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Three-Dimensional Analysis for the Effect of Piles Geometry and Arrangement on the Dynamic Response of Piled Raft Foundation

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Abstract: In the present study, three-dimensional analysis is presented to investigate the effect of pile dimensions and configuration on the dynamic response of piled raft foundation subjected to vertical vibration. The analysis considered several factors effecting on the maximum amplitude of vertical displacement of deep foundation such as length, diameter, number of piles and spacing between piles. Furthermore, a validation for an experimental piled raft models depending on a scale factor of (20) using (Plaxis 3D) computer software is presented. The sand is simulated using (mohr-coloumb) model, while the concrete is simulated as linear elastic material. It has been found that the increasing length and diameter of piles lead to decrease the maximum amplitude of displacement. On the other hand, the results showed that the increasing number of piles and increasing the spacing between piles can minimize the dynamic response of the foundation.

Keywords: *Amplitude of Displacement, Dynamic Response, Piled Raft, Pile Configration.*

تحليل ثلاثي الأبعاد لتأثير خواص الركائز على الإستجابة الحركية لأساس حصيري مدعم بالركائز مطمور في الرمل

الخلاصة: في هذه الدراسة، يتم إستعراض تحليل ثلاثي الأبعاد لدراسة تاثير أبعاد وترتيب الركائز على الإستجابة الحركية لاساس حصيري مدعم بالركائز معرض لإهتزاز عمودي. التحليل يتضمن عدة عوامل تأثر على السعة القصوى للإزاحة العمودية للأساس العميق مثل طول الركائز، قطر الركائز ، عدد الركائز و المسافة بين الركائز. علاوة على ذلك يتم أستعراض تحقق لنماذج عملية لأسس حصيرية مدعمة بالركائز إعتمادا على معامل قياس مقداره (20) بإستخدام البرنامج الحاسوبي (Plaxis 3D). الرمل تمت محاكاتة كنموذج (Mohr-Coloumb) بينما الخرسانة تمت محاكاتها كنموذج (Linear Elastic). وجد إن زيادة طول وقطر الركائز يؤدي إلى نقصان السعة القصوى للإزاحة. من ناحية أخرى، النتائج بينت إن زيادة عدد الركائز وزيادة المسافة بين الركائز في الأساس من الممكن أن تقلل الإستجابة الحركية للأساس.

1. Introduction

Finite Element Method (FEM) is the most commonly accepted analysis tool for solution of engineering problems. Effective pre and post processing capabilities make modeling and interpretation of results simple. It is relatively easy to incorporate changes if any repetition of the analysis is required without much loss of time. Viewing of

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animated modes, shapes and dynamic response makes understanding of the dynamic behavior of the machine foundation system, relatively simpler.

There are many issues that need careful examination before using finite element computer software such as modeling capabilities, analysis capabilities and processing but the most important one is the validation of results, which is necessary before accepting the results of numerical analysis [1].

Manna and Baidya, [2] studied the influence of nonlinearity on the dynamic response of cast-in-situ reinforced concrete piles subjected to strong vertical excitation. Forced vibration test of single piles (L/D = 10, 15 and 20) and group piles of (2×2) (S/D = 2, 3 and 4 for each L/D ratio) were conducted in the field for two different embedded conditions of pile cap. From the measured nonlinear response curves, the effective pile-soil system mass, stiffness and damping were determined and the nonlinear response curves were back-calculated using the theory of nonlinear vibration. The test results were compared with the continuum approach of Novak with dynamic interaction factor approach using both linear and linear-equivalent numerical methods. Reasonable match between the measured and predicted response was found for linear-equivalent methods by introducing a weak boundary-zone around the pile to approximately account for the nonlinear behavior of pile-soil system. The test data were used to establish the empirical relationship in order to estimate the extent of soil separation around the pile with soil under vertical vibration.

Padron et al., [9] studied the accuracy and effectiveness of the superposition method to assess the coefficients of the dynamic stiffness and damping of embedded footings supported by vertical piles set in uniform visco-elastic soil. Comparison between these coefficients of piled embedded footings and those obtained by superposing the separate coefficients of the corresponding pile groups and embedded footings reveals that the average of the relative differences is about (10–30%). The results were presented in a set of normalized charts and simple expressions, which can be used to estimate the dynamic stiffness and damping of piled embedded footings, on a condition that the coefficients of the two separate components were known. Since such impedance functions for both embedded footings and pile groups were available for a wide range of cases, the superposition approach studied here was attractive.

Abdulrasool, [3] studied the dynamic analysis of deep foundations on uniform dry sand experimentally and numerically by the finite element method. The numerical analysis involves the displacement response under the effect of dynamic loads of harmonic vertical mode of vibration. The aim of the study is to analyze the dynamic response of machine foundations, in addition to simulate the machine on deep foundation numerically by using the finite element method. It was concluded that when the piles length and the number of piles increases will lead to decrease in the displacement response of the pile foundation because of the increase in the mass of foundation. It was found that the dynamic response of the deep foundation is influenced by the spacing between piles also.

