Diyala Journal of Engineering Sciences

Journal homepage: https://djes.info/index.php/djes

ISSN: 1999-8716 (Print); 2616-6909 (Online)

Vertical Displacement of Pile Under Dynamic Machine Loading

Noor Q. AL-Kassim*, Mohammed N. Jaro and Bayar J. AL-Sulayvani

Department of civil Engineering, University of Mosul, Mosul, Iraq

ARTICLE INFO

Article history:
Received July 23, 2022
Accepted August 19, 2022

Keywords:
Vertical amplitude
Group Pile – Cap system
Dynamic machine loading
Stiffness
Friction pile
Damping ratio

ABSTRACT

The aim of this research is to calculate the vertical amplitude for pile foundations subjected to dynamic machine loading using a theoretical analysis based on some special formulus. The effect of each of machine frequency, pile length and diameter and embedded depth of pile cap on the vertical amplitude of the pile were studied. It was found that generally, by increasing the pile diameter, pile length, and embedment ratio of pile cap, the maximum vertical amplitude of group pile-cap system decreases. It can also be observed that the ratio of operating machine to natural frequencies (ω/ω_n) corresponding to maximum amplitude decreases with increasing of pile diameter, and ratio of pile cap embedment. On the other hand, it can be seen that the damping ratio of the system was increased with increasing pile diameter and ratio of pile cap embedment, while the stiffness of the system increases with increasing pile length.

1. Introduction

The study of vibrating amplitude of pile subjected to dynamic machine loading is important from practical point of view. The lack attention to design criteria of pile under machine loading may causes failure of pile system due to resonance condition. The analysis of foundations subjected to dynamic loads is a complex process that requires a good understanding of the theory of vibration and its relation with geotechnical engineering that is because it not only includes static loads, but also dynamic loads. This dynamic load is created due to unbalanced forces generated by the machine or its vibratory movement [1].

For low-speed machines subjected to vertical vibration, the natural frequency of the foundation-soil system should be at least double the working frequency to avoid resonance condition. If adjustments in the size and mass of the foundation do not lead to desirable criteria of frequency, a pile foundation may be considered. The using of piles raises the natural frequency of the soil–pile system and may also raises the amplitude of vibration during resonance. Machine vibration supported by pile foundations considered as low amplitudes of vibration (allowable motion is small) comparing with those encountered under earthquake (large strain conditions) [2].

In general, piles can be grouped into two types:

1. End-bearing piles: These piles penetrate through soft soil layers up to a hard stratum or rock. The hard stratum or rock can be considered as rigid.
2. Friction or floating piles: The tips of these piles do not rest on hard stratum. The piles resist the applied load by

* Corresponding author.
E-mail address: noorkosay.civil93@gmail.com
DOI: 10.24237/djes.2022.15302

means of frictional resistance developed at the soil-pile interface.

In dynamic analysis of pile subjected to dynamic machine loading, the two type of piles also be considered. The vertical vibrating amplitude of machine foundation at operating frequency is important value to be calculated for machine pile foundation design. The variation of both of stiffness and damping ratio of group pile – cap system plays an important role for estimating vertical amplitude of the system. There is a need for solution that would be able to calculate the vibrating amplitude of both of stiffness and damping ratio characteristics of group pile – cap system. The current work deals essentially with the effect of several parameters on the vertical amplitude of group pile – cap system subjected to dynamic machine loading.

2. A Short Review

Van Koten et al. (2012) conducted a study on the vibrations of machine foundations and the surrounding soil for both shallow and deep (piles) foundations, and the empirical formulas were selected to evaluate the amplitude of vibrations. They found that the soil on both sides of the foundations greatly increases the damping and reduces the displacement amplitude especially when the foundations are fully embedded. Also, they noticed that the vertical vibrations are well damped by the soil [3]. Ibtihal et al. (2014) used ANSYS V.11 finite element software to model a machine foundation resting on end bearing piles. They concluded that the frequency of oscillation of displacement is decreased as pile cap thickness is increased, and the maximum displacement is increased as pile diameter of the group increases [4]. The behavior of reciprocating machines resting on piles was described by Bharathi et.al (2015). They concluded that the natural frequency is reduced when the spacing between the piles is increased, and the amplitude is decreased when the difference between the natural and operating frequencies is increased. They also found that with increasing the pile's L/D ratio, the natural frequency increases to its maximum value as it moves away from the operational frequency [5]. Patel et al. (2017) conducted a comparison between two type of rotary vibratory machine foundations, hollow block foundation with piles and table mounted block foundation. The results showed that the first type of foundation is stiffer and its frequency is also higher due to the presence of pile in this type of foundation [6]. The effect of dynamic damping (C_{dyn}.) and dynamic stiffness (K_{dyn}.) on the maximum vertical displacement of a surface circular rigid foundation was investigated by Mohammed (2020). He concluded that the dynamic damping affects the maximum displacement more than dynamic stiffness for low values of dimensionless frequency (ao) [7]. Najm (2021) studied the effect of the depth of foundation embedment on the maximum vertical displacement for rectangular foundation. He found that the maximum vertical displacement estimated using numerical methods decreases with increasing the embedment ratio of foundation [8]. The previous studies lack to an experimental model to simulate pile – cap system subjected to dynamic loading. The current research is an attempt to study the effect of some variables on the vertical amplitude under vertical dynamic loading based on the theoretical formulas.

3. objectives and assumptions

3.1 objectives

In this research, the vertical amplitude of floating pile was studied. The effect of each of operating machine frequency (ω), pile length (L), pile diameter (D) and embedment depth ratio (D_f) i.e., the ratio of side wall of soil contact with pile cap, on the vertical amplitude of cap-pile system were taken into account.

3.2 Assumptions

The first step in pile machine foundation analysis is to calculate the vertical damping c_z and stiffness k_z. The following assumptions were adopted

1. The pile is vertical with circular cross section, elastic.
2. The pile is floating.
3. The pile cap is in contact with the soil.
4. The soil above pile tip behaves as thin, independent linearly elastic layers. [2].

As a result of the last assumption, the plane strain condition is assumed. Figure 1 shows the soil-pile-foundation model used to define vertical displacement of foundation. The contribution of the pile cap should be taken into consideration when calculating stiffness and damping constants. As shown in Figure (2), the pile can be idealized as a mass-spring-dashpot system.

