Finite Element Analysis of Machine Foundation Resting on End Bearing Piles

Ibtihal A. M. Al-Nakdy
Chief Engineer, Ministry of Education

Dr. Mohammed Y. Fattah ⓘD
Building and Construction Engineering Department, University of Technology/ Baghdad
Dr. Mohammed J. Hamood
Building and Construction Engineering Department, University of Technology/ Baghdad

ABSTRACT

Dynamic effects of the machines play a major role in sizing of the foundation where conditions, like resonance is avoided by varying the stiffness and the mass of the structure which leads to modifications in foundation sizes. In this paper, a piled machine foundation in sandy soil is analyzed. A detailed 3D finite element analysis approach is considered using finite element software (ANSYS v.11). Machine foundations resting on end bearing piles are modeled. Harmonic dynamic load is chosen. A parametric study is carried out to investigate the effect of several parameters including: geometry of the piled machine foundation, the amplitude of the dynamic load, and frequency of the dynamic load.

It is concluded that as the pile cap thickness increases, the oscillation of displacement decreases due to geometrical damping of the pile cap. There is a limit of pile cap size at which its stiffness governs its dynamic response, above this size, the weight of the cap overrides its stiffness effect, and the additional weight by cap leads to increase the foundation displacement. On the other hand, when the pile diameter of the group increases, the frequency, at which the maximum displacement occurs increases hence the system becomes more stable against resonance condition.

Keywords: Machine Foundation, End Bearing Pile, Pile Cap, Dynamic, Finite
      Elements.

التحليل بطريقة العناصر المحددة لأساس ماكنة مستند الى ركائز ذات تحمل قاعدي

الخلاصة

تلعب التأثيرات الديناميكية للمكائن دورا رئيسيا في تحديد حجم الأساسات حيث تتطلب الحالات التصميمية تجنب حالة الرنين من خلال تغيير صلادة و كتلة المنشأ مما يؤدي الى تغييرات في أبعاد الأساسات. في هذا البحث، تم تحليل أساس ماكنة مستند الى ركائز في تربة رملية. تم اختيار تحليل تفصيلي ثلاثي الأبعاد بطريقة العناصر المحددة باستخدام برنامج الحاسبة (ANSYS v.11). تم تمثيل

أسس مكـائن تسـتند الـى ركـائز ذات نهايـات حاملـة و أختيـر حمـل دينـاميكي انسـجامي، و أجريـت دراسـة
معاملات للتحري عن تأثير عدة معاملات منها الشكل الهندسي لأساس الماكنة المستند الى ركائز و القيمة
القصوى للحمل الديناميكي و تردده و المسافة بين الركائز.

و قد تم التوصل الى نتيجة مفادها أنه مـع زيادة سمك قبعـة الركـائز يتنـاقص تذبذب الازاحـة بسبب
الاخماد الهندسي الذي توفره قبعة الركائز. هنـاك حد لسمك قبعـة الركـائز عنده تكـون صـلادة القبعـة هـي
التي تحكم الاستجابة الديناميكية، و فوق هذا الحد يتجاوز وزن القبعة تأثير الصـلادة لهـا و الـوزن الاضـافي
للقبعة يؤدي الى زيادة الازاحات. من ناحية أخرى، عند زيادة قطر الركائز في المجموعـة، فـان التـردد الـذي عنده
تحدث الازاحة القصوى يزداد و عليه تصبح المنظومة أكثر استقرارا ضد حالة الرنين.

INTRODUCTION

In many cases, due to poor soil conditions, machine foundations are located on piles and obviously other than static load; they are also subjected to vibrations and dynamic loading. Dynamic loading for piles under buildings may cause large deformations and soil nonlinearity. On the contrary, machines may cause only small amplitudes of vibrations, and soils may behave as elastic materials.

MATHEMATICAL MODELS FOR MACHINE FOUNDATIONS

Three mathematical models are usually used to model machine piled foundation (Chowdhury and Dasgupta, 2009):

1. Considering the underlying soil and the pile as finite elements and executing a detailed analysis based on appropriate boundary conditions. This would be the most exhaustive model one could perceive. Actually, the most appropriate model would be in three dimensions, where the piles are modeled as beam elements, while the soil can be modeled as eight nodded brick element, and a comprehensive dynamic analysis of the whole system could be performed.

2. Piles are considered as beam elements connected to soil springs. In this method, the piles are modeled as beam elements connected to springs in horizontal and vertical directions.

3. Piles are considered as frequency independent equivalent springs based on Novak's Furmatation (1974). This is possibly the most popular method used in the design offices to evaluate springs for piles subjected to dynamic loads.

Novak (1974) computed the vertical response of a machine and its foundations. It was shown that the tip condition is particularly important in weak soils and it is only the upper part of a pile that undergoes a significant displacement in stiff soils. The dynamic stiffness of the soil-pile system varies only moderately with frequency. The damping decreases rapidly with increasing frequency but levels off in the range of moderate frequencies. With increasing stiffness of the soil below the tip, the stiffness of the pile increases, while the damping decreases. With increasing length, the stiffness of the end-bearing piles decreases, while stiffness of the floating piles increases. Damping increases with pile length in most cases.

Sheta and Novak (1982) presented an approximate theory for vertical vibrations of pile groups that account for the dynamic interactions of piles in a group, weakening of soil around the pile because of high strain, soil layering, and arbitrary tip conditions. The effect of pile interaction on damping and stiffness of pile groups, distribution of

internal forces in the piles, and response of pile-supported foundations to harmonic excitation have been studied. It was found that (1) the dynamic group effects differ considerably from static group effects and (2) the dynamic stiffness and damping of pile groups are much more frequency dependent than those of single piles.

Prakash and Puri (2006) studied the methods of analysis for determining the response of foundation subjected to harmonic excitation. Analogs based on the elastic-half space solutions were used, and soil stiffness considered frequency independent for design of machine foundations. They found that the embedment of a foundation strongly influences its dynamic response.

Livshits (2009) concluded that a model analysis is required for frequencies separation verification. Very strict limits for amplitude of vibrations at machine bearings should be checked by a harmonic forced vibration analysis. Response spectrum analysis gave an estimation of internal forces and displacements due to seismic excitation. Structural design of the turbine generator foundation, made of reinforced concrete, requires a series of static analyses on various static and quasi-static loads.

The finite element method is one of the most powerful tools for the analysis of piled foundations. It requires the discretion of both the structural foundation system and the soil. In order to reduce the computational effort, problems are sometimes simplified to an axisymmetric problem or a plane-strain problem.

Nakai et al. (2001) studied the behaviour of the piled raft foundation under dynamic/static horizontal loading using the finite element analysis. They proposed a simplified method of static analysis which is intended for use in practical design. They reported that the method can give good results compared to those obtained from the dynamic analysis. They found that the solid elements rather than the beam elements are preferable for modelling piles in the finite element analysis.

Moreschi and Farzam (2005) studied the application of the harmonic analysis technique for the accurate determination of resonant frequencies of individual structural members in large steam-turbine generator foundations. They proposed a methodology for the accurate determination of the local structural vibration properties. Details of the implementation of the proposed methodology using the GT STRUDAL software are presented.

Novak et al. (2005) concluded that the application of an available 3D finite element method in the analysis of a composite foundation had shown that the method to be feasible and to have many advantages over simplified methods. Therefore, modelling the structural element of the mat and piles in a piled raft, would simulate the interface between the structural components and the foundation soil, and will employ linear or nonlinear soil properties to achieve a satisfactory solution.

Bhatia (2008a and b) found that the suitability of machine foundations depends not only on the forces to which they will be subjected to, but also on their behaviour when exposed to dynamic loads, which depends on the speed of the machine and natural frequency of the foundation. Thus, a vibration analysis becomes necessary. Each and every machine foundation does require a detailed vibration analysis providing insight into the dynamic behavior of foundation and its components for satisfactory performance of the machine. The complete knowledge of load-transfer mechanism

from the machine to the foundation, and also the complete knowledge of excitation forces and associated frequencies are necessary for the correct evaluation of machine performance. This study includes studying the effect of different parameters on the behavior of the pile foundation, these parameters include (pile diameter, spacing between piles, cap thickness, and cap length).

