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PARAMETERS AFFECTING THE DYNAMIC BEHAVIOR OF THE MACHINE FOUNDATIONS

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ABSTRACT

Machine foundations are designed to limit their response to allowable amplitudes that satisfy the safe operation of the machine while not disturbing the personnel working in the vicinity. The dynamic analysis of machine foundations is complex in nature because it is affected by the interaction between large numbers of design parameters. The design of machine foundations is often conducted through consideration of several design trials. These trials involve several modifications in the parameters affecting the dynamic behaviour of the foundation. In this study, the dynamic response of a large pump-foundation system is investigated under excitations from the motor and pump impeller unbalance. Different design options of the foundation design are considered: shallow block foundation and deep block foundation. The effects of soil type, embedment depth, soil damping, foundation mass, pile length, and pile type on the dynamic behaviour of the foundation are discussed. The study presented would be helpful for the practising engineers to reduce the number of trials in the design process, and to arrive at the optimum design.

1. **Introduction**

The industrial facilities like oil sands plants, oil production facilities, power plants, etc., have a number of centrifugal and reciprocating machines. Foundation for these machines should be designed such that the dynamic forces of machines are transmitted to the soil through the foundation in such a way that harmful effects are eliminated (Gazetas 1983). If proper attention is not paid to the design of machine foundations, machines may malfunction or break down due to excessive vibration or settlement of the foundations. This can exceed many times the capital investment cost required for a properly designed and built foundation. The engineer must have a deep understanding of the dynamic behaviour of machine foundations for successful foundation designs.

Foundations that support reciprocating engines, such as generators, pumps and compressors are subject to vibrations caused by machine unbalanced forces. It is not practical to balance the machine rotor to eliminate unbalance; therefore, some unbalanced force will always exist (Gu 2010). The unbalanced force results from many factors such as the misalignment during installation, corrosion or wear of moving parts, axis of rotation which does not pass through the mass center of the rotor, deflection of the shaft due to gravity and uneven heat dissipation, various types of damages to machine bearings and uneven thermal expansion. The cumulative effect of these factors is the presence of unbalanced forces that are cyclic, having a frequency equal to the angular speed of the machine and an amplitude proportional to the speed squared. These forces point outward from the shaft, which are usually decomposed into two orthogonal components. The two components are both sinusoidal, and are 90° out of phase with each other.

The analysis of machine foundations under dynamic loads is considered a very complex problem because of the interaction of the structure, the subsurface soil, and the vibrating machine. This analysis and design became less complex after the introduction of digital computers and finite element software. For machine foundations, the engineer must consider, in addition to the static load, the dynamic forces cause by the operating machine. The design of machine foundations is usually governed by serviceability limit states performance considerations, not strength requirements (CFEM 2006). It has also been found that the suitability of machine foundations depend not only on the forces to which they will be subjected, but also on the frequency of the foundation support.

A typical machine foundation system consists of a machine connected to a foundation and the foundation in turn supported by the soil. Therefore, the machine, foundation and soil are the three main constituents that play the significant role in overall control for machine performance ACI 351.3R-04 2006). In this paper, the dynamic response of a large pump-foundation system is investigated with different design options. A computer program DYNA 6 is used to generate the impedance functions (stiffness and damping). Two options of the foundation design are considered: shallow block foundation and deep block foundation. The effects of embedment depth, soil stiffness, soil damping, pile length, foundation mass, and pile type on the dynamic behaviour of the foundation are discussed. The study presented would be helpful for the practising engineer to reduce the number of trials in the design process, and to arrive at the optimum design (Hassan et al. 2013 and Hassan et al. 2014).

2. Rigid Block Foundations and Design Criteria

Machine foundations are usually designed as block foundations. Block foundations are solid blocks of concrete with sizable thickness and large mass. A typical concrete block is regarded as rigid relative to the soil over which they rest. It may be assumed that the concrete block behaves as a rigid body, i.e. it undergoes only rigid-body displacements and rotations (Arya 1984). The block foundations can rest directly on soil (shallow foundations) or on piles (deep foundations). For rigid foundations resting directly on the soil or supported by pile groups, simplified analytical or numerical methods or both are commonly used. The procedure used to design machine foundations includes the following steps:

1. Estimate the dynamic loads.
2. Establish the soil profile and evaluate the soil properties required for the dynamic analysis.
3. Select the type and trial dimensions of the foundation based on experience.
4. Compute the dynamic response of the trial foundation supported by the given soil profile due to the estimated load.
5. Compare the response of the foundation with the performance criteria. If the response is not satisfactory, the dimensions of the foundation are modified and the analysis is repeated until a satisfactory design is achieved.

A machine foundation should meet the following conditions for satisfactory performance:

1. Static requirements
    a. Bearing pressure should be less than the allowable bearing capacity.
    b. Expected settlement should be less than the allowable settlement.
2. Dynamic requirements
    a. There should be no resonance.
    b. The calculated amplitude should be less than the allowable vibration limit.

The response of soils and foundations to dynamic excitation is frequency dependent and thus is a function of the stiffness and damping parameters of the soil and the foundation. Therefore, the evaluation of the appropriate stiffness and damping parameters (impedance functions) for the foundation soil or pile–soil system is a key step in the analysis.

3. Evaluation of Foundation Impedance Functions

The study of the dynamic response of foundations supporting vibration equipment requires that proper evaluation for the dynamic stiffness and damping of the foundation be used. The variation of these values with dynamic soil characteristics is usually notable, and consequently their effect on the foundation's response is critical (El Naggar 2003). Several approaches are available in the literature for the analysis of foundation systems to account for dynamic soil–structure interaction. The analyses used in the paper to determine the impedance functions of shallow and deep foundations are described briefly below.

