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Negative Skin Friction Development on Single Pile and Pile Group Embedded in Soft Clay

Ayman Altahrany and Esraa R. Elshehahwy*

KEYWORDS:
Foundation, Pile Group, Negative Skin Friction, Single Pile, Plaxis 3D, Soft Soil, Neutral plan

***Abstract*—Determination of negative skin friction force and The neutral plan is one of the challenges which face geotechnical engineers. Unfortunately, negative skin friction decreases the bearing capacity of pile because of the extra compressive force on the pile. In this research, a 3D FE models were used to investigate the behavior of single pile and pile group in soft soil for surcharge load as embankment fill. And what are the differences that will happen on the behavior of single and pile group. For embankment fill load, the maximum group effect is the center pile and the corner pile observed the minimum group effect. The depth of the neutral plan for center pile is less than observed in the corner pile. A simple parametric study has been done to study the group effect. Spacing to diameter ratio (S/D) in the pile group had changed in a view solution to develop the pile group effect. Increasing the ratio of spacing to diameter keep the group behaves as a single pile in large S/D. Besides, there is maximum effective spacing to diameter ratio taken into consideration, its behavior as a single pile behavior.**

I. INTRODUCTION

MANY projects constructed on soft soil and the soil surrounding a pile settles more the pile due to surcharge load. Therefore, Pile foundations are sometimes subjected to negative skin friction (NSF). According to Randolph (1994) & Poulos (2001), the soil can provide bearing capacity, by decreasing the pile carrying capacity and increasing the compressive stress in a pile. Therefore, the negative skin friction is becoming a significant issue in the application of piled raft through soft soil. The problem is obvious in the movement of the soil around piles at a high rate of settlement as for the settlement of pile. A neutral plan provides at the depth which no relative movement between the pile and the surrounding soil where no skin friction force.

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Ayman Altahrany, Associate Professor at Structural Engineering Department, Faculty of Engineering, Mansoura University, Egypt. (e-mail: atahrany@hotmail.com).

****Corresponding Author:** Esraa R. Elshehahwy, Teaching Assistant at The Department of Civil Engineering Mansoura Collage Academy, Mansoura, Egypt (e-mail: esraa_elshehawy92@yahoo.com).*

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The soft Bangkok clay remolded during pile driving and varies in thickness from 10 m to 15 m. The first ten meters of soil has high water content and a low number of bowels (N) in the standard penetration test (SPT). Besides, low density through this depth causes unacceptable settlement. The unacceptable settlement appears making down drag extent to great depths to around 20m in bored piles. (Likitlersuang et al. 2013). Unfortunately, most projects need to raise the ground surface about 1.5m: 2m of fill, to distribute negative skin friction on piles and settlement happened in upper layers of soft soil. (Indraratna et al. 1992)

A few successful applications of the piled raft on soft soil have been reported by Yamashita et al. 1998, Poulos., 2005, Tan et al., 2006. The numerical model was developed to describe the behavior of load transfer at soil-pile-soil interface during consolidation and loading-unloading conditions by Cheen et al. (2009). Finite element method (FEM) was used for solving the complex problem between pile and soil. It was used in recent researches (Reul,2004, Jaeyeon et al., 2012). However, the researches on negative skin friction are not deep enough. The mechanism on pile group effect of NSF is not still well.

In this research, the three-dimensional finite element method through the Plaxis 3D program was used to analyze the behavior of pile groups under embankment surcharge load. Comparing the behavior of center, edge, and corner piles to the behavior of a single pile. Finite element analysis of negative skin friction development was carried out, and the predicted behavior was compared with the measurements in situ. On the basis of these numerical findings, the dragload and skin friction along the piles shaft subjected to spacing to diameter ratio was discussed, with a view to improve methodology of design. The settlement of the soil surface inside and outside the groups was studied by Mehmet & Devrim (1995). The pile group effects were negligible as the soil was compressed by air pressure and pointed out at pile spacing at 5 to 6 pile widths.

The reduction in maximum drag load compared to a single pile is defined as the group effect. Within a group, the maximum group effect was observed on the center pile, while the less pile group effect was observed for the corner pile.

II. Reference Case Study of the single pile at Bangkok Soil

At 10 KM east of Bangkok city in Thailand, Indraratn et al. (1992) run full-scale field measurements on two piles. The two piles was prestressed, precast, and concrete type. One of them was coated with bitumen and the other was uncoated.

The pile compression and movements was adopted by the telltale system. A closed hydraulic piezometer was installed at 0.5m and 1m far away from the pile shaft at depths of 4, 8, 12, 16 and, 20m. Fig.1 illustrated instrumentation arrangements and the dimension of embankment surcharge.