This paper carries out a numerical solution by the finite element method to the machine foundation problem. The problem studies the effect of load frequency by taking a range of frequencies and dynamic load amplitudes into consideration through studying the response of pile machine foundation in sandy soil. The pile machine foundation is taken as a continuum including soil; the soil is not modelled as springs as in previous studies. The paper includes studying the effect of different parameters on the behaviour of the pile foundation, these parameters include pile diameter, spacing between piles, cap thickness, and cap length. Normalized factors are illustrated as curves to give the designer a clear vision by clarifying the settlement and moments induced in the pile cap.

DESCRIPTION OF THE PILE MACHINE FOUNDATION PROBLEM
Modeling Soil As A Continuum

Soil domain is an infinite domain, and for the analysis purposes, it becomes necessary to confine it to a finite domain when soil is considered as continuum. For finite element modeling, it is well known that a narrow domain with fixed boundaries is not likely to represent a realistic soil behavior, whereas a very large domain would result in increased problem size. As the soil domain is very large compared to foundation, a relatively coarse mesh of the soil is considered to be adequate.

Some authors (Bhatia, 2008a) considered soil domain equal to 3 to 5 times the lateral dimensions in plan on either side of the foundation and 5 times along the depth should work out to be reasonably correct.

In the finite element solution, circular cross section of piles is adopted, the soil is meshed with the 8-node brick elements, the lateral boundaries of the soil are chosen to be far enough from the zone of influence under the vertical load (five times the width of the pile cap). End-bearing piles with zero damping are taken. A lower boundary which simulates the depth of the soil layer, is also kept far enough from the pile bottom (0.25L, where L is the pile length) as the piles are assumed to be bearing piles (i.e., the piles are installed to a rigid stratum). Even the vertical displacement at the lateral and vertical boundary is zero; a boundary condition prescribing the vertical displacement with a value of zero is adopted. The horizontal displacement at the horizontal boundary is zero, while the vertical is not for the pile tips. The analysis process is considered at the top central point of the pile cap at which the vertical dynamic load is applied. In addition to computation of moments and displacements, these values are normalized along the center line of floating pile caps. Interface elements (contact surfaces) are used between concrete of the pile and its cap and the soil.

The analysis of pile machine foundation is performed for foundation resting on finite isotropic elastic homogenous soil as the machines may cause only small amplitudes of vibrations (Ottavini, 1975 and Liu and Novak, 1991). The concrete is considered linearly elastic also (Liu and Novak, 1991, Fleisher and Trombik, 2008),

because the harmonic analysis in ANSYS program does not work with non linearity (ANSYS Manual). The value of Poisson's ratio for most types of soils can be found in Bowles (1997), and values for the static stress-strain modulus, Es, for selected soils can be also assumed based on the guides of Bowles (1997).

The soil used in this study is sandy clay. Hence, a typical range of values of the modulus of elasticity for sandy clay soil: Es = (25-250) MPa. The Poisson's ratio range for sandy clay soil is (0.2 - 0.3). Three values for amplitude were taken in the analysis; 80 kN, 100 kN and 120 kN.

The harmonic forces in any direction perpendicular to longitudinal rotation axis are:

$$F(t) = P * \sin(\omega t) \qquad \dots (1)$$

Where:

$$P = m_i \, e \, \omega^2$$

    P = amplitude of harmonic dynamic load,
    m_i = proportional part of rotating mass,
    e = mass eccentricity,
    t = time,
    $\omega = 2 \pi f$ = circular operating frequency of the machine, and
    f = operating frequency.

In this work, Solid65 is used for 3D modeling of concrete, and Solid45 is used for 3D modeling of soil.

Nine cases of pile machine foundation with dimensions shown in Table (1) are chosen for analysis. Figure (1) presents the top view of the pile cap with different pile cap lengths. Material properties for concrete, steel and soil are given in Table (2).

Parametric Study

The behavior of pile foundation can be influenced by several factors such as the thickness of the pile cap, arrangement of piles, size of pile, material and geometrical damping, and amplitude of dynamic load. In the design of pile machine foundation, it is important to take into account these factors to achieve the objective of economic construction with satisfactory performance.

PARAMETERS AFFECTING END-BEARING PILE MACHINE FOUNDATION

Effect of pile cap thickness

The effect of the pile cap thickness can be studied through considering three values of (0.5 m, 0.75 m and 1 m) for the case of (2.5 m x 2.5 m) pile cap with pile diameter of 0.5 m, length of piles of 20 m, spacing to diameter ratio of 1.5.

Figure (2) depicts the frequency displacement curve for end-bearing pile machine foundation for three amplitudes of vertical dynamic load and for three thicknesses. The vertical displacement was found to increase slightly at first with the increase of pile cap thickness by about (10%) for (0.75 m) cap thickness and for the three amplitudes of dynamic load (80 kN, 100 kN, 120 kN) and then increases obviously in the case of

(1 m) thickness by about (252%) more than the (0.5 m) thickness; the reference case, for the three amplitudes of dynamic load due to increase of self weight of the pile cap.

For a specified pile cap thickness h, it was found that the maximum displacement occurred at a certain frequency which has a constant value for the three amplitudes of load. For h = 0.5 m, 1 m the frequency of maximum displacement was 60 rad/sec while it was 12 rad/sec for h = 0.75 m.

The maximum displacement was found to increase with the increase of amplitude of vertical dynamic load by about (25%) for (100 kN) and (50%) for (120 kN) than the maximum displacement at first amplitude; (80 kN) and for all thicknesses.

It can be noticed that as the pile cap thickness increases, the oscillation of displacement decreases due to material damping inherent in the concrete of the cap. Figure (3) shows the relation between frequency ratio and vertical displacement for three amplitudes of vertical dynamic load and for three thicknesses. The frequency ratio (rf) (defined as the ratio of operating frequency to natural frequency) should be either less than 0.5 or more than 2 for important machines to avoid resonance condition (Rao, 2011). The natural frequency of the whole system can be obtained from the equation:

$$\omega_n = \sqrt{\frac{K}{M}} \qquad \qquad \text{... (2)}$$

where:

K= total stiffness of piles plus pile cap, and

M= total mass of piles, pile cap and soil included in the pile group.

$$r_f = \frac{\omega}{\omega_n} \qquad \qquad \text{... (3)}$$

where:

r_f = frequency ratio,

ω = operating frequency, and

ω_n = natural frequency.

$$M = \Sigma V * \gamma / g \qquad \qquad \text{... (4)}$$

$$\Sigma V * \gamma = V_1 \gamma_1 + V_2 \gamma_2 + V_3 \gamma_3 \qquad \qquad \text{... (5)}$$

Where:

M = Total mass of piles, pile cap, and soil included by the pile group in (kg),

$V_1 \gamma_1$ = Volume of piles multiplied by its density in (m^3),

$V_2 \gamma_2$ = Volume of pile cap multiplied by its density in (m^3),

$V_3 \gamma_3$ = Volume of soil multiplied by its density in (m^3), and

g = acceleration of gravity, m/sec².

It was found that the increase in the dynamic load does not affect the magnitude of frequency ratio for the three amplitudes of dynamic load, as it was obtained the same. The maximum displacement for the (0.5 m) pile cap thickness was found to be in the

resonance condition at frequency ratio of (1.134) for the three amplitudes applied, while for the (0.75 m) thickness, it was obtained to be in the resonance condition at frequency ratio of (0.227), and for the (1 m) thickness, it was found to be also at the resonance condition at frequency ratio of (1.139).

The maximum frequency ratio was found to be the same when the operating frequency is fixed, as the natural frequency was not changed obviously when only the pile cap thickness increases.

Figure (4) shows the maximum vertical stresses, σ_z, as function of loading frequency for end-bearing pile machine foundation under three amplitudes of vertical dynamic load and for the three cap thicknesses. The maximum vertical stress was found to decrease by about (74%, 66% and 70%) for the amplitudes of dynamic load (80 kN, 100 kN and 120 kN), respectively in the case of pile cap of thickness (0.75 m) compared with (0.5 m) thickness. The stresses decreased also in the case of (1 m) thickness by about (30%, 32% and 40%) for the amplitudes of dynamic load (80 kN, 100 kN and 120 kN), respectively compared with the 0.5 m pile cap thickness case.

The vertical stress was obtained to be at maximum value at different frequencies for the three amplitudes of dynamic load.

The vertical stress was also found to increase with the increase of amplitude of vertical dynamic load by about (29%, 72% and 25%) for the (0.5 m, 0.75 m and 1 m) cap thickness for amplitude (100 kN) more than the (80 kN) amplitude and by (75%, 107% and 50%) for amplitude (120 kN) than the reference case where the amplitude is (80 kN) for the (0.5 m, 0.75 m and 1 m) cap thickness.

