

A Simplified Formular For Analysis Group Efficiency of Piles in Granular Soil.

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Abstract— The main purpose of this paper is to present a new method for analysis group efficiency of frictional piles in granular soils. This method is based on consideration of the shear around the perimeter of the group defined by the plan dimensions + the bearing capacity of the block dimension at the points. Thus, the analysis presented here is based on frictional resistance of piles combine to point load in granular or sand soil and some other factors similar to the analysis presented by Sayed and Bakeer. Besides, stiffness of the pile cap also confirmed that it influence significantly to the distribution of the structural loads to the individual piles and this factor was examined in the presented method. The results from numerical analysis and full-scale field test have obtained a good match together also shown that numerical modelling techniques may come to a suitable agreement with practical experiment results to analyse for group efficiency of piles.

Keywords: Group efficiency, frictional pile, stiffness of pile cap, full-scale field test, numerical analysis

1. INTRODUCTION

Piles are usually constructed in groups of vertical, batter, or a combination of vertical and batter piles and tied together by a concrete cap at the ground surface. The distribution of loads applied to a pile group are transferred nonlinearly and indeterminately to the soil. Interaction effects between adjacent piles in a group lead to complex solutions.

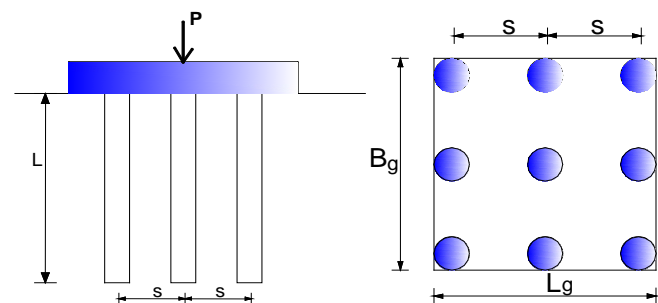
Piles in closely spaced groups behave differently than single isolated piles because of pile-soil-pile interactions that take place in the group. It is generally recognized that deflection of a pile in a closely spaced group are greater than the deflections of an individual pile at the same time load because of these interaction effects. The maximum bending moment in a group will also be larger than that for a single pile, because the soil behaves as if it has less resistance, allowing the group to deflect more for the same load per pile. However, In the current design method, estimating the load-bearing capacity or the settlement of groups has been taking lack of exactly compared to practice or geotechnical engineers also can face many difficult by complicated methods.

The main focus of this paper is to present a new method for analysis of group efficiency for friction piles, particularly in sand. This method is based on consideration of the frictional capacity and pile spacing as well as interaction of adjacent piles in granular soil. This method can estimate group efficiency for any pile group models with the load-bearing capacity and the settlement closely to practice. In addition, the results of this method have been compared with several current design methods to investigate its validity.

2. THEORETICAL STUDY

In most cases, piles are used in groups, as shown in figure 1, to transmit the structural load to the soil. A pile cap is constructed over group piles. The cap can be in contact with the

ground, as in most cases. Determining the load-bearing capacity of group piles is extremely complicated and has not yet been fully resolved. When the piles are placed close to each other, a reasonable assumption is that the stresses transmitted by the piles to the soil will overlap a much larger area and extend to a greater depth than that of a single pile (see Figure 2). Reducing the load-bearing capacity of the piles. Ideally, the piles in a group should be spaced so that the load-bearing capacity of the group is not less than the sum of the bearing capacity of the individual piles. In practice, the minimum center-to-center pile spacing, s , is 2.5 and, in ordinary situations, is actually about 3-3.5D.



Number of piles in group = $n_1 \times n_2$

Note: $L_g \geq B_g$; $L_g = (n_1 - 1)s + 2(D/2)$; $B_g = (n_2 - 1)s + 2(D/2)$

Figure 1. The model of piles group

The most widely recognized standard for quantifying group interaction effects in the group efficiency factor, η , which is defined in Equation (1) as the average lateral capacity per pile in a group divided by the lateral capacity of a single pile [1].

$$\eta = \frac{Q_{g(u)}}{\sum Q_u} = \frac{Q_{g(u)}}{n(Q_{s(u)})} \quad (1)$$

Where η = group efficiency; $Q_{g(u)}$ = ultimate load-bearing capacity of the group pile; $Q_{s(u)}$ = ultimate load-bearing capacity of the single pile; n = the number of piles in the group.