Shallow foundation

There have been many studies concerning evaluation the stiffness and damping constants of shallow foundations resting on the surface of a linear viscoelastic halfspace. Bycroft (1956); Luco and Westmann (1971); and Veletsos and Verbic (1973) have introduce analytical solutions, however, Veletsos and Wei (1971) and Luco and Hadjian (1974) introduced numerical solutions. For circular bases, the complex stiffness K_i associated with direction i is obtained by determining the relationship between the harmonic force acting on a massless disc that rests on the surface of the halfspace and the resulting displacement of the disc. This complex stiffness can be expressed in terms of the true stiffness constant, k_i, and the damping constant, c_i, as

[1] $$K_i = \bar{k}_i[k_i'(a_0) + i a_0 c_i'(a_0)]$$

in which k_i' is the static stiffness, $a_0 = \omega R / V_s$ is the dimensionless frequency, R is the disc radius, $V_s = \sqrt{G/\rho}$ is the shear wave velocity of the soil, and G and ρ are the soil shear modulus and mass density, respectively. The parameters k_i' and c_i' are stiffness and damping constants normalized as follows: $k_i' = \dfrac{k_i}{\bar{k}_i}$, $c_i' = \dfrac{V_s}{\bar{k}_i R} c_i$ (i.e., see Veletsos and Verbic 1973).

The response of embedded foundations can be approximated by assuming that soil reactions acting on the base are equal to those of a surface footing and that the reactions acting on the footing sides are equal to those of an independent layer overlying the halfspace assuming plane strain conditions. Beredugo and Novak (1972) found that this approximate approach yields reasonable results compared with the finite element predictions. In the current study, the plane strain solutions developed by Novak et al. (1978) for side reactions and the halfspace solution for base reactions developed by Veletsos and Verbic (1973) were used to evaluate the stiffness and damping constants of the shallow foundation. The first vertical and horizontal natural frequencies, ω_v and ω_u, respectively, of a shallow layer are

[2] $$\omega_v = \frac{\pi V_S}{2H}\sqrt{\frac{2(2-\nu)}{1-2\nu}} \quad \text{and} \quad \omega_u = \frac{\pi V_S}{2H}$$

where H is the layer thickness, and ν is Poisson's ratio of the soil layer. At frequencies lower than $\omega\nu$ and ωu, the only source of damping is the material damping. For frequencies below the first layer natural frequencies, it would be safe to ignore geometric damping completely, and the damping can be established as a fraction of stiffness giving c as

[3] $$c = \bar{k}k'\frac{2\beta}{\omega}$$

in which β is the material damping ratio of the soil.

Deep foundation

Dynamic stiffness and damping of piles are influenced by interaction of the piles with the surrounding soil. In a group of closely spaced piles, the character of dynamic stiffness and damping is further complicated by interaction between individual piles known as pile-soil-pile interaction or the group effect. To account for pile–soil–pile interaction effects, the superposition approach was used in the analysis. In this approach, the stiffness and damping of single piles are calculated first, then group effect is accounted for using the interaction factors. The dynamic stiffness (impedance function) of piles can be described as

$$K_i = k_i(a_o) + i\omega c_i(a_0) \qquad [4]$$

The stiffness constants, k_i, and the equivalent viscous damping constants, c_i, for individual motions of the pile head can be evaluated as a function of the pile and soil properties using the approach developed by Novak and Aboul-Ella (1978) for piles in a layered medium. The dynamic group effects can be evaluated approximately using the interaction factors approach and the approximate approach presented by Dobry and Gazetas (1988) and Gazetas and Makris (1991) in which the interaction problem is reduced to the consideration of cylindrical wave propagation. A simplified approximate analysis for the dynamic group effects is formulated on the basis of dynamic interaction factors, α, introduced by Kaynia and Kausel (1982) who presented charts for dynamic interaction. In this analysis, the impedance functions of single piles and the interaction factors are calculated first, then the group impedance functions are computed using the approach described in El Naggar and Novak (1995). All of the techniques used to calculate the impedance functions for the foundation are encoded in the computer code DYNA6 (El Naggar et at. 2011) that is used in the current study.

4. Description of the Machine

In this study, the foundation is assumed to support a 4500 HP slurry pump. The length and width of the pump are 8 m and 3 m, respectively. The pump weight is 77000 kg. The operation speed of the pump Impeller and the motor are 421 rpm. The weights of the pump and motor are 6425 kg and 3300 kg, respectively. The unbalanced dynamic forces provided by the manufacture are 36735 N for the pump impeller and 1500 N for the motor.

5. Numerical Examples

Several parameters can affect the dynamic behaviour of machine foundations, such as the foundation type, embedment depth, soil type, soil damping, pile type, foundation mass, pile length and pile type. In order to study the influence of these parameters, a parametric study is conducted by varying a wide range of these parameters. Two different design options are considered in this study: shallow block foundation and deep block foundation. The length of the foundation is assumed to be fixed, 9.0 m, however, the width of the foundation is considered as 5 m, 8 m, 11 m and 14 m, respectively, as shown in Figure 1. Three different values 1 m, 2 m, and 3 m are considered for the foundation thickness. Two different types of pile are used to support the foundation. Those are steel pipe piles and concrete piles. The properties and diameters of the piles are tabulated in Tables 2 and 3. The lengths of the pile are considered as 10 m, 15 m and 20 m, respectively. Three soil properties tabulated in Table 1 are used in the analysis. The foundations are analyzed with and without embedment. The embedment depth is assumed as the foundation depth. The maximum amplitude, dynamic stiffness and damping constant of the foundation are calculated, while varying the previous parameters. However, for presentation purposes, seven cases are considered.

Table 1: Dynamic Soil Properties

Soil	Shear Modulus, MPa	Shear Wave Velocity, m/sec	Damping Ratio	Poisson's Ratio
Soil (I)	18	100	0.01	0.30
Soil (II)	72	200	0.03	0.35
Soil (III)	162	300	0.05	0.40

Table 2: Steel Pipe Piles

Type	Diameter (mm)	Wall thickness (mm)	Unit weight (kN/m3)	Modulus of Elasticity (kN/m2)	Poisson's Ratio	Damping
Pile (I)	508	12.7	77	2.05 E+08	0.30	0.03
Pile (II)	762	15.9	77	2.05 E+08	0.30	0.03
Pile (III)	914	19.1	77	2.05 E+08	0.30	0.03

Table 3: Concrete Piles

Type	Diameter (mm)	Unit weight (kN/m3)	Modulus of Elasticity (kN/m2)	Poisson's Ratio	Damping
Pile (IV)	508	24	24.87E+06	0.20	0.05
Pile (V)	762	24	24.87E+06	0.20	0.05
Pile (VI)	914	24	24.87E+06	0.20	0.05

5.1. Effect of the Foundation Type

In this section, the foundation shown in Figure 1b is analyzed under the machine unbalanced forces using two options: shallow block foundation and deep block foundation. The following design parameters are maintained constant:

- The thickness of the foundation (ts = 2.0 m).
- The soil is assumed as Soil (II) (Table 1).
- The piles are taken as Pile (II) and to have a length of 15 m (Table 2).

