ANALYSIS ON LATERALLY LOADED GROUP PILES BY PLAXIS 3D FOUNDATION

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ABSTRACT

It has been known that a group pile lateral capacity is smaller than the sum of each pile capacity composing the group. A reduction factor, also known as efficiency factor, is required to determine the effective lateral capacity of group piles. To the authors knowledge, in most geotechnical text books, only the spacing of piles is considered in evaluating the pile group lateral capacity. No consideration on the effects of soil stiffness modulus and the total number of piles forming the group are taken into account. The availability of a geotechnical 3D finite element software, namely Plaxis 3D foundation, made it possible to evaluate those factors. It is found that the bigger the number of piles in a group the lower the efficiency factor, the higher the soil stiffness modulus the greater the efficiency.

Key Words:
Efficiency factor, group pile lateral capacity, PLAXIS 3D Foundation

1. BACKGROUND

Apart from axial loads, lateral loads induced by wind, earthquakes, berthing of ships, vehicle acceleration and braking forces on the bridges, etc, have to be taken into account in designing a foundation system. Therefore, determination of the lateral capacity of pile foundation is one of the utmost important in foundation engineering.
It is well understood that a group pile lateral capacity is smaller than the sum of each pile capacity composing the group. A multiplier is required to determine the effective lateral capacity of group piles. The multiplication factor is known as group efficiency factor or reduction factor. In the available geotechnical text books, the only factor considered in determining the reduction factor is the center to center spacing of the piles.
To the authors knowledge, no in depth study has been carried out to investigate the influence of the total number of piles forming the group and the effects of soil stiffness on the said efficiency factor. To answer whether there is any influence of these factors on the carrying capacity of the laterally loaded group pile, under the supervision of the second author, the first author carried out numerous analysis by using Plaxis 3D Foundation software version 2.2.

2. SCOPE OF RESEARCH

Due to time constraints, the extend of the study is limited to the following scope:

- Only 1m diameter bored pile of 40 meter length is considered.
- The center to center spacing of piles considered are 4D, 5D and 6D, where D is the diameter of the pile.
- In evaluating the effect of pile spacing, number of piles taken into account in a group is 4, 9, 16, 25, 36, 49 and 64 piles.
- The value of soil stiffness ranging from 3000 kN/m^2 to 25000 kN/m^2.
- In evaluating the effect of soil stiffness modulus, number of piles considered in a group is 2, 4, 6, 9, 12, 25, 36, 49 and 64.
- Non existence of axial load.
- Pile head deflection is limited to 6 mm.
- No pile cap effect is considered.
- Only fixed head capacity of piles is considered. As the present Plaxis version cannot determine the single pile fixed head capacity, the pile single pile capacity of pile is determined from finite difference method.

3. LITERATURE REVIEW

There are numerous methods available in determining the lateral capacity of a single pile, e.g. Reese Matlock method, Chang method, finite difference method, etc. Of all the available methods, only finite difference method can directly evaluate the pile lateral carrying capacity of layered soils without going through the averaging of the horizontal subgrade reaction coefficient. Therefore, this method is adopted in determining the lateral capacity of a single pile.

3.1 Finite Difference Method

Winkler's model (1867) stated that the reaction force of a laterally loaded pile is proportional to the displacement. Pressure (P) and deflection (y) are related through the coefficient of horizontal subgrade reaction (k_h),

$$P = k_h \cdot y \quad (1)$$

The pile is considered as a thin rod which satisfies the following equation:

$$E_p \cdot I_p \cdot \frac{d^4 y}{dz^4} = -P \cdot B \quad (2)$$

Where:
E_p = Modulus elasticity of pile
I_p = Moment inertia of pile
Z = Depth
B = Diameter of pile

Combining equation (1) and (2),

$$E_p \cdot I_p \cdot \frac{d^4 y}{dz^4} + k_h \cdot B \cdot y = 0 \quad (3)$$

The solution to the above differential equation can be obtained either analytically or numerically. An analytical solution is easy to obtain when the value of k_h is constant throughout the pile. When the value of k_h varies with depth, a numerical solution by finite difference method is employed (Palmer and Thompson, 1948; Gleser, 1953).