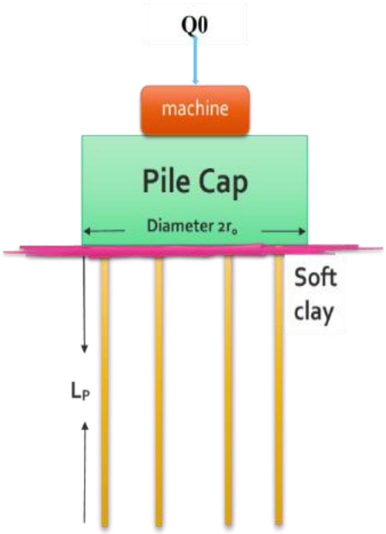


Figure 1. Soil – foundation model

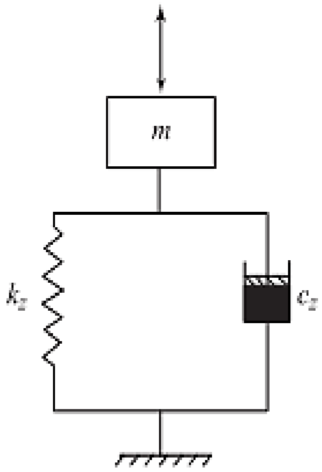


Figure 2. Mass spring-dashpot system

Both of vertical stiffness (k_z) and vertical damping (c_z) of pile can be calculated as [9]

$$k_z = \left(\frac{E_P A}{R}\right) f_{z1} \quad (1)$$

$$c_z = \left(\frac{E_P A}{\sqrt{Gs/\rho}}\right) f_{z2} \quad (2)$$

where:
E_P=modulus of elasticity of the pile material
A=area of pile cross section
R=radius of pile
G_s=shear modulus of soil
ρ_s=density of soil
f_{z1}, f_{z2}=nondimensional parameters shown in Figures (3) and (4)

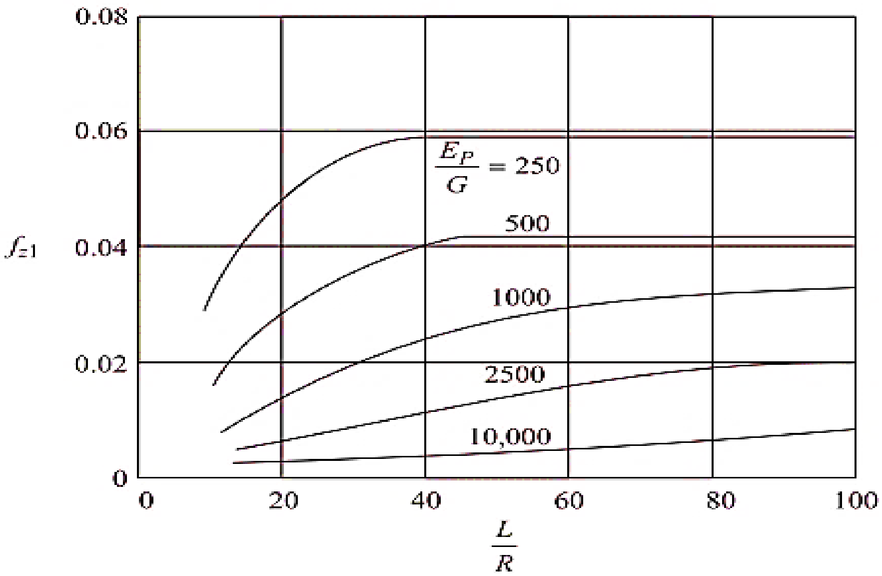


Figure 3. Variation of *fz*1 with *L*/*R* and *EP*/*G* for floating piles [9]

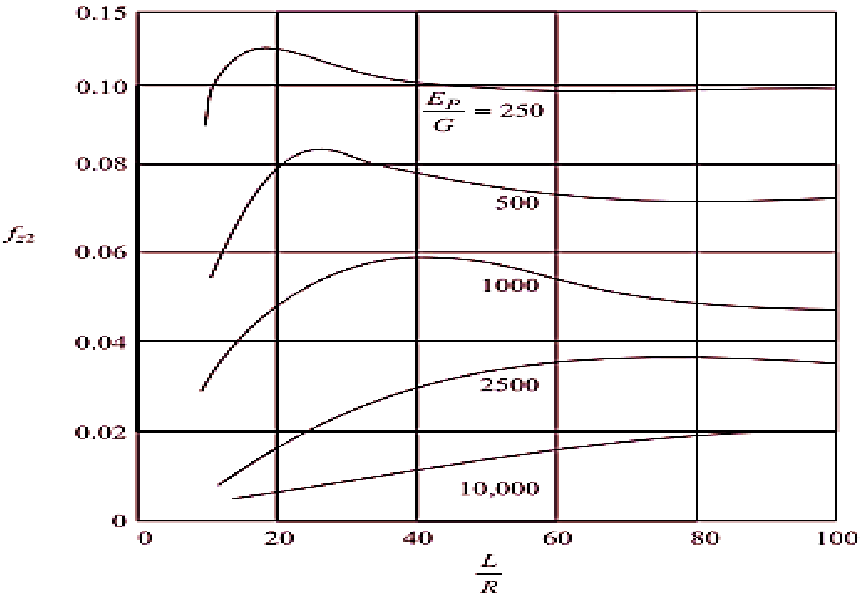


Figure 4. Variation of *fz*2 with *L*/*R* and *EP*/*G* for floating piles [9]

Where, L = length of pile

The following steps are used to estimate stiffness and damping of pile group as:

$$k_{z(g)} = \frac{\sum_1^n k_z}{\sum_{r=1}^n \alpha_r} \quad (3)$$

$$c_{z(g)} = \frac{\sum_1^n c_z}{\sum_{r=1}^n \alpha_r} \quad (4)$$

where: kz(g) = stiffness for the pile group

cz(g) = damping for the pile group

n = number of piles in the group

αr = the interaction factor describing the contribution of the rth pile to the displacement of the reference pile (that is αr =1). αr can be obtained from the static solution of Poulos (1968) [10]. This is shown in Figure (5).