Effect of pile diameter

Pile diameter affects directly the bearing capacity of the pile. In this study, three different diameters were considered (0.5 m, 0.8 m and 1.0 m). During this analysis, only the pile diameter was changed, while other parameters were kept unchanged. Figures (2), (5) and (6) show the frequency- displacement curves for end-bearing pile machine foundation for three amplitudes of vertical dynamic load and for three pile diameters. The vertical displacement was found to increase with the increase of pile diameter by about (468%) for (0.8 m) pile diameter and for the three amplitudes of dynamic load (80 kN, 100 kN and 120 kN) compared with the (0.5 m) pile diameter. An increase was also found in the case of (1 m) diameter by about (342%) more than the (0.5 m) pile diameter case for the three amplitudes of dynamic load (80 kN, 100 kN and 120 kN) , this increase may be attributed to self weight of concrete.

The displacement was found to be at maximum value at the same frequency for the three amplitudes of load for the three cases, it was obtained to be maximum at (60 rad/sec) for (0.5 m) pile diameter, (6 rad/sec) for (0.8 m) and (18 rad/sec) for (1 m) pile diameter.

The displacement was found to increase with the increase of amplitude of vertical dynamic load by about (25%) for (100 kN) and (50%) for (120 kN) than the reference case (80 kN) for all diameter values.

Figures (3, 7 and 8) manifest the relation between the frequency ratio and vertical displacement for three amplitudes of vertical dynamic load and for the three pile diameters. It was found that the increase in dynamic load does not affect the magnitude

of frequency ratio for the three amplitudes of dynamic load, as it was found the same. The maximum displacement for the (0.5 m) pile diameter was found to be at frequency ratio of (1.134) for the three amplitudes applied, while for the (0.8 m) pile diameter, it was found to be in the resonance condition at frequency ratio of (0.087), and for the (1 m), it is at resonance condition at frequency ratio of (0.211). The frequency ratio was obtained to decrease when the operating frequency is fixed as the pile diameter increases because of the increase in natural frequency that occurs as a result of increase of pile diameters as the increase in the diameter increases the stiffness of the pile machine foundation obviously more than the increase in the total mass of the pile machine foundation and soil included by the pile group.

Figures (4, 9 and 10) show the relation between the vertical stress and load frequency for end-bearing pile machine foundation under three amplitudes of vertical dynamic load and for three pile diameters. The maximum vertical stress was found to decrease by about (10%, 19%, 31%) for the amplitude of dynamic load (80 kN, 100 kN and 120 kN) in the case of pile diameter of (0.8 m) compared with 0.5 m diameter case. A decrease was also found in the case of 1 m diameter by (22%, 19% and 22%) for the amplitudes of dynamic load (80 kN, 100 kN and 120 kN) as compared with the reference case, (0.5 m) pile diameter. This decrease in stress is due to the increase in pile volume which will increase pile stiffness and its bearing capacity in static and dynamic loading conditions.

The vertical stress was found to be at maximum value at different frequencies for the three amplitudes of dynamic load.

The maximum vertical stress was found to increase with the increase of amplitude of vertical dynamic load by about (29%, 16% and 34%) for the (0.5 m, 0.8 m and 1.0 m) pile diameter case for amplitude (100 kN) and by (75%, 35% and 76%) for amplitude (120 kN) than the reference case (80 kN) amplitude.

Effect of spacing between piles

The interaction between piles inside the group is influenced by the spacing between piles. Therefore, spacing to diameter ratio was considered in the parametric study. The arrangement of piles can influence the vertical settlement of the pile cap and vertical stress due to the applied load. The square shape of the group was maintained unchanged, while three values of spacing was considered as follows (S = 1.25 m, 1.5 m, 1.75 m). The diameter of piles was chosen to be 0.5 m, length of piles was kept constant and equal to 20 m, and the cap thickness has a value of 0.5 m. Pile group with a small spacing between piles may tend toward the block behavior, therefore to perform the pile group concept properly, the spacing between piles needs to be wide enough to allow the cap to participate taking part of the load and using the piles strategically as settlement reducers.

Figures (2, 11 and 12) illustrate the frequency displacement curves for end bearing pile machine foundation under three amplitudes of vertical dynamic load and for three spacing values. The displacement was found to increase with the decrease of spacing by about (143%) for (1.25 m) spacing less than the (1.5 m) spacing case and for the three amplitudes of dynamic load (80 kN, 100 kN and 120 kN) and then increases in the case of (1.75 m) spacing by about (746%) more than the (1.5 m) spacing case for the three amplitudes of dynamic load (80 kN, 100 kN and 120 kN). Therefore, the

spacing of (1.5 m) value can be considered the best case for piles to act as settlement reducers.

The displacement was found to be at maximum value at the same frequency for the three amplitudes of load for the three cases, it was obtained to be maximum at (6 rad/sec) for (1.25 m and 1.75 m) spacing, and (60 rad/sec) for (1.5 m) spacing.

The displacement was found to increase with the increase of amplitude of vertical dynamic load at about (25%) for (100 kN) and (50%) for (120 kN) than the reference case.

Figures (3, 13 and 14) indicate the relation between frequency ratio and vertical displacement for three amplitudes of vertical dynamic load and for three pile spacing. It was found that the increase in dynamic load does not affect the magnitude of maximum frequency ratio for the three amplitudes of dynamic load as it was obtained the same. The maximum displacement for the (1.5 m) pile spacing was found to be at frequency ratio of (1.1344) for the three amplitudes applied, while for the (1.25 m) pile spacing, it was determined to be in the resonance condition at frequency ratio of (0.119), and for the (1.75 m) it was found to be in the resonance condition at frequency ratio of (0.11). These findings maintain that the frequency ratio is either less than 0.5 or more than 2 for important machines to avoid resonance condition except the case of 1.5 m pile spacing. The maximum frequency ratio was found to decrease when the operating frequency was fixed as the pile spacing increased because of the increase in natural frequency that occurred as a result of increase of pile spacing due to markable increase in stiffness more than the increase in the mass of the whole pile machine foundation and soil.

Figures (4, 15 and 16) reveal the change in vertical stresses with frequency for end bearing pile machine foundations under three amplitudes of vertical dynamic load and for three spacing values. The maximum vertical stress was found to increase by about (72%, 98% and 75%) for the amplitudes of dynamic load (80 kN, 100 kN and 120 kN), respectively in the case of spacing of (1.25 m) compared with the spacing case of (1.5 m). The stresses also increased in the case of (1.75 m) spacing by about (71%, 67% and 61%) for the amplitude of dynamic load (80 kN, 100 kN and 120 kN) as compared with (1.5 m) spacing case. This increase in stress in the pile cap in the case of decreasing spacing and then the increase in stress proved that the (1.5 m) spacing is the best spacing as it reveals moderate stresses in the pile cap.

The vertical stress was obtained to be maximum at different frequencies for the three amplitudes of dynamic load.

The maximum vertical stress was found to increase with the increase of amplitude of vertical dynamic load by about (49%, 29% and 26%) for the (1.25 m, 1.5 m and 1.75 m) spacing and amplitude of 100 kN more than the (80 kN) amplitude, and by (79%, 75% and 65%) for the (1.25 m, 1.5 m and 1.75 m) spacing and amplitude (120 kN) more than the (80 kN) amplitude.

Effect of pile cap size

Three values for pile cap length were considered: (2.5 m, 3.75 m and 5 m), during this analysis, only the pile cap length was changed while other parameters were kept unchanged. Figures (2, 17 and 18) exhibit the frequency- displacement curves for end-bearing pile machine foundation for three amplitudes of vertical dynamic load and for

three different pile cap lengths. The displacement was found to increase with the increase of cap length by about (771%) for (3.75 m) pile cap length and for the three amplitudes of dynamic load (80 kN, 100 kN and 120 kN) and increased in the case of (5 m) pile cap length by about (49%) more than (2.5 m) pile cap length case for the three amplitudes of dynamic load (80 kN, 100 kN and 120 kN). Therefore, the model with pile cap length of (3.75 m) recorded the highest settlement.

The displacement was determined to be at maximum value at the same frequency for the three amplitudes of load for the three cases. The displacement was obtained to be maximum at frequency of (60 rad/sec) for (2.5 m and 5 m) pile cap lengths, and (6 rad/sec) for (3.75 m) pile cap length.