2. Numerical Analysis

2.1. Computer Software

Computer packages based on finite element method is widely used to simulate geotechnical engineering complex problems. In this study, (Plaxis 3D) has been used to simulate the piled raft foundation with four piles in order to study the effect of various factors on the dynamic response of the foundation.

(PLAXIS 3D) is a finite element package that has been developed specifically for the analysis of deformation and stability in geotechnical engineering. The simple graphical input procedures enable a quick generation of complex finite element models, and the enhanced output facilities provide a detailed presentation of computational results. The calculation itself is fully automated and based on complex numerical procedures [4].

2.2. Three-Dimensional Dynamic Analysis of Piled Raft Foundation

In this analysis, the effect of vibrating machine on the dynamic response of the deep foundation is investigated. The piled raft foundation with four piles has been simulated in three dimensional modeling. Furthermore, the experimental model of Abdulwahhab [10] is transformed to a prototype model depending on a scale factor (n) of (20), which is recommended to use a scale factor greater than (10) to eliminate the overestimated results [5]. "Table 1" illustrates the scales of centrifugal modeling which is adopted in this analysis.

Table 1. Scales for Experimental modeling [6]

Quantity	Full Scale	Experimental Model
Linear dimension	1	1/n
Area	1	$1/n^2$
Volume	1	$1/n^3$
Time	1	1/n
Mass	1	$1/n^3$
Force	1	$1/n^2$
Density	1	1
Frequency	1	n

2.2.1 Soil Geometry and Properties

The scaled dimension of the soil are (15 × 15) m and the depth of the soil is (11) m is specified by single borehole at the first corner of the model. The boreholes are locations in the model at which the information on the soil profile. If multiple boreholes are specified, the program automatically interpolates between the boreholes [6]. "Fig. 1" shows the soil model.

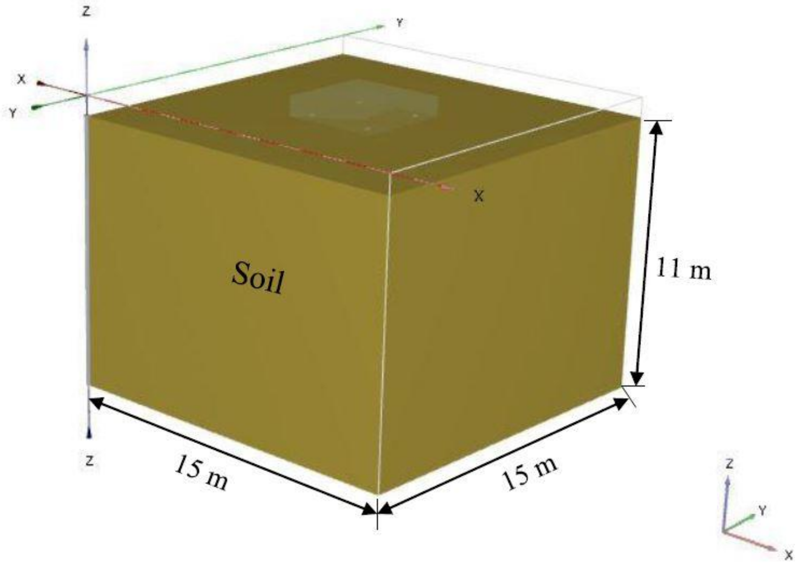

Figure 1. Soil model

In order to simulate the soil behavior, an appropriate material model and parameters must be assigned to the geometry. In (Plaxis 3D) soil properties are entered in material data sets. The (Mohr-Coloumb) model is chosen for the soil. The material properties of the soil which are taken from the experimental model are listed in "Table 2".

Table 2. Soil material properties

Parameter	Value	Unit
Material model	Mohr- Coulomb	-
Drainage type	Drained	-
Dry unit weight	16.87	kN/m^3
Voids ratio	0.535	-
Young's modulus	30×10^{3}	kN/m^2
Poisson's ratio	0.28	-
Cohesion	0.3	kN/m^2
Friction angle	37.5	^{0}
Lateral earth pressure coefficient (K_0)	0.4*	-

*(The coefficient K_0 is obtained automatically using the following equation $K_o=1-\sin\varphi$)

2.2.2 Definition of the Structural Elements

The deep foundation consists of two parts; the first is the pile cap which is simulated as volume with the dimensions of (4 × 4) m and a thickness of (0.8) m. The volume is created by extruding a created surface which has the pile cap of the same dimensions using the extrude tool. The soil material data sets can be assigned to volumes. The data set of the concrete listed in "Table 3" is assigned to the pile cap volume.