A 24x12m with a side slope of 2:1 of an embankment was constructed above the test area with a height of 2m to contribute to the negative skin friction. The pile was driven from 2m to -25m below the ground surface. The piles had 0.25m inner diameter and 0.4m as the outer diameter. The observation of settlements and loads were observed for nine months

In the case study of Indraratna et al. (1992), the five boreholes were drilled up to -35m below the ground surface, the layers were generalized as follows:

1. Weathered clay up to -4.0m from the ground surface
2. Soft clay is from -4.0m to -20m
3. Medium stiff clay is from -20m to -24m
4. Stiff clay is from -24m to -27m
5. The sand layer is beginning from -27m from the ground surface

The ground water level is located at depth -2.0m from the ground surface. The general properties of soil are shown in Fig.2.

A standard penetration test (SPT), pressure meter, Dutch cone (DC), field vane shear test (FV), oedometer test, direct shear (DS), and K0 consolidated undrained triaxial test (CK0U) were conducted. A comprehensive description of these tests is given in Jamiolkowski et al. (1985). The variation of Su undrained shear strength with depth was obtained from tests shown in Fig.2. The current case study is concerned with studying the uncoated pile behavior only.

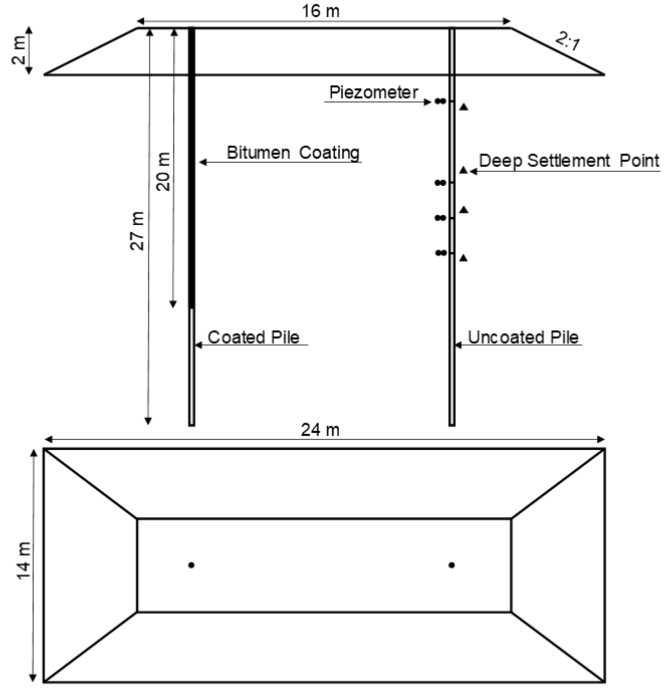

Fig. 1. Piezomter system, load cell, surcharge dimension, and piles (After Indraratna et al. 1992)

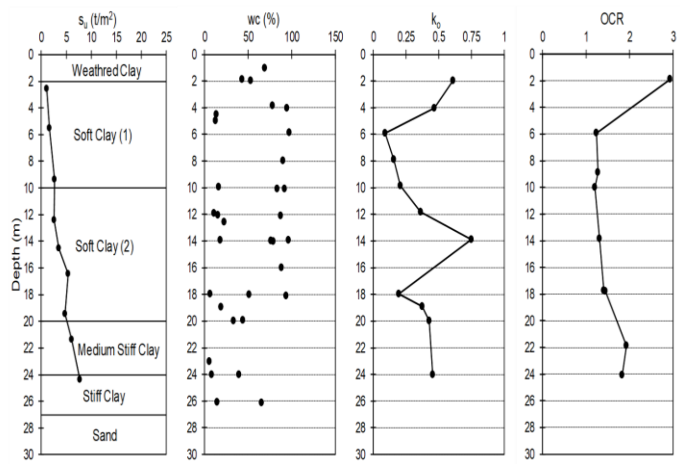

Fig. 2. Soil Properties Depending on Measurements of Indraratna et al., (1992)

III. Characteristics of Numerical Modeling

A. Material Properties

The three-dimension model had simulated the behavior of uncoated pile in the case study of Indraratna et al., 1992. The constitutive model used for all soil layers is the hardening soil model in drained conditions. The embankment surcharge fill was modeled by mohr-coulomb. The pile was modeled as an embedded pile. The hardening soil model required some input parameters including E50, Eoed, Eur. Salem M., et al. (2019)

had improved the modified cam clay model parameters, which was used in the Indraratna et al., case study, to hardening soil model and used the parameters of drained soil shown in Table.1. Also, divided the soft clay layer into two different layers, because of differential water content in the same layer as in Fig.2, the upper of soft clay layer had a high water content, vice versa in the lower of that layer.

