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The efficiency coefficient of 3×3 piles group in cohesion soil using small scaled pile group model

Hệ số hiệu quả của nhóm cọc 3×3 trong đất dính sử dụng mô hình vật lý tỷ lệ thu nhỏ

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ABSTRACT

This paper deals with the investigation of a model experimental study of group piles of different length to diameter ratio (L/D) as well as different spacing (S) between the piles in the group. The piles were installed in clayey soil and sand-clay alternative layering soil and sujected to axial loading condition. Group efficiencies of small scaled piles groups were determined at length to diameter ratio varying from 20 to 30 and at 3D and 6D spacing between the piles. The behavior of pile on the experimental model was then simulated by using Plaxis 3D Foundation software. Ratio of length to diameter has been found to be a major factor that influences ultimate axial resistance of the group and the group efficiency (η). The group efficiency (η) in these types of soils is less than 1. The results show that when increasing the pile length, η increases significantly. When the ratio of pile spacing to diameter (S/D) increases, η increases. The results also show that reducing the thickness of clayey soil and increasing the thickness of strong soil under the pile will strengthen the soil and increase the bearing capacity of pile group.

Keywords: Efficiency coefficient; group efficiency; pile group; distance of piles.

TÓM TẮT

Bài báo nghiên cứu thực nghiệm trên mô hình các cọc nhóm có tỷ lệ chiều dài trên đường kính (L/D) khác nhau cũng như khoảng cách (S) khác nhau giữa các cọc trong nhóm. Các cọc được đóng trong đất sét và đất có lớp cát-sét xen kẽ và chịu tải trọng tác dụng dọc trục. Hệ số nhóm của các nhóm cọc tỷ lệ thu nhỏ được xác định theo tỷ lệ chiều dài trên đường kính thay đổi từ 20 đến 30 và ở khoảng cách 3D và 6D giữa các cọc. Ứng xử của cọc trên mô hình thí nghiệm sau đó được mô phỏng bằng phần mềm Plaxis 3D Foundation. Kết quả thí nghiệm cho thấy tỷ lệ giữa chiều dài và đường kính là một yếu tố chính ảnh hưởng đến sức chịu tải dọc trục tới hạn của nhóm cọc và hệ số hiệu quả của nhóm cọc (η). Hệ số nhóm (η) trong các loại đất này nhỏ hơn 1. Khi tăng chiều dài cọc thì η tăng đáng kể. Khi tỷ lệ khoảng cách giữa cọc và đường kính (S/D) tăng, η tăng. Kết quả cũng cho thấy, việc giảm chiều dày lớp đất sét và tăng chiều dày lớp đất chắc dưới cọc sẽ làm đất cứng hơn và tăng khả năng chịu tải của nhóm cọc.

Từ khóa: Hệ số hiệu quả; hệ số nhóm; nhóm cọc; khoảng cách cọc

List of symbols

η	Efficiency coefficient of pile group
$Q_{g,ult}$	Maximum load capacity of the pile group
Q_{ult}	Maximum load capacity of a single pile
D	Diameter of pile
L	Length of pile
S	Spacing of pile
W	Moisture content
W_L	Limited magnitude of liquid state
W_P	Limited magnitude of plastic state
γ_w	Wet unit weight
γ_d	Dry unit weight
G_s	Specific gravity
φ	Internal friction angle
c	Unit cohesive force
E_0	Deformation modulus

1. INTRODUCTION

Pile foundations have been used largely in bridges, high-rise building, towers, and special structures. In practice, piles are usually used in groups. The pile group is connected with a cap to distribute the load on the plate among the piles and then transmit to the ground below. Piles may correspond to loading individually or as a group. In the latter case, the group and the surrounding soil will formulate a block to resist the column load. This leads to a group capacity different from the total capacity of the individual piles making up the group. Since a foundation has an important role in keeping the stability and structural safety in structures, it is thus necessary to accurately estimate the bearing capacity of piles.