It can be seen from Figure 2 that the amplitude of the shallow foundation is always higher than the amplitude of the deep foundation. It can be also seen that the vertical stiffness and damping constant of the deep foundation are higher than those of the shallow foundation.

5.2. Effect of the Embedment

In order to present the effect of the embedment, the foundation shown in Figure 1c is analyzed assuming two cases: shallow block foundation and deep block foundation. The amplitude, vertical stiffness and damping constant are calculated for each case with and without embedment. The other design parameters are maintained constant as provided in Section (5.1).

It can be seen from Figures 3 and 4 that the embedment always reduces the amplitude of the shallow and deep foundation. The results also show that the vertical stiffness and damping constant in the case of the embedment are higher than the case without embedment.

5.3. Effect of the Foundation Thickness

In order to demonstrate the influence of the foundation thickness, the foundation shown in Figure 1a is analyzed under the machine unbalanced forces assuming two cases: shallow block foundation and deep block foundation. In each case, the foundation is assumed to have a thickness of 1 m, 2 m and 3 m. The other design parameters are maintained constant as provided in Section (5.1).

It can be seen from Figure 5 that the increase of the foundation width, i.e., the mass of the foundation, always decreases the natural frequency of the foundation. It can be also seen that an increase of the foundation mass reduces the maximum amplitude of the foundation.

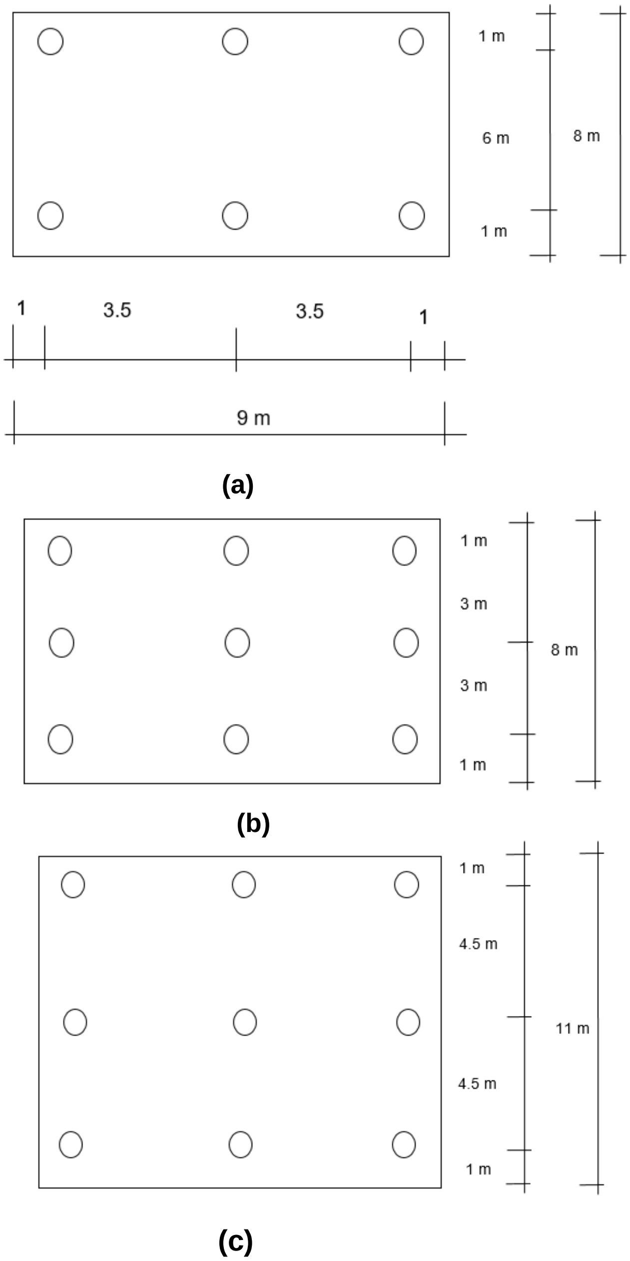

Figure (1): Geometry of the foundations used in the study.

5.4. Effect of Pile Diameter and Type

To illustrate the effect of the pile diameter and type, the foundation shown in Figure 1a is analyzed by using different piles as given in Tables 2 and 3. Therefore, 6 cases are included in this study. The other design parameters are maintained constant as provided in Section (5.1).

It can be seen from Figure 6 that the increase of the pile diameter decreases the maximum amplitude of the foundation. It can be seen that the piles (IV), (V) and (VI) reduce the amplitude when compared with the piles (I), (II) and (III) of the same diameter and length.

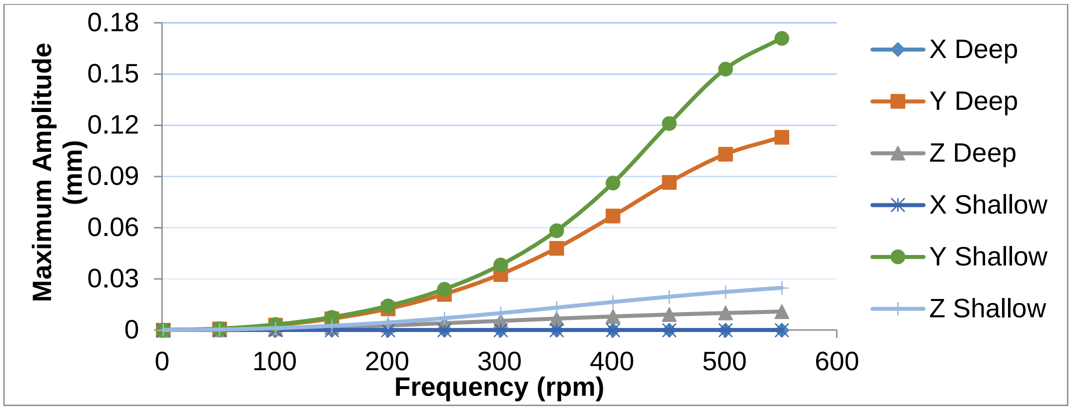

Figure 2a: Dynamic response of deep and shallow foundations.