In this method, the basic differential equation (3) is written in the form of finite difference as follows:

$$E_p I_p \left(\frac{y_{i-2} - 4y_{i-1} + 6y_i - 4y_{i+1} + y_{i+2}}{\delta^4} \right) + \left(k_h \cdot B \cdot y_i\right) = 0 \quad (4)$$

Equation (4) leads to:

$$y_{i-2} - 4y_{i-1} + \alpha_i y_i - 4y_{i+1} + y_{i+2} = 0 \quad (5)$$

With:

$$\alpha_i = 6 + \frac{k_{hi} \cdot L^4 \cdot B}{E_p \cdot I_p \cdot n^4} \quad (6)$$

Where:
n = number of interval throughout the pile
k_{hi} = Coefficient of horizontal subgrade reaction at point i.

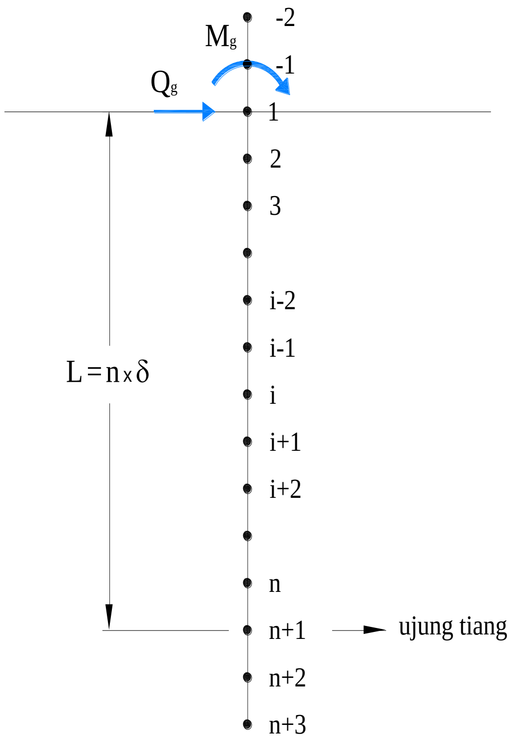

Figure 1 Finite Difference Method for Laterally Loaded Pile

A total simultaneous equation n+5 is needed to calculate the n+5 displacement which is unknown at the point (-2, -1, n +2 and n +3). Equation (6) can be employed from point 2 to point n in order to provide (n-1) equations. Further equations can be obtained from boundary conditions at the pile head.

At the pile head there are two conditions to consider, i.e. Free head and fixed head conditions.

3.1.1. <u>Free head pile</u>
Shear force:

$$E_p \cdot I_p \cdot \frac{d^3 y}{dz^3} = Q_g \quad (7)$$

thus:

$$-y_{-2} + 2y_{-1} - 2y_2 + y_3 = \frac{Q_g \cdot L^2}{E_p \cdot I_p \cdot n^3} \quad (8)$$

Moment:

$$E_p \cdot I_p \cdot \frac{d^2 y}{dz^2} = M_g \quad (9)$$

hence:

$$y_2 - 2y_1 + y_{-1} = \frac{M_g \cdot L^2}{E_p \cdot I_p \cdot n^2} \quad (10)$$

3.1.2 <u>Fixed head pile</u>
Shear force:

$$E_p \cdot I_p \cdot \frac{d^3 y}{dz^3} = Q_g \quad (11)$$

thus:

$$-y_{-2} + 2y_{-1} - 2y_2 + y_3 = \frac{Q_g \cdot L^2}{E_p \cdot I_p \cdot n^3} \quad (12)$$

Rotation:

$$E_p \cdot I_p \cdot \frac{dy}{dz} = 0 \text{ ....} (13)$$

hence:

$$y_2 - y_{-1} = 0 \text{ ....} (14)$$

The pile tip is considered free, so:

- Shear Force at pile tip:

$$E_p \cdot I_p \cdot \frac{d^3y}{dz^3} = 0 \text{ ....} (15)$$

hence:

$$-y_{n-1} + 2y_n - 2y_{n+2} + y_{n+3} = 0 \text{ ....} (16)$$

Moment at pile tip:

$$E_p \cdot I_p \cdot \frac{d^2y}{dz^2} = 0 \text{ ....} (17)$$

hence:

$$y_n - 2y_{n+1} + y_{n+2} = 0 \text{ ....} (18)$$

Two more required equations are obtained from equilibrium condition of horizontal force and moment.