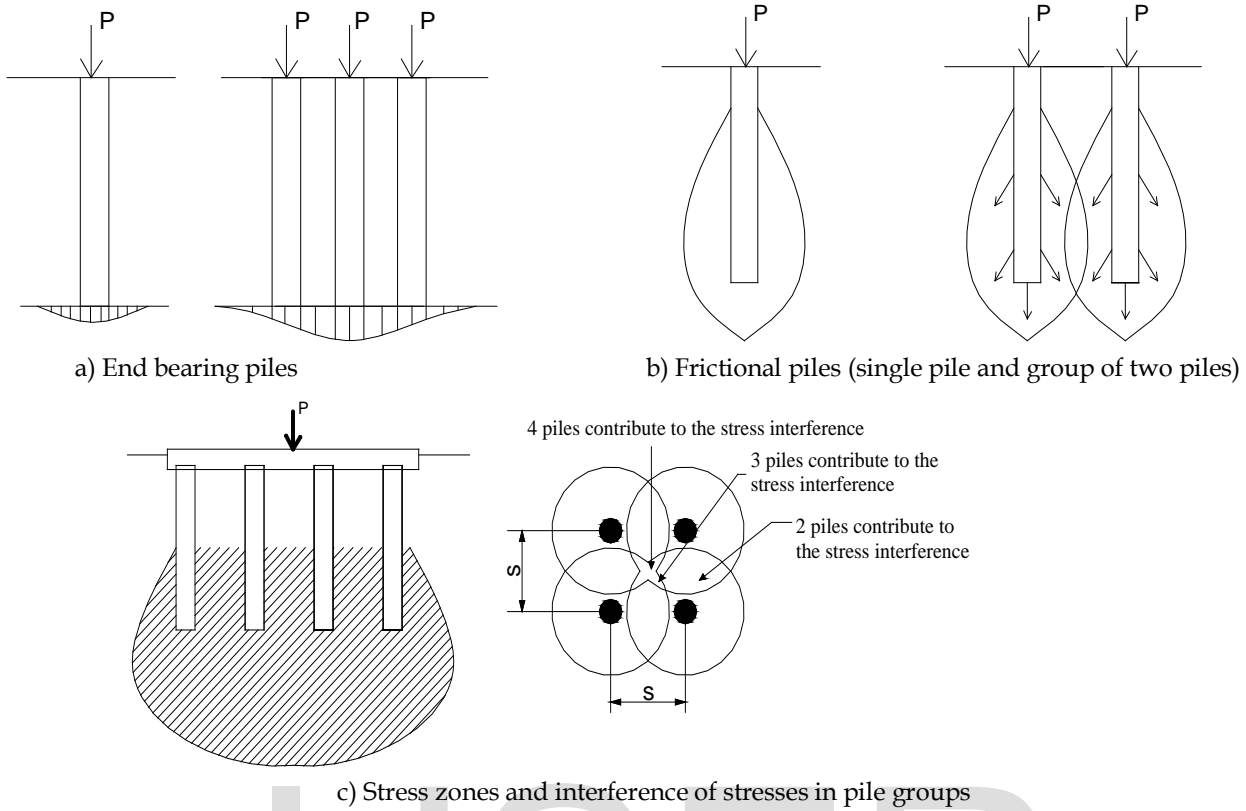


Figure 2. Stresses in soil due to loads on single pile and pile groups

A number of considerable methods about group efficiency relationships have been proposed for estimating group efficiency and the load-bearing capacity of pile groups: Focht and O'Neill (1985), Converse-Labarre (1968), Sayed and Bekeir (1992), Los Angeles Group Action, Seiler-Keeney (1944), Polous (1993), Feld (1981), Iyer (1995). However, these methods are quite complicated or difficult for engineers when they design pile groups that require suitable and close results with practice.

When a concrete pile cap is poured directly on the ground, as is the most common case, the group capacity is at least the block capacity based on the shear around the perimeter of the group defined by the plan dimensions + the bearing capacity of the block dimension at the points. Thus, the analysis presented here is based on frictional resistance of piles combine to point load in granular or sand soil and some other factors similar to the analysis presented by Sayed and Bakeer. This type of analysis can be explained with the aid of Figure 2. Depending on their spacing within the group, the piles may act in one of two ways: (1) as a block, within dimensions $L_g \times B_g \times L$, or (2) as individual piles. If the piles act as a block, the frictional capacity is as equation (2). Similarly, for each pile acting individually, the frictional capacity is as equation (3).

$$Q_{g(u)} = f_{av} \cdot p_g \cdot L \quad (2)$$

$$Q_u = f_{av} \cdot p \cdot L \quad (3)$$

Note: p_g = perimeter of the cross section of block,
 $p_g = 2(n_1 + n_2 - 2)s + 4D$

p = perimeter of the cross section of beach pile.