The displacement was found to increase with the increase of amplitude of vertical dynamic load by about (25%) for (100 kN) compared with the (80 kN) amplitude. The increase was about (50%) for (120 kN) amplitude compared with the reference case of (80 kN) amplitude.

Figures (3, 19 and 20) show the relation between frequency ratio and vertical displacement for three amplitudes of vertical dynamic load and for three pile cap lengths. It was obtained that the increase in dynamic load does not affect the magnitude of frequency ratio for the three amplitudes of dynamic load as it was found the same. The maximum displacement for the (2.5 m) pile cap length was determined to be at frequency ratio of (1.134) for the three amplitudes applied while, for the (3.75 m) pile cap length, it was found that the resonance condition occurs at frequency ratio of (0.138), and for the (5 m) pile cap length, it was obtained to be at frequency ratio of (1.588).

The frequency ratio for the selected pile cap sizes was found to be either less than 0.5 or more than 2 to avoid resonance condition. The frequency ratio was found to increase when the operating frequency was fixed as the natural frequency decreased with the increase of pile cap length. Figures (5, 21 and 22) exhibit the change in vertical stresses with load frequency for end-bearing pile machine foundation for three amplitudes of vertical dynamic load and for three pile cap lengths. The maximum vertical stress was obtained to decrease by about (6.5%, 4.25% and 14%) under the amplitudes of dynamic load (80 kN, 100 kN, 120 kN) in the case of pile cap length of (3.75 m) and then decreased also in the case of (5 m) pile cap length by about (28%, 26% and 38%) for the same amplitudes of dynamic load as compared with the reference pile cap length case, (2.5 m).

The vertical stress was found to be at maximum value at different frequencies for the three amplitudes of dynamic load. The maximum vertical stress was determined to increase with the increase of amplitude of vertical dynamic load by about (29%, 32% and 32%) for the (2.5 m, 3.75 m and 5 m) pile cap lengths under amplitude load (100 kN) more than the (2.5 m) pile cap length case and by about (75%, 61% and 50%) under amplitude load (120 kN) more than the (80 kN) amplitude load reference case.

CONCLUSIONS
1. The maximum vertical displacement changes linearly when changing the same parameter for any dynamic load amplitude. It was found that the maximum vertical displacement increases by about (25%) when increasing the dynamic load

amplitude from (80 kN) to (100 kN) and increased also by (50%) when increasing the dynamic load amplitude from (100 kN) to (120 kN) for any parameter.

2. As the pile cap thickness increases, the oscillation of displacement decreases due to geometrical damping of the pile cap.
3. There is a limit of pile cap size, at which its stiffness governs its dynamic response. Above this size, the weight of the cap overrides its stiffness effect, and the additional weight by cap leads to increase in the pile foundation displacement. The increase in size of pile cap machine foundation increases the geometrical damping of the structure by about 11% for 0.75 m and by about 21% for 1 m thickness. The increase in spacing between piles causes an increase in the geometrical damping by about 8% for 1.5 m more than 1.25 m and by about 4% for 1.75 m more than 1.5 m spacing.
4. The increase in dynamic load does not affect the magnitude of frequency ratio for the three amplitudes of dynamic load as it was found the same.

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Table (1) Parameters for the end bearing pile machine foundation.

case	B (m)	W (m)	h (m)	d (m)	L (m)	$S_{c/c}$ (m)
1	2.5	2.5	0.5	0.5	20	1.5
2	2.5	2.5	0.75	0.5	20	1.5
3	2.5	2.5	1.0	0.5	20	1.5
4	2.5	2.5	0.5	0.8	20	1.5
5	2.5	2.5	0.5	1.0	20	1.5
6	2.5	2.5	0.5	0.5	20	1.25
7	2.5	2.5	0.5	0.5	20	1.75
8	3.75	2.5	0.5	0.5	20	1.5
9	5	2.5	0.5	0.5	20	1.5

where:

B = length of pile cap, W = width of pile cap,
h = thickness of pile cap, d = diameter of pile, L = length of pile, and
$S_{c/c}$ = spacing between piles, center to center.

Table (2) Material properties. (* Assumed values, and   ** from ACI code.)

	Name	Definition	Values	
Concrete	E	Young's modulus (MPa)	$4700\sqrt{fc'}$**	25742.96
	γ_c	Density of concrete (kg/m^3)	2400	2400
	υ	Poisson's ratio	0.15*	0.15
	β_o	Open shear transfer coef	0.2*	0.2
	β_c	Closed shear transfer coef	0.7*	0.7
	f_t	Uniaxial Cracking stress (MPa)	$0.62\sqrt{fc'}$**	3.3958
	f'_c	Uniaxial Crushing stress (MPa)	f´c*	30.000
	f_{cb}	Ultimate biaxial compressive strength (MPa)	1.2f´c**	36.000
	σ_h^a	Hydrostatic stress	1.157f´c**	34.710
	f_1	Ultimate compressive strength for a state of biaxial compression superimposed on (σ_h^a) (MPa)	1.45f´c**	43.500
	f_2	Ultimate compressive strength for a state of uniaxial compression superimposed on(σ_h^a) (MPa)	1.725f´c**	51.750
Steel	ρ_{st}	Steel ratio	0.002*	0.002
Interface	μ	Coefficient of friction	0.5*	0.5
Soil	Es	Young's modulus (MPa)	30000*	30.000
	γ_s	Density of soil (kg/m^3)	1800*	1800
	υ	Poisson's ratio	0.3*	0.3

L = 20 m , h = 0.5 m
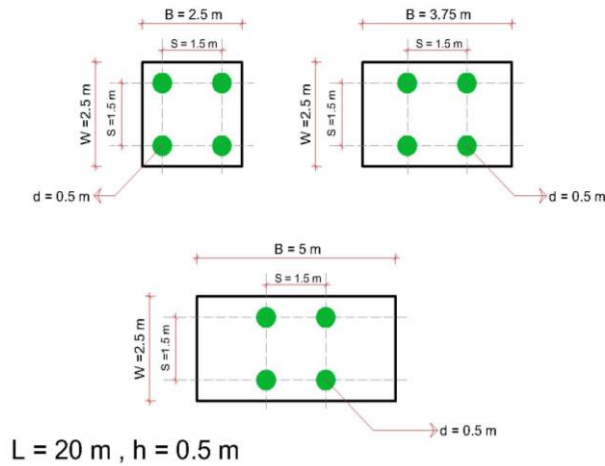
Figure (1) Top view of pile cap with different cap lengths.
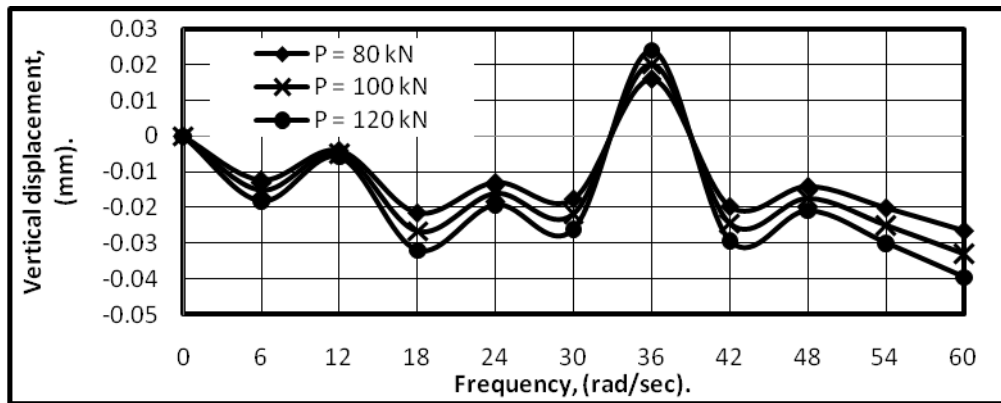
a. h = 0.5 m.
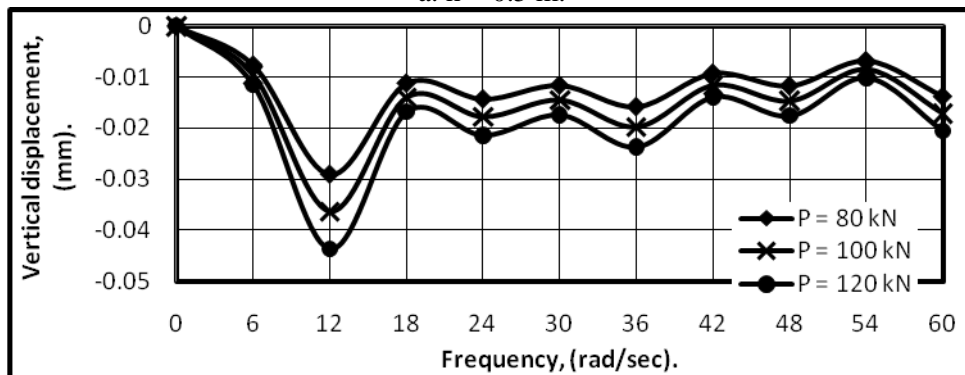
b. h = 0.75 m.
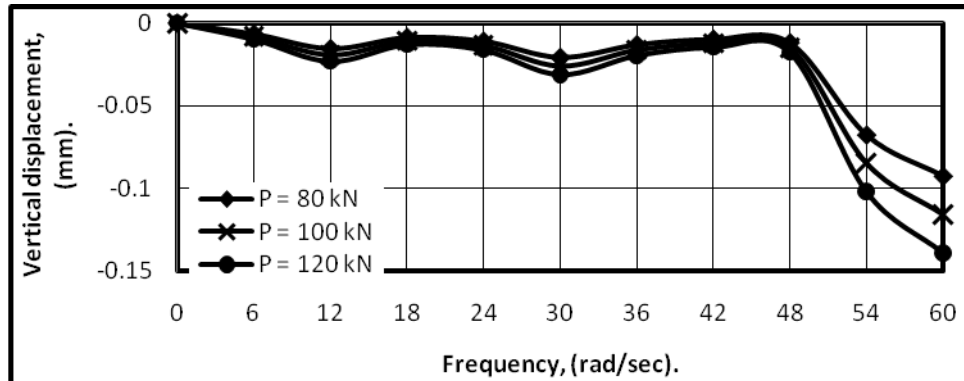
c. h = 1.0 m.