Stiffness and damping of pile cap can be calculated as:

$$k_{z(\text{cap})} = G_s D_f \bar{S}_1 \quad (5)$$

$$c_{z(\text{cap})} = D_f r_0 \bar{S}_2 \sqrt{G_s \rho_s} \quad (6)$$

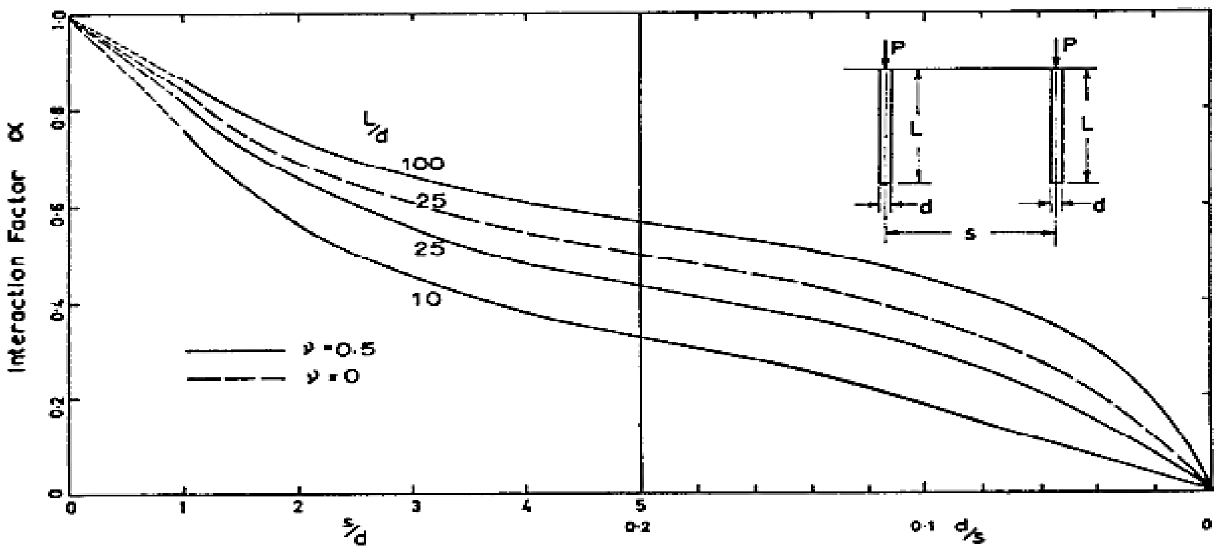


Figure 5. Settlement interaction between two piles [10]

The total stiffness and damping representing the algebraic addition as:

$$k_{z(T)} = \frac{\sum_1^n k_z}{\sum_{r=1}^n \alpha_r} + G_s D_f \bar{S}_1 \quad (7)$$

$$c_{z(T)} = \frac{\sum_1^n c_z}{\sum_{r=1}^n \alpha_r} + D_f r_0 \bar{S}_2 \sqrt{G_s \rho_s} \quad (8)$$

$$D_z = \frac{c_{z(T)}}{2\sqrt{k_{z(T)} m}} \quad (9)$$

Where, G_s= shear modulus of soil
D_f= embedded depth of pile cap
$\bar{S}_1$ =2.7, $\bar{S}_2$= 6.7
D_z=Damping ratio
m= mass of the pile cap and the machine.

The natural frequency (ω_n)can be calculated as:

$$\omega_n = \sqrt{\frac{k_{z(T)}}{m}} \quad (10)$$

Amplitude of vibration at frequency other than resonance can be calculated using the following formula:

$$A_z = \frac{\frac{Q_0}{k_{z((T)}}}{\sqrt{\left(1-\frac{\omega^2}{\omega_n^2}\right)^2 + 4D_z^2\frac{\omega^2}{\omega_n^2}}} \quad (11)$$

Where, Q_o= force amplitude

ω=operating frequency

4. Parametric Study of System (pile foundation- soil - machine)

The effects of each of vibrating machine frequency (ω), pile length (L), pile diameter (D) and embedment depth ratio of pile cap (D_f) on the vertical amplitude of the (group pile – cap) system were studied. The thickness of the pile cap was taken as 2 m with square shape of (3 × 3) m. The number of piles was taken as 4. A harmonic vertical force was applied to the foundation at frequencies ranging from 30 to 200 rad\sec. For each frequency, the force amplitude (Q_o) remained constant at 100 kN. Table (1) shows the variation of parameters used in this study. The ratio of embedment depth of pile cap was taken as (0, 50, 100) %, i.e., surface, half embedded and fully embedded cap respectively.

Table 1: Various Parameters Selected for the Parametric Study

Pile Dimeter (m)	Pile Length (m)	Ratio of embedment depth of pile cap (%)
0.3	8, 10, 12	(0,50,100)
0.5	8, 10, 12	(0,50,100)
0.7	8, 10, 12	(0,50,100)

Table (2) shows the properties of soil and pile. It is assumed that the soil is confined saturated soft clay, therefore the Poisson's ratio is close to 0.5, and shear modulus G_s is about of 8000 kPa [11].

Table 2: The engineering properties of soil and pile [11]

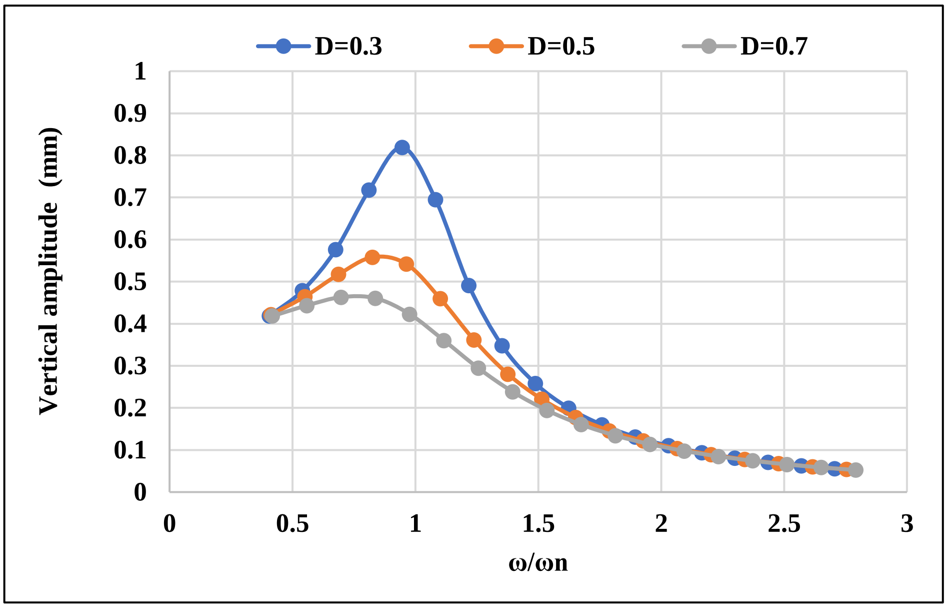
Unit weight of concrete kN/m^3	24
Poisson's ratio of concrete υ_c	0.15
Modulus of elasticity of the pile material kPa (E*p*)	21×10^6
Shear modulus of soil G_s kPa	8000
Unit weight of soil kN/m^3	16
Poisson's ratio of soil υ	0.5