Table 3. Concrete material properties

Parameter	Value	Unit
Material model	Linear Elastic	-
Drainage type	Non-Porous	-
Dry unit weight	24	kN/m^3
Young's modulus	27.6×10^{6}	kN/m^2
Poisson's ratio	0.1	-

The second part of the deep foundation is the four piles which have the same dimensions of (0.42) m diameter and (8) m length. Each pile is simulated as embedded pile, and the skin resistance is simulated as linear. The input is defined by the skin resistance at the pile top ($T_{top\ max}$) and at the pile bottom ($T_{bot\ max}$). This way of defining the pile skin resistance is mainly applicable to piles in a homogeneous soil [6]. The tip bearing is defined by (F_{max}). The total pile bearing capacity (N_{pile}) is given by:

$$N_{pile} = F_{max} + 0.5\ L\ (T_{top\ max} + T_{bot\ max}) \qquad (1)$$

where: *L* is the pile length.

The piles properties are shown in "Table 4".

Table 4. The Piles properties

Parameter	Value	Unit
Young's modulus	27.6×10^{6}	kN/m^2
Unite weight	24	kN/m^3
Predefined pile type	Massive Circular	-
Diameter	0.42	m
Skin resistance type	Linear	
$T_{top\ max}$	0	kN/m
$T_{bot\ max}$	94.6	kN/m
F_{max}	1589	kN

The type of the connection of the top of the pile is selected as a rigid, which makes the rotation and displacement are both coupled with the rotation and displacement of the structural or soil element. On the other hand, the type of the connection at the bottom of the pile is selected as free which allows the connection point to rotate and moving relatively to the soil.

The pile interaction with the surrounding soil is simulating by special interface elements. "Fig. 2" shows the simulated piled raft foundation with four piles.

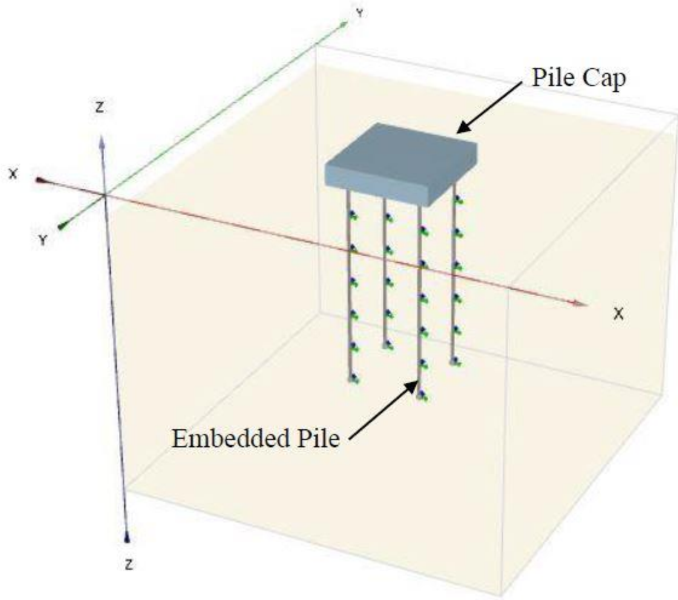

Figure 2. The simulated piled raft foundation with four piles

2.2.3. Definition of the static and dynamic loads

In this part, the static load which represents the weight of machine and the dynamic load which represents the vertical excitation due to the rotating mass are defined. First of all, the surface representing the base of the machine is created on the top of the pile cap volume with dimensions of (2 × 2) m, subsequently the static and the dynamic loads are created on the cap as shown in "Fig. 3".

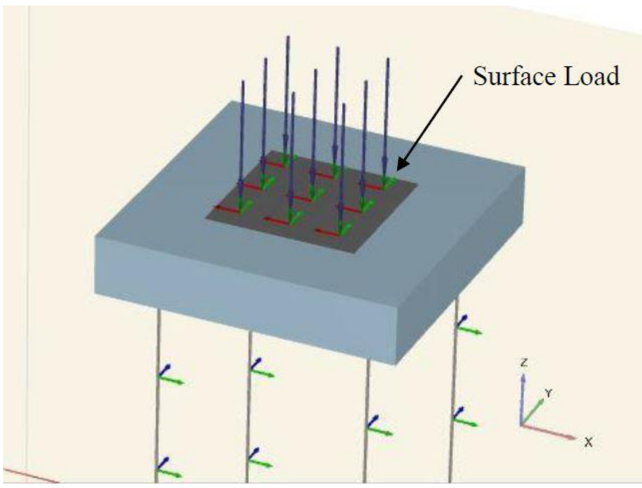

Figure 3. The surface of machine base

The static load is representing the scaled weight of the machine, which is defined as surface load on the base of the machine, whereas the dynamic load is calculated due to The scaled parameters which is defined using a harmonic load multiplayer as shown in "Fig. 4".