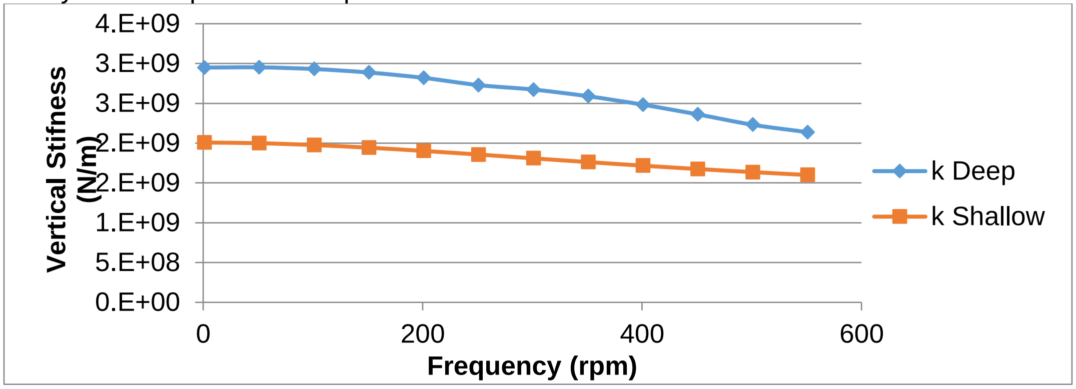

Figure 2b: Vertical stiffness of deep and shallow foundations.

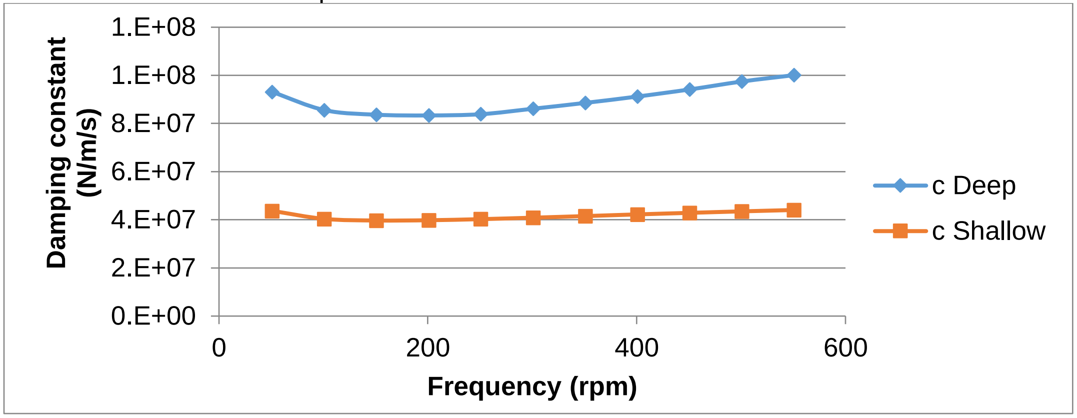

Figure 2c: Vertical damping constant of deep and shallow foundations.

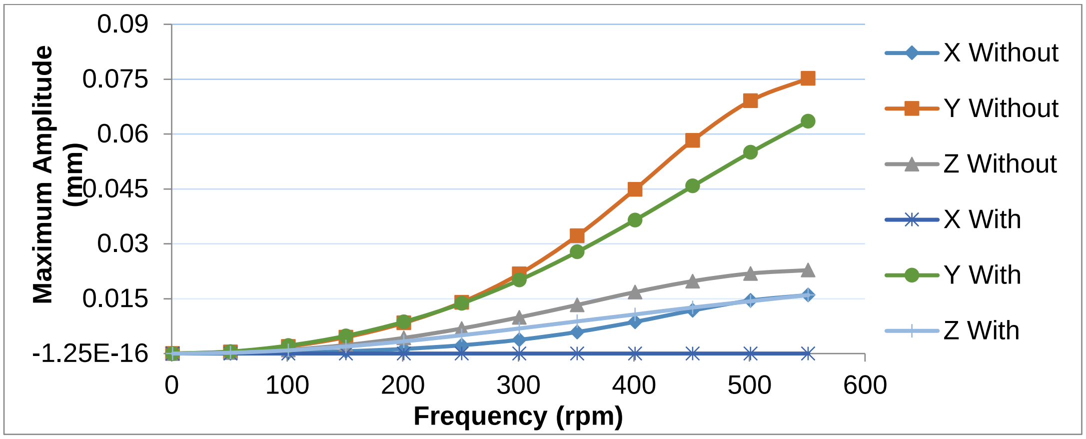

Figure 3a: Dynamic response of shallow foundations with and without embedment.

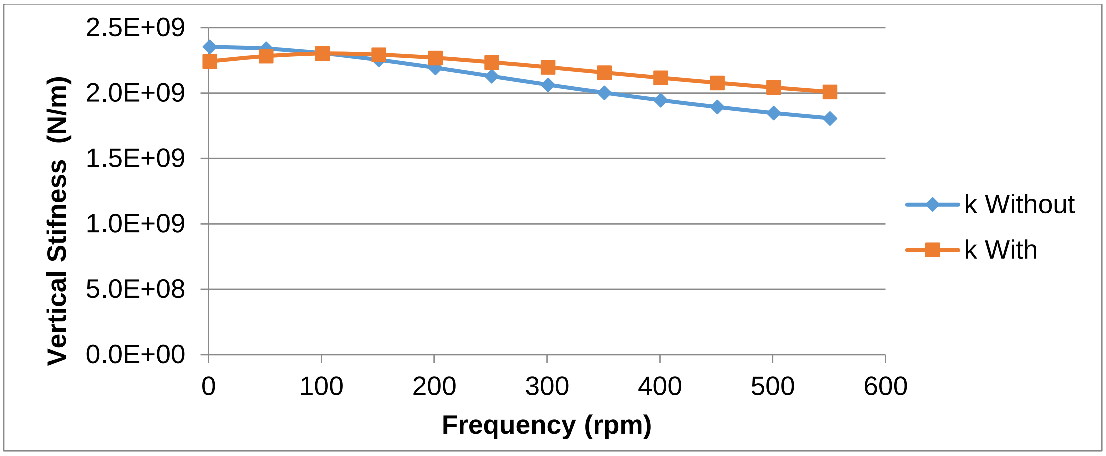

Figure 3b: Vertical stiffness of shallow foundations with and without embedment.

