Comparing the effect of negative friction on the design bearing capacity of precast piles with different assumed embankment thicknesses

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ABSTRACT

This paper compares the negative skin friction effects of soil on the load-bearing capacity of precast squarsection reinforced concrete containers in areas 4 and 5 of the Rach Gia Kien Giang (formerly) land reclamation project, assuming different embankment layers and surface cross-sections. The depth of acoustic influence can vary depending on the height of the embankment layer (or the magnitude of the load) and the thickness of the weak soil layer. The survey results show that negative friction can occur in weak soil areas when the settlement of the soil layer is greater than the settlement of the pile. As the thickness of the load increases, the design bearing capacity of the pile decreases due to the effect of negative friction. At the same time, as the pile cross-section increases, the design bearing capacity is still affected by negative friction, but to a lesser extent. Thus, the results obtained contribute to evaluating the influence of negative friction on the bearing capacity of piles based on the thickness of the embankment layers in some areas of the Rach Gia reclaimed land.

Keywords: Negative friction effect, pile bearing capacity, precast piles

1. INTRODUCTION

Negative friction is the phenomenon where the consolidation settlement of the soil surrounding the pile is greater than the downward displacement due to the compressive deformation of the pile; this creates an additional downward load on the pile. In cases where the pile is located in soil that is settling due to surface loads (newly leveled soil, warehouses, etc.) or groundwater level lowering, the settlement. The surrounding soil tends to "hang" on the pile, so the weight of that soil mass is transferred to the pile through lateral friction. The frictional force generated under these conditions acts in the opposite direction to the load of the structure above and is called positive friction.

For structures using pile foundations, when piles are driven into compressible soil or newly filled soil with the pile tip placed in a compacted layer, simultaneous settlement of the soil and pile occurs after driving and loading. Immediately after driving and during the driving process, a portion of the load is resisted by the soil due to the cohesion between the soil and the pile. However, once consolidation occurs, it will transfer the entire load to the pile tip. In some cases, the settlement of the soil may be greater than that of the pile; this relative displacement generates a downward pulling force of the soil layer against the pile, known as negative friction.

Since negative friction became known in the work of pile foundations, there has been a considerable number of studies worldwide on this issue with the aim of determining the nature and value of negative friction in the development stages of the soil. According to [1], the influence of negative friction on

the work of piles is shown in two aspects: increasing the load applied to the pile and reducing the load-bearing capacity of the pile. Therefore, many pile foundation failures caused by negative friction have been recorded in countries such as the USA [2,3], France [4], the Soviet Union [5], Canada [6] and Japan [7], a study has delved deeper into the impact of pile group effects on the negative skin friction encountered by offshore wind turbine pile foundations on artificial islands. The study measured pile settlement at different locations in single piles and rectangular pile groups, as well as the settlement of the surrounding soil and negative skin friction [8]. A small-scale physical model was used to study the load-bearing capacity and strength of driven piles in high-gypsum soils, taking into account the development of negative friction to avoid failure. In this study, the influence of initial saturation, dry specific gravity, and length/diameter ratio (L/D) on negative friction development on piles subjected to bottom loading was investigated [9]. However, most studies focus on the influence of negative friction on the load-bearing capacity of piles, and common problems include some piles in a pile cluster losing their load-bearing capacity and being pulled out of the foundation, or, more seriously, the entire structure built on pile foundations settling excessively.

In Vietnam, negative friction on piles can be a major cause of foundation failures in some construction projects, such as: the building of the Physics Department at Hanoi Pedagogical University, where the foundation of the building subsided due to the lowering of the groundwater level around the Mai Dich water treatment plant, damaging the superstructure; A factory in the Dinh Vu Industrial Park, Hai Phong, was constructed in a newly leveled area on weak soil with a large thickness. The piles were driven into rock, while the piles for the shorter production line rested only on a

layer of hard clay beneath the silty clay layer. Test results and static compression showed that all test piles met the required load-bearing capacity. After foundation construction and equipment installation, it was discovered that the foundation for the production line had settled by more than 10 cm, and the settlement continued to develop. The cause of pile foundation settlement was determined to be negative friction, which was not considered when calculating the load on the piles.