Table .2 summarizes the material properties of the embedded pile used in the analyses. All the analyses were based on the drained condition in this paper. Interface roughness Rinter between the embedded pile and surrounding soil is assumed in a range from 0.6: 0.75 showed in details for each layer in table .2. Shaft resistance and end resistance controlled the side friction force and end bearing force, respectively which developed on the embedded pile. Embedded pile depended on its shaft resistance force per unit length and foot resistance force. Engine et al. (2007,2008) described the embedded pile formulations depending on the stiffness of surrounding soil, pile length, equivalent radius, spacing, and stiffness

These limited conditions were based on a static manual calculation of pile capacity without taking the first 1m of the soil out of calculation in addition to the distance equal to the diameter from the bottom. Taking into consideration shear strength values shown in Fig. 2. It's a simulation for field measurements, not designed with a factor of safety. The shaft resistance per unit length was specified by the multi-linear function, which a linear variation of each soil layer between the top and bottom interfaces was defined in Table .2 in detail.

Plaxis 3D 2020 was carried out in this study. The 3D model soil was represented by volume element. A relatively fine mesh generation was used for all models. The boundary conditions were displacement restraints with roller supports applied on vertical sides and pin supports for the mesh base. The staged construction was 4 stages, a. initial phase, b. pile installation, c. embankment installation plastic stage, and d. embankment consolidation stage.

IV. Validation Between Field Measurements and Numerical Prediction

The verification between the measured settlement of the case study and predicted ground surface settlement at a 0.25m distance far away from the center of the pile, was illustrated in Fig.3. The predicted settlements after 3 days as a short term and 265 days (nine-month) as a long term, showed a good agreement to the measured distribution of ground surface settlement. The immediate settlement during the first 3 days can predict well using undrained soil properties, but a better estimation for the settlement after 265 days was by using drained soil analyses.

The long-term predicted and measured drag load was observed for uncoated pile after nine months. The location of neutral plans was also for comparison in Fig. (4.a). For a measured curve, the neutral point was at depth 20m happened at the maximum load which was 300 kN approximately. On the other side, the neutral point of a predicted curve at maximum load 283 kN at 17.3m depth.

Fig. 4.b shows a typical comparison between the predicted numerically and measured skin friction distributed along pile shaft after 265 days as a long term using drained soil conditions. The development of negative skin friction (NSF) was well predicted within the soft clay layer.

Passing on Fig. (4.b), represented negative skin friction with depth. The turning point from negative skin friction to positive skin friction was called neutral plan position. The neutral point was predicted, by the finite element method through Plaxis 3D, is at depth of 17.3m. It is of interest to note that, the neutral plan was measured by Indraratna seems to be at a depth of about 18m.

So, the neutral point at zero skin friction by finite element method deviates by about 3.7% from the actual measured location. Relatively good agreement and similarity observation between Indraratna et al. 1992& Lee 2002 and predicted curve.

From the two curves Fig. 4(a & b), the predicted neutral plan was at 18m, for the dragload and friction force charts. But the measured neutral plan from the field had a deviation, and that was not clear at Indraratna et. al, measurements.

TABLE I
MATERIAL PROPERTIES OF EACH SOIL LAYER, AFTER SALEM M., ET AL (2019)

Layer	**Depth (m)**	**Model Type**	**γ (kN/m^3)**	**e (void ratio)**	**Drained Parameters**			**m**	**c**	**φ**	**K (m/day)**	**R_{inter}**	**OCR**
					E_{50} (Kn/m^2)	**E_{oed} (kN/m^2)**	**E_{ur} (kN/m^2)**						
Fill	+2 – 0	MC	17	1.67	15000	-	-	1	0.1	30	0.006	0.6	1
Weathered clay	0 : -4	HS	17	1.67	1830	1464	4525	1	0.1	26.5	0.006	0.6	3
Soft clay 1	-4 : -10	HS	15	3.05	986	789	4346	1	0.1	24.7	0.0026	0.75	1.1
Soft clay 2	-10 : -20	HS	16	2.09	1194	955	4404	1	0.1	24.9	0.0026	0.75	1.1
Medium stiff clay	-20 : -24	HS	19	1.2	2368	1894	7342	1	0.1	23	0.0037	0.75	1.8
Stiff clay	-24 : -27	HS	19.5	1.2	15000	12000	45000	1	0.1	23	0.0037	0.75	1.8
Sand	From -27	HS	20	0.5	55000	44000	165000	0.5	0.1	35	1	-	1

TABLE 2

MATERIAL PROPERTIES OF EMBEDDED PILE ELEMENT

Parameters	Symbol	Unit	Value
Young`s modulus	E	**kN/m²**	3x10⁷
Unit weight	γ	**kN/m³**	15
Pile type	Massive circle pile		
Diameter	d	m	0.4
Skin resistance	Multi-layer		
		L(m)	**T(kN/m)**
		0	0
		4	10.055
		10	10.05
		20	30.79
		24	34.55
		25	45.87
F_{max}		kN	90.48

