Experimental Studies and Finite Element Modeling of Piles and Pile Groups in Dry Sand under Harmonic Excitation

Saad Faik Abbas Al-Wakel
Lecturer
University of Technology-Baghdad
Saadfaik231@yahoo.com

Mahmoud Rasheed Mahmoud
Assistant professor
University of Technology-Baghdad

Ahmed Sameer Abdulrasool
Lecturer
University of Technology-Baghdad

ABSTRUCT

Foundations supporting reciprocating engines, radar towers, turbines, large electric motors, and generators, etc. are subject to vibrations caused by unbalanced machine forces as well as the static weight of the machine. If these vibrations are excessive, they may damage the machine or cause it not to function properly. In the case of block foundation, if changes in size and mass of the foundation do not lead to a satisfactory design, a pile foundation may be used.

In this study, the dynamic response of piles and pile Groups in dry sand is investigated experimentally. The analysis involves the displacement response under harmonic excitation. In addition, a numerical modeling by using finite element method with a three-dimensional formulation is adopted to simulate the experimental model. The results of the numerical model showed that a good agreement is achieved between the predicted dynamic response and that measured from the experimental model.

Key words: dynamic analysis, finite element method, pile foundations.

دراسات عملية ونمذجة العنصر المحدود للركائز ومجموعات الركيزة في الرمل الجاف تحت تأثير الأستثارة المتناسقة

سعد فايق عباس
مدرس
الجامعة التكنولوجية - بغداد

محمود رشيد محمود
أستاذ مساعد
الجامعة التكنولوجية - بغداد

أحمد سمير عبد الرسول
مدرس
الجامعة التكنولوجية - بغداد

الخلاصة

الأسس التي تسند المحركات الترددية، أبراج رادارِ، توربينات، محرّكات كهربائية كبيرة، ومولّدات، الخ تكون خاضعة للإهتزازاتِ التي تسببها قوى الماكنةِ غير المتوازنةِ بالإضافة إلى الوزنِ الساكنِ للماكنةِ. إذا كانت هذه الإهتزازاتِ مفرطة، قَدْ تسبب ضرر للماكنةَ أَو قد لا تشتغلَ بشكل صحيح. في حالة الأسس ذات الكتلة ، إذا كان التغيير في حجمِ وكتلةِ الأساسِ لا يُؤدّيانِ إلى تصميم مقنع , فأن أسس الركائز يمكن أنْ تُستَعملُ.في هذه الدراسةِ، الأستجابة الديناميكية للركيزة ولمجموعة ركائز في الرملِ الجافِ يُتحرّى عنها بشكل عملي. يَتضمّنُ التحليلُ رَدَّ الإزاحةَ تحت الأستثارة المتناسقة. بالإضافة الى ذلك, النمذجة العددية بإستعمال طريقةِ العنصرِ المحدودةِ مَع صياغة ثلاثية الأبعاد تم تبنيها لتمثيل النموذجِ العملي. تبين نَتائِجَ النموذجِ العدديِ بأنّ هنالك توافق جيد تم تحقيقه في النتائج بين الرَدِّ الديناميكيِ المُتَوَقّعِ وذلك الذي تم قياسه مِنْ النموذجِ العملي.

1. INTRODUCTION

In the recent years, there is a dramatic progress in the develop-merit of theories for dynamic analysis of piles. The rapid development of pile analysis is prompted by the growing use of pile foundations in traditional areas. As well as it's used as a deep foundation for building, it's used also as a machine foundations and their large scale application used in new application of civil engineering such as nuclear power plants and offshore towers. Many methods have been used to examine the foundation behavior under dynamic loadings; they are basically classified as experimental and theoretical approaches. The experimental approach includes models and field studies on existing foundations while the theoretical approach includes analytical and numerical solutions.

There are various types of dynamic tests of piles are conducted, they differ primarily according to the size of piles, test medium, technique employed, and aim as following **, Novak, 1987.**

(1) Full scale field tests

In these tests full scale piles are installed in natural deposit. Sometimes the piles are instrumented with strain gauges to monitor strains and thus axial forces or bending moments. Often the piles are loaded by a rigid concrete or steel test body. The purpose of this loading is to lower the pile resonant frequencies and to bring them within the frequency range of the exciter, if an exciter is used, and to lower the damping ratio which facilitates the analysis of the experimental data.

(2) Small prototype field tests

Field experiments with small prototype piles are less demanding than full scale experiments in terms of equipment, cost and effort, and make it easier to control the conditions of experiments while still allowing for unobstructed propagation of elastic waves.

(3) Small scale laboratory tests

Small scale laboratory tests are conducted with very small model piles in test bins or tanks. The small scale laboratory tests are popular because they are inexpensive, easy to organize, and independent of the weather. Their deficiencies are their inability to work with an undisturbed natural deposit (which limits the experiments to artificially prepared deposits of sand or remolded clay), the difficulty in achieving meaningful confining pressure on which soil stiffness depends and, finally, the limited size of the test box.