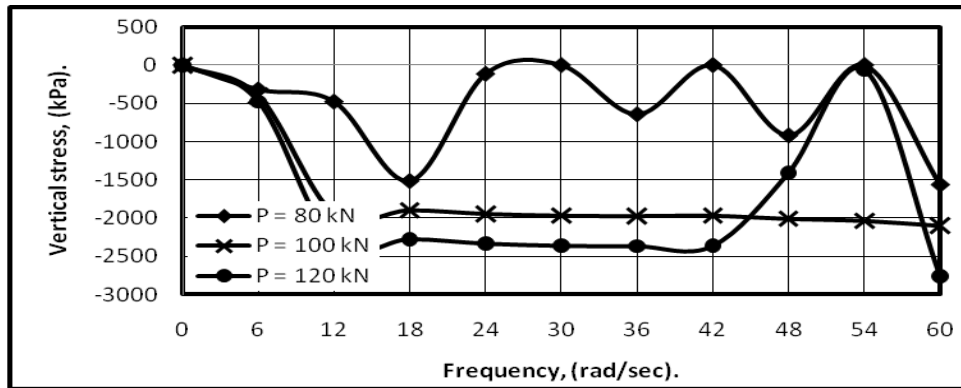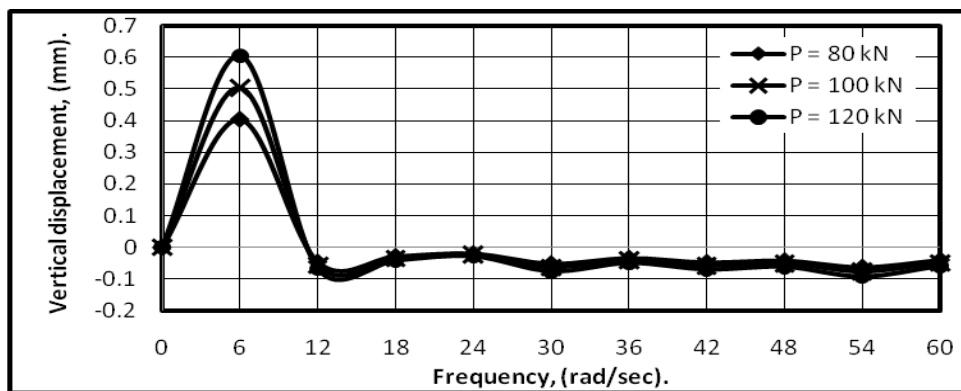**Figure (2) Variation of vertical displacement with frequency of load for the pile machine foundation (d = 0.5 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.**
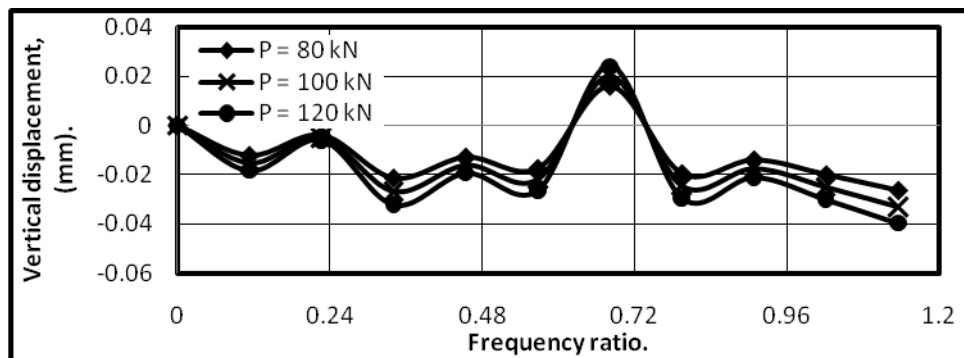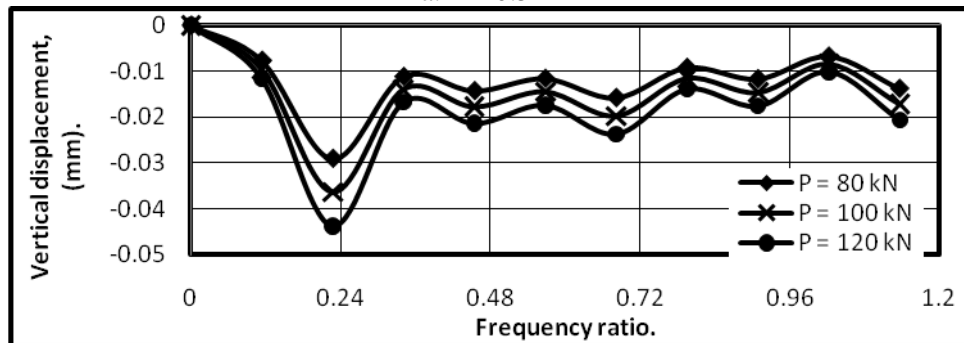
a. h = 0.5 m

b. h = 0.75 m.
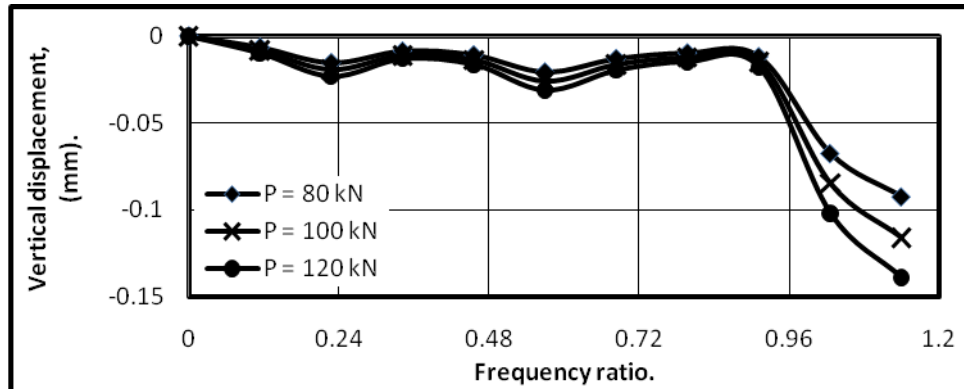
c. h = 1.0 m.