Substituting (2) or (3) into (1) gives:

$$\eta_f = \frac{Q_{g(u)}}{\sum Q_u} = \frac{f_{av} [2(n_1 + n_2 - 2)s + 4D]L}{n_1 n_2 p L \cdot f_{av}} = \frac{2(n_1 + n_2 - 2)s + 4D}{pn_1 n_2} \quad (4)$$

For group efficiency at point pile η_p , because the stresses transmitted by the piles to soil will overlap (2c) and lead to the value of the stress zones of a pile group is much larger and extends deeper than that of a single pile, Figure 2. Hence, reducing the point bearing capacity in particular and the load-bearing capacity in general of the piles.

From several previous results that studied and reported by many different authors through various models such as full-scale field tests: O'Halloran (1953), Davision (1970), O'Neill and Blaney (1989), Townsend (1997); Centrifuge test model: Mcvay et al (1995), Schofield (1980), Barton(1984); 1g model tests: Cox et al. (1984), Liu (1991); P-y Method of analysis: Reese (1980), Horvath (1984); Elasticity Theory: Polous (1980), Davis (1980). Based on the results which have collected in final reported of Minnesota Department of Transportation [4], group-reduction factor are identified as follow:

$$\eta_p = \begin{cases} 0.5 + 0.05 * (s / D) & 1 \leq s / D \leq 5 \\ 1.0 & S / s > 5 \end{cases} \quad (5)$$

From equation (4) and equation (5), group efficiency of the group piles η can be obtained by:

$$\eta = \frac{\eta_f + \eta_p}{2} = \frac{1}{2} \left[\frac{2(n_1 + n_2 - 2)s + 4D}{pn_1 n_2} + \eta_p \right] \quad (6)$$

Hence,

$$Q_{g(u)} = \eta \sum Q_u = \frac{1}{2} \left[\frac{2(n_1 + n_2 - 2)s + 4D}{pn_1 n_2} + \eta_p \right] \sum Q_u \quad (7)$$

From Eq. (5), if the center-to-center spacing d is large enough, $\eta > 1$. In that case, the piles will behave as individual piles. Thus, in practice, if $\eta < 1$, then

$$Q_{g(u)} = \eta \sum Q_u \quad (8)$$

and if $\eta > 1$, then $Q_{g(u)} = \sum Q_u \quad (9)$

3. EXPERIMENT STUDY AND NUMERICAL ANALYSIS

3.1. Experiment study and calibration numerical model

To ensure the reasonable numerical model to be used for the parametric study, a field case study as described below was selected for the calibration of this numerical model. The details of this calibration can be found in [6]. Therefore, a brief description of this calibration is presented below.

In the selected project to analyze here, a single model, a model of group 3 piles and a model of group 5 piles are chosen to evaluate and calibrate for numerical model as figure 3.

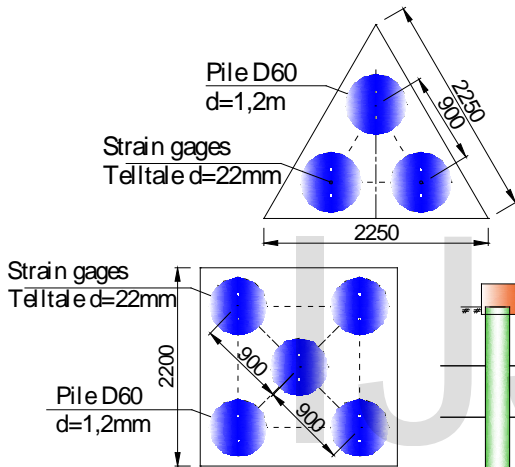


Figure 3. Model of pile group for full-scale field test and numerical model

Table 1. Material properties used in the numerical analysis

Soil layer	Altitude	γ_w (kN/m ³)	γ_k (kN/m ³)	E_0 (kN/m ²)	μ	c (kN/m ²)	ϕ (kN/m ²)
Fine-grained sand	0-2.0	18.99	15.07	18030	0.28	1.17	26.72
Sandy fat clay	2.0-4.0	18.09	13.40	2395	0.30	8.90	4.59
Solid fine-grained sand	4.0-8.5	19.08	15.30	17853	0.28	1.30	28.57
Fine sand, silty sand	8.5-10.5	19.77	16.09	16005	0.28	1.05	30.56
Sandy silt clay	10.5-16.5	18.84	14.43	12373	0.30	21.98	13.24