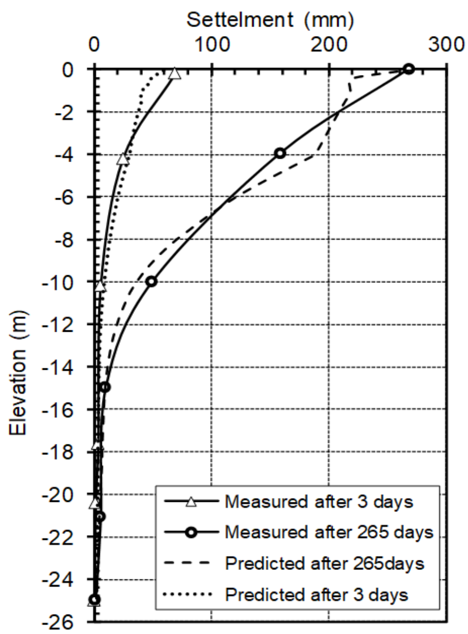

Fig. 3. Ground Surface settlement of Measured and Predicted with depth measured at 0.25m away from pile center after 3days and 265days.

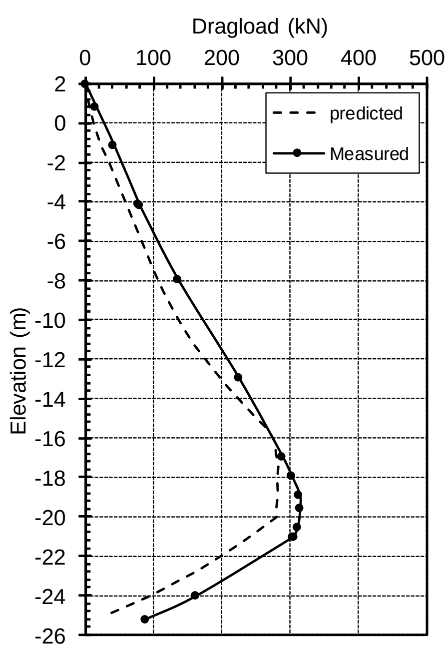

Fig. 4. (a)

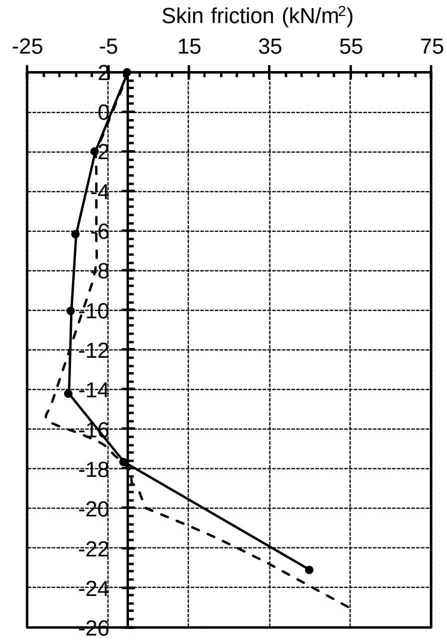

Fig. 4. (b)

Fig. 4. Distribution of (a) Dragload and, (b) Skin Friction along pile shaft after 265 days for Measured and Predicted.

V. PILE GROUP BEHAVIOR COMPARING TO SINGLE PILE

A. Parametric Study of Pile Group Spacing to Diameter Ratio

A finite element model was developed to investigate the group effect under embankment surcharge on the distribution of dragload in pile group embedded in soft soil layers. Soil settlements and negative skin frictions (NSF) were generated by the application of embankment surcharge on the top of the ground level, without an applied load on the pile head individually.

In coastal areas in Thailand, it was used to raise the ground surface by 1.5m: 2m fill to avoid flooding. Consequently, this high in height make settlements in soft clay layers leading to negative skin friction on piles. At this research, embankment surcharge load on pile group was subjected to settlement in soft soil layers, due to consolidation which generates negative skin friction (NSF).

In the current study, the embankment surcharge load was applied by raising the ground surface around the piles by 2m of fill with the same properties of Indraratna et al, (1992) case study shown in the table.1.

The embankment surcharge had a slope of 2:1 horizontal to vertical respectively, which started at 3m far away from the boundary of the outer piles` centers at the top area of fill then takes the slope down as shown in Fig. 5. The piles were modeled as free-headed and rigid end piles in a group the piles in a group were not connected with pile cap or pile raft foundation, but every pile responded to applied loading separately.

Single pile and 4x4 pile groups were posed under embedded load at fig 5.a and 5.b respectively. 4x4 Pile groups were studied with different spacing to diameter ratios: S/D= 3, 4, 6, and 8. The finite element (FM) model mesh is fine as a case study and presented in Fig. 5. The arrangement of piles in a group and their positions are shown in Fig.6.

