



Experimental and Numerical Study of Bearing Capacity of Circular Footings on Layered Soils With and Without Skirted Sand Piles

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Abstract

The present paper investigates the behaviour of circular shallow footings on soft clay soils with skirted and non-skirted sand piles. The main goal of this study is to evaluate the settlement and bearing capacity of a circular foundation, which is placed on a soft clay layer, based on a sandy soil layer. Different piles with varying length to clay layer thickness ratios ranging from 0.25 to 1 were modelled experimentally, as well as numerically, both with and without skirt. The effects of using a steel skirt and the length to clay layer thickness ratio of the piles, compared to the case in which the footing is placed on a pile without any skirt, and in the case of a shallow foundation without piles, were also investigated in this study. A model generated by finite element software was also used for numerical analysis. The results indicate that the use of skirted piles can affect the load–settlement curves and increase the bearing capacity. By increasing the ratio of pile length to clay thickness, the bearing capacity of the shallow foundation will be increased and the corresponding settlement will be decreased. Therefore, the bearing capacity failure mechanism of a footing resting on soft clay can be modified from the punching failure to the general shear failure at the tip of the confined replaced sand column. Load–settlement diagrams and bearing capacity obtained by numerical results are in accordance with the results derived from experimental observations.

Keywords Skirted pile · Bearing capacity · Circular footing · Soft clay soil · Experimental study · Numerical analysis

1 Introduction

Recently, there has been increased construction on soft clay soils due to the development of urban areas. Soft clay soils generally experience large settlements and have low shear strength. Construction on soft soils requires soil improvement techniques. Various methods are used to prevent the occurrence of settlement and increase the bearing capacity of foundations on these types of soils, including the use of geosynthetics, cement slurry, high-pressure lime injection, single piles, pile groups, micropiles, stone columns, preloading and the use of vertical drains.

Deep piles are used both singly and in groups to transmit stress from the layer below the foundation to deeper layers with higher shear strength and density. The effects of using

a single sand pile on increasing the bearing capacity of a circular footing, which is located on layered soil, composed of a soft clay layer and a sand layer are investigated in this paper. In order to consider the effects of skin friction, this pile is modelled under two conditions, once with confinement around it and once without any confinement. In this study, these two conditions are referred to as skirted and non-skirted piles, respectively. One of the advantages of choosing this type of pile, compared to concrete piles, is to decrease the costs of materials and installation. In this study, experiments were carried out using an experimental loading system, including a loading pneumatic jack and a digital device for the determination of settlement (LVDT). The aforementioned circular footing was also modelled using the finite element Plaxis 2D software, and the effect of a single sand pile on its bearing capacity has been investigated. Eventually, the experimental results will be compared with the outputs of the software and the numerical model will be validated. Some equations are also presented at the end of the paper in order to predict the behaviour of these piles in terms of variables, such as the thickness of the soft clay layer and the length of the skirted and non-skirted piles.

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Several methods have been studied and proposed by researchers to increase the bearing capacity of shallow foundations located on soft clay soils. The utilization of additives, such as lime, cement and ash, has been investigated in the studies of Khemissa and Mahamedi (2014), Cong et al. (2014) and Garzón et al. (2016). One of the most common techniques to improve the weakness of these types of soils is the use of polymer reinforcements, as reported by Boushehrian and Hataf (2008), Boushehrian et al. (2011), Boushehrian and Afzali (2016), Boushehrian et al. (2017), Hataf et al. (2010), Shin et al. (1993), El Sawwaf (2007) and Hedge and Sitharam (2015). In addition, the utilization of soil–cement piles is another solution, which has been presented by Huang et al. (2013), Luo et al. (2012) and Liang et al. (2009). Some studies evaluated the influence of the level of groundwater table on the bearing capacity of shallow footings (Ausilio and Conte 2005; Ajdari and Esmail Pour 2015).

In another category of soil improvement methods, structural elements are employed to transmit stresses to deeper layers and bypass the loose soil. Dash et al. (2001) investigated the use of vertical reinforcement along with horizontal reinforcement. Reinforcement consisted of a series of interlocking cells, constructed from geogrids, which contain and confine the soil within its pockets. El Sawwaf and Nazer (2005) studied the behaviour of circular footing on confined sand. They used confining cylinders with different heights and diameters to confine the sand. Nazir and Azzam (2010) experimentally investigated the increase in the bearing capacity of footings on soft clay using skirted and non-skirted sand piles. Veiskarami et al. (2011) analysed end-bearing capacity of driven piles in sand using the stress characteristics method. Ornek et al. (2012) studied the capacity of circular foundations on soft clay in improving granular soils using large-scale experiments and neural networks. Eid (2012) studied the bearing capacity and settlement of skirted footings on sandy soil. Pachauria et al. (2014) experimentally investigated the behaviour of circular footings on loose sand. They used piles and PVC pipes with different diameters for physical modelling. Chandrawanshi and Kumar (2015) investigated the improvement in the bearing capacity of footings on dense sand confined by soft clay soils. Bashir et al. predicted the axial anchorage capacity of the concrete-filled steel box (CFSB) as footing by using the 3D finite element program CAMUI was developed by authors' laboratory (Bashir et al. 2016). Deb and Pal studied the uplift behaviour and failure pattern of single belled anchor with 3D and 2D models in cohesionless soil bed (Deb and Pal 2019). Some researchers studied the influence of stone columns to increase the bearing capacity of shallow foundations (Bhattacharya and Kumar 2017; Ng et al. 2014; Ng 2017a, b; Jagadeesan et al. 2018; Debnath and Dey 2017; Frikha et al. 2015).