A localized failure occurred at a pile foundation in Ba Ria - Vung Tau. The design had already considered the additional load due to negative friction, and the piles had been coated with bitumen to reduce friction; therefore, the structures supported by the pile foundations were stable. The failure was localized to a single pile positioned beneath a lightweight column. The pile tended to be pulled down due to negative friction, while the column neck, connected to the superstructure, had sufficient stiffness. Therefore, the assessment of the load-bearing capacity of piles considering negative friction with different embankment heights on weak soil is of interest to research [10]. Consequently, the phenomenon of negative friction has also been increasingly considered in the design and construction of deep foundations, especially in areas with weak soil such as District 7 - Ho Chi Minh City [11]; central Hanoi [12], Mekong Delta [13],.. from which measures can be taken to minimize the influence of negative friction on piles [14],..

2. MATERIALS AND METHODS

Studying geotechnical data helps determine the location of the impact and the placement of the pile tip, and then determine the bearing capacity of reinforced concrete piles before and after considering the effect of negative friction.

According to TCVN 10304:2025 [15]

standard for pile foundation design, the soil in which the pile is located can be deformed due to consolidation, expansion, or loading… Negative friction force (anti-friction force) is generated on the pile shaft due to settlement of the surrounding soil mass, directed vertically downwards and considered in many cases including the requirement that the thickness of the backfill layer is more than 1.0 m.

This study utilizes the geological conditions in areas 4 and 5 of the Rach Gia land reclamation project, assuming different thicknesses of the embankment layers. The study aims to determine the bearing capacity of reinforced concrete piles, considering and excluding the negative friction caused by the embankment layers. From this, the design bearing capacity of the piles can be compared.

2.1 Geological characteristics of the Rach Gia reclaimed land area.

Layer 1: Here, we assume the fill layers are 1.5m, 3m, and 4m thick, respectively. Composition: Clayey silt, new fill soil. According to the Geological Report, it is 0.5m thick and has $\gamma = 19.50$ kN/m³.

Layer 2: The average thickness of this layer is 8.10m, with varying thicknesses from 8.00m to 8.20m. Composition: Cement-gray to bluish-gray clayey silt; fluid state. The upper layer is fill mud, the lower layer is original mud. SPT test results range from 0-2 blows. This layer is distributed in the borehole as follows: Layer surface depth 1.5m; Layer bottom depth 9.5m; Layer thickness 8.0m;

Layer 3: The average thickness of this layer is 1.40m, with thickness varying from 1.30m to 1.50m. Composition: Grayish-blue clay with laterite pea-sized gravel; soft, plastic clay. SPT test yielded 7-8 blows. This layer is distributed in the borehole as follows: Layer surface depth 9.5m; Layer bottom depth 11m; Layer thickness 1.5m;
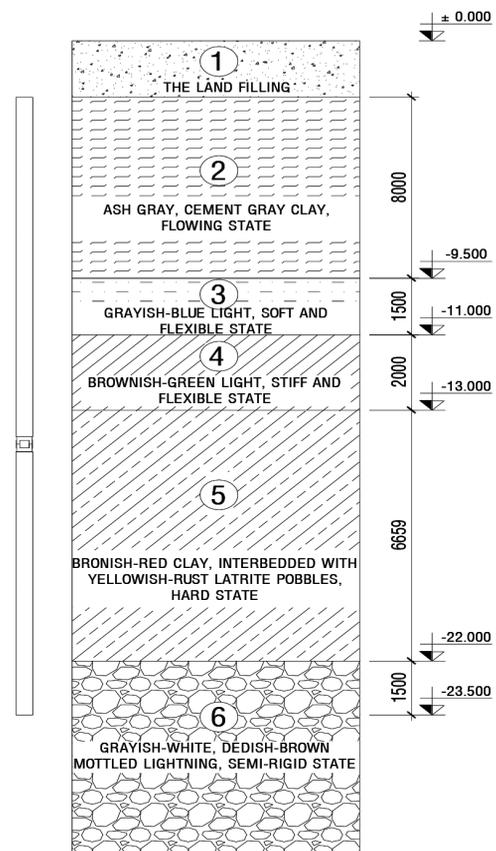