5. Results and discussion

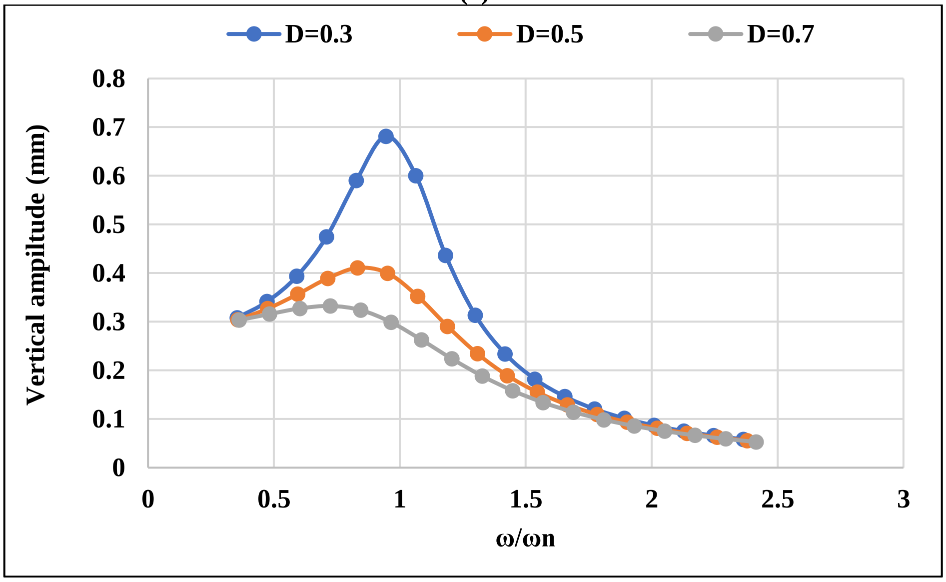
5.1 Study the effect of pile diameter

Figure (6a-c) shows the variation of vertical amplitude (A_z) with the ratio of machine to natural frequencies (ω/ω_n).

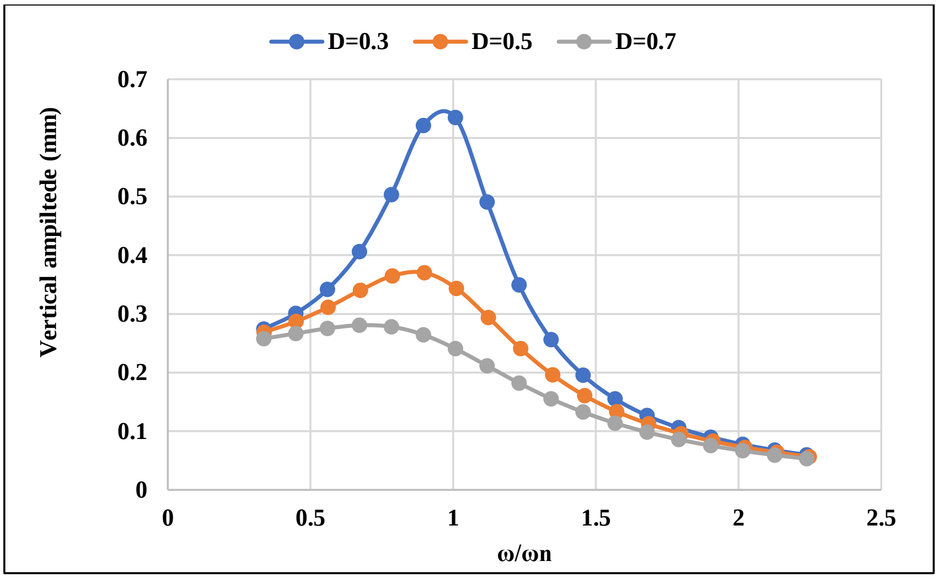
This Figure also shows the effect of pile diameter on the vertical amplitude of cap-pile system for pile length (L=8, L=10, L=12) m respectively. Totally, the vertical amplitude decreases with increasing pile diameter. It can be also seen that the (ω/ω_n) corresponding to max. displacement decreases from almost (1.0 – 0.7) when pile diameter increases from (0.3-0.7) m for all pile lengths. This mean that the system turns far away from the resonant state when the pile diameter increases.



(a)



(b)



(c)

Figure 6. vertical amplitude versus ω/ωn for pile length (a) L=8m, (b) L=10m and (c) L=12m

This decrement of vertical amplitude and (ω/ω_n) with pile diameter is due to the increase in the damping ratio with increasing pile diameter. Figure (7) shows this behaviour.