The ideal method for examining foundation engineering issues is to carry out full-scale tests. However, these methods are limited due to practical and economic problems. To solve these problems, small-scale models are used as alternatives, which also include limitations such as boundary conditions of the test box, sample disturbance and scale effect. Different empirical and semi-empirical equations have been proposed by researchers such as Meyerhof and Hanna (1978) for determining the bearing capacity of footings on an experimental study. According to the comparisons by Merifield et al. (1999), empirical and semi-empirical methods can cause errors up to 20% in some cases.

With the growth and development of cities and the reduction of suitable land, some construction projects will inevitably be built on poor soils such as soft clay. As can be seen in the literature review, some of the studies in recent decades have been conducted on the increased shear stress parameters and the reduced settlement of the soils by additives, while others have focused on the role of structural elements, such as piles, in increasing the bearing capacity of foundations. The purpose of this study is to provide an experimental and numerical investigation for determining the effects of skirted piles on the bearing capacity of circular footings on soft clay soils. In addition, a comparison has been made between the obtained results and the condition in which the non-skirted piles were used. The thickness of the clay layer located on the sand layer and the length of the pile are the variables of this study.

2 Tests Loading Model

2.1 Loading Device

Figure 1 demonstrates a schematic view of the experimental model apparatus used in this study, which consists of a test box with the dimensions of $1 \times 1 \times 1$ m. On top of the test box is a hydraulic jack, which applies static loads to the foundation on the contained soil with the aid of a pump. The tank walls were braced by horizontal and vertical stiffeners to prevent lateral deformation. Part of the side of the tank is made from glass with a thickness of 20 mm, which makes it possible to observe the soil beneath the footing. The inside walls of the tank are polished smoothly. The axial symmetry conditions have been set in all tests. The model footing was made of a steel circular plate with a diameter of 10 cm, a thickness of 5 cm and a weight of 2.405 kg. All experiments were carried out so that the footing bottom was located on the soil surface. A rigid frame is used to apply vertical loads to the footing. A digital measuring gauge with a precision of 0.01 mm is mounted on the footing to record its settlement. This gauge is fixed to the tank wall by a magnetic connector. A circular mild steel pipe with knife edge is used as