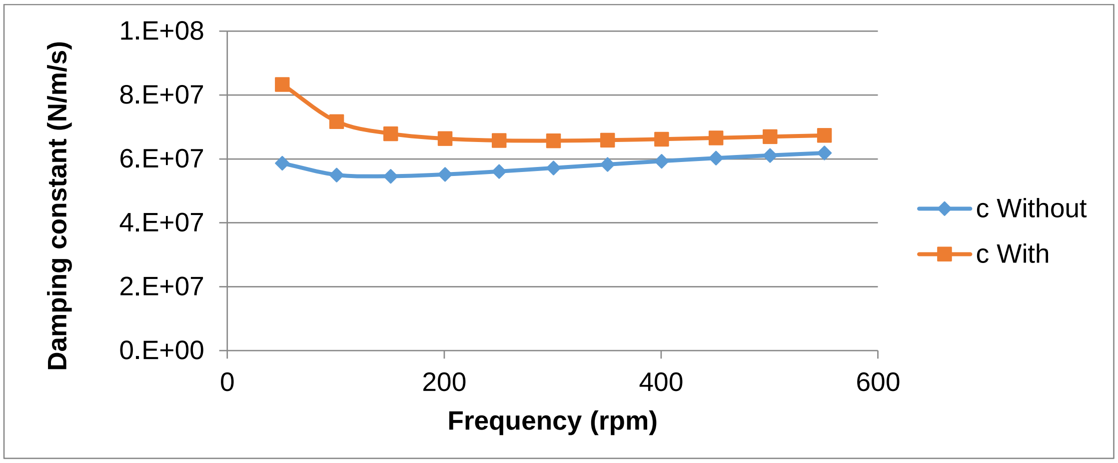

Figure 3c: Vertical damping constant of shallow foundations with and without embedment.

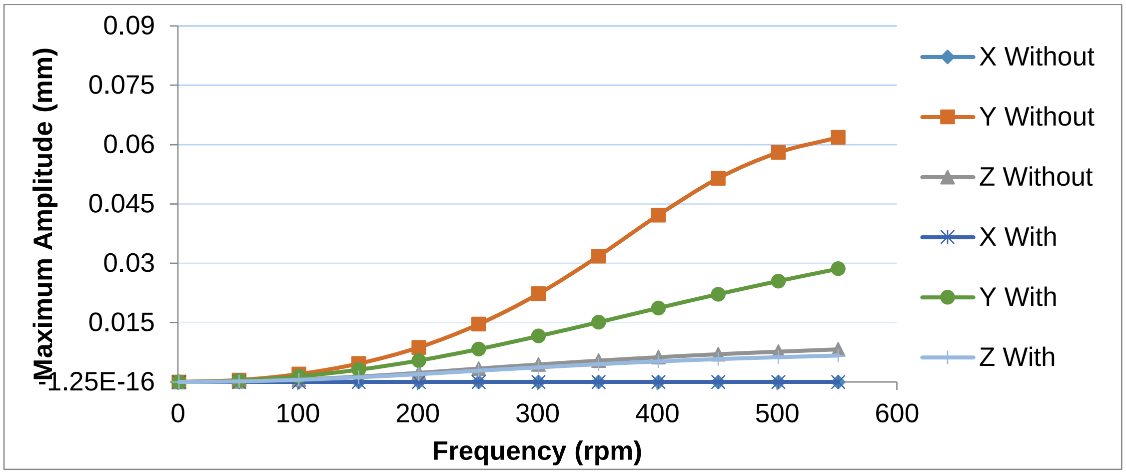

Figure 4a: Dynamic response of deep foundations with and without embedment.

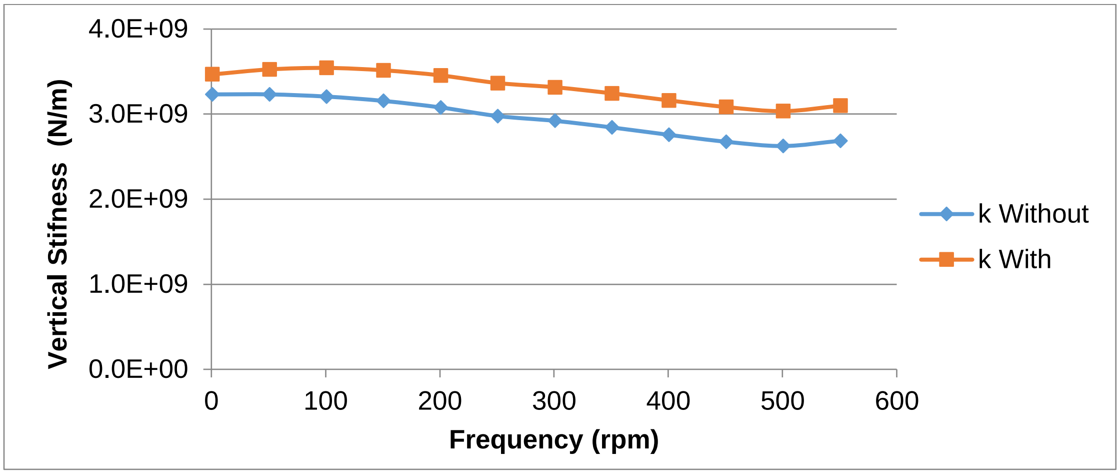

Figure 4b: Vertical stiffness of deep foundations with and without embedment.