Another way to solve the above is to ignore the shear force equation at the pile end (tip) and the pile head (top), i.e., equations (8) or (12) and (16), therefore, ignore the two displacement variables at the point -2 and n +3 . In this case only n +3 equations have to be solved. This procedure gives similar results to the previous procedure.

3.2 Group Pile Analysis

To find the lateral capacity of the group pile, Prakash (1962) proposed to reduce
the value of coefficient of horizontal subgrade reaction (k_h), as shown in Figure 2. The group pile can then be performed using the finite difference method described earlier by entering reduced k_h values.

4. MODELING IN PLAXIS 3D

Plaxis 3D Foundation is a three-dimensional Plaxis program, developed for the analysis of three dimensional foundation and geotechnical problems. It is part of the Plaxis suite finite element software used worldwide for geotechnical engineering design. The software allows the complex finite element model to be solved quickly. The various available output facilities can be used to display the detail computational results.

In this study the effect of pile cap is not considered. To eliminate friction between the soil and the pile cap, a dummy soil of 10 cm thick beneath the pile cap is introduced in the modeling (Figure 3). The dummy soil has the characteristics of water, so as to eliminate the friction.

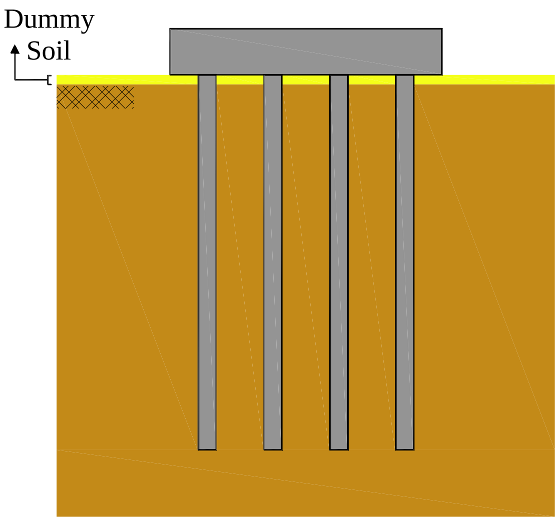

Figure 3 Plaxis 3D Foundation Modeling

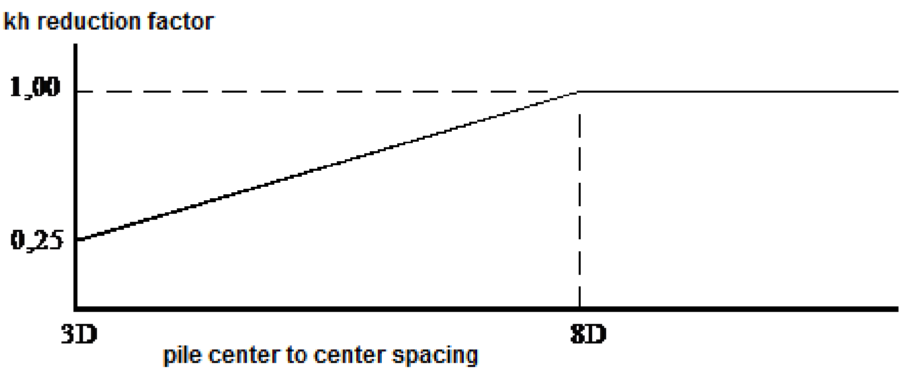

Figure 2 Group Pile Reduction Factor (After Prakash, 1962)