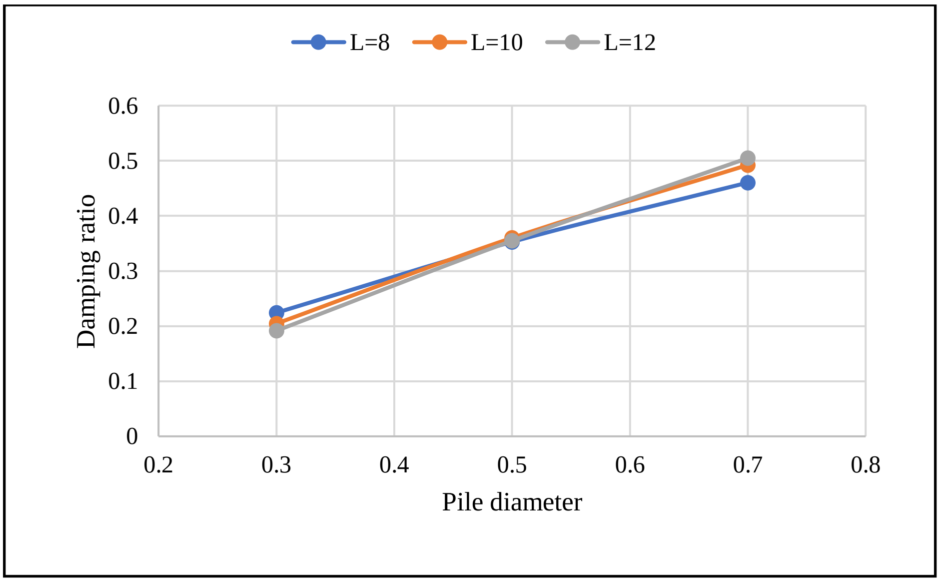
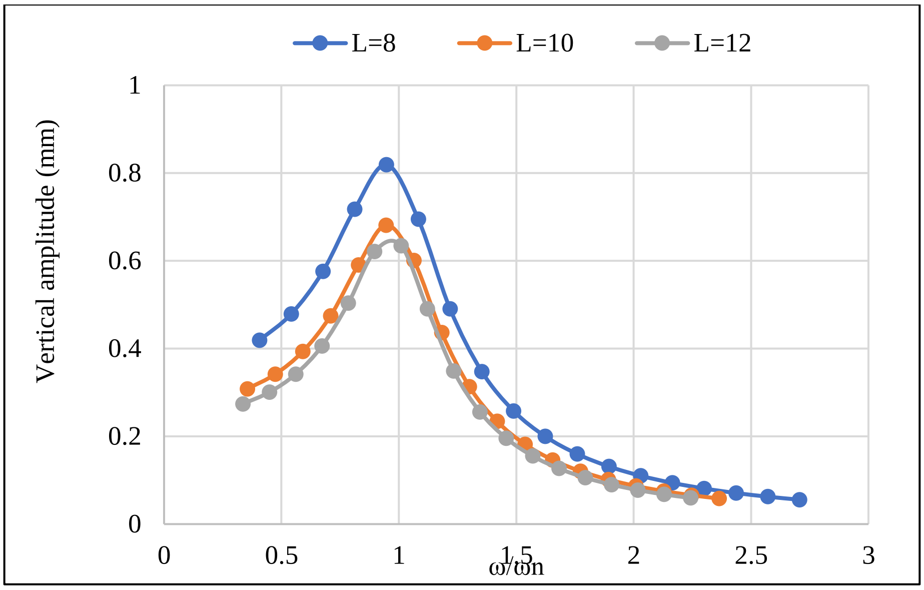


Figure 7. Damping ratio versus pile diameter

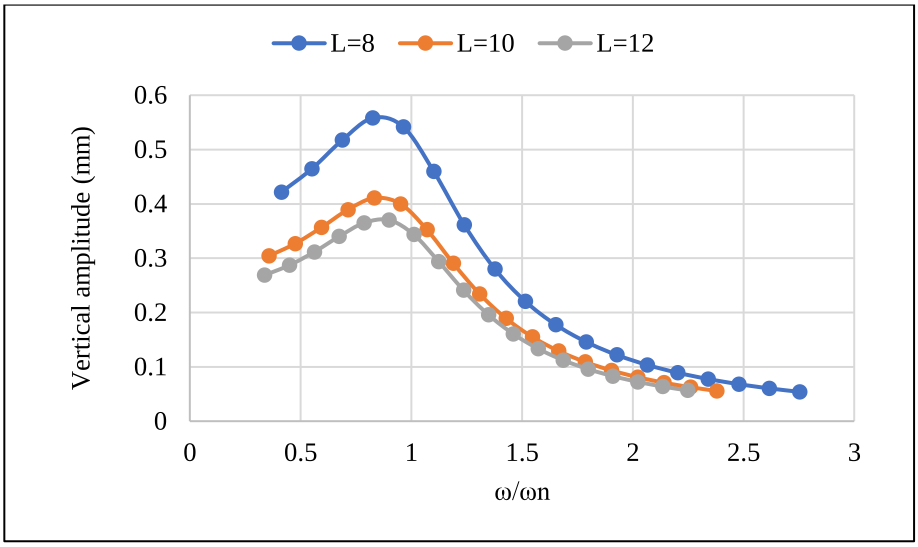
The effect of pile diameter on the vertical amplitude is very little for (ω/ω_n <0.5) and for (ω/ω_n >1.75) i.e., for low and high frequencies respectively. The significant effect of pile diameter on the amplitude is ranged for (ω/ω_n) between (0.5-1.75). This is due to the increases of damping ratio (D_z) with increasing the diameter of pile.

5.2 Study the effect of pile length

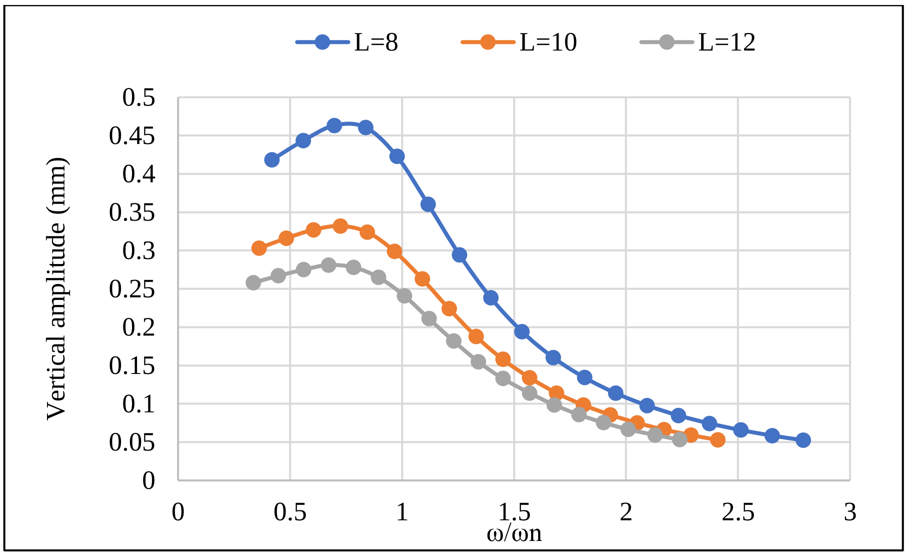
Figure (8) shows the effect of pile length on the vertical amplitude of cap-pile system for pile diameter (D=0.3, 0.5, 0.7) m respectively. The vertical amplitude decreases with increasing pile length.