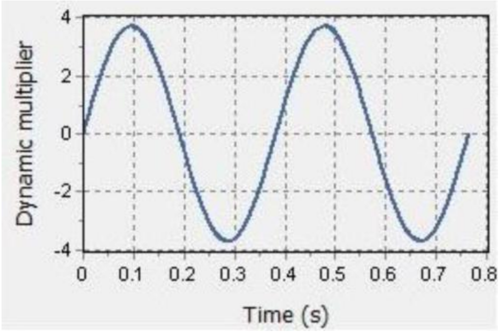

Figure 4. The harmonic load.

2.2.4. Mesh Generation

The soil volume is modelled using (10 node) tetrahedral elements which are created in an automatic mesh generation procedure. The geometry is divided into volume elements and structure elements if excited. The mesh generation takes in account the position of the volumes in the geometry model [7]. Furthermore, the exact position of loads and structures is taken in consideration in the finite element meshing. A local refinement is considered in the pile cap volume. The created mesh consists of (2871 node). Special boundary conditions called viscous boundaries have been defined to account the reflected waves from the model boundaries. The finite element discretization of the piled raft model is shown in "Fig. 5".

2.2.4. Performing Calculations

The calculations consist of multiple phases defined due to sequence of structures construction and loading in the staged construction mode. This case includes initial phase, static loading phase and dynamic loading phase.

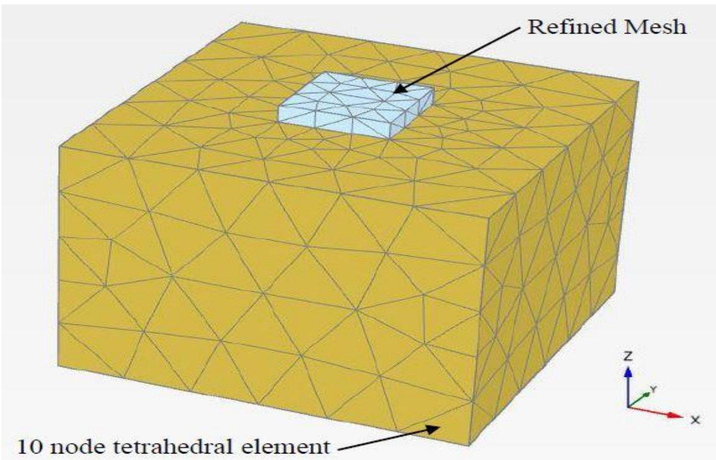

Figure 5. The finite element discretization of the piled raft model.

The Initial phase represents the initial conditions of the soil, which include the initial geometry configuration and the initial stress state. The soil and the pile cap volumes in addition to the embedded piles are activated in this phase to simulate the initial condition of the model. K_o procedure is selected as calculation type for this phase. The static and dynamic loads are deactivated during this calculation phase. The static load which represents the weight of the machine is activated in the static loading phase and K_o procedure is also selected as calculation type.

The dynamic load is activated in the next phase and the calculation type is defined as dynamic with a time interval of (5 seconds) consists of (256 step) of calculations. Special boundary conditions have been defined to account the reflected waves from the model boundaries.

After the creation of the phases, the node at the center edge of the pile cap is selected to be considered in the curves of the results then the calculation process is executed.

3. Results and Discussion

3.1. Validation of the Experimental Model

The piled raft model and embedded piled raft model with four piles configuration at the frequency of (52.3 Hz) have been simulated in three dimensional finite element modeling using (Plaxis 3D) software in order to validate the experimental model using a scale factor of (20). Novak, (1987) recommended to use a scale factor greater than (10) to eliminate the overestimated results. The maximum amplitude of dynamic force ($F_{dy.max.}$) equals to (14.8 kN).

The Predicted displacement with time of the piled raft model and embedded piled raft model are shown in "Fig. 6" and "Fig. 7", respectively. A good agreement has been achieved between the predicted and the measured results from Abdulwahhab, 2017 [10] as shown in "Table 5". This is means that the numerical modeling which is adopted in this study to simulate the machine foundations on dry soil is satisfied.

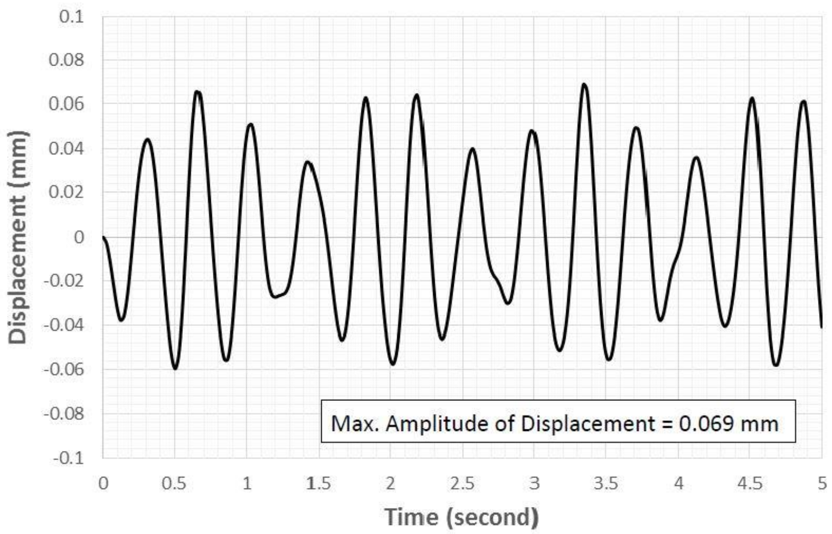

Figure 6. Predicted vertical displacement with time for the piled raft model with four piles configuration.