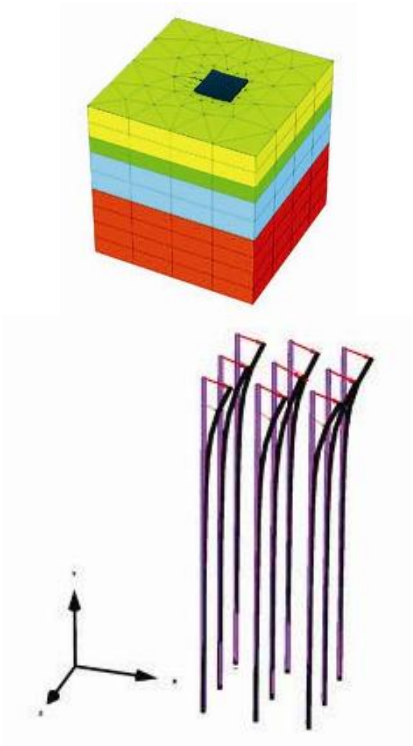

Figure 4 Output of Plaxis 3D Foundation For The Group of 9 Piles

5. THE INPUT PARAMETERS

Pile parameter:

- Diameter = 1 m
- Length = 40 m
- $E_p = 2{,}59 \times 10^7 \text{ kN/m}^2$

Table 1 Soil Parameters

Soil	MH 1	MH 2	MH 3	MH 4
Depth (m)	0 – 12	12 – 18	18 – 33	33 – 60
γ_d (kN/m^3)	11	10	11	13
γ_{sat} (kN/m^3)	17	16	17	18
E (kN/m^2)	8000	14000	20000	25000
c (kN/m^2)	10	15	20	25
ϕ	21°	22°	25°	25°

6. THE RESULTS

The results of the study are presented in the tables and graphs below,

Table 2 Lateral Capacity of Single Pile Based on Finite Difference

Method	Lateral Capacity	
	Free Head Pile	Fixed Head Pile
Finite Difference	124 kN	215 kN

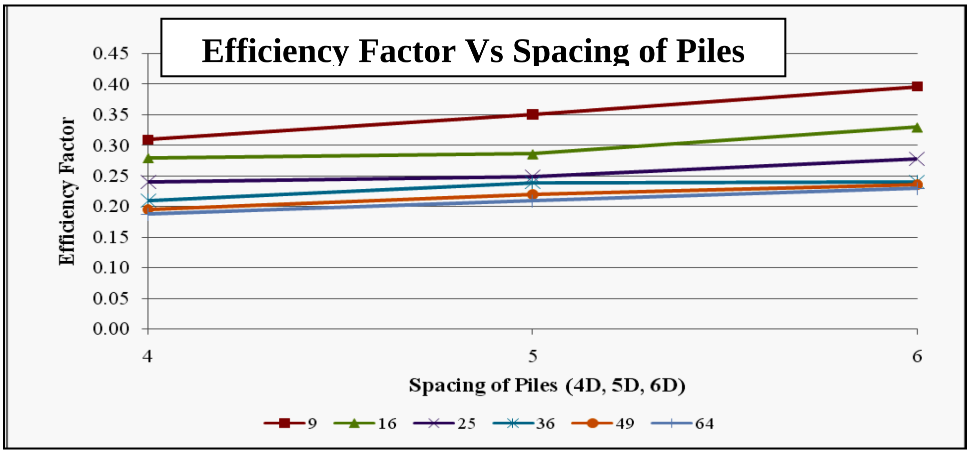

Figure 5 Efficiency Factor vs Pile Spacing (center to center) based on Plaxis Analysis