(a)

(b)

Fig. 5 Finite Element Model Mesh for (a) Single Pile and (b) Pile Group.

B. Embankment loading effect

Pile groups were defined for embankment load as a reduction in a maximum drag-load comparing with the single pile. The variation of Predicted drag-load and skin friction along the length of the pile shaft in 4x4 pile group with spacing to a diameter equal to 3 compared to that for single pile in Fig.7. The neutral plan of the single pile is at 17.00m depth under the ground surface almost 68.08% of pile shaft embedded in soft layers.

The behavior of piles in 4x4 pile groups, which had S/D=3, was close to the behavior of a single pile. A similar dragload was observed to corner pile with the single pile. The maximum group effect was noted for the center pile, while the minimum effect was observed for the corner pile. Still the single pile had a maximum dargload. The group effects for corner, edge, and center piles are 7.7%, 26.5%, and 42.5%, respectively.

As the spacing to diameter ratio increased in the 4x4 pile group to reach S/D=4, the group effects decreased but still, maximum observation for center pile. The group effect decreased to 17.8%, 26%, and 32.7% for corner, edge, and center pile respectively, that obviously in Fig. 8.

As increased the spacing to diameter ratio equal to 6, the pile group effect is -3.8%, 11.8%, and 16.7% for corner, edge, and center piles respectively, see Fig.9. Finally, in Fig.10. at a spacing, to diameter ratio equal to eight, the pile group effects decreased more to reach -18.7%, -7.8%, and -3.9% for corner, edge, and center pile respectively.

Studying the neutral plan position for piles in a group comparing to the single pile is observed in Table.3. The results appear that the single pile neutral plan is close to the neutral plan of piles in a pile group, that what approved by Matyas et al, (1994) and Elshehawy E. et al. (2020). Also, at a high spacing to diameter ratio, the piles in the group behave as a single.

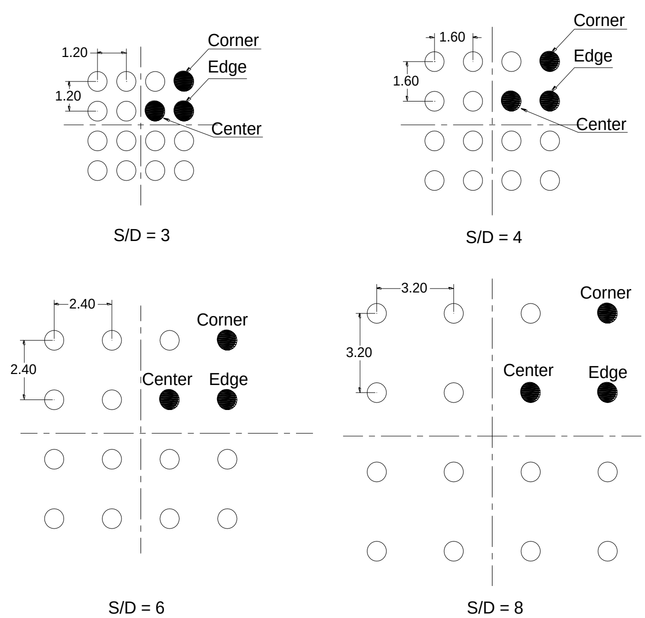

Fig. 6 Positions of Piles in a 4x4 Pile Group under Embankment surcharge load for Different Spacing to Diameter Ratio.