3.2. Numerical modeling

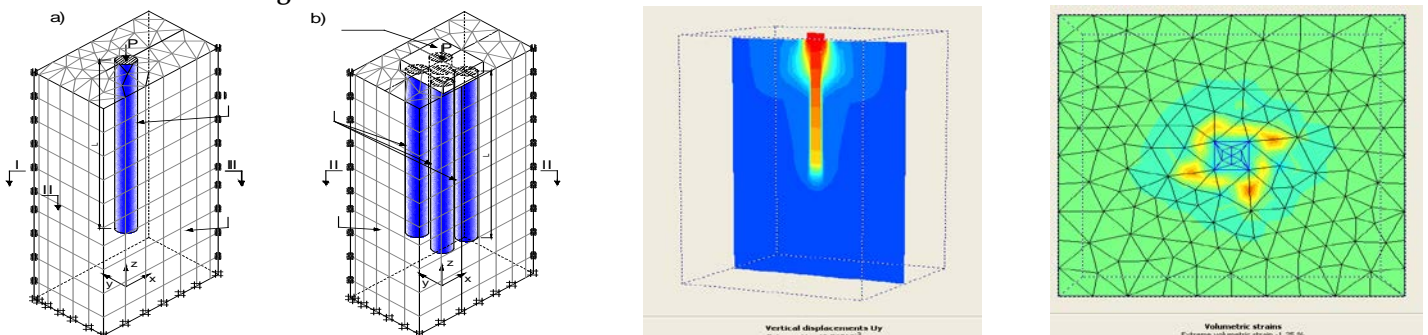


Figure 5. Dimension and boundary conditions in the numerical model

Some basic parameters of pile and pile cap as follow: Diameter of pile = 0.6m, Length of pile = 7.5m, elastic modulus of pile = $1.2 \cdot 10^4$ MPa, poisson factor = 0.15. Pile cap has elastic modulus = $2.9 \cdot 10^4$ MPa, the thickness of pile cap = 0.5m.

After as full-scale field tests carried out for three models (see figure 3). The process of numerical analysis also was conducted to examine and evaluate the agreement with practical results. The results obtained from calibration numerical model compared with full-scale field tests are shown as in figure 4. There is a good match between the measured and calculated for all three models, the discrepancy between the measured and calculated is only approximately 5%-7% for single pile, 8%-11% for group 3 piles and 6%-9% for group 5 piles. In addition to, at the position of $5\%D=30\text{mm}$ (D is diameter of pile), the measured and calculated results are very comparable and nearly cross at the same point. This shown that calibration numerical model has brought a good match and from this, the analyses will be developed for model of group 9 piles with variable in spacing of pile from $1.5D$ to $8D$.

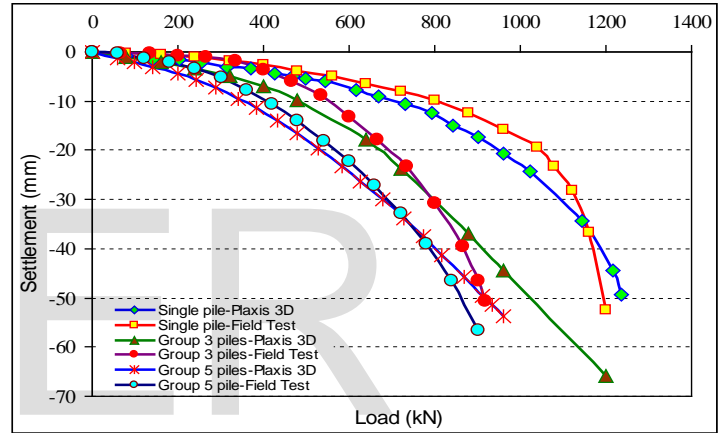


Figure 4. The results of calibration numerical model with full-scale field test

A 3D finite difference method, incorporated in fast Lagrangian analysis continue (PLAXIS 3D) version 2.1 was adopted in this study. The numerical model for calibration against this case study is presented in figure 5. In this study, A group include 9 piles which arranged as box type will be analyzed to evaluate the group efficiency (Figure 1).