Efficiency coefficient of group is defined as follows [1]:

$$\eta = \left(\frac{Q_{g,ult}}{n\,Q_{ult}}\right) \qquad (1)$$

Where : ($Q_{g,ult}$) - maximum load capacity of the pile group; Q_{ult} - maximum load capacity of a single pile; n - the number of piles in the pile group.

In general, efficiency coefficient of group depends on many factors, such as 1- soil type and density, 2- the method of installation of pile, 3- how to sort pile, 4- ratio between the length and the diameter of pile, 5- pile spacing, 6- friction coefficient between the pile and soil, and so on [2]. In AASHTO standard (1998), group effects are mentioned, but no specific calculation instructions are provided. According to AASHTO [3], the pile group efficiency depends on the type of soil, whether it is cohesive or cohesionless. Even in Vietnamese Standard TCVN 11823:2017 "Highway bridge design specification – Part 10 Foundation" [4] and other Vietnamese Standard related to pile design, the efficiency of group piles is only mentioned vaguely and there has not been any detailed calculation.

Many authors have studied the formula for determining pile group efficiency η. A very common formula is Converse–Labarre one, often applied to cohesive soil [5]:

$$\eta = 1 - \left[\frac{(n-1)m+(m-1)n}{nm}\right]\tan^{-1}\left(\frac{D}{S}\right)\frac{1}{90} \qquad (2)$$

Where n is number of pile rows; m is number of piles in a row; S is distance between the piles; D is diameter of a pile. Limitations of the above formula are that it does not include the length of the pile L or the ratio (L/D), the mechanical properties of the soil layer at the tip of piles and the soil layers through which the pile passes.

Feld (1943) [1] proposed the principle of determining the group factor as follows: The load capacity of each pile in the group will be reduced by an amount of 1/16 when it is directly affected by a neighboring pile. The biggest limitation of this method is that it can only be used with small pile groups and has the same layout as Feld's diagram.

In the literature, researchers have performed an extensive number of field and laboratory tests as well as numerical modelling to evaluate the efficiency of pile groups. Because of the unknowns and uncertainties involved in working with some of the underground conditions, it is very difficult to predict the bearing capacity of piles and needs to execute such a large number of pile loading tests in situ. In practice, conducting a pile loading test at actual size is very expensive, so small scaled physical pile models, known as laboratory models, are often used.

Lan B. V. H. [6], conducted experiments on aluminum round piles in clay soil and showed that η is always less than 1 and increases as the ratio (S/D) increases with the constant ratio (L/D). When the ratio (S/d) is fixed η decreases as the ratio (L/D) increases. Gogoi et al. [7] conducted experiments on steel pipe piles with an outside diameter of 1.2 cm in sandy soil. Experimental results indicated that η increased from a value less than 1 to approximately 1 (may be greater or smaller) when (S/d) increased (with (L/D) fixed), then tended to be stable. Harish [8], performed experiments on 2 cm diameter steel piles in clay. The obtained η was always less than 1 and increased as (S/d) increased. Darsi [2] conducted experiments on steel pipes with an outer diameter of 33 mm in sandy soil. If the ratio (S/D) was equal to three (S/D = 3) and (L/D) was fixed, η tended to increase as the number of piles in the group increased. However, when (S/D) = 6 and (L/D) was fixed, η tended to decrease as the number of piles in the group increased. In all cases, η is always greater than 1.

Hana A. M. et al (2004) [9] proposed an artificial neutral network model to predict the efficiency of pile groups installed in cohensionless soil and subjected to axial loading. The model considers the planar geometry of the group (pile diameter, pile spacing and pile arrangement) and incorporates the effect of pile installation, pile length, cap condition, soil condition, and type of loading on the group efficiency.

Although many theoretical and practical studies in the past have been done to predict the performance and bearing capacity of piled foundation in both cohensive and granular soils, the mechanism is still not fully understood. The main objective of this research is to model some single pile and 3 × 3 pile group experiments and to compare load curve – displacement of piles with different space between them and different pile length. With these tests, the efficiency coefficient of pile groups was calculated and compared for different scenarios. These results were also compared with those obtained from Plaxis3D model.