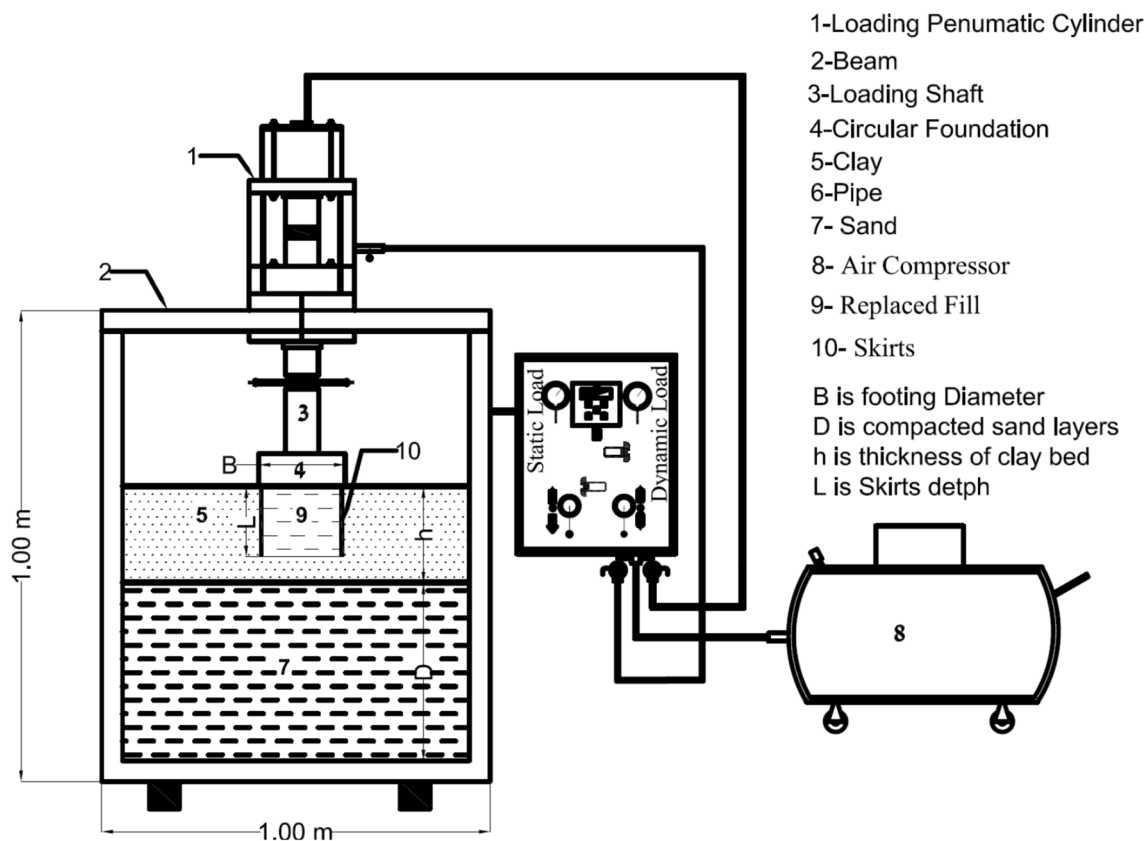


Fig. 1 Schematic layout of the apparatus

structural skirt with 4 mm thickness. These steel pipes with lengths of 12.5, 25, 37 and 50 cm were used for physical modelling of the piles.

2.2 Test Material

The soils used in this study are clay and sand, referred to as CL and SW, according to the unified soil classification system. Moisture content of the soil layers was kept below 2% during the experiments. To keep this value constant, plastic sheet isolators have been used. The soils' grain-size distribution curves are shown in Figs. 2 and 3. The relative density of sand was also kept between 35.5 and 40 per cent in all tests, and the specific gravity of clay ranged from 1.65 to 1.70 g/cm³ in experiments. A direct shear test on the soil sample with the same density in the laboratory showed an internal friction angle of 34° for sand and 20° for clay. Some characteristics of sand and clay are presented in Tables 1 and 2. Steel tubes with lengths of 12.5, 25, 37.6 and 50 cm and an inner diameter of 10 cm were used as skirts. To compact the sand layers inside the skirt zone and reach the desired compaction, a circular wooden hammer was used with a diameter a little less than pile diameter (9.8 cm).

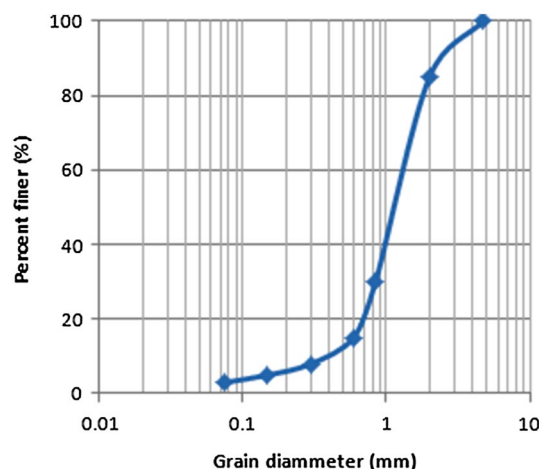


Fig. 2 Sand grain-size distribution curve

To compact the soil layers and reach the desired compaction, a wooden hammer was used with a weight of 7.65 kg and 30×30 cm dimensions. The sand was compacted with a smooth wooden hammer dropped from 300 mm height, 20 times. To ensure the sand density in question was achieved, a small metal vessel with a given volume was placed randomly

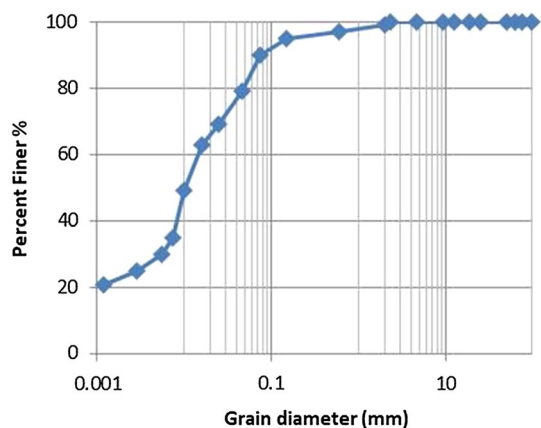


Fig. 3 Clay grain-size distribution curve

Table 1 Properties of sand used in the experiments

| Property | Value |
|---|-------|
| Specific gravity, G_s | 2.65 |
| Effective particle size, D_{10} (mm) | 0.40 |
| Average particle size, D_{50} (mm) | 1.20 |
| Uniformity coefficient, C_u | 3.26 |
| Coefficient of curvature, C_c | 1.36 |
| Average wet unit weight, γ (kN/m ³) | 17.75 |
| Angle of internal friction, ϕ (°) | 34 |
| Average relative density D_r (%) | 38 |
| Maximum dry unit weight, γ_{dmax} (kN/m ³) | 18.87 |
| Minimum dry unit weight γ_{dmin} (kN/m ³) | 16.30 |
| Minimum void ratio, e_{min} | 0.38 |
| Maximum void ratio, e_{max} | 0.60 |