Figure 1. Length of pile section affected by negative friction

Layer 4: Average thickness is 1.75m, varying from 1.50m to 2.00m. Composition: Brown clay with green streaks; stiff plastic state. SPT test yielded 15-16 blows. This layer is distributed in boreholes as follows: Layer surface depth 11m; Layer bottom depth 13m; Layer thickness 2m;

Layer 5: Average thickness is 9.25m, varying from 9.00m to 9.50m. Composition: Brown clay, reddish-brown underneath, with interbedded thin layers of rust-colored laterite in some places; hard to semi-hard state. SPT test yielded 19-29 blows. This layer is distributed in boreholes as follows: Layer surface depth 13m; Layer bottom depth 22m; Layer thickness 9m;

Layer 6: The average layer thickness is 8.00m. The thickness varies from 7.00m to 9.00m. Composition: Reddish-brown, yellowish-brown clay. Hard clay state. This layer is distributed in the boreholes as follows: Layer surface depth 22m; Layer bottom depth 31m; Layer thickness 9m;

Table 1: Soil Layer Specifications

Soil layer	Soil moisture W (%)	Natural specific gravity γ (kN/m³)	Dry specific gravity γ_d (kN/m³)	Proportion G_s	Porosity n (%)	Void ratio e	Internal friction angle φ Degree (°)	Soil cohesion C (kN/m²)	Consistency B
Layer 2	58.783	15.21	9.59	2.616	63.33	1.733	4⁰20'	0.86	1.107
Layer 3	30.44	18.42	14.12	2.706	47.81	0.916	10⁰44'	3.03	0.50
Layer 4	25.94	19.38	15.39	2.719	43.39	0.767	14⁰51'	4.58	0.260
Layer 5	23.443	19.70	15.96	2.714	41.16	0.702	17⁰39'	5.98	0.115
Layer 6	22.963	19.79	16.09	2.725	40.957	0.694	19⁰14'	6.73	-0.003

2.2 The design load capacity of the pile without considering the effect of negative friction.

Select the 6th soil layer to place the pile tip, and the calculated pile length is 22.7m excluding the pile tip, which is 1d. The pile tip is driven down to layer 6 to a depth of approximately 1.5m. Use B30 concrete with: R_b=17000 (kN/m²), R_{bt}=1150 (kN/m²);

Reinforcement steel: the load-bearing steel in the pile cap is CB300-V steel with: R_s=260000 (kN/m²), stirrup steel is CB240-T.

According to the Foundation Engineering document of [16] and the Foundation and Footing document of [17] along with the selected pile parameters, we can find the design bearing capacity of the pile according to different cross-sections:

Table 2: Summary of design bearing capacity of piles without considering negative friction effects

Pile cross-section (mm)	Steel	Steel reinforcement content (%)	Pile design load capacity (kN)
300x300	4Φ18	1.131	613.3
350x350	4Φ20	1.026	724.1
400x400	4Φ22	0.95	836.8

2.3 The design load capacity of the pile without considering the effect of negative friction.

Table 3: Thickness and specifications of soil layers

Parameter	Symbol	Unit	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Thickness	h	(m)	As assumed	8.00	1.50	2.00	9.00	1.50
Natural density	γ	(kN/m^3)	19.5	15.21	18.42	19.38	19.70	19.79
Elastic module	E	(kN/m^2)	0.00	700.67	660	2953	3229	3321
Soil cohesion	C	(kN/m^2)	0.00	8.60	30.3	45.8	59.8	67.3
Internal friction angle	φ	(°)	0.00	4⁰20'	10⁰44'	14⁰51'	17⁰63'	19⁰17'
Poisson's ratio	μ	-	0.43	0.45	0.45	0.45	0.45	0.45

The Poisson coefficients depend on the state of the soil layer and are looked up in the Foundation Engineering document [16]. According to the document Pile Foundation Analysis and Calculation [18] and Soil Mechanics [19], we determine the depth of influence of negative friction on the pile as follows:

Pressure causing subsidence:

$$\Delta p = \gamma_d \times h_d \qquad (1)$$

Where: γ_d: specific weight of the embankment layer, (kN/m³); h_d: Thickness of the embankment layer, (m).