2. THE DYNAMIC RESPONSE OF PILE FOUNDATIONS

Das , 1983. presented a method to determine the natural frequency of vertical vibration of the pile using elastic waves in a bar method. The benefit derived from the use of piles depends on several factors such as the type of piles to be used, the length of piles, and the portion of load carried by each pile. The problem was treated as a vertical rod fixed at the base (i.e., at the rock layer) and free on top.

Novak , 1987. Studied the dynamic behavior of pile and pile groups experimentally. Three types of test are conducted: steady-state vibration tests using a mechanical oscillator, free vibration (plucking) tests, and static deflection tests. The excitation forces are produced by means of a Lazan mechanical oscillator. A typical set of vertical response curves measured with different intensities of harmonic excitation is considered. The experimental response curves are compared with theoretical predictions. The first observation made is that the vertical stiffness of the pile strongly depends on the tip condition unless the pile is quite long or the soil very stiff. Assuming an end bearing pile, where the floating tip condition is more proper, may result in a very substantial overestimation of stiffness and a significant underestimation of damping. A proper relaxation of the tip, depending on the stiffness of the stratum underlying the tip, is necessary. This observation is in good agreement with theoretical results.

El-Marsafawi et al. 1992. conducted a field experiments on group of piles supporting rigid foundations and subjected to harmonic loading. The objective is to investigate the ability of linear elastic theories of pile-group modeling to predict the response curve characteristics including the resonant frequency and amplitude. Harmonic vibration tests are conducted on the pile group in vertical and horizontal directions. In addition, a single pile is tested under harmonic loading in the vertical direction and in free vibration in the horizontal direction. The theoretical results are also verified using the more rigorous direct analysis approach. The comparison with the experiments shown that, the linear theory gives a good estimate of the group stiffness but overestimates damping of the group.

Boominathan and Lakshmi , 2000. studied the influence of pile-soil interaction on dynamic characteristics of pile groups. The vertical vibration tests are conducted in a carefully designed small scale pile test facilities at the laboratory. The analysis of the test results indicate that the group stiffness increases with increase of frequency up to limiting frequency and then decreases. The damping constants are substantially high at the low frequencies and decreases with the increase of the frequency. In addition, it is found that the stiffness is increasing and the damping is decreasing as the spacing between the piles decreases.

3. PROPERTIS OF MATERIALS USED IN THE EXPERIMENTAL MODEL

The materials used in this study are divided into two parts they are; dry sand and reinforced concrete for the pile foundation. The standard tests are performed to determine the physical properties of the sand as follows:

(1) Relative density: The test is carried out according to the (ASTM-D4253 and D4254) specification.

(2) Specific gravity: The standard test for the specific gravity of the soil particles is performed according to (ASTM-D854) specification using water the pycnometer method. The physical properties of the soil are shown in **Table 1**.

(3) Grain size analysis: The test is carried out according to the (ASTM-D422) specification; the grain size distribution of the soil is shown in **Fig. 1**.

(4) Direct shear test: The direct shear test is used to obtain the stress-strain relationship. In addition, the angle of internal friction (∅) of the sand with a unit weight of 15.0 kN/m^3 is obtained from the same test.. The mechanical properties of the soil obtained from the test are shown in **Table 2**.

The tests performed to determine the properties of the concrete and the reinforcement is:

(1) Compression test: The standard test of compressive strength according to (ASTM-C39M) specification is performed for three samples of cylinders.

(2) Tensile test: The Tensile test of the reinforcement is carried out according to the (ASTM-E8M) specification.

4. PRPARATION OF EXPERIMENTAL MODEL

The experimental tests are conducted on deep foundations under the effect of harmonic vertical mode of waves with two groups of piles. In addition, a deep foundation consists of single pile is tested. A steel mold is used to construct the frame of the deep foundation. The mold for the single pile consists of two parts linked together with screws. The molds of the experimental model with two and four piles consist of three parts linked together with screws. The reinforcement of the pile consists of four bars with 3.0 mm in diameter and the length of the bar is 545.0 mm. The spacing between the reinforcement of the pile center to center is 8.0 mm. The yield strength of the reinforcement (fy) is 290 MPa.

A circumferential wire is used as stirrups, and the spacing between stirrups is 136.0 mm center to center. The cap is reinforced in two directions where the number of bars in each direction is 9 bars. The length of each bar is 206.0 mm with diameter of 2.0 mm. The space between the reinforcement center to center is 24 mm and the cover of cap reinforcement is 7.5 mm. The yield strength of the reinforcement (fy) is 175.0 MPa. In addition, the end of each bar is twisted in the vertical direction with length of 15.0 mm, and the reinforcement of the pile and cap are linked together with a wire. The molds and the reinforcement of the experimental model are shown in **Plate 1**. Four screws are used to link the mechanical oscillator with the cap of the foundation to act as a one unit where the screws are fixed at the bottom of the cap. A steel base plate is used to ensure the spacing between the bolts to put a mechanical oscillator at a specific location, and then the plate is lifted up.