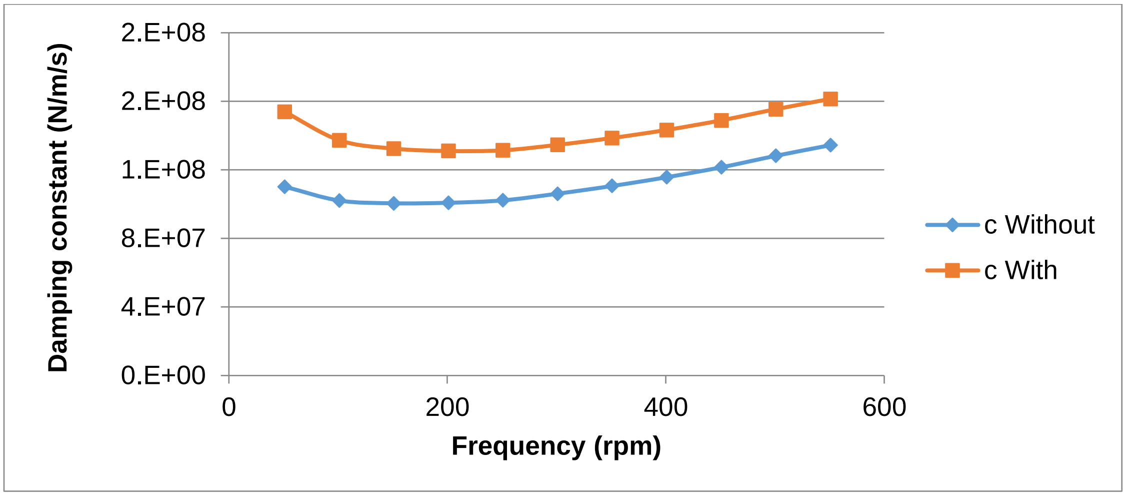

Figure 4c: Vertical damping constant of deep foundations with and without embedment.

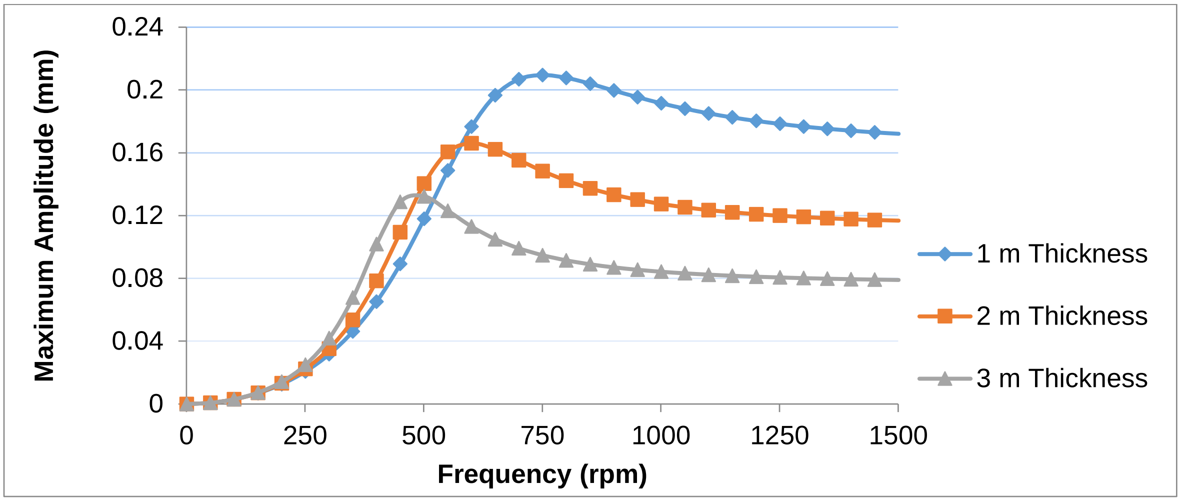

Figure 5a: Variation of dynamic response of shallow foundation with thickness of the foundation.

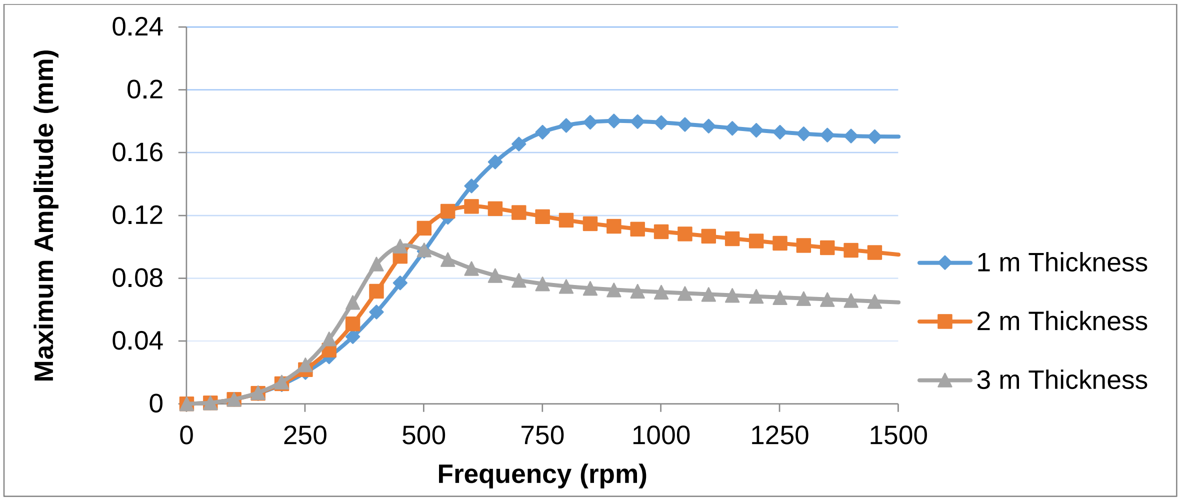

Figure 5b: Variation of dynamic response of deep foundation with thickness of the foundation.