2. METHODOLOGY

The object of this research is to study the efficiency coefficient of pile group in cohension soil using small scaled physical model. Two series of tests were conducted including clayay soil and sand-clay alternative layering soil. Based on the synthesis of variable recent research on the physical model for piles as presented in the Table 1, the pile dimensions, the size of the soil tank were decided in order to not disturb the strain and stress caused by piles in the soil.

In order to search for static loading tests and control the quality of piles integrity, and how to perform axial static loading test, this work refers to Vietnamese standard TCVN 9393:2012 "Piles – Standard test method in situ for piles under axial compression load" [10]. There are 2 types of cohension soils: clayey soil, and sand-clay alternating layers soil. Six different modes were tested in each geological condition. Two experiments were conducted on a single pile with different pile length (L = 900 mm and 1350 mm) and four modes of the experiments were on the group of 3×3 piles with different length (L/D = 20 and 30) and various spacing of piles (S/D = 3 and 6) (**Fig. 1**). Experimental results were then compared to those obtained from Plaxis3D model.

Table 1. Summary of some pile group experiments on small scaled physics models

Researchers	Soil type	Pile material	D (mm) L (mm)	Pile Group arragement	Pile spacing	Size of test tank	Test tank material
Abdulla I.Al-Mhaidib (2007) [11]	Clay	Steel	D=25mm L = 550mm	2×1; 3×1; 2×2; 2×3 and 3×3	3D; 9D	500mm (length) × 800mm (width) × 800 mm (height)	Steel
Gogoi *et al*. (2016) [7]	Sand	Aluminium	D=10mm L/D = 30; 50; 70	1 pile; 2×2	2.5D; 5D	1700mm (length) × 1500mm (width) × 930 mm (height)	Steel
Mahmod A.Q. *et al.* (2013) [12]	Clay	Concrete	D=25mm L/D = 16	1 pile; 1×2 and 2×2	3D	750mm (length) × 750mm (width) × 500 mm (height)	Steel
Bach Vu Hoang Lan (2017) [6]	Clay	Aluminium	D=16mm L/D = 20; 25; 30	2×2; 2×3 and 3×3	3D; 4D; 5D and 6D	700mm (length) × 700mm (width) × 800 mm (height)	Steel

2.1. Experimental Model

2.1.1. Experimental tank

To performed laboratory tests, an experimental tank was designed and built. The tank has dimensions of 2000 mm width × 4500 mm length × 2500 mm height. The pile and groups of test piles were arranged in the experimental tank so that the minimum distance from the piles to the tank wall is 10D, and the distance from the tip of the piles to the bottom of the tank is at least 15D (where D is the pile diameter) (**Fig. 1**).