A concrete with mix of (1:1.5:3) is used to construct the model of the pile foundation, the gravel is passing through a sieve No.6 (3.35 mm). **Chowdhary** and **Dasgupta , 2009.** Recommended that the water-cement ratio shall be not exceeding 0.45 for a machine foundation. In this work, the water-cement ratio (w/c) was 0.4. An additive of Structuro 520 (Suporplasticisers) is added to the concrete mix with a ratio of 1 liter/m3. This additive allows producing a concrete with a high performance and workability. The concrete of the pile and cap is board continuously and integrally, and then the mold is placed on a vibration table for 45 second to ensure that no voids in the concrete and to have a smooth surface of concrete. After 24 hours, the concrete of the pile foundation is cured for a 28 days.

5. SET-UP OF THE EXPERIMENTAL MODEL

The group interaction factor which has been observed to have a significant effect on the dynamic response on the system especially for the pile spacing between 2.5D to 3D where D is the overall diameter of the pile. To ignore the effect of group interaction factor, the distance between the piles center to center is at least more than 5D **, Chowdhary** and **Dasgupta, 2009**. In this study, the distance between the piles center to center was 6D.

The model of the deep foundations consists of pile with a square cross-section of width 25.0 mm and length of 550.0 mm. The cap of the piles is made of a reinforced concrete of thickness 30.0 mm. The base of the cap is rising 50.0 mm above the soil surface to avoid the effect of pile raft condition. The layout of the deep foundation is shown in **Fig. 2**. A container of steel plate with dimensions of (600×600) mm and 700 mm height is used, so that the distance from the edges of the cap and tip of the piles to the boundary of the container is more than 5D of the pile which is satisfying a non-reflection wave. This behavior can be examined by the numerical model when the displacement response for this type of foundation returns to zero (i.e., no reflection of the wave at the boundary).

To prepare the soil of the experimental model, a sandy soil passing through sieve No.18 (1.0 mm) and retained on sieve No.100 (0.150 mm) is used. In the first stage, a soil of 130.0 mm thickness is placed in the steel container to prepare the bed of soil. Then, the pile foundation is placed in the container so that the base of the cap is resting on a steel plate with fixed ends as shown in Plate (2). After that, the container is filled with sand by five layers with thickness of 100 mm for each layer. The density of the soil used 15.0 kN/m^3 is specified previously. The required amount of the soil is weight, and then put in the container. The general procedure of ASTM-D4253 is adopted to obtain the dry unit weight of the soil. A surcharge load of 37.32 kg/m^2 is added on the surface of the soil to avoid vertical movement of surface particles. An external source of vibration with frequency of 3600 cycles/min is applied up to the soil is occupying a specific volume (cross-section area of the container with height of the layer) to give the required density of the soil. The time required to apply the vibration was found in the laboratory experimentally and depends on the thickness of layer which is 37 seconds for the bed layer and 30 seconds for each other layers. The steel plate which supports the foundation is removed during the test.

To create a small scale model of a dynamic system, a mechanical oscillator consists of an electrical motor having a maximum rated speed of 6500 rpm through a shift is used to introduce a harmonic vertical mode of sinusoidal wave. The mechanical oscillator consists of a rotating disc manufactured from steel with diameter 70.0 mm and thickness 5.0 mm. A single mass (m_e) is placed on the rotating disc at an eccentricity, e of (25.0) mm from the axis of rotation. This arrangement rotates in one direction when it is driven by a motor having a maximum rated speed of (6500) rpm through a shift, where such an arrangement induces a dynamic force at the base of the oscillator.

The speed of the motor and hence the mechanical oscillator can be varied which, in turn, causes a change in frequency of vibration. In addition, a mechanical assemblage is fixed on the disc of the mechanical oscillator and connected to a tachometer to measure the frequency of the dynamic system. The dynamic force induced is a frequency dependent for a given mass on the rotating disc. By varying the mass by means of an external control, it is possible to change the amplitude of dynamic force for a specific frequency. The amplitude of vertical dynamic force produced as in Eq. (1):

$$F_o = m_e \, e \, \omega^2 \tag{1}$$

where ω = circular frequency of the dynamic system,

The displacement response of the foundation can be measured by a vibration meter which converts the electrical signal to a displacement. The main objective of the apparatus is to apply a harmonic vertical mode of vibration on a pile foundation to determine the displacement response. The frequency of the dynamic force is controlled by a speed control unit which is connected to the mechanical oscillator. The displacement of the foundation is measured by the vibration meter. For all tests, the displacement response is measured at the edge and center of the cap. The amplitude of the applied dynamic force is ± 99.41 and ± 155.34 N and the circular frequency (ω) is 209.4 and 261.7 rad/sec, respectively. The displacement of the foundation is recorded when the steady state is occurred.