Table 2 Properties of clay used in the experiments

| Property | Value |
|--|-------|
| Specific gravity, G_s | 2.62 |
| Liquid limit (%) | 31 |
| Plastic limit (%) | 20 |
| Plasticity index (%) | 11 |
| Shrinkage limit (%) | 17 |
| Average particle size, D_{50} (mm) | 0.002 |
| Average wet unit weight, γ (kN/m ³) | 16.75 |
| Average moisture content (%) | 2 |
| Angle of internal friction, ϕ (°) | 20 |
| Cohesion (kPa) | 10 |
| Undrained uniaxial strength (kPa) | 30 |

in different layers. The surface of the prepared layer was precisely levelled immediately after compaction. This method of compaction may lead to a change in the state of stress

in the soil; consequently, it will no longer be in a normally consolidated state. Since the soil is moist, the precipitation technique is not suitable for soil placement in the apparatus because uniform density is needed. To model the soil–foundation interaction, the bottom of the foundation was chosen appropriately rough using a thin sandpaper sheet glued to it using aquarium glue.

2.3 Test Program

The program for tests carried out in the library consists of load–settlement tests for circular footings on soft clay with skirted and non-skirted piles. The load–settlement diagrams depict the raw output of the experiments, from which the values of the bearing capacity of the footing can be found. For ease of description in terms of experimental and numerical results, the bearing capacity ratio (BCR) is used, which is a parameter defined through the following relationships:

$$BCR_{sp} = \frac{q_{sp}}{q} \quad (1)$$

$$BCR_{nsp} = \frac{q_{nsp}}{q} \quad (2)$$

where q , q_{sp} and q_{nsp} represent the bearing capacity of the footing on soil without piles, with skirted piles and with non-skirted piles, respectively. BCR_{sp} and BCR_{nsp} indicate the BCR of circular footings for the states of using piles with and without skirts, respectively.

The laboratory program, which consists of five tests to study the effects of skirted piles and their geometry on the load–settlement behaviour of circular footings, is summarized in Table 3. As shown in the table, the tests' variable parameter is the ratio of the length of the pile to the clay layer thickness (L/h). The ratio of the pile length (h) to the sand layer thickness (D) is constant in all tests.

2.4 Test Results

2.4.1 Effects of Pile Length

In Fig. 4, the load–settlement curves for circular footings on layered soil with skirted piles, as derived from the experimental results, are demonstrated for different ratios of pile length to clay layer thickness (L/h), including 0.25, 0.5, 0.75 and 1. The values of the BCR under these conditions are summarized in Table 4.

Figure 5 shows that increasing the pile length increases the efficiency of the footing and consequently improves the amount of BCR and soil stiffness, which is due to the increase in skin friction. On the other hand, when the L/h ratio is equal to 1, it means that the pile is rested on the

Table 3 Summary of the tests

| Test series | Constant parameters | Constant parameters | Variable parameters |
|-------------|-----------------------------|-----------------------------------|---|
| TS00 | Normal footing without pile | $D = 40 \text{ cm}$, $h/D = 1.0$ | – |
| TS01 | Skirted piles | $D = 40 \text{ cm}$, $h/D = 1.0$ | $L/h = 0.25$, 0.50, 0.75 and 1.00 |

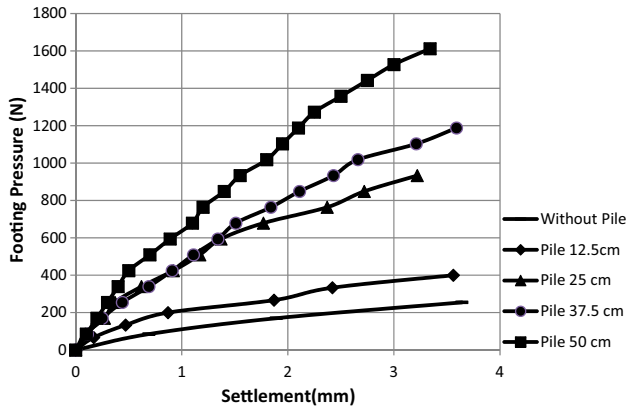


Fig. 4 Load–settlement diagrams of circular footing with skirted pile

Table 4 Bearing capacity ratio (BCR_{sp}) for circular footing with skirted piles (experimental data)

| Test series | h/D | L/h | Bearing capacity (kPa) | Bearing capacity ratio (BCR_{sp}) |
|-------------|-------|-------|------------------------|---------------------------------------|
| TS00 | 1.0 | – | 254.5 | 1.00 |
| TS01A | 1.0 | 0.25 | 399.6 | 1.57 |
| TS01B | 1.0 | 0.50 | 933.2 | 3.67 |
| TS01C | 1.0 | 0.75 | 1187.8 | 4.67 |
| TS01D | 1.0 | 1.00 | 1612.0 | 6.33 |