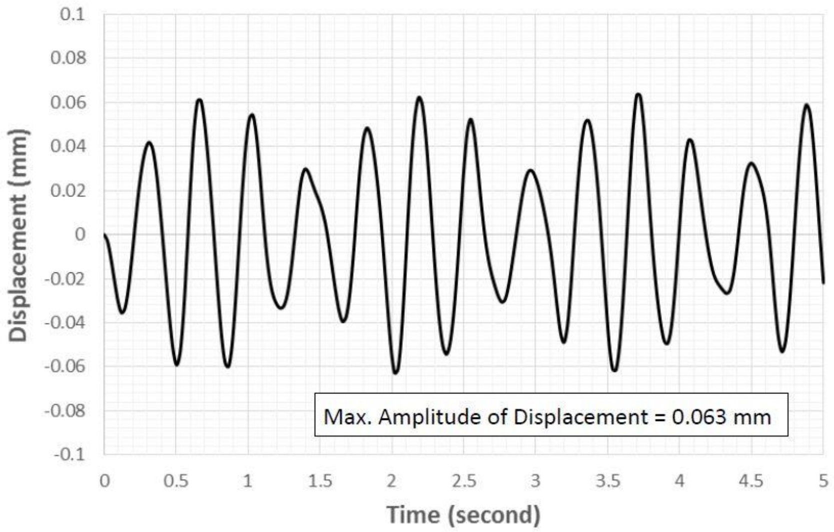

Figure 7. Predicted vertical displacement with time for the embedded piled raft model with four piles configuration.

Table 5. The measured and predicted amplitude of displacement of the piled raft foundation.

Type of Foundation	Measured Amplitude (mm)	Predicted Amplitude (mm)
Piled Raft	0.07	0.069
Embedded Piled Raft	0.061	0.063

3.2. Effect of Pile Length on the Dynamic Response

Three different lengths of pile models are considered (4m, 6m and 8m) to investigate the effect of the pile length on the dynamic responses of the foundation. During this analysis the skin friction and the end bearing were recalculated due to the change in the piles length. The other parameters are kept constant. The results of the dynamic response of the piled raft model for different pile lengths are shown in "Fig. 8", while "Table 6" shows the maximum amplitude of the vertical displacement and the percentage of reduction due to increasing the pile length with respect to using (4m) piles length.

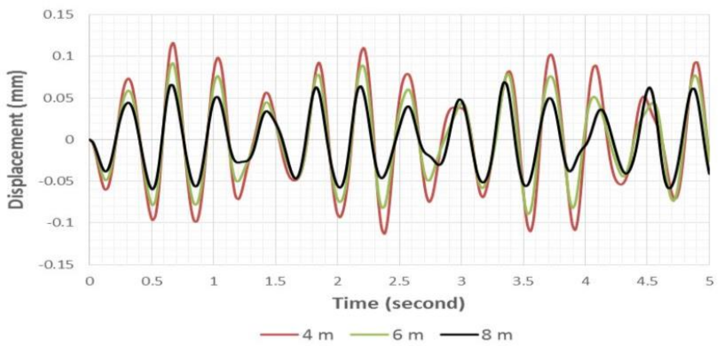

Figure 8. Effect of the pile length on the dynamic response.

Table 6. Percentage of reduction in the dynamic response due to increasing the piles length.

Piles Length (mm)	Increase in the Pile Length (%)	Max. Amplitude of Displacement (mm)	Percentage of Reduction (%)
4	-	0.116	-
6	50	0.092	21
8	100	0.069	41

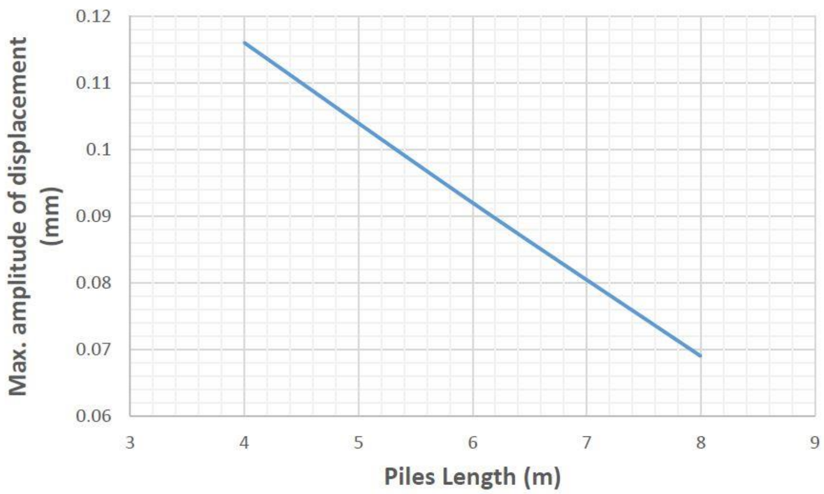

Figure 9. Reduction in the maximum amplitude of displacement due to increasing the piles length.

