findings of Qu and Shi (2008) who concluded that, as to pile group, while the number of pile and its layout scheme are settled, S/D is an important indicator whose change has certain impact on the acceleration and time-frequency characteristics of the displacement at pile top. With the increasing of S/D, the internal forces are slightly reduced. Banerjee (2009) noted the soil around the piles does not just support the piles, they also exert inertial loading (caused by soil movement) on the piles. Pile head loading cannot replicate this effect.

**Figure 5.** Acceleration time history in soil bed of group pile (2x2), s/d= 3 in loose dry sand under different frequencies.
Figure 6. Acceleration time history in soil bed of pile group (2×2), in medium dry sand under different frequencies (a.0.5 Hz, b.1 Hz, c.2 Hz).
Figure 7. Acceleration time history in foundation of group pile (2×2), s/d= 3 in medium dry sand under different frequencies (a.0.5 Hz, b.1 Hz, c. 2 Hz).
Distribution of the vertical soil pressure with time

The stresses inside the soil medium before and after shaking were measured too. The earth pressures were recorded using vertical earth pressure cells placed at three levels; pile tip, pile mid and at the corner at level of pile mid.

Figures 8 to 10 present the variation of the net total soil pressure with time from the shaking start to the end of test for single pile and group of piles with s/d=3, different number of piles and operating frequencies measured for different states of soil (loose and medium states). It is important to mention that the net total soil pressure presents the excess pressure (pressure minus overburden pressure).

![Net earth pressure time history](image1)

**a:** $f = 0.5$ Hz

![Net earth pressure time history](image2)

**b:** $f = 1$ Hz

![Net earth pressure time history](image3)

**c:** $f = 2$ Hz

**Figure 8.** Soil pressure ($\Delta P$) time history of single pile in loose dry sand under different frequencies.
Figure 9. Soil pressure ($\Delta P$) time history of pile group (1×2) in loose dry sand under different frequencies.
By examining the figures, it can be stated that the soil pressure shows slight change with increasing frequency. In general, the values of soil pressure decrease with increasing frequency and relative density. While, no clear changes appeared between pile groups with different pile spacings. The maximum values of soil pressure were recorded at pile tip and pile mid than pile mid at corner, since the wave is coming from the model base. The confinement provided by the piles in the group inhabits the transfer of stress waves between piles.

Fattah et al. (2017) found that the axial strain along the pile becomes frequency-dependent, which means that it increases with increasing the operating frequency, and its oscillation increases, too. The amplitude of vibration at pile head also being frequency-dependent, it increases with increasing the operating frequency.
Conclusions:
The main conclusion is that the manufactured vibrating box can simulate accurately the earthquake motion induced on foundations, especially on pile groups. The major conclusions drawn from the test are summarized as follows:

1. For a soil bed in dry state, the acceleration amplitudes increase with frequency for both soil relative densities (loose and medium) and different pile patterns (number; single or group and different spacing ratios s/d). The maximum acceleration in the foundation is lower than in the soil bed for all operating shaking frequencies, pile spacing ratios and soil states. The decreasing of the maximum acceleration recorded in the foundation as compared to that in the soil bed is between 10-100 % for loose and medium state of soil, and the decrease in loose state is more than in medium state. This means that there is damping effect or attenuation of vibration waves.

2. In general, the values of soil pressure decrease with increasing frequency and relative density. The soil pressure shows slight change with increasing frequency, while no clear changes appeared between pile groups with different pile spacings. The maximum values of soil pressure were recorded at the pile tip and pile mid than pile mid at corner, since the wave is coming from the model base. The confinement provided by the piles in the group inhabits the transfer of stress waves between piles.

3. The increase in shaking frequency leads to reduce the oscillation of wave propagation values recorded due to densification of soil during shaking.

4. The pile spacing is an important indicator that affects the acceleration and time-frequency characteristics of the displacement at pile top. With the increasing of S/D, the internal forces are slightly reduced.

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