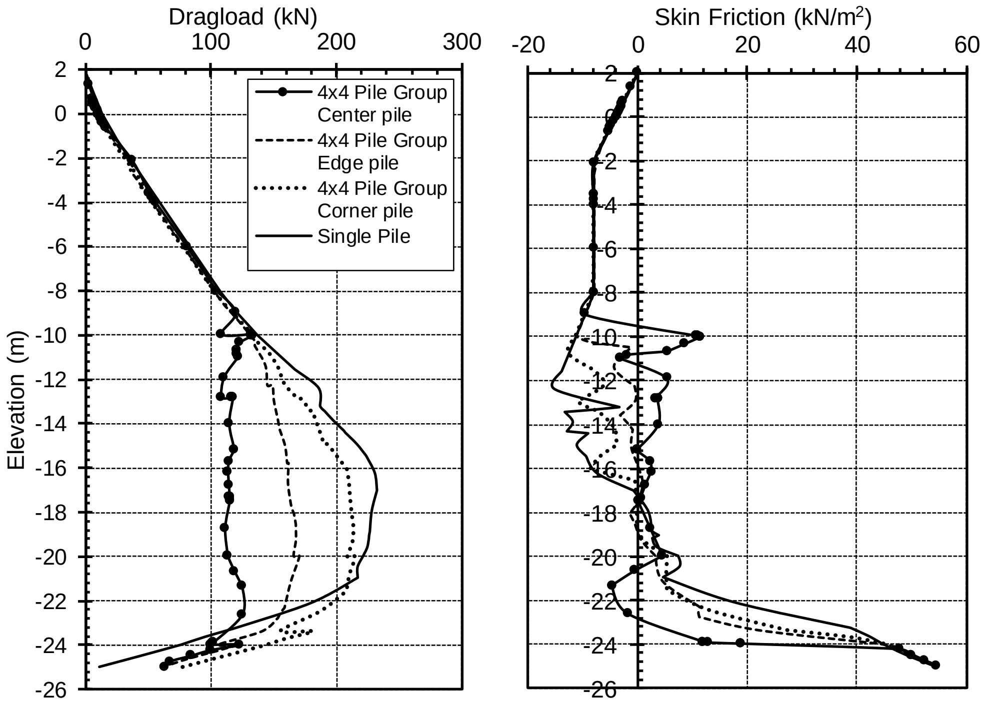

Fig. 7: 4x4 Pile Group effect on (a) Dragload and (b) Skin Friction under Embankment load for Spacing to Diameter ratio S/D = 3

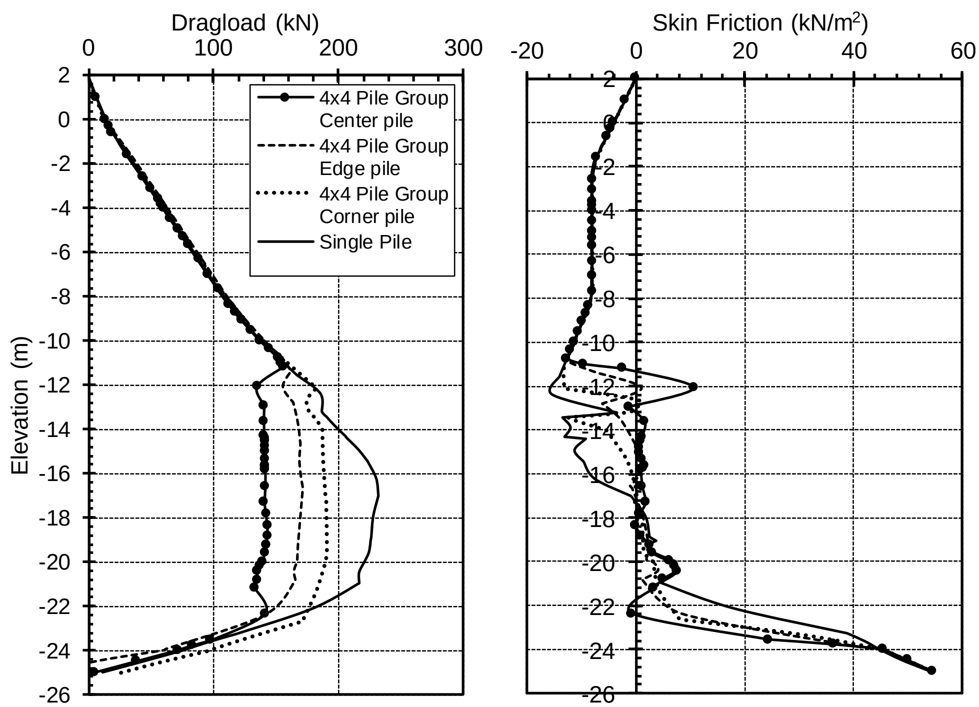

Fig. 8: 4x4 Pile Group effect on (a) Dragload and (b) Skin Friction under Embankment load for Spacing to Diameter ratio S/D = 4