The properties of soil layers in full scale test and numerical model are presented in table 1.

3.2. Results and comparisons

The results of numerical analysis for group 9 piles are presented in Fig 6 and Fig.7. As can be seen that the settlement of pile groups is smaller considerably than the settlement of single pile. This can be explained by influence of group efficiency. In this study, group efficiency will be identified from Equation (1), $Q_{g(u)}$ and $Q_{s(u)}$ are identified at the position where the settlement is reach to value of 5%D respectively. The results of group efficiency are shown in table 4.

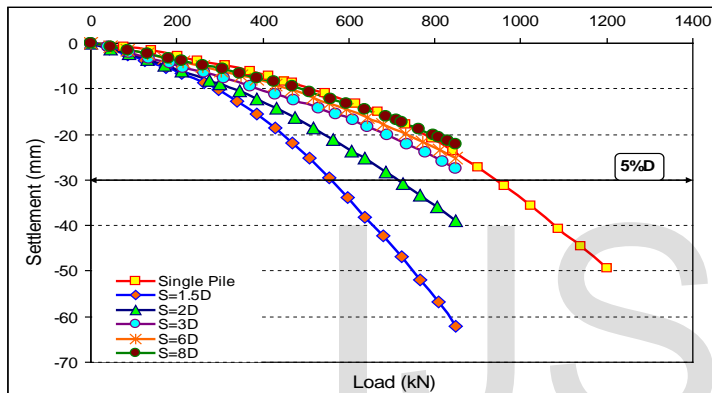


Figure 6. The results of analysis for group of 9 piles with different ratio s/D (with pile cap)

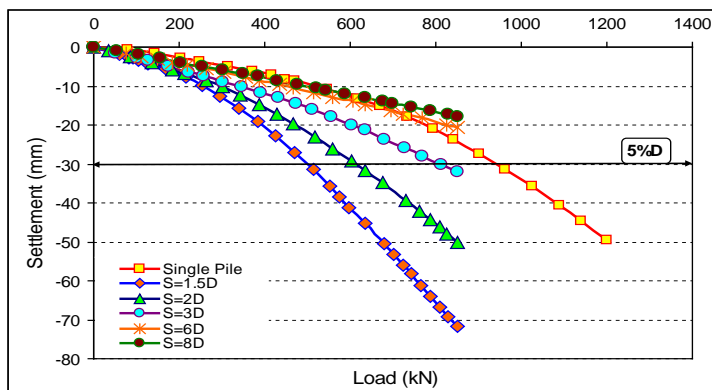


Figure 7. The results of analysis for group of 9 piles with different ratio s/D (without pile cap)

The results in table 5 shown that group efficiency η depend significantly on spacing of piles and pile cap. However, when

the spacing of piles $> 6D$, group efficiency is approximately 1 and the impact of group efficiency is not considerably.

Fig.6 and Fig.7 also demonstrate that value of settlement in model without pile cap is significant larger than model with pile cap ($\approx 14 - 20\%$). This confirmed that the stiffness of the pile cap will influence the distribution of the structural loads to the individual piles. The thickness of the pile cap must be at least four times the width of an individual pile to cause a significant influence on the stiffness of the foundation. A rigid cap can be assumed if the stiffness of the cap is 10 or more times greater than the stiffness of the individual piles, as generally true for massive concrete caps.

4. SEVERAL CURRENT EFFICIENCY FORMULAE

Several efficiency formulae are used to relate group efficiency to pile spacing for piles in soils, as follows:

4.1. Converse-Labarre formula (1980)

$$\eta = 1 - \left[\frac{(n_1 - 1)n_2 + (n_2 - 1)n_1}{90n_1n_2} \right] \theta \quad (10)$$

Where: $\theta = \tan^{-1}(D/s)$

n_1 = number of columns of piles in the group

n_2 = number of rows of piles in the group

D = diameter of the pile; s = spacing of the piles in the group.

4.2. Los Angeles Group Action formula (

$$\eta = 1 - \frac{D}{\pi s n_1 n_2} \left[n_1(n_2 - 1) + n_2(n_1 - 1) + \sqrt{2}(n_1 - 1)(n_2 - 1) \right] \quad (11)$$

Where: n_1 = number of columns of piles in the group

n_2 = number of rows of piles in the group

D = diameter of the pile; s = spacing of the piles in the group.