(a)



(b)



(c)

Figure 8. vertical amplitude versus ω/ωn for pile diameter D=0.3(a), D=0.5(b), D=0.7(c)

This decrement in vertical amplitude is due to the increase of stiffness with increasing pile length and not due to the increase of damping ratio. Figures (9) and (10) shows the variation of stiffness and damping ratio with pile length respectively.

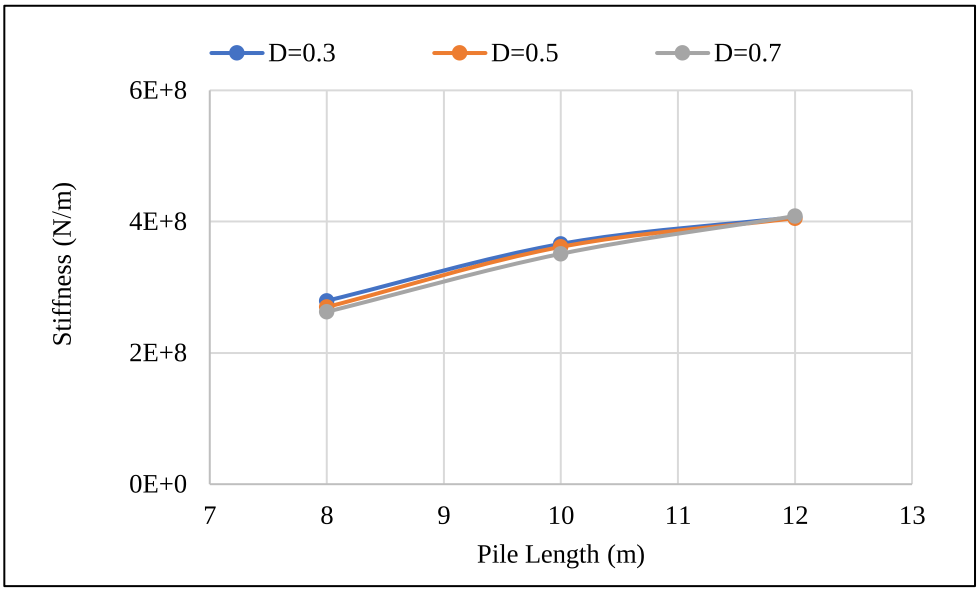


Figure 9. Stiffness versus pile length

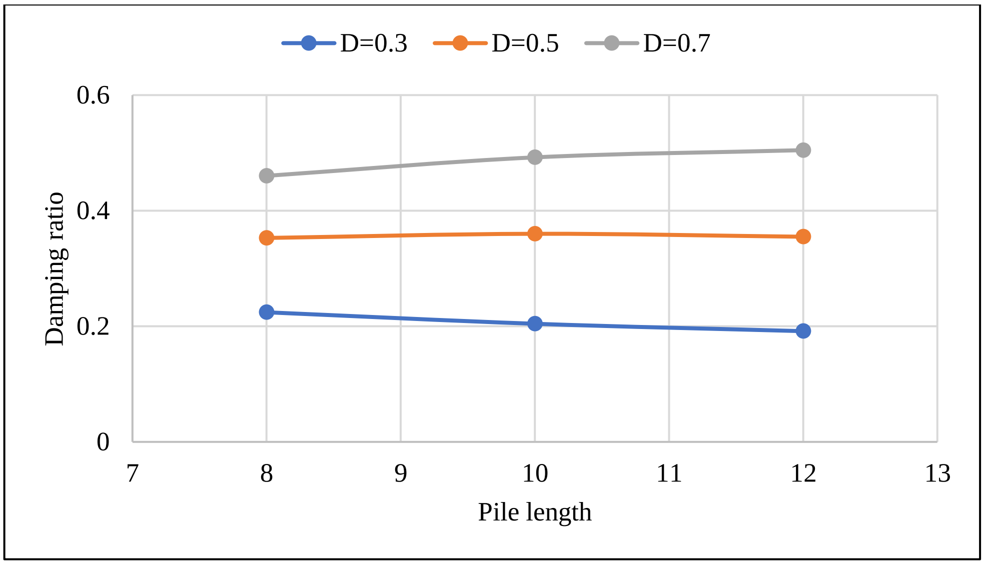
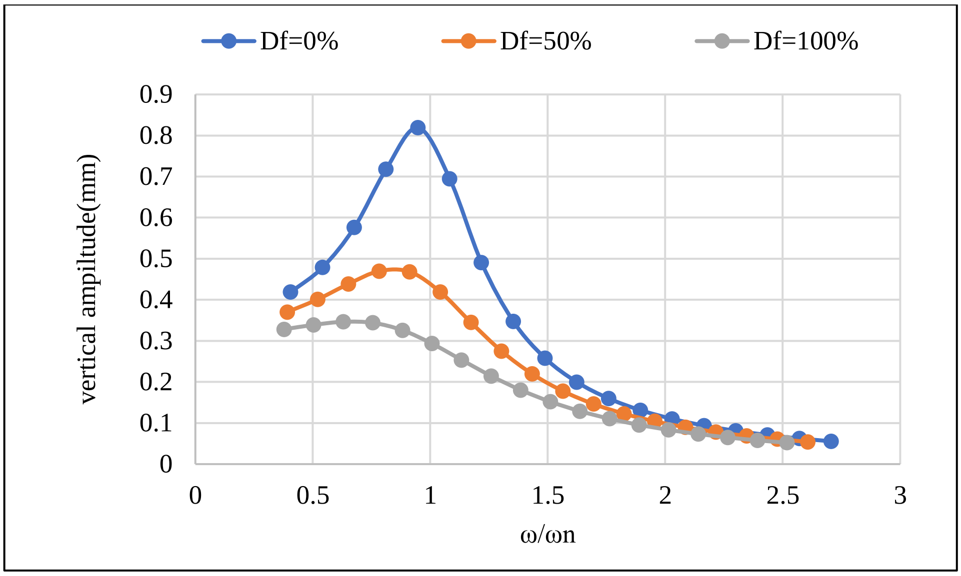