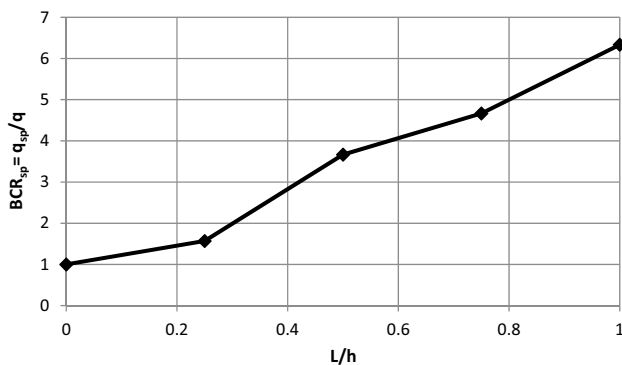


Fig. 5 BCR_{sp} changes with L/h for the footing on skirted piles

sand layer, while the end bearing portion of the pile bearing capacity is also increased.

To verify and compare the experimental results with analytical methods, it is possible to calculate the bearing capacity of the circular footing on clay using the Terzaghi equation, based on the specifications obtained in the laboratory:

$$q_u = cN_cS_c + 0.5B\gamma N_\gamma S_\gamma \tag{3}$$

Regarding the bearing capacity coefficient of weight (N_γ), the bearing capacity coefficient of cohesion (N_c), cohesion shape factor (S_c), soil weight shape factor (S_γ) and the average soil wet density in the laboratory that, respectively, equal 5.0, 17.7, 1.3, 0.6 and 16.775 kN/m³, the bearing capacity of a circular footing with a width of 10 cm on soft clay soil will be 232.6 kPa, which represents an acceptable difference of about 9% with the amount obtained in tests (254.5 kPa). The total stress analysis (TSA) was utilized to find bearing capacity.

3 Numerical Model

Extensive finite element analysis was carried out using the Plaxis 2D software package. A numerical model validated by laboratory results can reduce the need for experiments under different conditions, which results in a return on invested capital. Plaxis 2D is a two-dimensional finite element software package, which is used for the static and dynamic analysis of soil and rock, and has been applied in this study (Plaxis Manual 2009). This software is able to show load–settlement diagrams and determine the bearing capacity of foundations and circular piles. Circular footing can be created, based on the capability of the software in axisymmetric modelling. Figure 6 presents one of the models created by Plaxis 2DV8.6 software. The shear strength parameters in Tables 1 and 2, which were obtained from direct shear tests, have been applied to define clay and sandy soils. Soil friction angles have been measured at peak. Other parameters were obtained based on numerous attempts to match numerical and experimental results. Meanwhile, 35 numerical models were created according to the description presented in Table 5. The elastic–perfectly plastic model with Mohr–Coulomb yield criterion was used for analytical purposes.

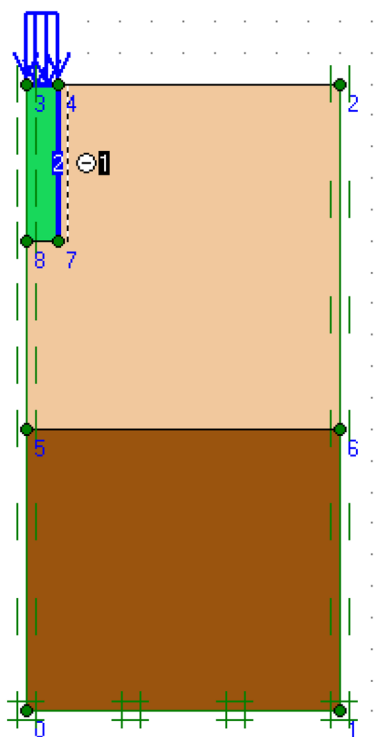


Fig. 6 Numerical model

3.1 Numerical Model Results

Tables 6 and 7 show the results of the numerical analysis of the circular footings on clay with and without skirted piles, respectively. Figures 7 and 8 also present load–settlement diagrams for circular footings with skirted and non-skirted piles.

3.2 Effects of Clay Layer Thickness

According to the numerical results presented in Tables 4 and 5, as well as the experimental evidence, it can be conclusively stated that the piles’ length to clay layer thickness ratio significantly affects the bearing capacity of the

layered soil. Figures 9 and 10 show the changes in the BCR along with the h/D ratio for piles with and without skirts, respectively. It can be observed that in the constant pile length, the BCR decreases significantly by increasing the h/D ratio. The reason for these changes is the reduction in the shear strength of the soil under the footing. At h/D ratio greater than 1.5 ($h/D > 1.5$), the slope of the BCR changes versus h/D is noticeably reduced, which indicates that the thickness of the clay layer is greater than the influence zone beneath the footing.