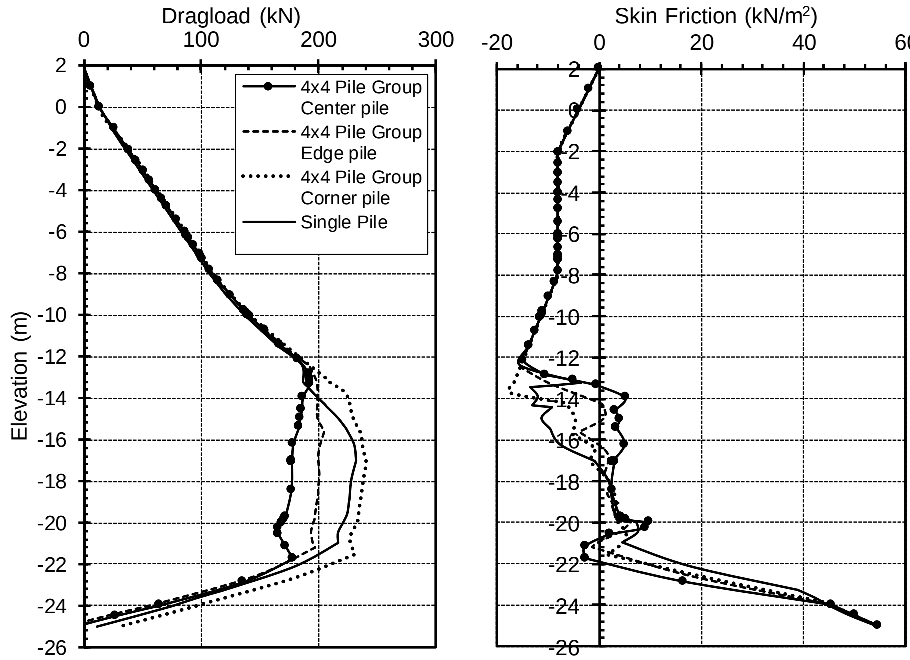

Fig. 9: 4x4 Pile Group effect on (a) Dragload and (b) Skin Friction under Embankment load for Spacing to Diameter ratio S/D = 6

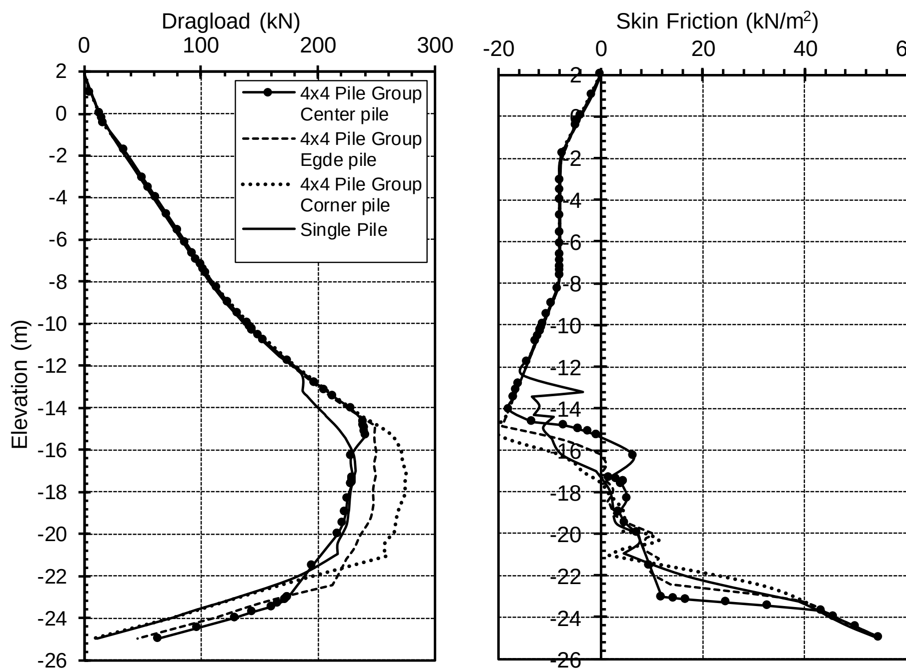

Fig. 10: 4x4 Pile Group effect on (a) Dragload and (b) Skin Friction under Embankment load for Spacing to Diameter ratio S/D = 8

TABLE 3
PERCENTAGE OF NEUTRAL PLAN POSITION AT DIFFERENT SPACING TO DIAMETER RATIOS

Pile position in pile group	**Spacing to Diameter Ratio**				**Single pile**
	3	4	6	8	
Center Pile	40.16 %	53.20 %	53.20 %	60.80 %	
Edge Pile	66.60 %	62.60 %	62.60 %	64.40 %	68.08%
Corner Pile	77.56 %	68.40 %	68.40 %	68.08 %	

	E_{ur} (kN/m^2)
Center Pile	-
Edge Pile	4346

Fig.11 presents the group effect with the different spacing to diameter ratios (S/D). The more spacing to diameter ratio, the less pile group effects, and still the center pile effect in a group is higher than edge pile effect then corner pile. These negative percentages of group effects comparing piles in the group to single pile mean that pile group was not effective at a high spacing to diameter ratio in soft soil layers. The dragload is higher than the resistance load at pile tip (end) plus the positive skin friction resisted the load. The piles were diving after spacing to diameter ratio equal to 4. That is not suitable or preferred in design.

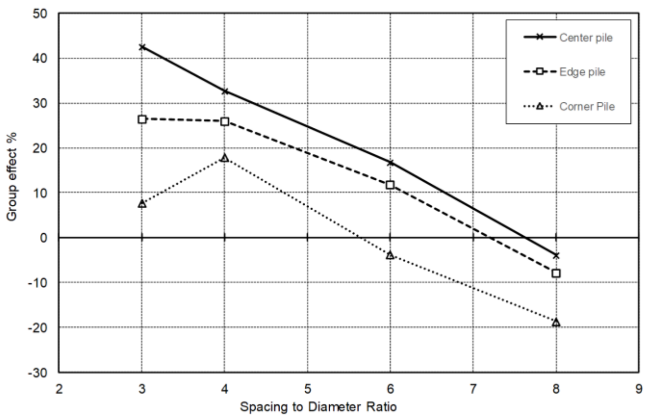

Fig. 11: Variation of Pile Group Effect with different Spacing to Diameter Ratio under Embankment load

VI. CONCLUSION

The developed three-dimensional finite element model was used to investigate the behavior of pile groups in soft clay layers under embankment surcharge load.