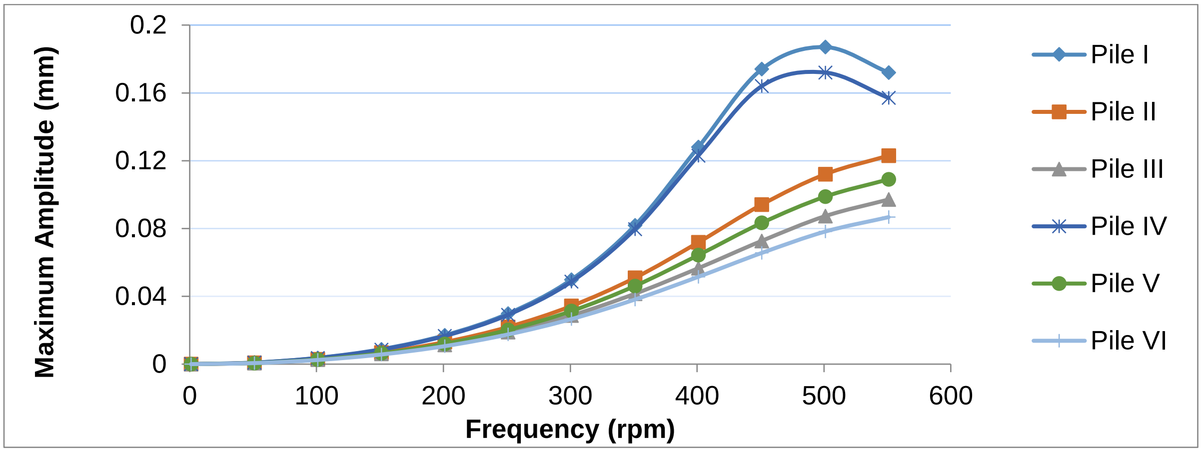

Figure 6: Variation of dynamic response of deep foundation with pile diameter and pile type.

5.5. Effect of the Pile Length

In the section, the foundation shown in Figure 1a is analyzed using the Pile (II), tabulated in Table 2. The lengths of the piles are taken as 10 m, 15 m and 20 m. Figure 7 shows that the length of the pile has a very slight effect of the amplitude of the foundation.

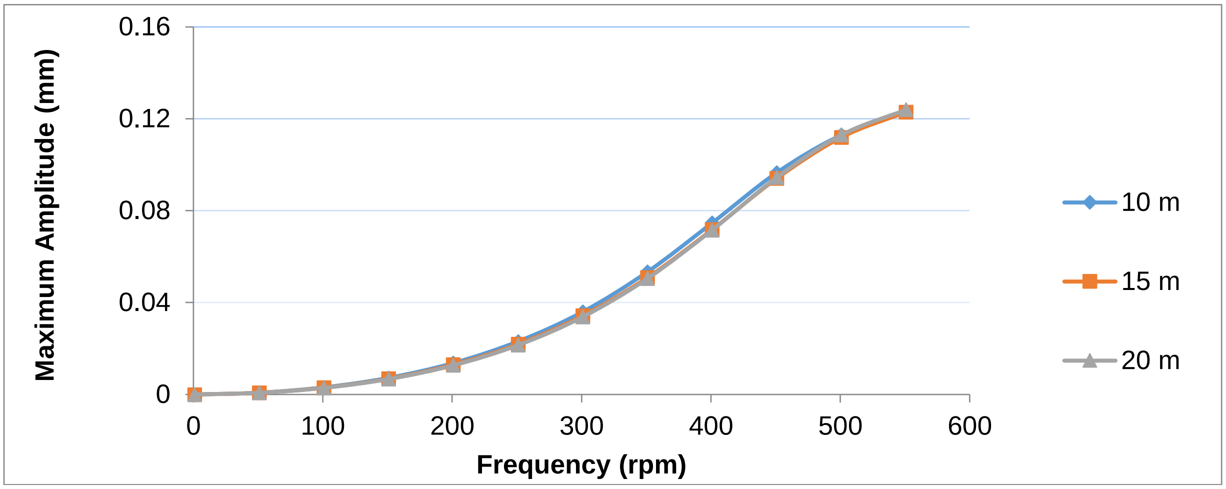

Figure 7: Variation of dynamic response of deep foundation with pile length.

5.6. Effect of the Soil Type

In order to demonstrate the effect of the soil type, the dynamic amplitude of the foundation shown in Figure 1a is calculated assuming the three different soils in Table 1. In this study and in order to clarify the effect of the shear modulus of the soil, the damping ratios of the three soils are kept constant and equal to 0.01. In Figure 8 the soil type has a significant effect on the dynamic response of the foundation. It is obvious that the increase in the soil shear modulus decreases the amplitude of the foundation. However, beyond a certain frequency (450 rpm in deep foundation and 300 rpm in shallow foundation), such a decrease becomes counter-productive.

5.7. Effect of the Soil damping

The aim of this section is to assess the influence of soil damping of the dynamic behaviour of the deep foundation. The foundation shown in Figure 1a is analyzed, assuming three different values of soil damping; 0.01, 0.03 and 0.05. The shear moduli of the soil are kept constant and equal to 72 MPa. It can be seen that the increase in soil damping is always accompanied with a slight decrease in dynamic amplitude of the foundation, as shown in Figure 9.

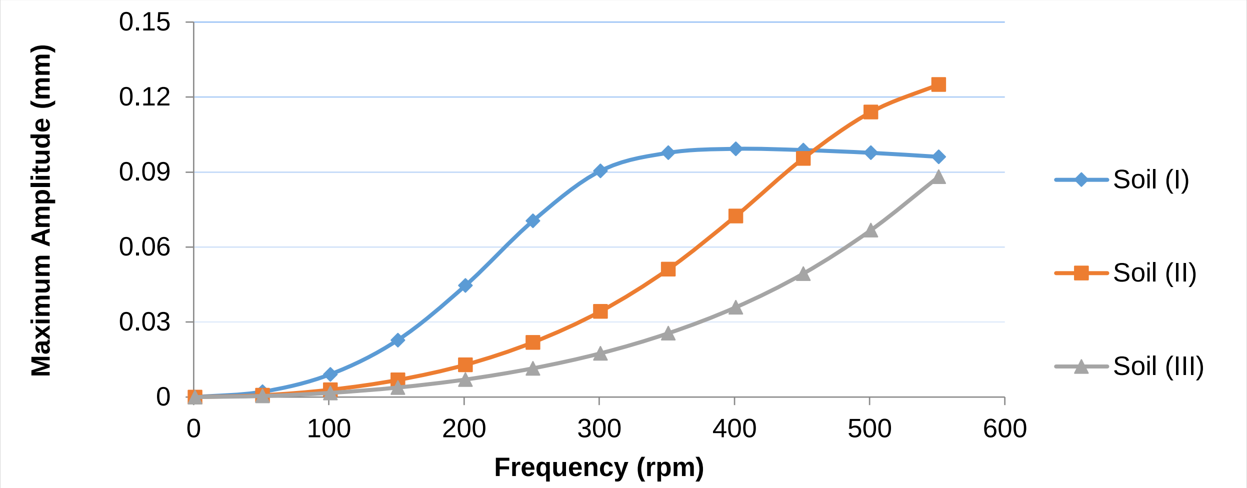

Figure 8a: Variation of dynamic response of deep foundation with soil type.