4.3. Iyer formula (1995)

There is empirical rule in which the calculated load capacity of each pile is reduced by a proportion η for each adjacent pile where:

$$\eta = \frac{1}{8} \frac{s}{D} \quad (12)$$

Where: D = diameter of the pile; s = spacing of the piles in the group.

4.4. Ramiah and Chickanagappa formula (1981)

When only point resistance is considered, the ultimate capacity of a pile is reduced by one-sixteenth by each adjacent diagonal or row pile ($(1-n_{ad})/16$). The technique can be explained if one examines Figure 3, which shows the plan of a group pile. For pile type A, there are eight adjacent piles, for the pile type B, there are five and for type C, there are three. With this in mind, the following table can be prepared:

Table 4: The result of group efficiency from numerical analysis and full-scale field test

Group efficiency η	s/D	1.5	2	3.0	6.0	8.0
η	With pile cap	0.585	0.747	0.82	0.982	1.0
	Without pile cap	0.526	0.636	0.756	0.953	1.0

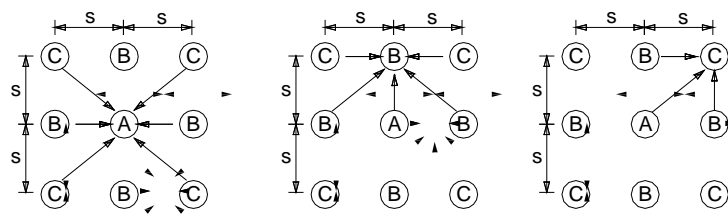


Figure 6. Feld's method for estimating the group capacity of friction piles

Pile type	No. of Piles n_p	No. of adjacent piles n_{ad}	Reduction factor for each pile	Ultimate capacity
A	1	8	$1 - \frac{n_{ad}}{16} = 1 - \frac{8}{16}$	$0.5Q_u$
B	4	5	$1 - \frac{n_{ad}}{16} = 1 - \frac{5}{16}$	$2.75Q_u$
C	4	3	$1 - \frac{n_{ad}}{16} = 1 - \frac{3}{16}$	$3.25Q_u$
$Q_{g(u)} = \sum 6.5Q_u$				

$$\eta = \frac{Q_{g(u)}}{\sum Q_u} = \frac{6.5Q_u}{9Q_u} = 72\% \quad (13)$$

4.5. Sayed and Bakeer formula (1992)

Reference [1] introduced an efficiency equation of the form based considering both frictional resistance and point resistance. This is similar to what mentioned in the new method that presented above. Sayed and Bakeer formula is expressed as equation (14):

$$\eta = 1 - (1 - \lambda.K) \frac{\sum Q_s}{\sum (Q_s + Q_p)} \quad (14)$$

Where: Q_s = shaft friction resistance for each pile in group, kN
 Q_p = point load for each pile in group, kN

λ = Geometric efficiency parameter, which can be computed using an equation similar to Eq.(14) giving values generally in the range of 0.6 to 2.5

K = group interaction factor (also to be estimated); ranges from 0.4 to about 9.0

4.6. Group efficiency from empirical results proposed by Zhong Zhao, H.K. Stolarski (1999)

The problem of closely-spaced piles in a group can be characterized as one of soil-pile interaction. Reference [4] examined all testing models, and then gave to a way to solve the problem is to introduce the p-factor and apply it to the p-y curves for a single pile, thus generating a new set of p-y curves that include the group effect. The p-factor is less than one and the magnitude depends on the configuration of piles in a group. The result is shown in the following table:

Table 5. Group reduction factor

s/D	1.5	2	3	4	5
η = p-factor	0.60	0.72	0.85	0.96	1.0

4.7. Summary of several pile group efficiency test data

Several results about pile group efficiency from test data carried out by some authors are presented in table 5. There include from Full scale field with free head of Brown and Reese (1985), Morrison and Reese (1986); Full scale field with fixed head of Ruesta and Townsend (1997) and data from centrifuge test of Shibata et.al (1989) as well as McVay et.al (1995)