The results of the experimental model which are represent the frequency versus displacement of the pile foundation at the edge and center for different values of amplitude of dynamic force are shown in **Tables 3** and **4**. From results of the experimental model, it can be stated that the maximum amplitude of displacement of the deep foundations occurs at the center of the foundation. In addition, as the number of piles increases this will lead to a decrease in the displacement response of the pile foundation due to increase the mass of foundation.

6. THE NUMERICAL SIMULATION OF THE EXPERIMENTAL MODEL BY USING FINITE ELEMENT METHOD

The Finite element method is one of the most popular numerical methods used for obtaining an approximate solution for complex problems in various fields of engineering. In this study, a numerical modeling in prototype scale using a three-dimensional condition is adopted to simulate the physical model. In addition, the numerical simulation is performed by using the finite element method with Tcl command language which is implemented in OpenSees program.

The basic equations of the displacement field in three dimension for the elastic analysis of the finite element method can be written as in Eq. (2), **Zienkiewicz** and **Taylor, 2005**:

$$u = \sum_{i=1}^{n} N_i u_i \tag{2 a}$$

$$v = \sum_{i=1}^{n} N_i v_i \tag{2 b}$$

$$w = \sum_{i=1}^{n} N_i w_i \tag{2 c}$$

where: N_i = the shape function at a given node, u_i, v_i and w_i are the nodal displacement.

In matrix form Eq. (3):

$$\{u\}=[N]\{d_i\} \tag{3}$$

The strain vector can be derived as in Eq. (4)

$$\{\varepsilon\} = [B]\{d_i\} \tag{4}$$

where $[B]$ = nodal strain-displacement matrix.

Then stiffness matrix $[K]$ can be as in Eq. (5)

$$K = \int_v [B]^T D\, [B]\, dv \tag{5}$$

where D = elastic coefficient matrix.

The general equation of motion as in Eq. (6)

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\}=\{F\} \tag{6}$$

where $[M]$ = the mass matrix, $[C]$ = the damping matrix, $[K]$ = the stiffness matrix, $\{\ddot{u}\}$ = nodal acceleration vector, $\{\dot{u}\}$ = nodal velocity vector, $\{u\}$ = nodal displacement vector, and $\{F\}$ = applied load vector.

The considerations of similitude lead to model scale listed in **Table 5**, the linear dimensions are scaled 1 to it and the stresses are represented 1 to 1 **, Novak, 1987**. In this study, the scale factor (n) was 10. For the full scale model, the dimensions of the pile cap are (2.25× 2.25) m with thickness of 0.3 m. The length of pile is 5.5 m with a cross-section of (0.25× 0.25) m. A brick element of 8-node linear isoparametric is used for the finite element discretization. Each node of element has three degrees of freedom for displacements. To achieve a three-dimensional analysis, the boundary conditions are applied so that the bottom of the soil is fixed in displacement while the top surface of the soil is set to be free. To model the steel container, the constraint on displacement in X and Z directions is applied on nodes at the boundary in Y-Z and X-Y planes, respectively and the finite element mesh is shown in **Fig.3**.

The response of pile foundations is greatly affected by the behavior of soil, in which piles are embedded. Considerable research has been conducted for the analysis of pile groups, in most of the literature the behavior of the soil is assumed elastic , **Maheshwari** and **Watanabe, 2005**.The poisson's ratio of the fine-grained sand used in the numerical model is 0.25 **, Kaniraj, 2008**. According to the laboratory experiments the modulus of elasticity of the soil as shown in

Table 2.

The material properties of the concrete of foundation, as shown in **Table 6**, are calculated according to the ACI code (ACI-318-83), where the compression strength of the concrete, f_c is 44.24 MPa. The unit weight of the reinforced concrete is 24.0 kN/m^3.

The dynamic load is applied at the surface of the foundation for a specific node at the edge and center of the cap. The foundation is subjected to a steady state load of sinusoidal function of the form $F = F_o \sin(\omega t)$ with amplitude of force 9.941 and 15.534 kN and circular frequency of 20.94 and 26.17 rad/sec, respectively. To cure the artificial oscillation, the numerical damping is introduced into the analysis which is achieved by using $\gamma = 0.6$ and $\beta = 0.3025$ in the Newmark algorithm, **Jeremic, 2006**. The time step (Δt) of the dynamic analysis for circular frequency 20.94 and 26.17 rad/sec are 0.19882 and 0.31068 second, respectively with a total of 50 steps are performed.

The displacement responses of the deep foundation with a group of four piles obtained from the numerical model are shown in **Figs. 4** to **7** From these figures, it can be seen that the displacement reaches maximum amplitude and then rumbling is occurred after that it is return to zero. This behavior can be attributing to the decay of the wave with time, i.e., the reflection of the wave at the boundary is not occurred. The comparison between the displacement response of the foundation with group of four piles which is obtained from the experimental and the numerical model is shown in **Tables 7** and **8** By comparing these results it can be seen that, a good agreement is achieved.