From the results, it can be observed that the maximum amplitude of vertical displacement is decreased linearly by increasing the piles length as shown in "Fig. 9". This reduction occurred due to the mass excess of the system from the increased piles length which led to increase the damping of the system.

3.3. Effect of Pile Diameter on the Dynamic Response

Three pile diameters are considered in this study (0.3m, 0.42m and 0.54m) to investigate the effect of increasing the piles diameter on the maximum amplitude of displacement due to dynamic loading. The skin friction and the end bearing are recalculated due to the change in the pile diameter. The piles length is (8m) for all models and the other parameters are kept constant. "Fig. 10" shows the dynamic response of the deep foundation with three different pile diameters. The maximum amplitude of displacement and the percentage of reduction due to increasing the piles diameter are illustrated in "Table 7".

The results showed that increasing the piles diameter decreases the maximum amplitude of displacement due to the increase in the weight of the system as a result to the enlargement of the piles cross sectional area. As the piles diameter decreases, the reduction in the maximum amplitude of displacement decreases as shown in "Fig. 11".

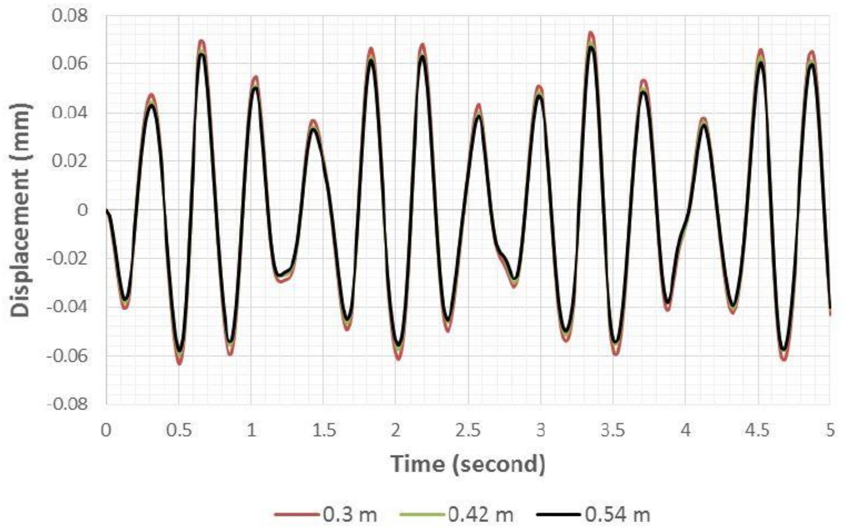

Figure 10. Effect of the piles diameter on the dynamic response.

Table 7. Percentage of reduction in the dynamic response due to increasing the piles diameter.

Piles Diameter (mm)	Increase in the Pile Diameter (%)	Max. Amplitude of Displacement (mm)	Percentage of Reduction (%)
0.3	-	0.073	-
0.42	40	0.069	5.5
0.54	80	0.067	8.2

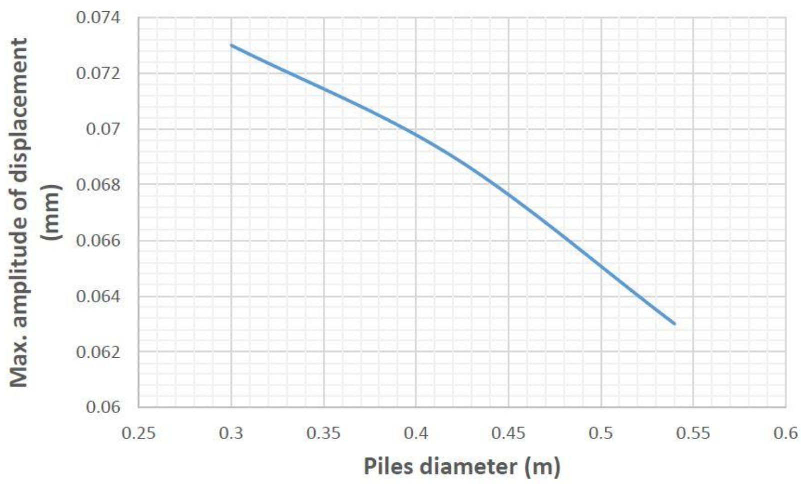

Figure 11. Reduction in the maximum amplitude of displacement due to increasing piles diameter.