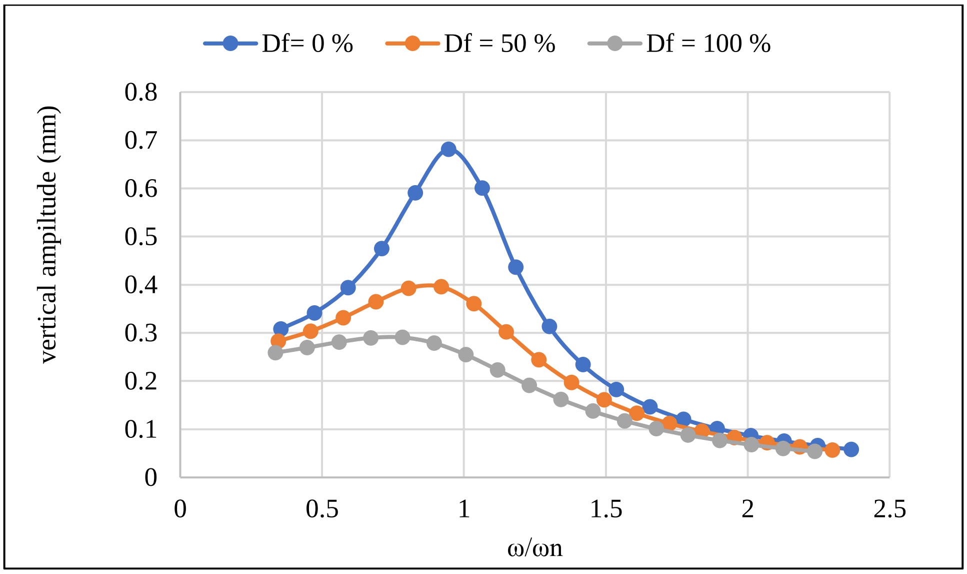
Figure 10. Damping ratio versus pile length

5.3 Study the effect of depth of pile cap

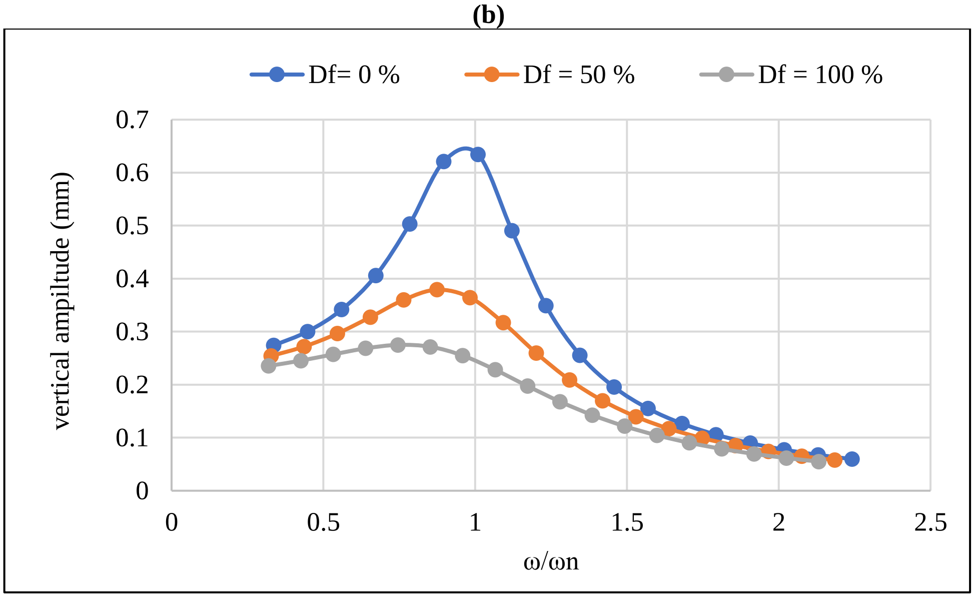
Figure (11 a-c) shows the effect of embedment depth ratio of pile cap on the vertical amplitude (A_z) of group pile-cap system for the pile length of L=8, 10 and 12 m respectively and for constant pile diameter D=0.3 m. The vertical amplitude decreases with increasing the ratio of embedment depth of pile cap. It can be also seen that the (ω/ω_n) corresponding to max. displacement decreases from almost 0.95 to 0.4 when the ratio of embedment depth of pile cap increases from 0 to 100 % for all pile diameters and lengths.



(a)