7. CONCLUSIONS

(1) From the experimental model it can be stated that the maximum amplitude of displacement of pile foundations occurred at the center. In addition, for a specific frequency, the amplitude of displacement of the foundation increased with increasing the amplitude of dynamic force.

(2) The displacement response of the pile foundation under effect of dynamic force, decreases with the increasing in number of piles due to the increase in the mass of foundation

(3) The numerical modeling using the finite element method can be used to analyze pile foundations under effect of harmonic excitation.

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Table 1. Physical properties of the sand.

Parameters	Value	Units
Max dry unit weight, $\gamma_{dry\ max}$	16.7	kN/m^3
Min dry unit weight, $\gamma_{dry\ min}$	14.3	kN/m^3
Relative density (%)	32.5	_
Specific gravity, Gs	2.661	_

Table 2. Mechanical properties of the sand.

Parameters	Value	Units
Modulus of elasticity, E_s	40202	kN/m^2
Angle of internal friction, Ø	34^o	_

Table 3. Displacement of the pile foundation at the edge obtained from the experimental model .

Type of Model	Frequency (rad/sec)	Amplitude of Dynamic Force (N)	Amplitude of Displacement (mm)
Single Pile	261.7	155.34	0.635
Group of Two Piles	209.4	99.41	0.471
	261.7	155.34	0.581
Group of Four Piles	209.4	99.41	0.048
	261.7	155.34	0.053

Table 4. Displacement of the pile foundation at the center obtained from the experimental model **.**

Type of Model	Frequency (rad/sec)	Amplitude of Dynamic Force (N)	Amplitude of Displacement Edge (mm)
Single Pile	261.7	155.34	0.810
Group of Two Piles	209.4	99.41	0.502
	261.7	155.34	0.710
Group of Four Piles	209.4	99.41	0.051
	261.7	155.34	0.057

Table 5. Scales for centrifugal modeling (after Novak, 1987).

Quantity	Full scale	Centrifugal model
Linear dimension	1	1 / n
Time (in dynamic terms)	1	1 / n
Force	1	$1 / n^2$
Stress	1	1
Strain	1	1
Density	1	1
Frequency	1	n

Table 6. Material properties of the concrete**.**

Parameters	Value	Units
Poisson's ratio, υ	0.20	_
Modulus of elasticity, E	31261184	kN/m^2

Table 7. The displacement response of the pile foundation at the edge.

Frequency (rad/sec)	Scaled Frequency (rad/sec)	Experimental Amplitude of Dynamic Force (kN)	Numerical amplitude of Dynamic Force (kN)	Measured Displacement (mm)	Predicted Displacement (mm)
209.4	20.94	0.09941	9.941	0.0485	0.0543
261.7	26.17	0.15534	15.534	0.0535	0.0609

Table 8. The displacement response of the pile foundation at the center.

Frequency (rad/sec)	Scaled Frequency (rad/sec)	Experimental Amplitude of Dynamic Force (kN)	Numerical Amplitude of Dynamic Force (kN)	Measured Displacement (mm)	Predicted Displacement (mm)
209.4	20.94	0.09941	9.941	0.051	0.0547
261.7	26.17	0.15534	15.534	0.057	0.0628