3.4. Effect of Number of Piles on the Dynamic Response

To study the effect of number of piles in the foundation on the dynamic response, three models have been analyzed numerically with different pile number (Single pile, 4 piles and 9 piles). The length and diameter of the piles, pile cap dimensions and the material properties are kept constant for all models. "Fig. 12" shows the dynamic response for the three models. The maximum amplitude of the vertical displacement and the percentage of reduction due to increasing number of piles are shown in "Table 8".

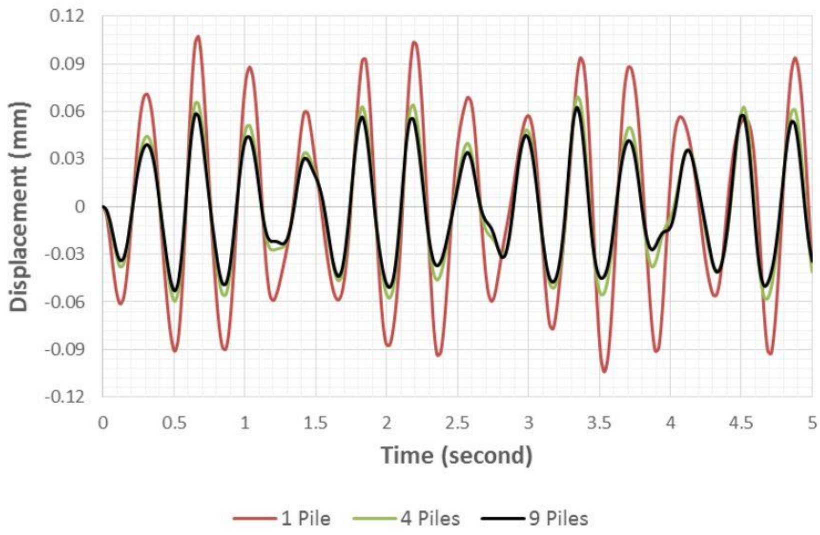

Figure 12. Effect of the number of piles on the dynamic response.

Table 8. The maximum amplitude of displacement and the percentage of reduction due to increasing the number of piles.

Number of Piles	Max. Amplitude of Displacement (mm)	Percentage of Reduction (%)
1	0.107	-
4	0.069	36
9	0.063	41

From the dynamic response results it can be seen that the maximum amplitude of the vertical displacement for the four piles model is less than the single pile model. Moreover, the nine piles model showed a small reduction than the four piles model as shown in "Fig.13". This behavior can be related to the interaction of the waves transmitted from the piles.

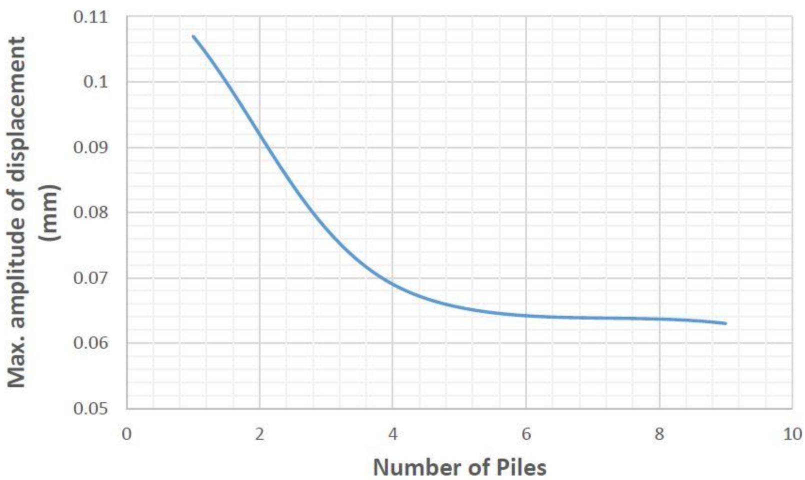

Figure 13. Reduction in the maximum amplitude of displacement due to increasing the number of piles.

3.5. Effect of Spacing between Piles on the Dynamic Response

When a group of piles is pushed vertically, it is possible that the vertical stiffness of the system be less than the sum of the stiffness of individual soil-pile systems. This is due to the piles interaction which occurs when the spacing between piles is small. For pile design, the group effects vanish for in-line piles at spacing equal to five diameters or more [8]. According to spacing to diameter ratio which considered in this part, three values of spacing to diameter ratio are considered (3.6D, 5D and 6.4D). Dimensions of the piles are unchanged with (8m) length and (0.42m) diameter and other parameters are kept constant.

"Fig.14" illustrates the dynamic response for piled raft foundation with different spacing between piles. The maximum amplitude of displacement and percentage of reduction due to increase the spacing between piles is shown in "Table 9".