Settlement of the clayey silt layer:

$$S = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} \frac{\beta_i}{E_i} \Delta p_i h_i \qquad (2)$$

Where: β_i: coefficient of lateral expansion, take $\beta_i = 0.8$;

h_i: thickness of the i-th soil layer, (m);

Δp_i: settlement stress in the middle of the i-th element layer, (kN/m²);

E_i: average deformation modulus of the compressible soil layer under the pile tip, (kN/m²).

Calculate the elastic deformation of the pile itself:

$$\Delta l = \frac{Q_{tb} \times L}{A_p \times E_c} \qquad (3)$$

Where: L: pile length (m); E_c: elastic modulus of the pile material (kN/m²);

Q_{tb}: force acting on the pile cap (kN); Δl: elastic deformation of the pile itself (m).

$$Q_{tb} = Q_p + \xi(N - Q_p) = Q_p + \xi Q_s \qquad (4)$$

Where: N: load from the structure transmitted to the pile, (kN); Q_p: tip resistance at design load, (kN); Q_s: side resistance at design load, (kN); ξ: is a coefficient depending on the form of the friction distribution diagram on the pile shaft. If f_s is uniformly distributed or parabolic in shape with depth, then; if f_s is linearly distributed with depth then $\xi = 0.67$ [17]

Calculate the settlement of the soil at the pile tip:

$$S_b = \frac{q_p B \omega (1 - \mu^2)}{E_0} \qquad (5)$$

Where: B: pile width (m); μ: Poisson's ratio of the "i"th soil layer, $\mu = 0.45$;

E_0: modulus of the soil under the pile tip (kN/m²); $E_0 = 332.100$ (kN/m²);

ω: coefficient depending on the pile shape, if the pile is square, take $\omega = 0.88$; if the pile is round, take $\omega = 0.79$.

q_b: resistance strength of the soil under the pile tip (kN).

Calculate the settlement of the soil at the pile shaft (calculated separately for each soil layer):

$$S_b = \frac{f_s B \omega_b (1 - \mu^2)}{E_0} \qquad (6)$$

Where: f_s: unit side resistance at average working load for the entire pile segment, (kN/m²);

ω_b: coefficient depending on the slenderness of the pile; E_0: modulus of the soil under the pile tip, (kN/m²);

B: pile width, (m); μ: Poisson's ratio of the i-th soil layer.

From this, we can determine the depth of influence of negative friction on the pile:

$$z = \left(1 - \frac{S_d}{S}\right) H \qquad (7)$$

Where: S_d: settlement of a single pile, (m); S: stable settlement of the foundation, (m);

H: thickness of the weak soil layer, (m).

To calculate the bearing capacity of a pile considering negative friction, we need to determine the unit side friction resistance of each soil layer with the pile shaft, including the pile section affected by negative friction located in the second weak soil layer.

Table 4: Influence of negative friction on the bearing capacity of piles at different cross-sections with different embankment thicknesses

Pile cross-section (mm)	Thickness of the embankment layer (m)	Length of pile section affected by negative friction (m)	Design pile bearing capacity considering negative friction (kN)	The percentage of load-carrying capacity decrease when negative friction is taken into account (%)

	1.5	3.539	584.09	4.77
300x300	3.0	5.619	570.67	7.89
	4.0	6.147	569.73	8.66
	1.5	3.06	695.32	3.97
350x350	3.0	5.365	678.74	7.36
	4.0	5.956	677.77	8.21
	1.5	2.581	809.87	3.22
400x400	3.0	5.11	789.81	6.86
	4.0	5.743	789.17	7.74

3. RESULTS AND DISCUSSION

Table 5: Pile sections affected by negative friction in the second weak soil layer with different embankment layer thicknesses.