Plate 1. The molds and reinforcement of the experimental model **.**

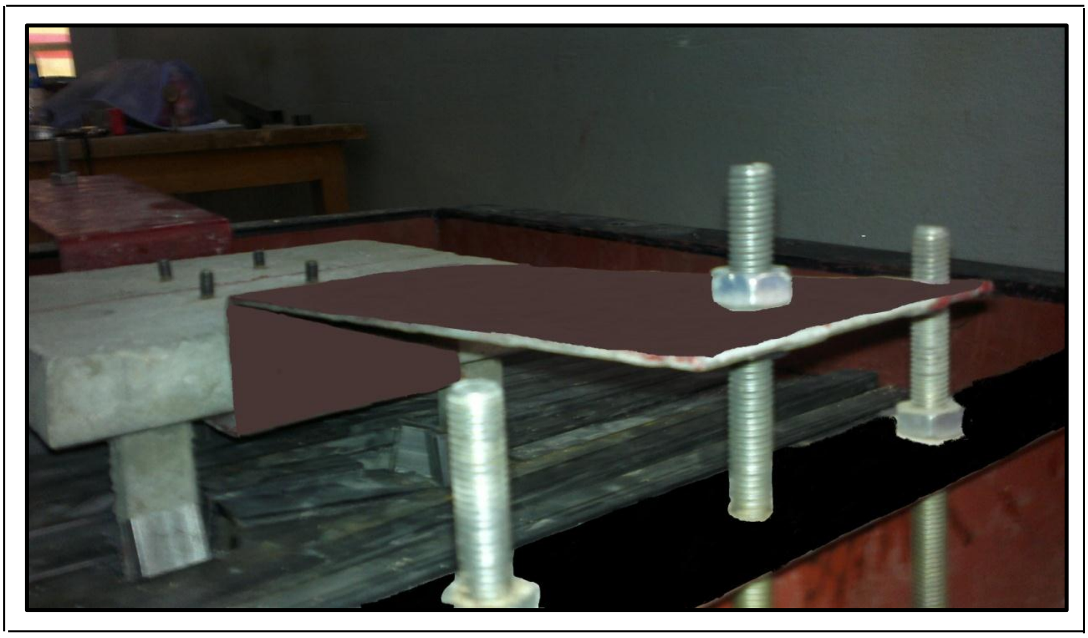

Plate 2. The pile foundation with the steel plate under the cap .

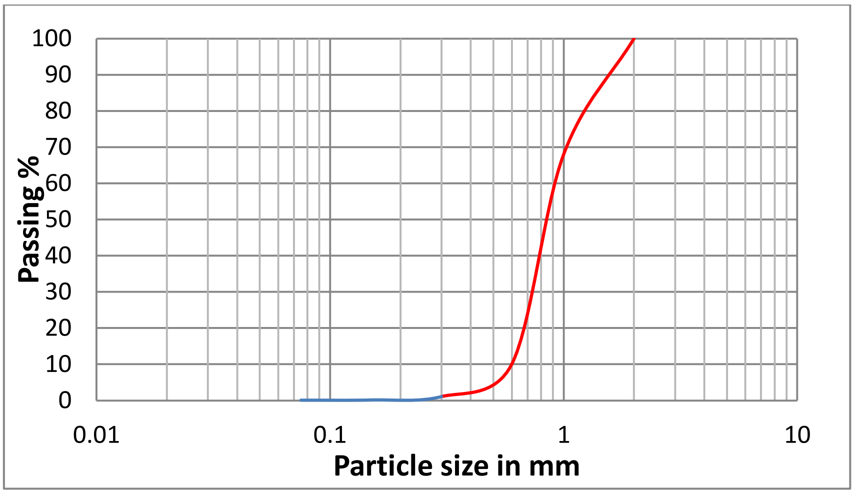

Figure 1. Particle-size distribution curve from the grain size analysis test of sand.

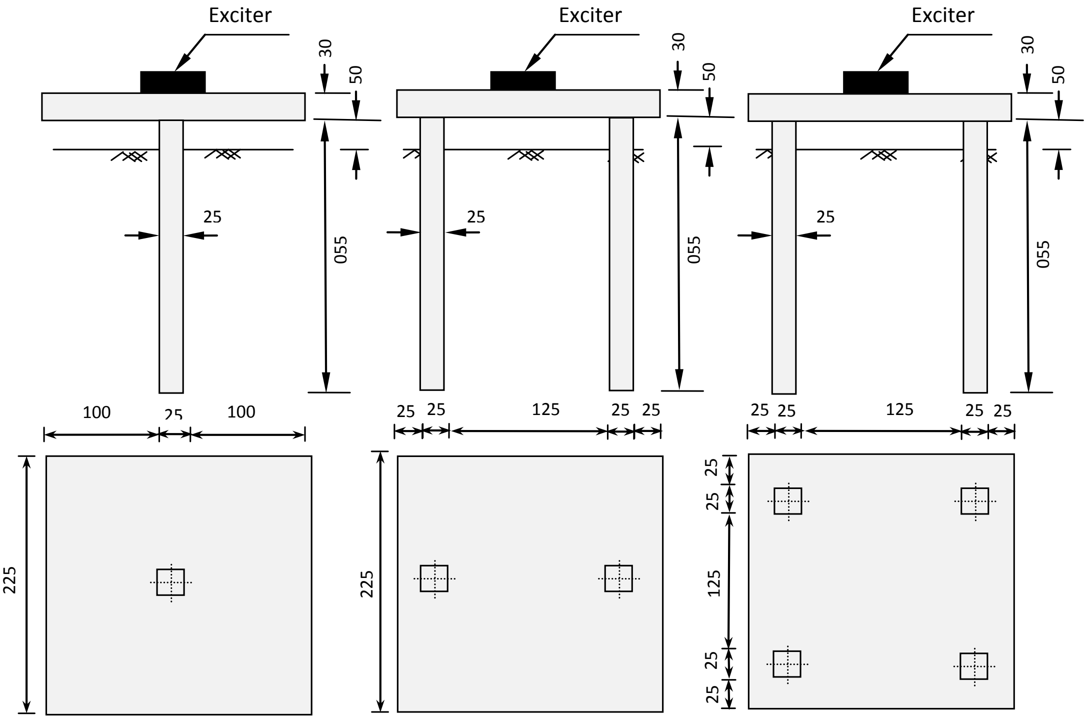

Figure 2. The layout of the deep foundation (All dimensions in mm).