3.3 Effects of Skirts on the Bearing Capacity of the Footing

To investigate the effects of using skirts for piles on the bearing capacity of circular footings, another factor, the BCR of the pile, is defined according to the following equation:

$$BCRP = \frac{q_{sp}}{q_{usp}} \tag{4}$$

where the BCRP is the ratio of the bearing capacity of the piles and is obtained by dividing the bearing capacity of a circular footing on the skirted piles by the bearing capacity of the footing on non-skirted piles in equal ratios of L/h and h/D . Figure 11 shows the variation in the BCRP of the footing on skirted and non-skirted piles versus L/h and h/D . It can be seen that using confining skirts around the piles will increase the BCRP to 1.98, which is due to the greater contact friction between the surrounding clay and the skirt, compared to the contact friction between clay and sand when using a non-skirted pile. This reduction in friction reduces the skin resistance and thus reduces the bearing capacity of the footing when using non-skirted piles.

The vertical skirt also acts as a confining cell for the replaced sand column and effectively decreases both the vertical and the horizontal strains under the footing, compared with the other case. It also controls the settlement

Table 5 Summary of the created models in finite element software

| Test series | Constant parameters | Constant parameters | Variable parameters |
|-------------|-----------------------------|---------------------|---------------------------------|
| NM00 | Normal footing without pile | $D=40$ cm | $h/D=1.0, 1.5$ and 2.0 |
| NM 01 | Non-skirted pile | $h/D=1.0, D=40$ cm | $L/h=0.25, 0.50, 0.75$ and 1.00 |
| NM 02 | Non-skirted pile | $h/D=1.0, D=40$ cm | $L/h=0.25, 0.50, 0.75$ and 1.00 |
| NM 03 | Non-skirted pile | $h/D=1.5, D=40$ cm | $L/h=0.25, 0.50, 0.75$ and 1.00 |
| NM 04 | Non-skirted pile | $h/D=2.0, D=40$ cm | $L/h=0.25, 0.50, 0.75$ and 1.00 |
| NM 05 | Skirted pile | $h/D=1.0, D=40$ cm | $L/h=0.25, 0.50, 0.75$ and 1.00 |
| NM 06 | Skirted pile | $h/D=1.0, D=40$ cm | $L/h=0.25, 0.50, 0.75$ and 1.00 |
| NM 07 | Skirted pile | $h/D=1.5, D=40$ cm | $L/h=0.25, 0.50, 0.75$ and 1.00 |
| NM 08 | Skirted pile | $h/D=2.0, D=40$ cm | $L/h=0.25, 0.50, 0.75$ and 1.00 |

Table 6 Bearing capacity ratio (BCR_{nsp}) for circular footings with non-skirted piles (numerical results)

| Test no. | h/D | L/h | Bearing capacity (kPa) | Bearing capacity ratio (BCR_{nsp}) |
|----------|-------|-------|------------------------|--|
| NM00 | 1.00 | – | 223.0 | 1.00 |
| NM01A | 1.00 | 0.25 | 450.0 | 2.02 |
| NM01B | 1.00 | 0.50 | 975.0 | 4.37 |
| NM01C | 1.00 | 0.75 | 1040.0 | 4.66 |
| NM01D | 1.00 | 1.00 | 1420.0 | 6.37 |
| NM02A | 1.25 | 0.25 | 330.0 | 1.48 |
| NM02B | 1.25 | 0.50 | 550.0 | 2.47 |
| NM02C | 1.25 | 0.75 | 664.0 | 2.98 |
| NM02D | 1.25 | 1.00 | 934.0 | 4.19 |
| NM03A | 1.50 | 0.25 | 325.0 | 1.46 |
| NM03B | 1.50 | 0.50 | 432.0 | 1.94 |
| NM03C | 1.50 | 0.75 | 519.0 | 2.33 |
| NM03D | 1.50 | 1.00 | 786.0 | 3.26 |
| NM04A | 2.00 | 0.25 | 324.0 | 1.45 |
| NM04B | 2.00 | 0.50 | 380.0 | 1.70 |
| NM04C | 2.00 | 0.75 | 487.0 | 2.18 |
| NM04D | 2.00 | 1.00 | 581.0 | 2.60 |

Table 7 Bearing capacity ratio (BCR_{sp}) for circular footings with skirted piles (numerical results)

| Test no. | h/D | L/h | Bearing capacity (kPa) | Bearing capacity ratio (BCR_{sp}) |
|----------|-------|-------|------------------------|---------------------------------------|
| NM05A | 1.00 | 0.25 | 470.00 | 1.00 |
| NM05B | 1.00 | 0.50 | 1094.0 | 0.91 |
| NM05C | 1.00 | 0.75 | 1296.0 | 0.88 |
| NM05D | 1.00 | 1.00 | 1940.0 | 0.80 |
| NM06A | 1.25 | 0.25 | 469.0 | 1.00 |
| NM06B | 1.25 | 0.50 | 1093.0 | 0.91 |
| NM06C | 1.25 | 0.75 | 1280.0 | 0.88 |
| NM06D | 1.25 | 1.00 | 1820.0 | 0.80 |
| NM07A | 1.50 | 0.25 | 428.0 | 0.76 |
| NM07B | 1.50 | 0.50 | 500.0 | 0.83 |
| NM07C | 1.50 | 0.75 | 572.0 | 0.77 |
| NM07D | 1.50 | 1.00 | 780.0 | 0.74 |
| NM08A | 2.00 | 0.25 | 362.0 | 0.70 |
| NM08B | 2.00 | 0.50 | 409.0 | 0.79 |
| NM08C | 2.00 | 0.75 | 487.0 | 0.75 |
| NM08D | 2.00 | 1.00 | 581.0 | 0.72 |