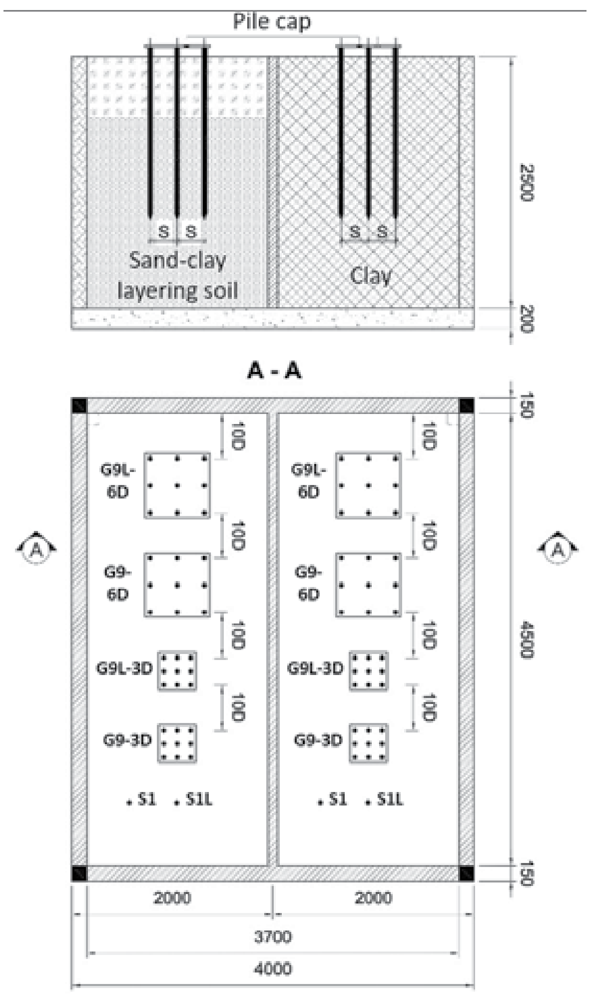

Fig. 1. Plan and vertical section of soil tank. 6 test modes: S1- Single pile test, length pile L = 900 m; S1L - Single pile test, length pile L = 1350 mm; G9-3D - 3×3 piles group test, distance between piles S = 3D, L = 900 mm; G9L-3D - 3×3 piles group test, distance between piles S = 3D, L = 1350 mm; G9-6D - 3×3 piles group test, distance between piles S = 6D, L = 900 mm; G9L-6D - 3×3 piles group test, distance between piles S = 6D, L = 1350 mm

2.1.2. Properties of Soils and soil preparation for testing

The soils including sandy soil and clayey soil from an area in the Mekong Delta were used as the testing soil. Sandy soil is fine-grained sand with a diameter of 0.05 mm to 0.315 mm. As shown in Table 2, the measured parameters of sandy soil: the moisture content W is 7.53%, the wet unit weight γ_w = 18.13 kN/m^3, the dry unit weight γ_d = 11.33 kN/m^3, the specific gravity G_s = 2.67, the internal friction angle φ = 10^{0}60′ and the deformation modulus E = 7200 kN/m^2. Clayay soil were taken at a depth of 2.0 m to 2.5m in the Mekong Delta. The measured parameters of sandy soil: the moisture content W is 44.81%, the wet unit weight γ_w = 15.42 kN/m^3, the dry unit weight γ_d = 10.65 kN/m^3, the specific gravity G_s = 2.68, the limited magnitude of liquid state W_L = 52.85%, the limited magnitude of plastic state W_p = 30.5%, the unit cohesive force c = 10.5 kN/m^2 and the deformation modulus E_0 = 1864 kN/m^2.

Table 2. The physical and mechanical properties of soil

Properties	Symbol (unit)	Sandy soil	Clay soil
Grain size distribution	Sand 0.315-0.05 mm	92.36	12.0
	Silt 0.05-0.005mm	5.64	25.2
	Clay <0.005mm	2.0	62.8
Moisture content	W (%)	7.53	44.81
Wet unit weight	γ_w (kN/m^3)	18.13	15.42
Dry unit weight	γ_k (kN/m^3)	11.33	10.65
Specific gravity	G_s	2.67	2.68
Liquid limit	W_L	-	52.85
Plastic limit	W_d	-	30.5
Unconfined compression	Q_U(kN/m^2)	-	22.35
Cohesive force	c (kN/m^2)	0	10.5
Internal friction angle	φ (°)	10^{0}60′	6^{0}24′
Total deformation modulus	E_0 (kN/m^2)	7200	1864

Two experimental soil tanks were prepared corresponding to two series tests in cohesion soil including clayay soil and sand-clay alternative layering soil:

For clayey soil tests: The soil after transported to the experimental area was dried and then put into the tank by layers of about 25 cm to 30 cm. A compactor was used to compact the soil for each layer. In the compaction process, water was sprayed on the surface of the soil to obtain a good density. A non-woven geotextile layer was used to cover the surface of the soil. A uniformly distributed load of 4 kN/m^2 was conducted onto the soil surface with bricks and kept continuously for 6 months so that the soil was quasi consolidated. Water was sprayed frequently to moisturise soil during the loading process.

For sand-clay alternative layering soil tests: The soil has two layers. The first one is a sandy layer of 0.6 m of thickness, equivalent to 30% of the total thickness. The second one is a clayey soil layer of 1.9 m of thickness, equivalent to 70% of the total thickness. The creation of sand-clay alternating layers was carried out in the same procedure as mentioned above.