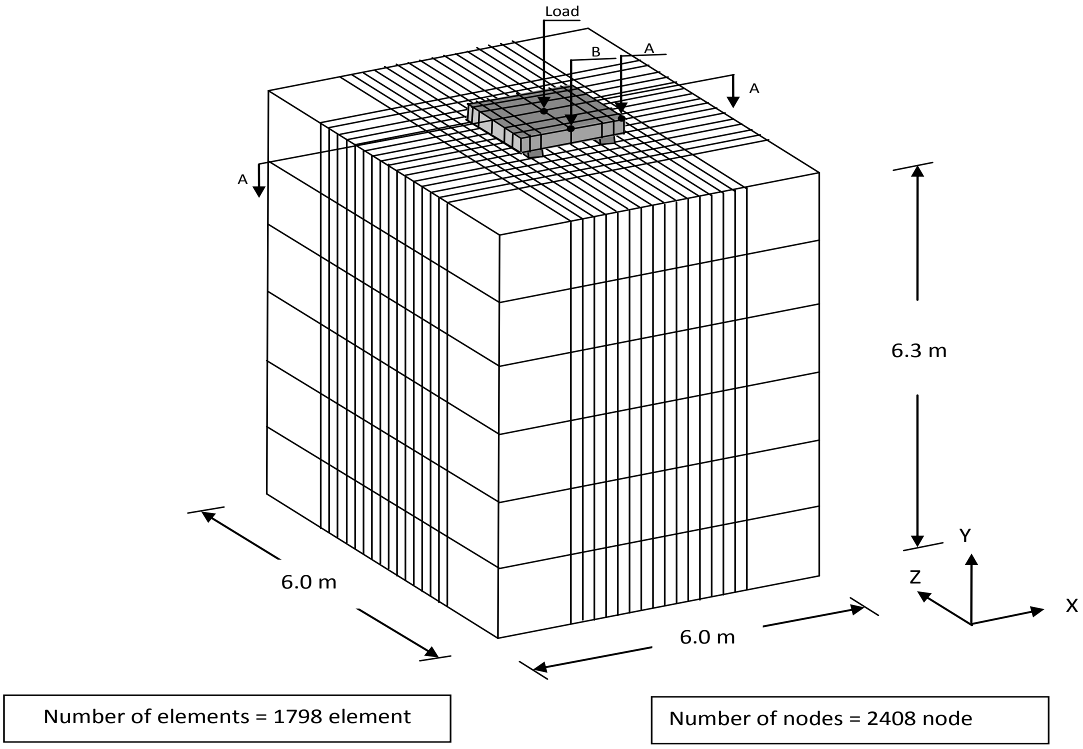

Figure 3. Three-dimensional finite element model.

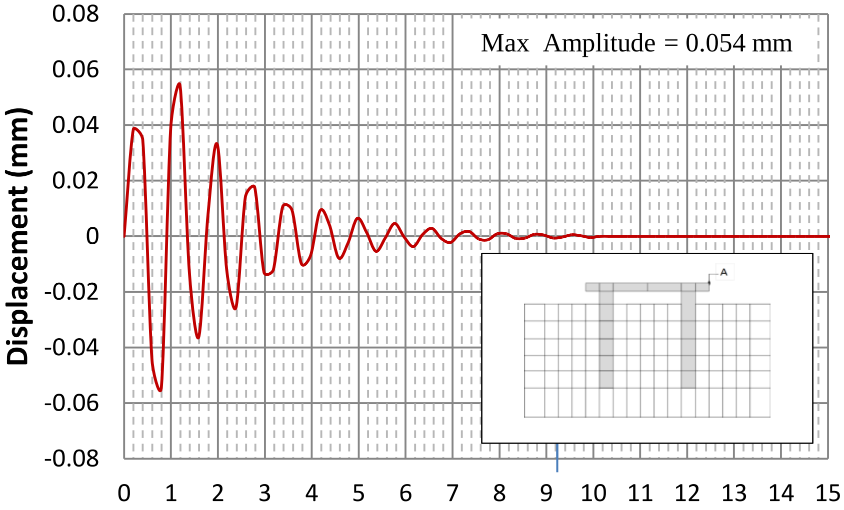

Figure 4. Displacement of foundation with group of four piles at the edge (Point A) of the numerical model (scaled frequency = 20.94 rad/sec).