of the footing/soil system according to the skirt’s depth. On the other hand, the presence of skirts can remove the lateral bump of the sand column.

In summary, it can be seen that skirts have a great effect in terms of increasing the degree of improvement, compared with the case of a footing on a sand column without

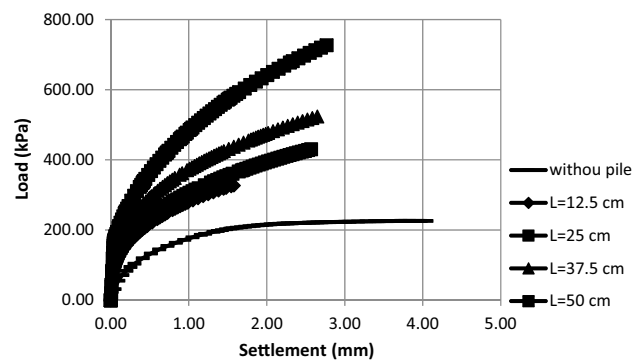


Fig. 7 Load–settlement diagram for circular footings with non-skirted piles (numerical results)

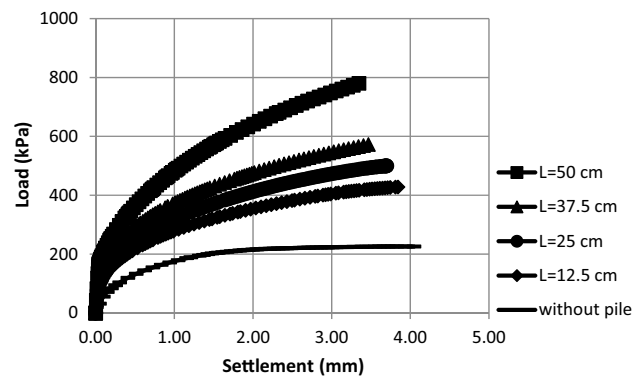


Fig. 8 Load–settlement diagram for circular footings with skirted piles (numerical results)

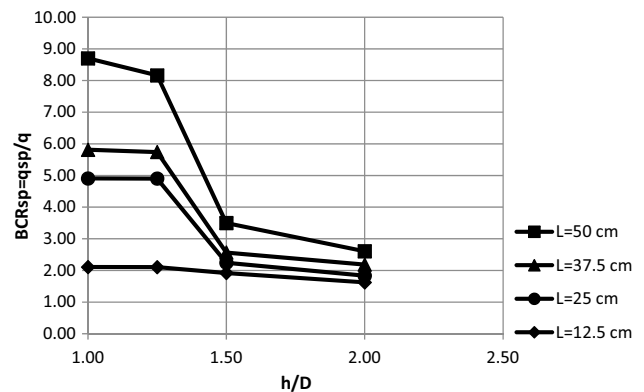


Fig. 9 BCR_{sp} changes with h/D for the footing on skirted pile

confinement. The skirt increases the bearing capacity by up to 870% of the initial bearing capacity of soft clay at $h/D = 1$ and 260% at $h/D = 2$. Alternatively, in the case of no confinement, the bearing capacity is increased by up to 640% at $h/D = 1$ and 260% at $h/D = 2$. This variation in the degree of improvement in the two cases is related to the