Figure (3) Variation of displacement with frequency ratio for pile machine foundation (d=0.5m, B*W =2.5m*2.5m, L=20m, S=1.5m) due to vertical dynamic load.
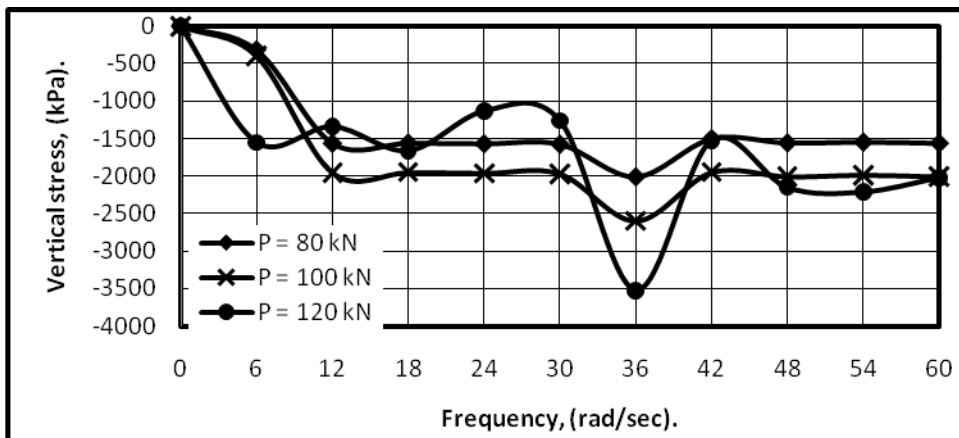
a. h = 0.5 m.

b. h = 0.75 m.
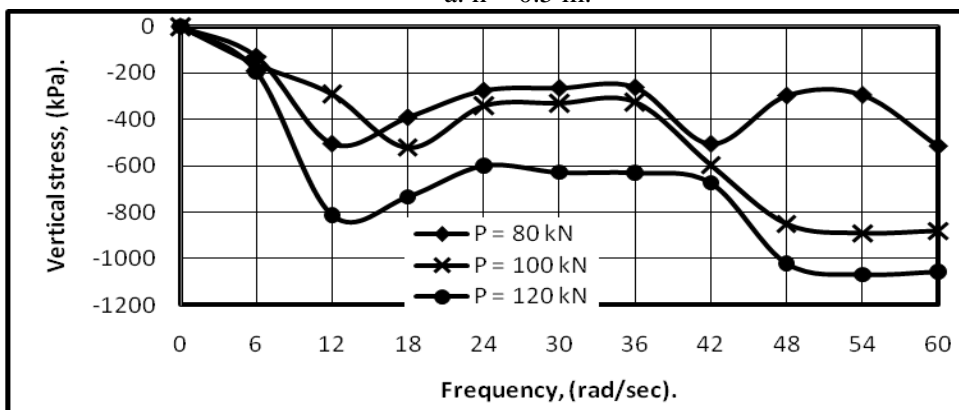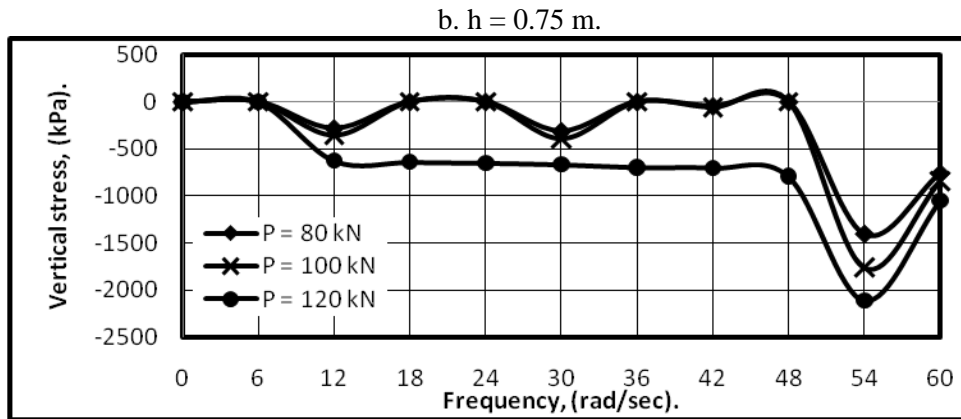
c. h = 1.0 m.

Figure (4) Variation of vertical stress with frequency of load for the pile machine foundation (d = 0.5 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.
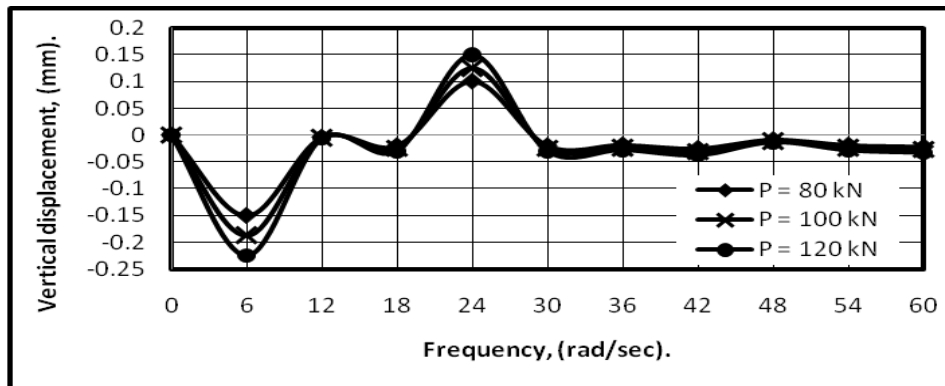
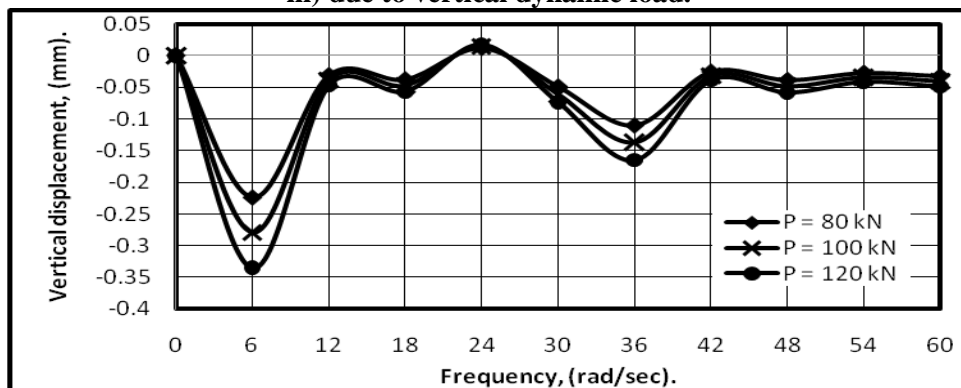**Figure (5) Variation of vertical displacement with frequency of load for the pile machine foundation (h = 0.5 m, d = 0.8 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.**
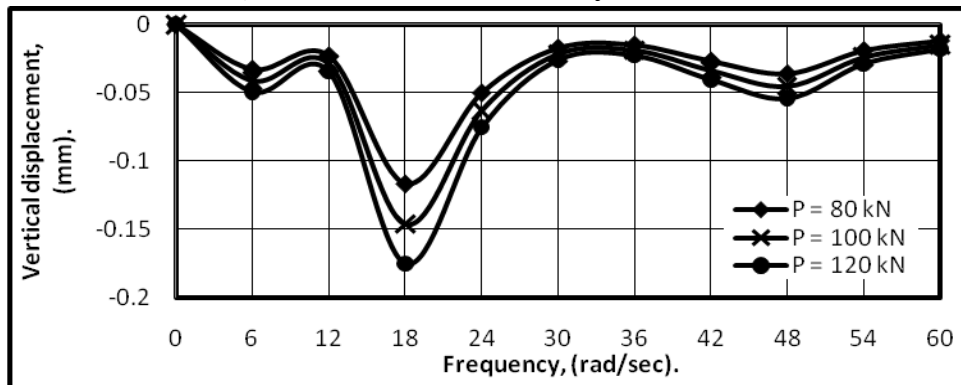
Figure. (6) Variation of vertical displacement with frequency of load for the