From the results it can be observed that the maximum amplitude of the displacement is decreased with the increase of spacing between piles. The reduction decreases by using spacing between piles more than (5D) compared to the closely spaced piles due to the interaction of the piles as shown in "Fig.15".

Table 9. The maximum amplitude of displacement and percentage of reduction due to increase the spacing between piles.

Spacing between Piles (D)	Max. Amplitude of Displacement (mm)	Percentage of Reduction (%)
3.6	0.077	-
5	0.071	8
6.4	0.069	10

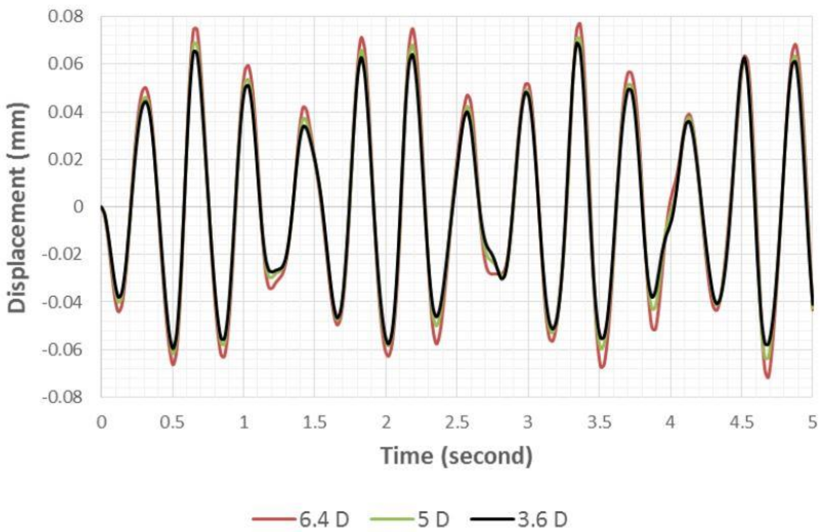

Figure 14. Effect of the spacing between piles on the dynamic response.

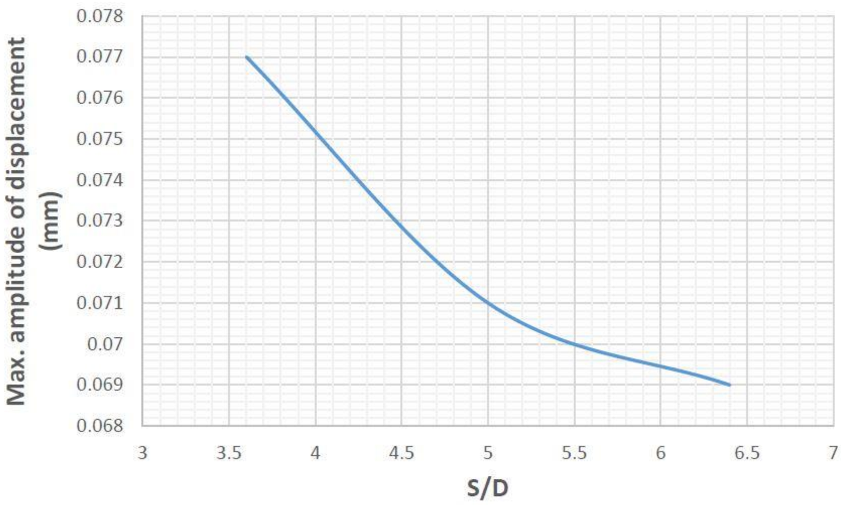

Figure 15. Reduction in the maximum amplitude of displacement due to increasing the spacing between piles

4. Conclusions

From the present study, several conclusions have been made:

1. A good agreement has been achieved between the predicted and the measured results. This is mean that the numerical modeling which is adopted in this study to simulate the machine foundations on dry soil is satisfied.
2. The maximum amplitude of displacement is decreased linearly by increasing the piles length due to the mass excess of the system. The increased piles length led to increase the damping of the system.
3. The increase of piles diameter led to decrease the maximum amplitude of displacement. Moreover, as the piles diameter decreases, the reduction in the maximum amplitude of displacement decreases.
4. The maximum amplitude of the vertical displacement for the four piles model is less than that of single pile model. On the other hand, the nine piles model showed smaller reduction than the four piles model.
5. The maximum amplitude of the displacement is decreased with the increase in the spacing between piles. The reduction decreases by using spacing between piles more than (5D) compared to the closely spaced piles.

Abbreviations

A list of symbols should be inserted before the references if such a list is needed

L	Pile length
D	Pile Diameter
S	Spacing between piles
φ	friction angle
$T_{top\ max}$	Skin resistance at the pile top
$T_{bottom\ max}$	Skin resistance at the pile bottom
F_{max}	Tip bearing

K_0	Lateral earth pressure coefficient
$F_{dy.max.}$	The maximum amplitude of dynamic force
n	Scale factor

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