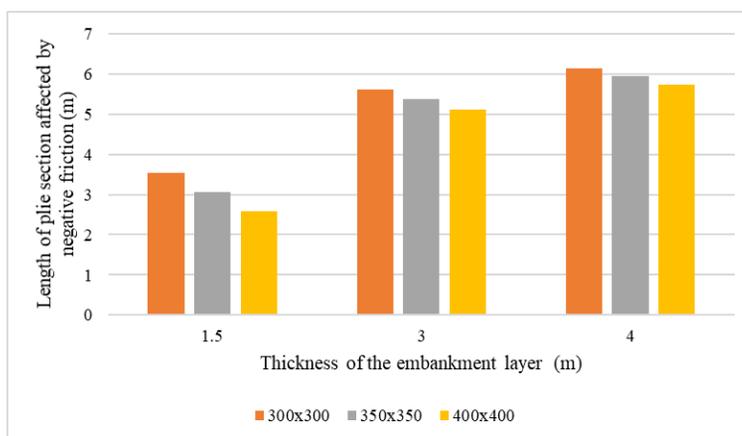| Pile cross-section (mm)	1.5m	3m	4m
300x300	3.539	5.619	6.147
350x350	3.06	5.365	5.956
400x400	2.581	5.11	5.743

Figure 2. Length of pile section affected by negative friction.

Regarding the bearing capacity of piles under the influence of negative friction, the value is lower than when negative friction is not considered. This is because when negative friction is considered, a section in the second soil layer (silty clay in a fluid state) causes negative friction, due to the settlement of this soil layer being greater than the settlement of a single pile. According to the diagram above, although the pile cross-sections differ, they share a common point: the larger the embankment layer, the greater the section of the pile affected by negative friction, and this decreases gradually with increasing pile cross-section.

Table 6: Design bearing capacity of piles considering negative friction with different thicknesses of embankment layers.

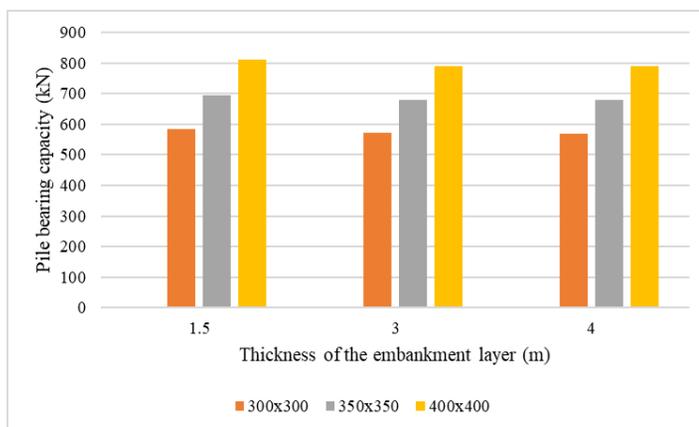| Pile cross-section (mm)	1.5m	3m	4m
300x300	584.09	570.67	569.73
350x350	695.32	678.74	677.77
400x400	809.87	789.81	789.17

Figure 3. Design bearing capacity of piles considering the effect of negative friction.

Table 7: Percentage of pile design bearing capacity considering negative friction with different embankment thicknesses.

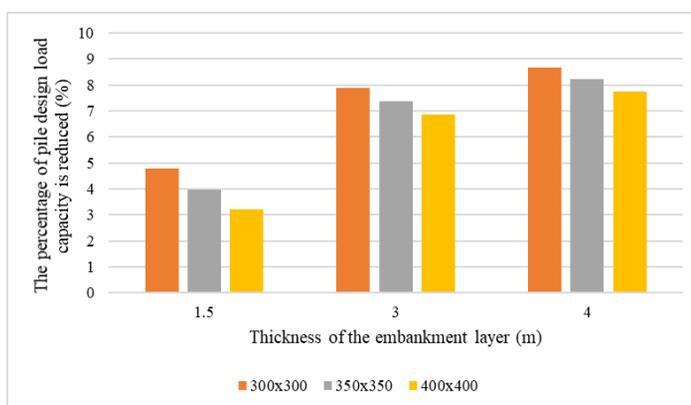| Pile cross-section (mm)	1.5m	3m	4m
300x300	4.77	7.89	8.66
350x350	3.97	7.36	8.21
400x400	3.22	6.86	7.74

Figure 4. Design bearing capacity of piles considering the effect of negative friction.