Table 5 Summary of several pile group efficiency test data

Reference	Group size	Pile spacing	η	Type of test	Pile type	Soil	Deflection (dia.)
Brown and Reese (1985)	3x3	3D	0.75	Full scale field free-head	10.75 in dia pipe piles	Stiff OC clay	0.05D
Morrison and Reese (1986)	3x3	3D	0.77	Full scale field free-head	10.75 in dia pipe piles	Med. dense sand	0.05D
Shibata et.al (1989)	3x3	2D	0.58	1g model free-head	0.87 in dia. chloridized-vinyl tubes	Uniform sand $D_r=20\%$	0.1D to 0.3D
	3x3	2.5D	0.78				
	3x3	5D	1.0				
	4x4	2D	0.43				
	4x4	2.5D	0.60				
McVay et.al (1995)	3x3	3D	0.73	45g centrifuge fix-head	17 in dia. prototype	Loose sand $D_r=33\%$	0.15D
	3x3	5D	0.92				
Ruesta and Townsend (1997)	4x4	3D	0.80	Full scale field fix-head	30 in square pre stressed concrete	Loose fine sand	0.05D to 0.1D

4.8. Comparison results

The geometry of the group and design parameters used for comparison are same as used above. For convenient calculation, a spacing of pile center to center is 3D and a groups of 9 piles are chosen. The results obtained from several current design formulae are compared with the results obtained from present method and summarized in table 6.

Result show that Converse-Labarre formula predicted group efficiency lower compared with present method, numerical analysis, Sayed and Bakeer formula and other formulae

due to that Converse-Labarre formula do not consider influence of the stiffness of the pile cap. As a result, present method, Sayed and Bakeer formula, Shibata et.al, numerical analysis overpredict the group efficiency compared with Converse-Labarre formula. It can be also noted that the result of present method are in good agreement with the results of numerical analysis, empirical formula of Sayed and Bakeer, the results of Shibata et.al, Ruesta and Townsend from full scale field test and centrifuge test.

Table 6. Comparison of results from theoretical solution, numerical analysis and other formulae

Reference	Group size	s/D=1.5	s/D=2.0	s/D=3.0	s/D=5.0	s/D=6.0	s/D=8.0
Present method	3x3	0.570	0.654	0.82	0.875	1.0	1.0
Numerical analysis	3x3	0.585	0.747	0.82	0.913	0.982	1.0
Converse-Labarre formula	3x3	0.50	0.606	0.727	0.832	0.86	0.894
Sayed and Bakeer formula	3x3	0.582	0.662	0.816	0.889	0.964	1.0
Zhong Zhao, H.K. Stolarski	3x3	0.60	0.72	0.85	1.0	1.0	1.0
Brown and Reese	3x3	-	-	0.75	-	-	-
Morrison and Reese	3x3	-	-	0.77	-	-	-
Shibata et.al	3x3	-	-	0.818	1.0	-	-
Ruesta and Townsend	3x3	-	-	0.80	-	-	-

5. CONCLUSION

A new theoretical analysis is similar to the analysis proposed by Sayed and Bakeer has been presented for analysis of group efficiency of granular soil, particular in sand soil. The main refinements were: the block capacity based on the shear around the perimeter of the group defined by the plan dimensions + the bearing capacity of the block dimension at the points, the group efficiency of piles by the stresses transmitted by the piles to the soil will overlap a much larger area and extend to a greater depth than that of a single pile, influence of soil modulus, stiffness of pile cap. In particular, the proposed formula has the advantage over formula of Sayed and Bakeer (1992) in that it is simple to get the solution of the developed equations and there is no need for use experimental values to get the solution of unknown parameter. The formula shows that group efficiency depend significantly on frictional resistance and point resistance of pile. The formula also shows that that stiffness of pile cap increases group efficiency.

Comparison of the present formula results to current design formulae shows a good agreement with the results of the Sayed and Bakeer and the results of, Shibata et.al. It seems that the formula of Converse-Labarre underestimate the group efficiency. As a result, formula of Converse-Labarre underestimate the load-bearing capacity of pile groups.

Further studies using full-scale or centrifuge prototypes are required and would be useful to investigate the validity of the theoretical model. The studies should examine the effect of stiffness of pile cap, modulus of soil, type arrangement.

The results from numerical analysis and full-scale field test have obtained a good match together. This show that numerical modelling techniques may come to a suitable agreement with practical experiment results. From that, it can be developed to consider the interaction of group efficiency. The results from numerical analysis and full-scale field test also have a good match with present formula.

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