pile machine foundation (h=0.5m, d=1m, B*W =2.5m*2.5m, L=20m, S=1.5m) due to vertical dynamic load.
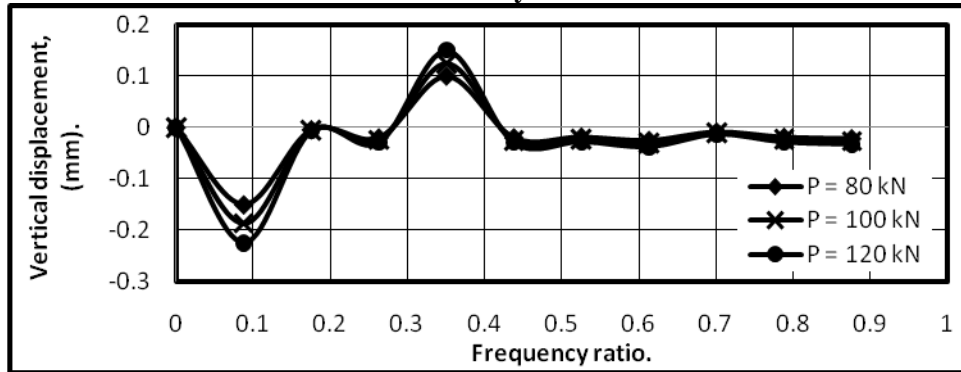
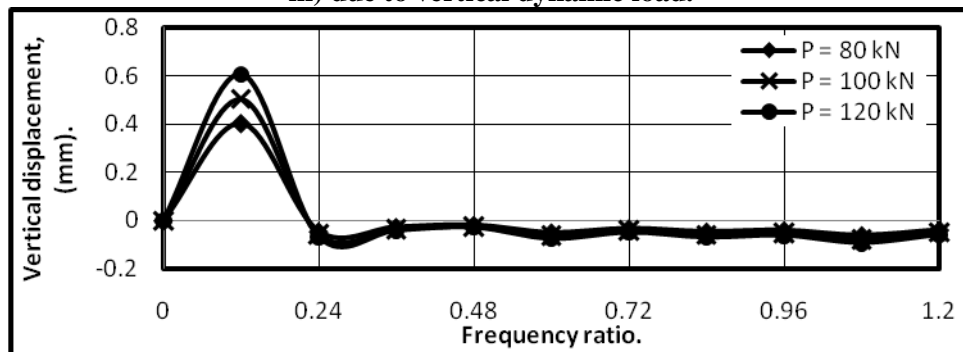**Figure. (7)   Variation of displacement with frequency ratio for pile machine foundation (h = 0.5 m, d = 0.8 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.**
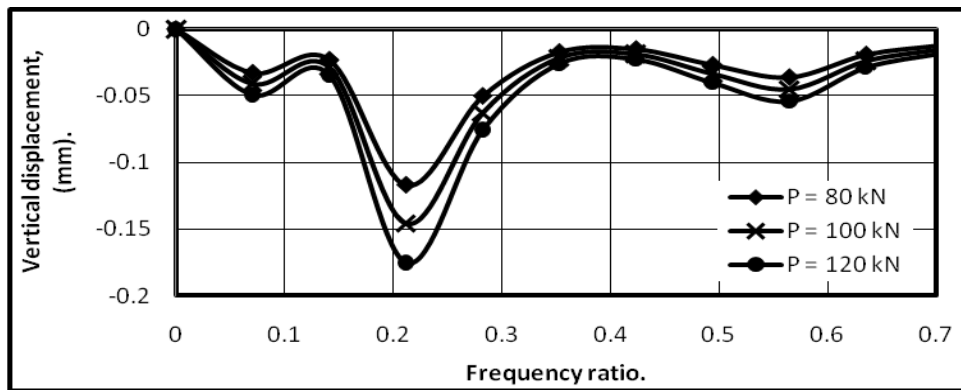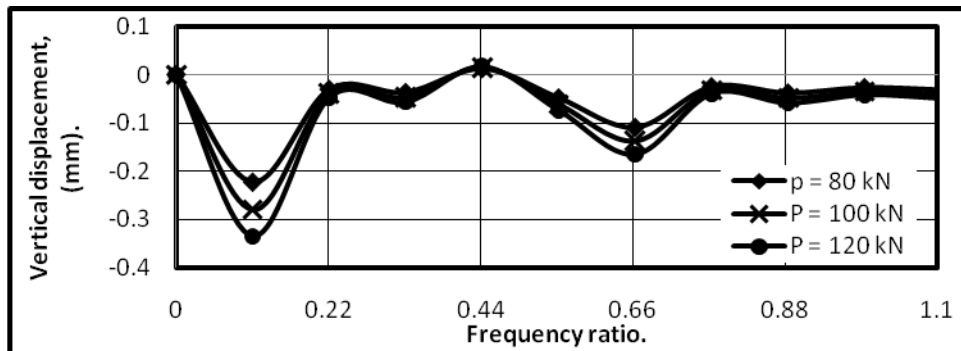

Figure (8) Variation of displacement with frequency ratio for pile machine foundation (h = 0.5 m, d = 1 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.
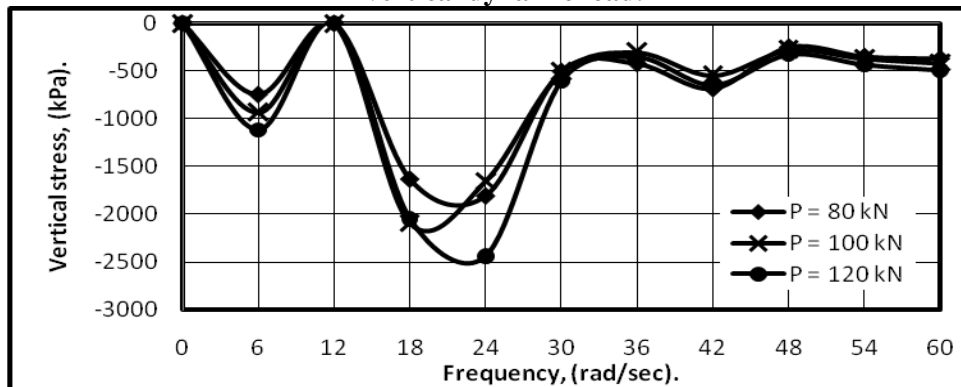
Figure (9) Variation of vertical stress with frequency of load for the pile machine foundation (h = 0.5 m, d = 0.8 m, B*W = 2.5 m*2.5 m, L =20 m, S = 1.5
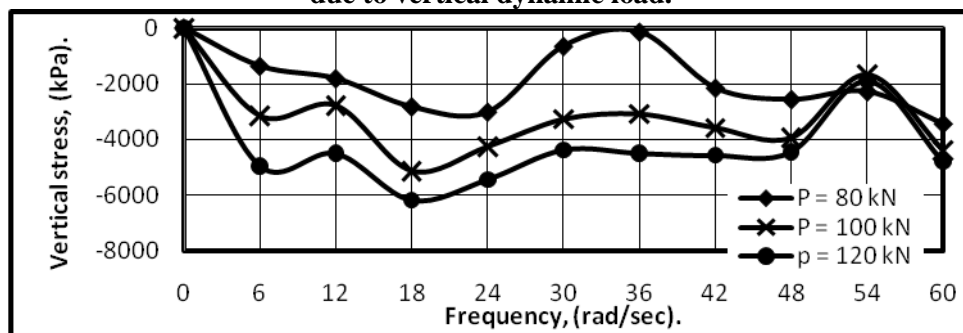
m) due to vertical dynamic load.

Figure (10) Variation of vertical stress with frequency of load for the pile machine foundation (h = 0.5 m, d = 1 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.

Figure (11) Variation of vertical displacement with frequency of load for the pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.25 m) due to vertical dynamic load.
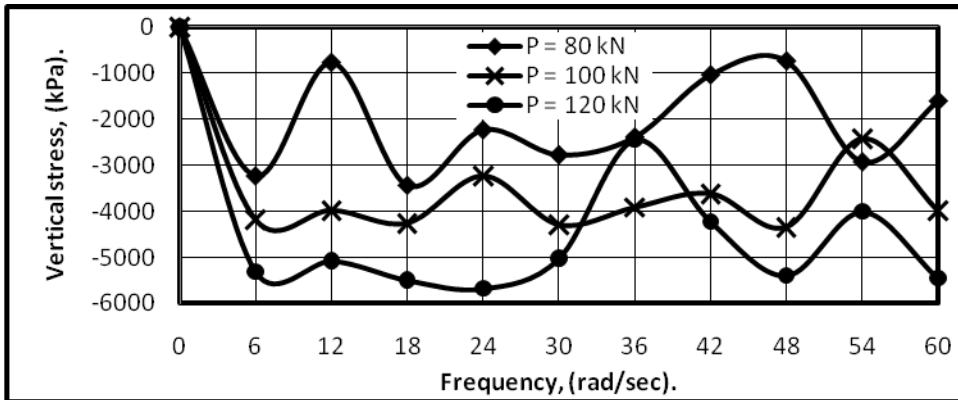