2.1.3. Piles and pile arrangement

Piles were fabricated as reinforced concrete piles with diameter D = 45mm. The test pile lengths are 900 mm and 1350 mm. The pile static compression tests were performed on a group of piles with an arrangement of 3×3 piles, with the ratio between the distance and the pile diameter in the group (S/D) of 3 and 6. The ratio between the length and the diameter of pile (L/D) of the pile group is: L/d = 20 and 30. Fig. 2 shows the connection structure of the pile group and pile cap. A plank of steel with suitable dimensions was used as a cap in every group. The pile head has a pre-existing bolt head to connect to pile cap.

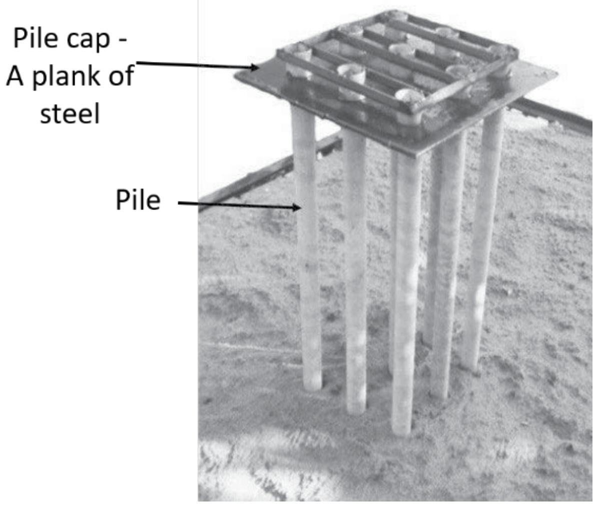

Fig. 2. Details of the connection structure of the pile group - pile cap. Pile group arragement 3×3 piles, pile spacing S = 3D and 6D

2.1.4. Loading device

Because many experiments have to be conducted, in order to facilitate the experi-ments, a mobile counterbalance system is designed and installed. The platform of mobile counterbalance system is made of profiled steel, running along and on the steel rails fixed to the top of the tank walls (Fig. 3).

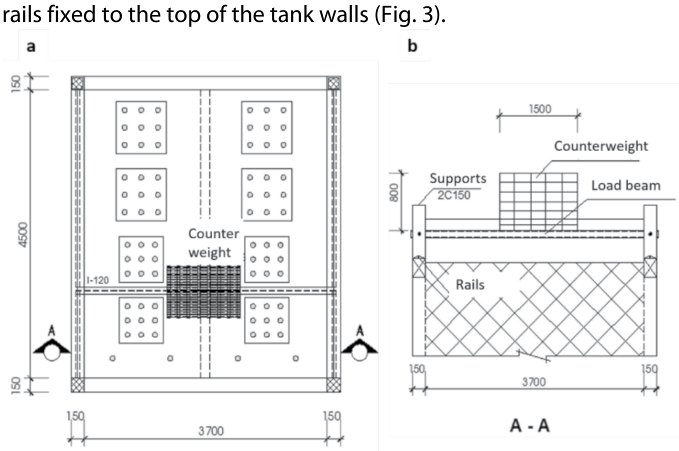

Fig. 3. Mobile counterbalance system: a. Plan of the mobile counterbalance system, b. Vertical section of soil tank and counterbalance system

The loading device composes a hydraulic jack with a capacity of 15 tons. This jacking system is placed on the top of the pile caps. The compressive force acting on the pile caps is measured by a load cell. The displacement is measured by four dial gages fixed on two reference beams fixed on the soil tank walls (Fig. 3).