The negative skin friction can be predicted by the finite element method. Also, the maximum negative skin friction was mobilized after 6 months for the uncoated pile. Consequently, it was studied after 9 months from the observation measurement of the instrumented driven pile.

Piles were spaced at 3, 4, 6, and 8 times the pile diameter for all investigated cases compared to a single pile, it is noted that under embankment surcharge load:

- The center pile has the maximum pile group effect special at a small spacing to diameter ratio than the large S/D and the minimum for all corner piles.
- The group effect decreases at an increasing the spacing to diameter ratio
- At the high ratio of spacing to a diameter of pile group embedded in soft soil layers, the pile group is not effective because of piles diving, as a result to increasing negative skin friction than the resistance of end pile or positive skin friction.
- The suitable S/D ratio under embankment load and 4x4 pile group embedded in soft soil are S/D=4.
- With the large S/D ratio, piles in the group behave as a single pile.
- The depth to neutral plan was larger for corner piles compared to central piles.
- The neutral plan depths for all pile types in the pile group are very close to the neutral plan of a single pile.

To decrease the negative skin friction, installation of piles may be carried out long period on many segment installations. The long period of installation leads to consolidate the soil under piles, thus, decreasing negative skin friction. Besides, a thin layer of bitumen coated the pile to dictate the shear stress distribution along the pile shaft.

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AUTHORS CONTRIBUTION

1- Conception or design of the work: *Esraa R. Elshehahwy* 80%, *Dr. Ayman Altahrany* 20%
2- Data collection and tools: *Esraa R. Elshehahwy* 95 %, *Dr.Ayman* 5%
3- Data analysis and interpretation: *Esraa R. Elshehahwy* 80 %, *Dr. Ayman Altahrany* 20%
4- Investigation: *Esraa R. Elshehahwy* 20 %, *Dr. Ayman Altahrany* 80%
5- Methodology: *Esraa R. Elshehahwy* 95 %, *Dr. Ayman Altahrany* 5%
6- Supervision: *Esraa R. Elshehahwy* 10 %, *Dr. Ayman Altahrany* 90%
7- Drafting the article*: Esraa R. Elshehahwy* 50%, *Dr. Ayman Altahrany* 50%
8- Critical revision of the article: *Esraa R. Elshehahwy* 20%, *Dr. Ayman Altahrany* 80%
9- Final approval of the version to be published *Esraa R. Elshehahwy* 10%, *Dr. Ayman Altahrany* 90%

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TITLE ARABIC:

الاحتكاك الجانبي السالب المتولد علي الخازوق الواحد او مجموعة الخوازيق المدفونة في التربة الطينية الرخوة

ARABIC ABSTRACT:

واحدة من التحديات التي تواجه المهندسين الجيوتقنيين هي تحديد قوة الاحتكاك الجانبي السالب للخاروق . ولسوء الحظ فان الاحتكاك الجانبي يقلل من قدرة تحمل الخاروق ويرجع هذا لزيادة قوي الضغط علي الخازوق.
في هذا البحث مجموعة نماذج ثلاثية الابعاد بطريقة تحليل FINITE ELEMENT تستخدم لمراجعة سلوك الخازوق المفرد و مجموعة الخوازيق في التربة الطينية الرخوة المعرضة لحمل اضاقي خارجي . وما هي الفروق التي تحدث علي سلوك الخازوق او مجموعة الخوازيق.
بالنسبة للحمل الخارجي وتاثيره علي محموعة الخوازيق ، فالخازوق الاوسط يرصد اعلي تاثير بالحمل الخارجي منه عن الخازوق الزاوي.
اما بالنسبة لعمق خط التعادل بين الاحتكاك الموجب والسالب ، فالخازوق الاوسط يرصد اقل عمق لخط التعادل منه عن الخازوق الزاوي بالنسبة لبعده عن سطح الارض.
تم عمل دراسة بعدية بسيطة لدراسة سلوك محموعة الخوازيق. من ضمنها، تغيير المسافة من مركز الخازوق للخازوق الاخر بالنسبة لقطر الخازوق لملاحظة سلوك المجموعة ، فكلما زادت النسبة زاد تصرف مجموعة الخوازيق وكانها خازوق واحد.
بجانب هذا تم رصد هذة النسبة للوصول للنسبة المثلي والتي بعدها لا تتصرف مجموعة الخوازيق كل خازوق واحد.