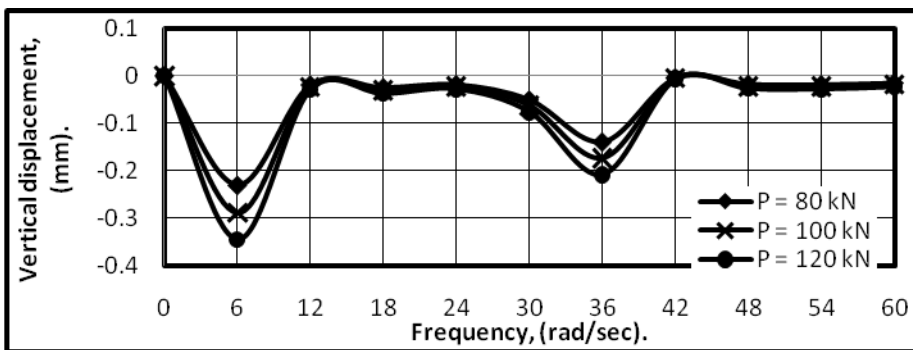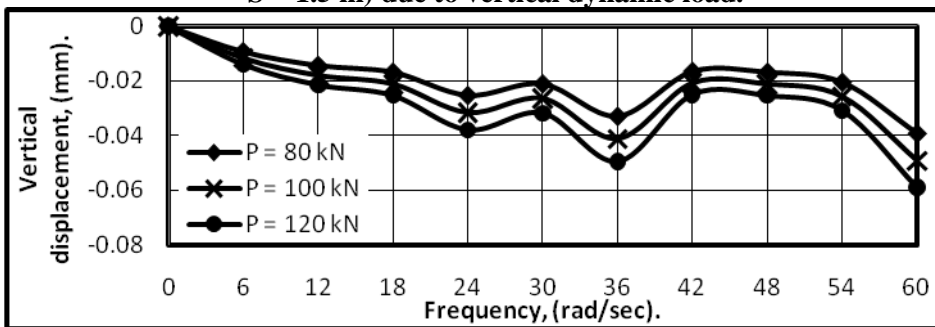**Figure (12) Variation of vertical displacement with frequency of load for the pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.75**

m) due to vertical dynamic load.

Figure (13) Variation of displacement with frequency ratio for pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.25 m) due to vertical dynamic load.

Figure (14)   Variation of displacement with frequency ratio for pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.75 m) due to vertical dynamic load.

Figure (15) Variation of vertical stress with frequency of load for the pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.25 m) due to vertical dynamic load.

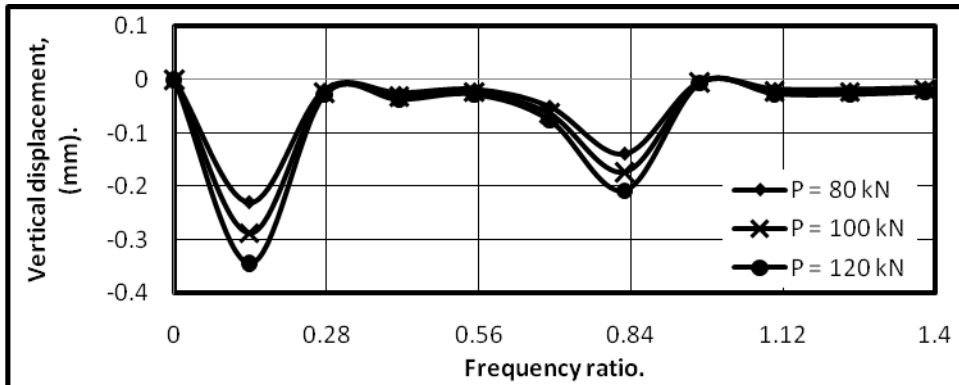**Figure (16) Variation of vertical stress with frequency of load for the pile machine
foundation (h = 0.5 m, d = 0.5 m, B*W = 2.5 m*2.5 m, L = 20 m, S = 1.75 m) due
to vertical dynamic load.**

**Figure. (17) Variation of vertical displacement with frequency of load for the
pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 3.75 m*2.5 m, L = 20 m,
S = 1.5 m) due to vertical dynamic load.**

**Figure. (18) Variation of vertical displacement with frequency of load for the
pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 5 m*2.5 m, L = 20 m, S
= 1.5 m) due to vertical dynamic load.**

Figure (19) Variation of vertical displacement with frequency ratio for pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 3.75 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.
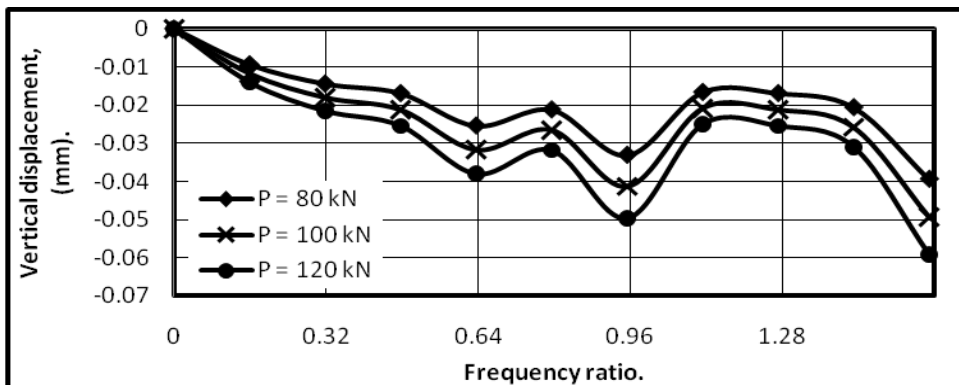

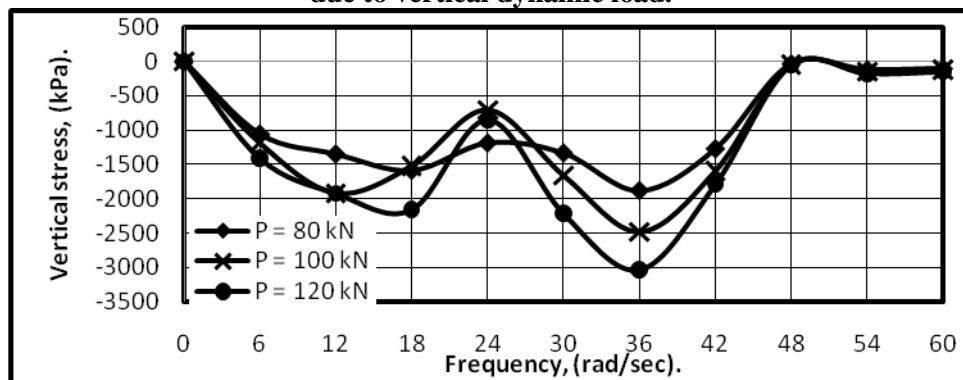**Figure (20) Variation of vertical displacement with frequency ratio for pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 5 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.**
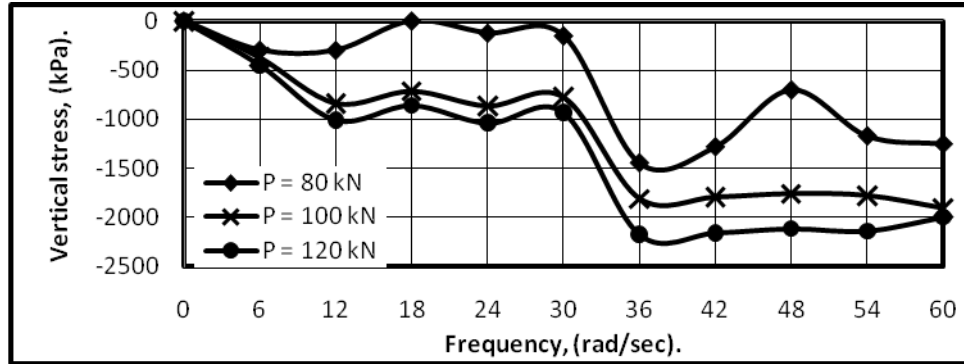

Figure (21) Variation of vertical stress with frequency of load for the pile machine

foundation (h = 0.5 m, d = 0.5 m, B*W = 3.75 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.

Figure (22) Variation of vertical stress with frequency of load for the pile machine foundation (h = 0.5 m, d = 0.5 m, B*W = 5 m*2.5 m, L = 20 m, S = 1.5 m) due to vertical dynamic load.