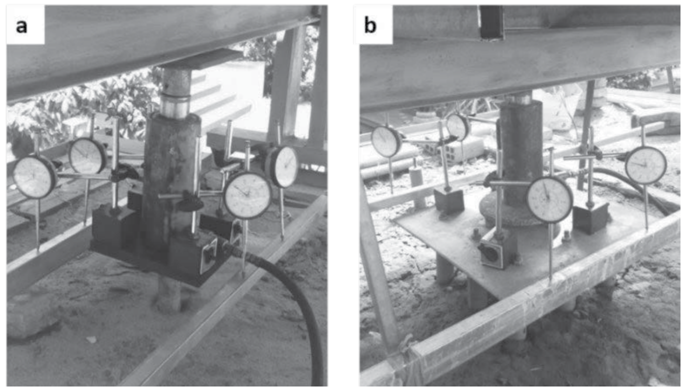

Fig. 4. Disposition of devices: a. Single pile test, b. Pile group test

2.2. Plaxis 3D Foundation description

The 3D model is built by Plaxis 3D Foundation software. The Mohr-Coulomb model is used as a soil behavior model. Using Plaxis 3D-Foundation software, behavior of pile on the experimental model was simulated with the following data: Concrete pile, diameter D = 450 mm, pile length L = 9m and 13.5 m, 3×3 piles group arrangement.

Due to the difference in data types in the Plaxis simulation software, the data obtained from the field experiments on the conventional model must be re-calibrated so that the calculated results from the simulation must be consistent with the actual model. economic and does not depend on the survey domain as well as the unit system. The main parameters are the Young's modulus of the soil material, the internal friction angle of the soil φ, the cohesive force c , and the R_{inter} contact. The geotechnical parameters are described in the following table:

Table 3. Geotechnical parameters of Mohr-Coulomb model

Mohr-Coulomb model	Unit	Value
E, Young's modulus	kN/m^2	7 - 15
φ, friction angle	^{0}	3 - 5
c, cohesion	kN/m^2	1.2 - 2
R_{inter}, contact coefficient	-	0.75 - 1

3. RESULTS AND DISCUSSION

3.1. Experimental results and pile group efficiency

In this study, the conventional ultimate bearing capacity of single piles and of pile group is equal to the load value causing a settlement of 10% pile diameter (4.5 mm for pile diameter of 45mm). For the experiments conducted, the ultimate bearing capacity of the piles determined by the above method is close to the one determined by the method of determining the point on the load versus settlement curve where the slope changes abruptly (the method of two-tangent intersection). For the tests on single piles, each experimental condition was repeated two times. The results of the tests having the same condition were slightly different, less than 5%.

The results of the static load tests are shown in Fig. 5 and Fig. 6. The ultimate bearing capacity of single piles and of pile groups and the pile group efficiencies are gathered in Table 4. In two geological cases, with a fixed (L/D) ratio, the coefficients of pile group efficiency η increases remarkably as the (S/D) ratio increases. With the same (S/D) ratio, η increases when increasing (L/D).

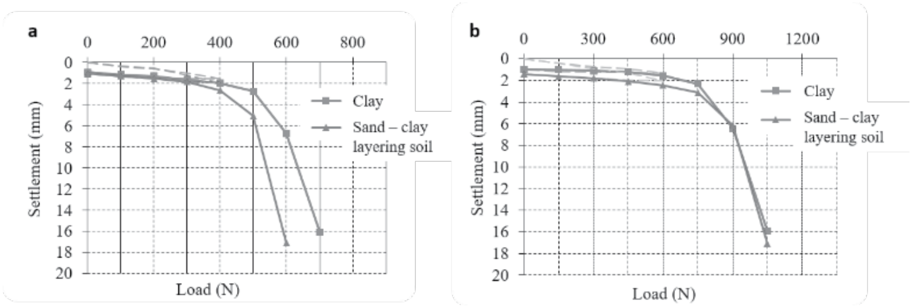

Fig. 5 Settlement versus load of single pile: a. Pile length L = 900 mm, L/D = 20; b. Pile length L = 1350 mm, L/D = 30