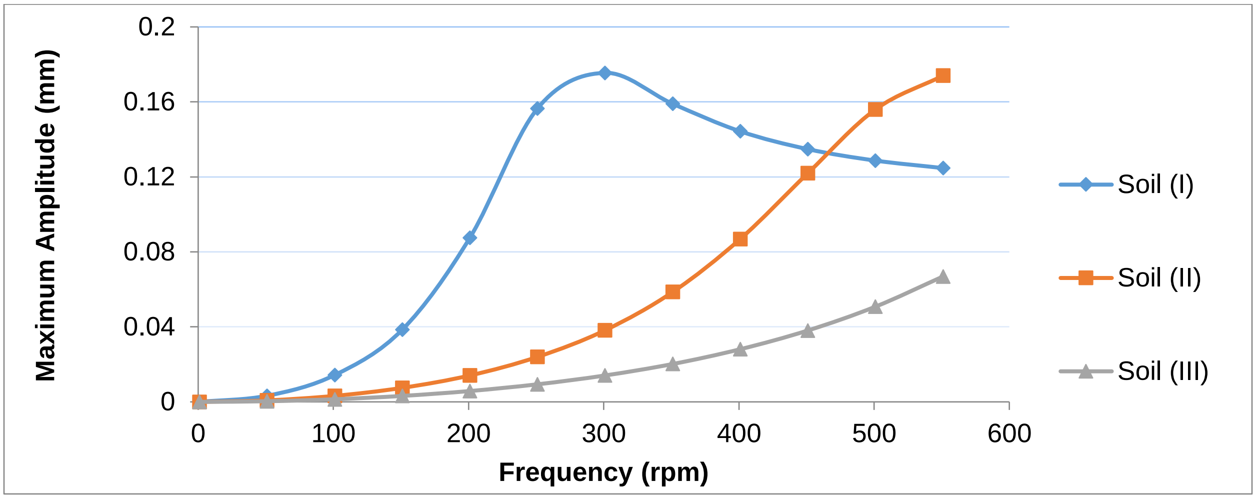

Figure 8b: Variation of dynamic response of shallow foundation with soil type.

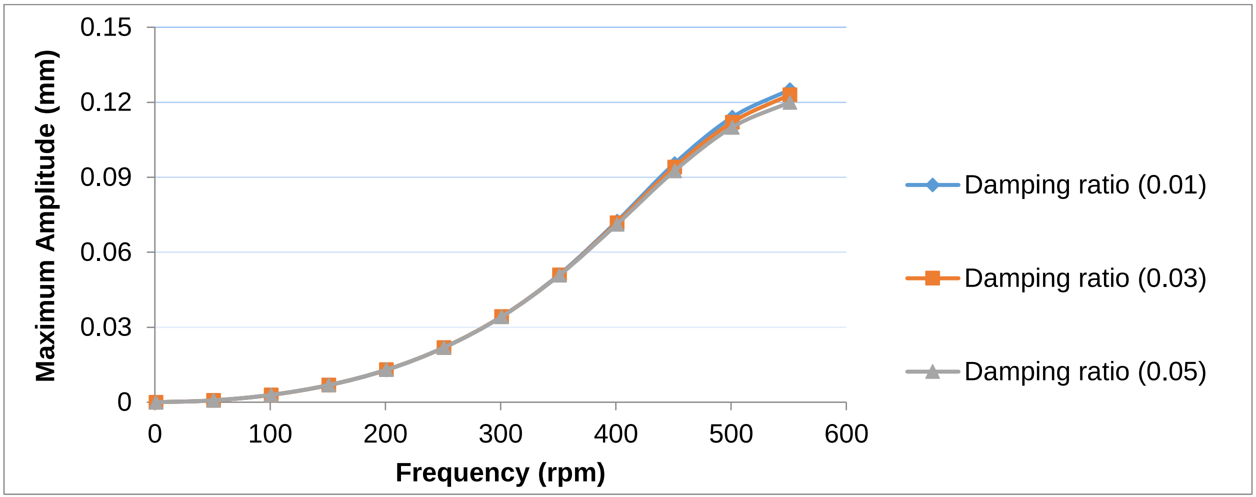

Figure 9: Variation of dynamic response of deep block foundation with soil damping.

6. Conclusions

There are many parameters that affect the behaviour of foundations under a machine with unbalanced force. These parameters are the foundation type, embedment depth, soil type, pile length soil damping, pile length and pile type. Therefore, the design of a machine foundation is a trial-and-error procedure that should lead an engineer to a safe and economical foundation block taking the acceptance criteria into account. The paper examines the impact of these design parameters on the stiffness, damping constant and dynamic response of the foundation. Over a range of frequencies used in the study, the following conclusions can be made:

1. The amplitude of the shallow block foundation is higher than the amplitude of the deep block foundation, when they have the same dimensions.
2. The embedment reduces the vibration amplitude of shallow and deep foundations. In addition, the embedment increases the vertical damping constant for both shallow and deep foundations.
3. The mass of the foundation always decreases the first natural frequency of the foundation.
4. The increase of the pile diameter decreases the maximum vibration amplitude of the foundation.
5. Concrete piles reduce the amplitude when compared with steel pipe piles of the same diameter and length.
6. The increase of the pile length beyond a certain limit has a slight effect of the amplitude of the foundation.
7. Shear modulus of the soil, has a significant effect on the dynamic response of the foundation.
8. The increase in soil damping slightly decreases the vibration amplitude of the foundation

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