From the results and graphs above, we can see that when considering negative friction, the bearing capacity of piles tends to decrease in the case of assuming a thick layer of embankment soil on weak soil; similarly, when assuming the thickness of the embankment layers gradually increases by 3m, 4m, the percentage reduction in the design bearing capacity of the piles increases. At the same time, the study helps us to see realistically how considering the bearing capacity of piles when the influence of negative friction is added. The appearance of negative friction significantly increases the settlement during the consolidation process of the structure due to the reduced bearing capacity of the piles, even though the design bearing capacity increases when the pile cross-section increases.

The results above show that increasing the thickness of the weak soil layer gradually reduces the design bearing capacity of the pile when considering the influence of negative friction. In addition, the paper also addresses the issue of changing the cross-section of the pile. Through calculations, the research team found that increasing the pile cross-section reduces the influence of negative friction, and considering each cross-section individually with increasing embankment layers, the bearing capacity also decreases due to the influence of negative friction.

Negative friction only occurs at locations where the weak soil layer has a settlement greater than that of a single pile. Therefore, we need to select a suitable, good soil layer for pile driving. In this case, negative friction will gradually disappear with increasing pile depth and transform into positive friction, thus not affecting the pile's bearing capacity during operation. This helps us to choose a reasonable pile design and a safe pile construction method.

In the Rach Gia reclaimed land area, significant development is expected in the near future. With this development trend, the problem of negative friction has been receiving considerable attention. Methods for addressing negative friction affecting pile load-bearing capacity include: changing pile cross-sections, pile materials, pile construction methods, or combining the use of various soil treatment materials, etc.

In addition, the results of the problem depend on many factors such as the working condition coefficients of the soil, the importance coefficient of the structure, the reliability coefficient of the number of piles in the foundation, and the choice of expansion coefficient (Poisson coefficient) depending on the type of soil, etc. Although the calculation results in this article are for reference only with a specific coefficient choice, the results show the influence of negative friction caused by the embankment piles higher than 1m in the weak soil layer on the load-bearing capacity of the piles. The relationship between soil settlement deformation and pile settlement deformation is the fundamental basis for the occurrence of negative friction.

Negative friction depends on many factors (type of pile, pile length, soil characteristics, thickness of the weak soil layer, embankment height, load, etc.). In general, studying a pile problem affected by negative friction is quite complex. Negative friction develops over time and reaches its maximum value when consolidation ends. The negative friction force is proportional to the lateral pressure of the soil acting on the pile and the rate of consolidation settlement of the soil. The negative friction phenomenon will end when consolidation settlement ceases, at which point the friction between the soil and the pile will become positive friction.

Negative friction acts not only on the side of the pile but also on the side of the pile cap. As the height of the embankment (or load) increases, negative friction increases rapidly in the initial stage and slows down in the later stages. When the embankment height reaches a certain limit, the negative friction increases insignificantly (possibly to const). A similar result occurs with respect to the depth of the affected zone z. Depending on the height of the embankment (or the magnitude of the load) and the thickness of the weak soil layer, the depth of the zone affected by negative friction may extend beyond the weak soil layer and may also affect the underlying good soil layer (when the settlement of the good soil layer is greater than the settlement of the pile).

4. CONCLUSION

Evaluating the interaction between piles and soil is crucial. For weak soils, it's a decisive factor in determining the effectiveness of pile performance, especially when a backfill layer thicker than 1 meter is present. This includes comparing the pile's bearing capacity with varying backfill thickness and pile cross-section. Research and calculations show a reduction in the pile's design bearing capacity when considering the influence of negative friction. Larger pile cross-sections reduce the impact of negative friction, but this tends to increase with increasing backfill within the same cross-section. Therefore, considering and incorporating negative friction into design calculations to increase the safety factor of the structure is essential.

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