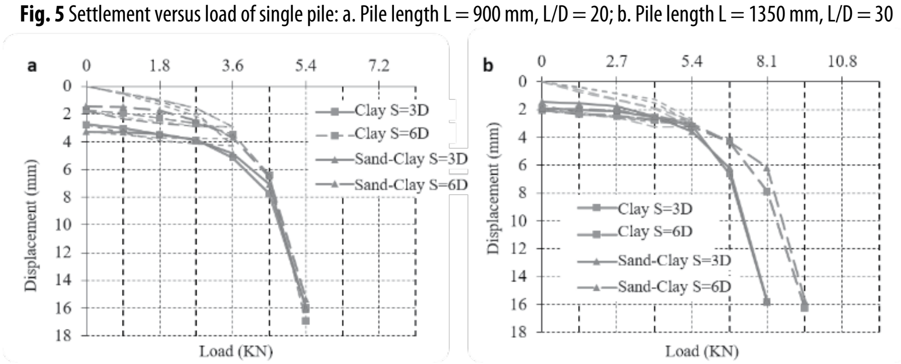

Fig. 6 Settlement versus load of 3×3 piles group: a. Pile length L = 900 mm, L/D = 20; b. Pile length L = 1350 mm, L/D = 30

Table 4. Ultimate bearing capacity of sigle pile, pile group, and efficiency factor for Clayey soil and Sand-clay alternating layers soil

L/D	S/D	Clayey soil			Sand-Clay layering soil		
		Single pile	Pile group	Efficiency factor	Single pile	Pile group	Efficiency factor
		Q_{ult}(kN)	$(Q_g)_{ult}$(kN)	η	Q_{ult}(kN)	$(Q_g)_{ult}$(kN)	η
20	3	0.544	3.146	0.642	0.477	3.259	0.759
	6	0.544	3.914	0.799	0.477	3.865	0.900
30	3	0.829	5.925	0.794	0.817	5.881	0.800
	6	0.829	6.825	0.915	0.817	6.989	0.938

Table 5 presents the ultimate bearing capacity of single piles and of pile groups and the pile group efficiencies obtained by Plaxis 3D Foundation software. The results of the simulation model are compatible with the results of the above the static load tests model. When the distance of 2 piles increases from 3D to 6D, the ultimate load capacity of the pile group increases markedly. When increasing the ratio of length to pile diameter (L/D), the value of pile group efficiency coefficient η increases.

3.2. Comparison with previous literature

Comparison of η values obtained through static load test results with η predicted by different formulas is shown in Table 6 and Fig. 7.

For clayey soil. The experimental values of efficiency were compared with the predictions of the Converse – Labarre's formula and Feld's formula (Fig. 6). There is a correlation between the two results that the efficiency in the clay soil is always less than 1, and η increases as the distance of the piles increases. This experimental result is also consistent with the research of Al-Mhaidib et al. [11] and Lan B. V. H. [6].

The value predicted by Converse - Labarre's does not depend on (L/D). These values are in the range between experimental values with (L/D) = 20 and (L/D) = 30. The difference between experimental and predicted values is small, <10% for all (L/D) and (S/D) ratios surveyed.

Table 5. Ultimate bearing capacity of sigle pile, pile group, and efficiency factor for Clayey soil and Sand-clay alternating layers soil obtained by Plaxis 3D Foundation software

L/D	S/D	Clayey soil			Sand-Clay layering soil		
		Single pile	Pile group	Efficiency factor	Single pile	Pile group	Efficiency factor
		Q_{ult}(kN)	$(Q_g)_{ult}$(kN)	η	Q_{ult}(kN)	$(Q_g)_{ult}$(kN)	η
20	3	184.5	1101.6	0.663	243	1701	0.778
	6	184.5	1466.1	0.883	243	2122.1	0.97
30	3	322.2	2122.2	0.732	376.2	2924.1	0.864
	6	322.2	2640.6	0.911	376.2	3365.55	0.994

For sand-clay alternative layering soil. The experimental values of efficiency were compared with the predictions of the Converse – Labarre's formula and Feld's formula (Fig. 6). Similar to the case of clayey soil, there is a correlation between the two results that the efficiency η is always less than 1, and η increases as the distance of the piles increases. The difference between experimental and forecast values is small, <10% for all (L/D) and (S/D) ratios surveyed.