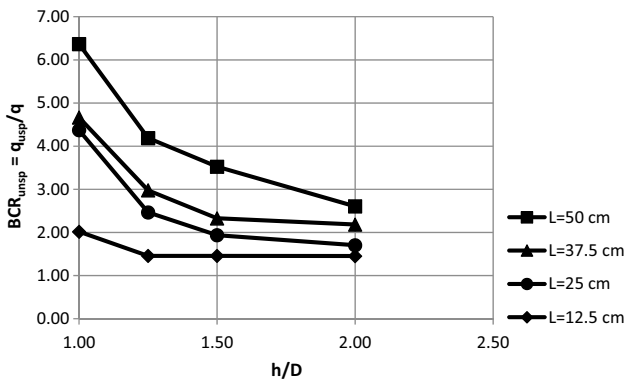


Fig. 10 BCR_{unsp} changes with *h/D* for the footing on non-skirted pile

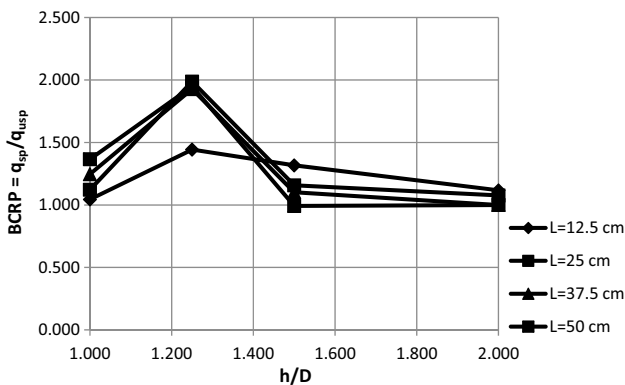


Fig. 11 BCRP changes with *h/D*

bulging behaviour of the unconfined condition. This could also confirm the effectiveness of skirts as confined tools.

On the other hand, in the case of skirted pile, when the *L/h* value is high enough for the pile to exit from the clay layer and enter the sandy layer, the bearing capacity of skirted piles increases. One of the reasons for this increase is the greater contact friction of sand soil with piles, compared to clay. The other reason for this behaviour is the higher pile end bearing on the sand, instead of the clay layer. The entry of a non-skirted sandy pile in the sand layer does not sensibly change the bearing capacity due to the similarity of the materials and the same density of both soils.

Considering the bearing capacities of the footing at different ratios of *L/h* and *h/D*, the following equations are presented to calculate the bearing capacity of circular footings on skirted and non-skirted pile, using Table Curve software, a linear and nonlinear surface fitting software package for engineers and scientists that automates the surface fitting process (Table Curve 2002). Presented equations have the most root-mean-square value (more than 0.99) among the results and simultaneously the simplest ones.

A. The relationship for skirted piles

$$q_u = 0.45 - 0.06\text{Ln}(\text{LR}) + (0.22)/\sqrt{\text{DR}} \quad (5)$$

B. The relationship for non-skirted piles

$$q_u = 1.13 - 0.05\text{Ln}(\text{LR}) + (0.24)/\sqrt{\text{DR}} \quad (6)$$

In the above relationships, $\text{LR} = L/h$, $\text{DR} = h/D$, $L > 0$ and $0 < \text{LR} < 1$.

Figure 12 compares the results of experimental tests and numerical modelling under the same conditions for the footing on soft clay soil where *h/D* is equal to 1. As can be seen, there is good agreement between the results. The maximum difference between experimental and numerical results is about 23 per cent.

4 Conclusion

In this study, the bearing capacity of a circular shallow foundation on layered soil, consisting of soft clay and dense sand, was investigated using a static loading device for conditions involving skirted piles, non-skirted piles and without piles. The experimental studies on the circular foundation behaviour of skirted piles with different length to clay layer thickness ratios, compared with the results of finite element modelling and the following results, were obtained.

The results of physical modelling and numerical simulation show that the use of skirted and non-skirted piles leads to an increase in the bearing capacity of the circular footing located on them.

Increasing a pile’s length to clay layer thickness ratio causes a significant increase in the bearing capacity of the footing located on it, such that, for the ratios of 0.25, 0.5, 0.75 and 1, the increase in bearing capacity, compared to the condition without piles, is, respectively, 157, 367, 467 and 633% for the skirted piles conditions.

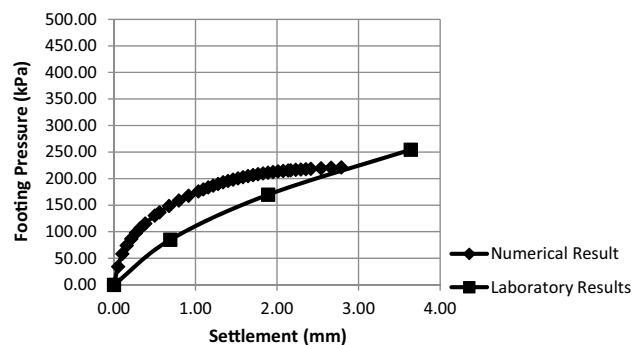


Fig. 12 Comparison of the load–settlement diagrams of circular footing on clay (*h/D*=1)

BCRs in all studied cases show that the use of skirts in the pile increases the bearing capacity.

As the variations in the thickness of the clay layer also affected the bearing capacity of the footing on skirted and non-skirted piles, it was concluded that, by increasing the thickness of the soft clay layer, the bearing capacity of the skirted and non-skirted piles should decrease up to 333 and 244%, respectively. It means that the maximum differences between with and without skirted pile conditions are about 89%.

Comparison of numerical and experimental data indicated acceptable agreement between the results of the physical and numerical models.

At the end of the study, some relationships are presented in order to predict the bearing capacity of a circular footing with a specific diameter on layered soil, according to the length to clay layer thickness ratio and the clay layer thickness to the sand layer thickness ratio. These presented relationships make it possible to avoid time-consuming calculations and costly tests.

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