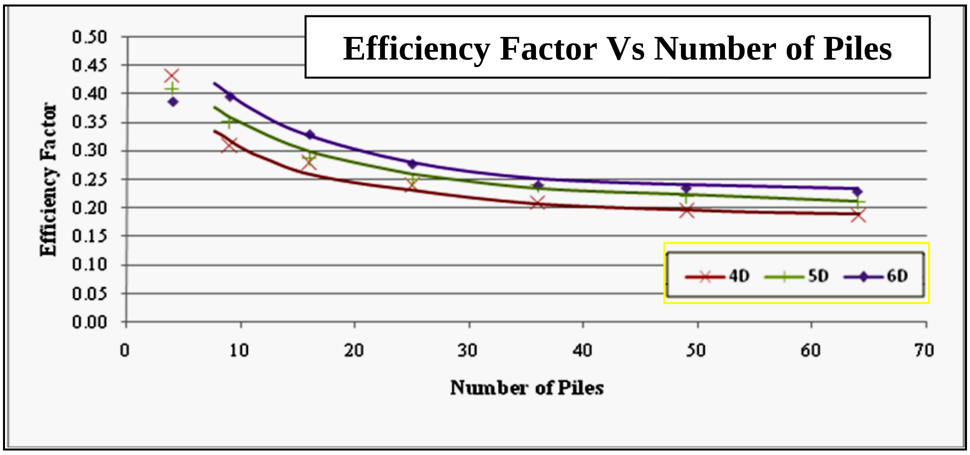

Figure 6 Efficiency Factor vs Number of Piles based on Plaxis Analysis

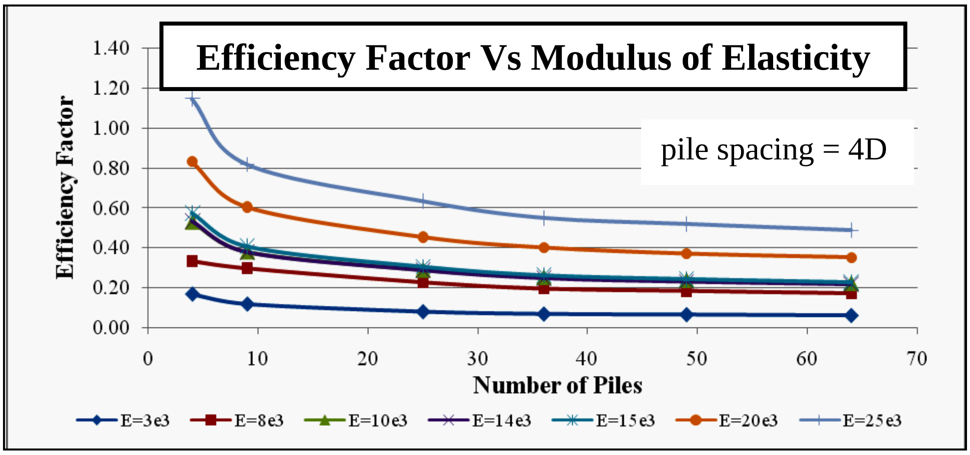

Figure 7 Influence of Soil Stiffness Modulus for Symmetrical Pile Configuration; E = Soil Stiffness Modulus in kN/m^2

7. CONCLUSION

Based on the analysis using Plaxis 3D Foundation program, it is found out that the spacing and the number of piles, as well as the soil stiffness do have significant effects to the lateral capacity of group pile. The conclusions are summarized below:

a. The greater the spacing between piles in a group pile, the greater the efficiency factors. This is due to the fact that the reaction area of the soil behind each pile is larger, therefore, the interaction region among the piles (i.e. the overlapping reaction areas) become smaller. Hence, the lateral capacity of the group pile becomes greater.
b. The total number of piles in a group have significant influence on the efficiency factor of the group pile. The greater the number of piles in a group pile, the lower the efficiency factor. Giving a lowest efficiency factor to around 0.20.
c. The stiffness modulus of the soil also affects the efficiency factor of the group pile. The efficiency factor increases with the higher stiffness modulus of the soil.

8. CLOSURE

The above is the interim results of the study. To make the study complete, the following shall be investigated further:

a. Pile spacing of 2, 3, 7 and 8 times pile diameter.
b. Various pile lengths and diameter
c. Pile cap effects.
d. Comparative study by using different geotechnical finite element program, such as the GeoStudio or other.

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