The value of group coefficient according to Vietnamese Standard 11823:2017 in clay and sand-clay layering soil depends greatly on the friction composition around the pile body and the distance of the piles. As the distance of the piles is increased, the value of the group efficiency coefficient (η) increases. When the ratio S/D = 6, η approaches a value of 1.

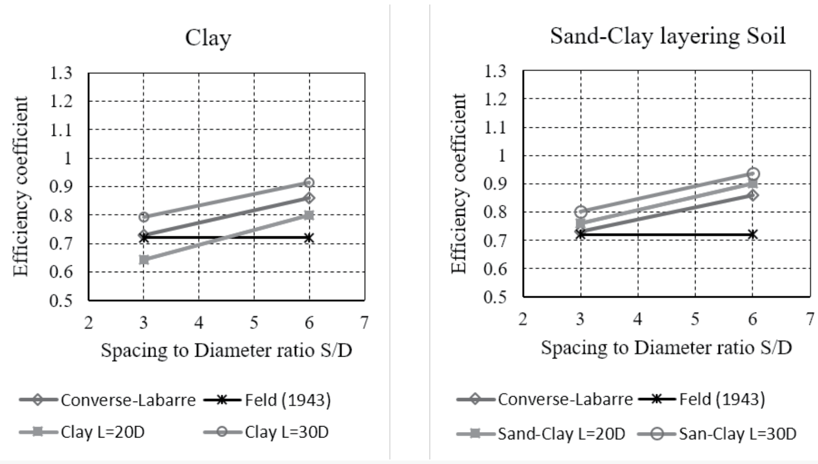

Fig. 7. Efficiency coefficient of pile group in clay and sand-clay layering soil compared with Converse-Labarre (1941), Feld (1943)

Table 6. Comparison of efficiency coefficient between experimental results and previous literature

Calcul method	Piles			Efficiency coefficient η	
	Pile group arrangement	Pile length L	Pile spacing S	Clay	Sand-clay layering soil
Converse-Labarre (1941)	3×3	-	S=3D	0.73	
			S=6D	0.86	
Feld (1943)	3×3	-	S=3D	0.72	
			S=6D	0.72	
Vietnamese standard 11823:2017	-	-	S=3D	0.7	0.7
			S=6D	1.0	1.0
Experimental results	3×3	L=20D	S=3D	0.642	0.759
			S=6D	0.799	0.9
		L=30D	S=3D	0.794	0.8
			S=6D	0.915	0.938

3.5. Comparison with results obtained by Plaxis 3D Foundation software

The value of the pile group efficiency coefficient (η) obtained from the simulation model gives similar results in terms of rules with the results from the experiments on the small scale physical model. The error of variation in clay is about [0.439%÷ 8.393%]; in sand - clay layering soil is about [1.878%÷6.364 %].

4. CONCLUSIONS

In general, according to the conducted tests, the following results can be obtained:

1. The length of piles in the group and the distance between the piles have a significant impact on the capacity of bearing and coefficient of performance in pile group.

2. In both clay soil and sand-clay alternative layers soil, the efficiency η is always less than 1. Experimental results show that when increasing (L/D), η increases significantly. Therefore, the effect of pile length should be considered when piles work in cohesive soil. When (S/D) increases, η increases.

3. The pile group efficiency coefficient values in sand-clay alternating layers are higher than those in clayey soil with the same parameters such as the number of piles and the (S/D) and (L/D) ratios.

4. Reducing the thickness of clayey soil and increasing the thickness of strong soil under the pile will strengthen the soil and increase the bearing capacity of pile group.

5. The experimental tests and numerical model have shown that determining the efficiency according to Converse - Labarre's formula for cohesive soil, and the formula in Vietnamese standard related to pile design is not suitable in many cases. It is necessary to develop a formula for calculating coefficients for mixed soil including both cohesionless and cohesive soil layers, in which the thickness of soil layers must be taken into account.

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Data Availability Statement: The data presents in this study are available on request from the corresponding author.

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