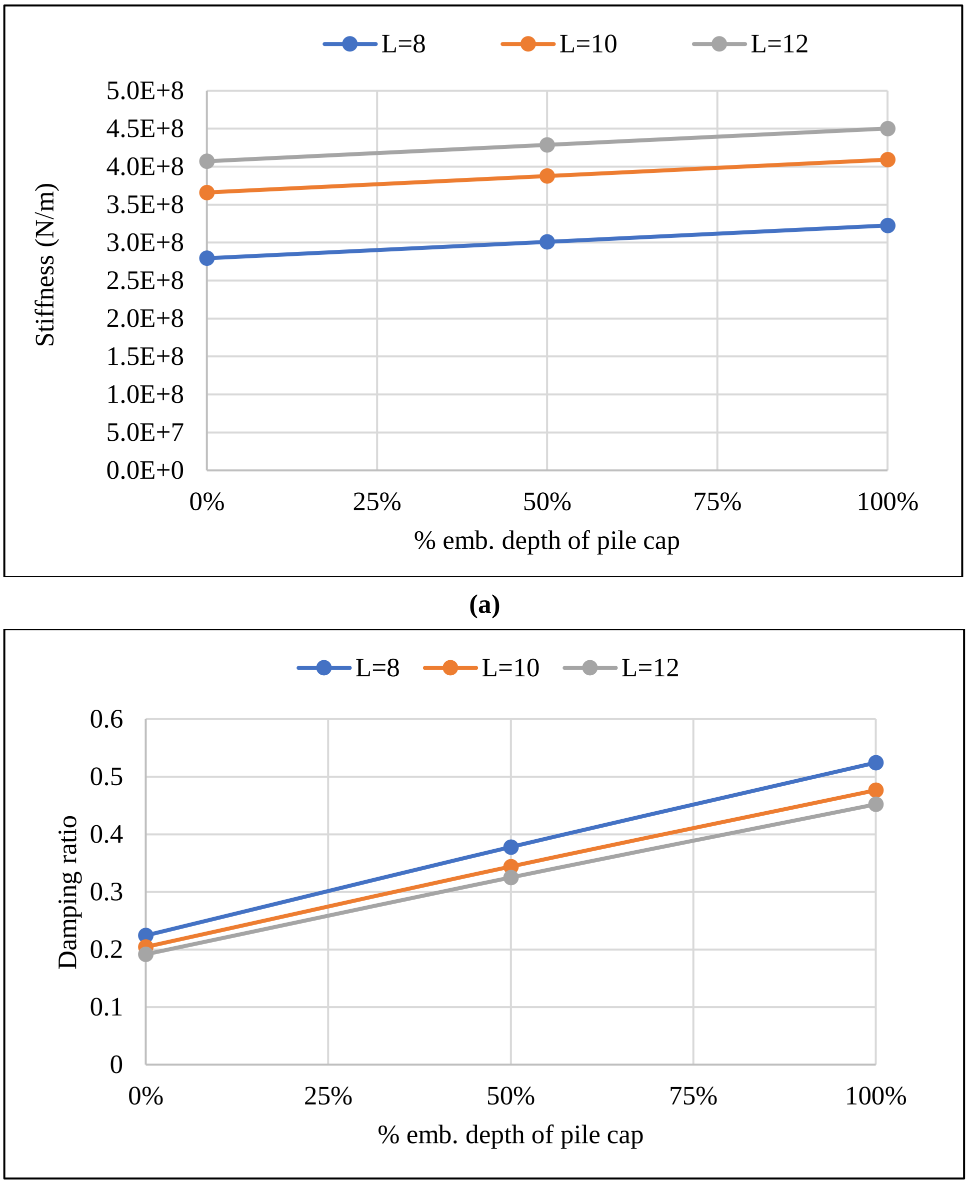
(b)



(c)

Figure 11. Vertical amplitude versus ω/ωn for pile diameter of 0.3 m and pile length L=8 (a), L=10 (b) and L=12 (c)

This decrement is because of increasing both of damping ratio and stiffness with increasing the ratio of embedment depth of pile cap. Figure (12 a and b) shows the increasing of stiffness (k_z) and damping ratio (D_z) with increasing of cap embedded ratio respectively.



(b)

Figure 12. stiffness (a) and Damping ratio (b) versus pile cap embedment ratio

The effect of the ratio of embedment depth of pile cap on the amplitude is scarce for (ω/ω_n <0.4) and (ω/ω_n >1.8) i.e. for low and high frequency. The significant effect of cap embedment ratio on the amplitude is ranged for ($\omega/\omega n$) between 0.4 to 1.8.

6. Conclusions and suggestions for future works.

6.1 Conclusion

Based on the results of the analysis of pile under dynamic machine loading, the following conclusions can be pointed:

1. The ratio of operating machine to natural frequencies (ω/ω_n) corresponding to maximum vertical amplitude decreases

with increasing of pile diameter, and ratio of pile cap embedment.

2. In general, by increasing the pile diameter, pile length and pile cap embedment ratio, the maximum vertical amplitude of group pile-cap system decreases.
3. The damping of group pile-cap system increases with increasing pile diameter, while the stiffness of the system increases with increasing pile length.
4. As the ratio of embedment depth of pile cap is increased, both of damping and stiffness are increased.

6.2 Suggestion for future works

1. Studying the effect of depth of bedrock from the surface on the vertical amplitude of the group pile – cap system under dynamic machine loading.
2. Studying the effect of shear modulus on the vertical amplitude of the system under dynamic loading.
3. Studying the effect of variables in this research on the vertical displacement and vibration numerically using some special programs such as PLAXS.

References

[1] S. Ayan.and K. B. Piyush, "Dynamic Analysis Of MachineFoundation ", International Journal of Innovative Research in Science, Engineering and Technology ,2014.

[2] B.M. Das. and G. V. Ramana, "Principles of Soil Dynamics ", Cengage Learning 2nd, 2011.

[3] H. Van Koten, Zoetermeer and P.C.J Hoogenboom, "Vibrations of machine foundations and surrounding soil ", Delft University of Technology, Delft, the Netherlands , HERON Vol. 57 , No. 1, 2012

[4] A. M. Ibtihal, Y. F. Dr. Mohammed, J.H. Dr. Mohammed, "Finite Element Analysis of Machine Foundation Resting on End Bearing Piles ", Eng. & Tech. Journal, Volume 32, Part A, No. 1, 2014.

[5] M. Bharathi & S. Swami and M. Shyamal, "Analysis of Reciprocating Machine Foundations Resting on Piles ", PP. C018., 2015.

[6] H.A. Patel , H.K. Dhameliya and Y.R. Tank, "Dynamic Analysis of Separate Foundation for Low Frequency Machine With Soil Interaction " , International Journal of Engineering Trends and Technology (IJETT) , Volume 46 No. 8, 2017.

[7] A. I. Mohammed, "Analytical and numerical study of vertical vibration of foundations for the machines resting on the soil surface ". Msc thesis, Civil Engineering Department, Engineering College, university of Mosul, Iraq, 2020.

[8] A. A. Najm, "Analytical and Numerical Study of Embedded Foundation Subjected to Vibratory Loads ". Msc thesis, Civil Engineering Department, Engineering College, university of Mosul, Iraq, 2021

[9] M. Novak,, and B. El-Sharnouby, "Stiffness and Damping Constants of Single Piles "*Journal* of the Geotechnical Engineering Division, ASCE, Vol. 109, No. GT7, pp. 961-974, 1983.

[10] H. G. Poulos, "Analysis of Settlement of Pile Groups,"Geotechnique**,**Vol. 18, No. 4, pp. 449-471, 1968.

[11] B. G. Look, "Handbook of Geotechnical Investigation and Design Tables and Francis ", ISBN978-0-415-43038-8 , 2007.