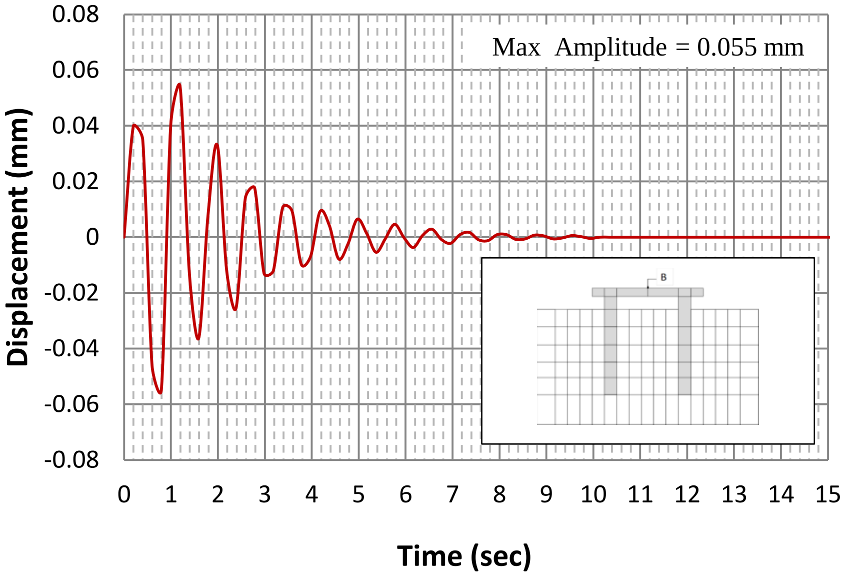

Figure 5. Displacement of foundation with group of four piles at the center (Point B) of the numerical model (scaled frequency = 20.94 rad/sec).

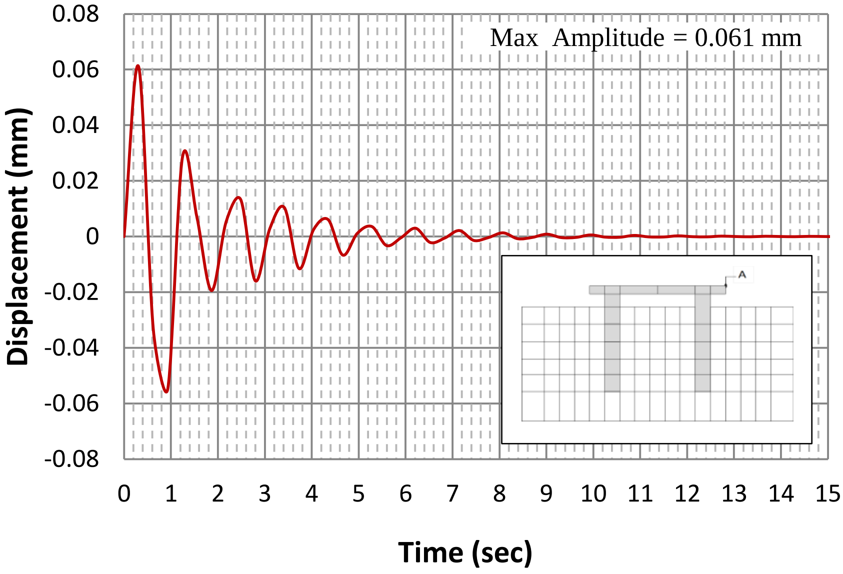

Figure 6. Displacement of foundation with group of four piles at the edge (Point A) of the numerical model (scaled frequency = 26.17 rad/sec).

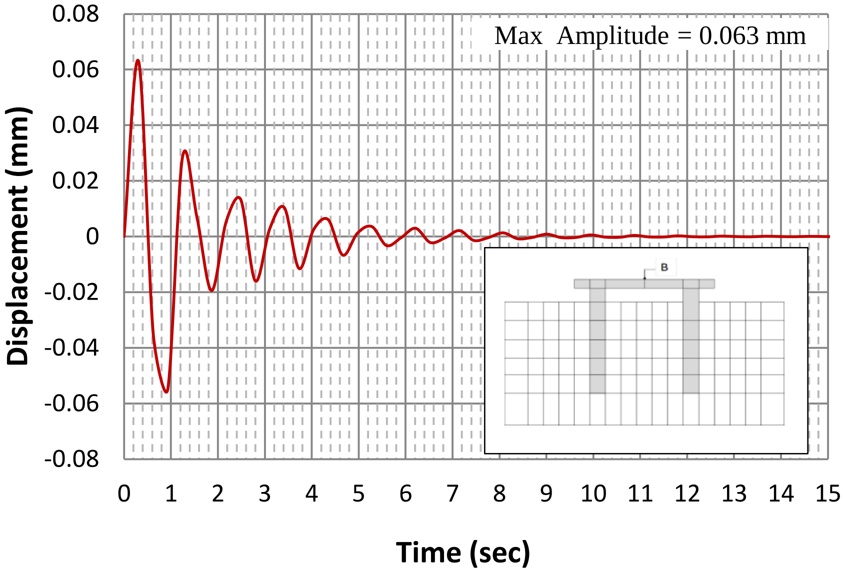

Figure 7. Displacement of foundation with group of four piles at the center (Point B) of the numerical model (scaled frequency = 26.17 rad/sec).