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The Group Effect on Negative Skin Friction on Piles

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Abstract

When piles are constructed in consolidating ground, negative skin friction (NSF) is induced as a result of the downward movement of the soil relative to the pile. Model tests on negative skin friction on pile groups in sand were designed and conducted. Pile stress, pile top displacement and layered settlement of soil were tested under different kinds of surcharge load. The results indicate that when surrounding load increases from 20kPa to 120kPa, the neutral plane of the single pile varies from 0.8 L (length of pile in sand) to 0.95 L. Pile head settlement and negative skin friction under side load were smaller compared with the results of the test under surrounding load, while the location of neutral plane was higher. NSF and neutral plane depth increase sequentially in order of interior pile, interior-perimeter pile, corner-perimeter pile and corner pile for the pile group under side load. Based on the test results, the group effect is not obvious when pile spacing reaches 5 times pile diameter.

Keywords: pile; negative skin friction; group effect; model test; settlement;

1. Introduction

When the settlements of soil next to a pile are more than those of the pile, negative skin friction (NSF) may occur. It is believed that NSF is caused by downward vertical soil stress near the pile transferred to the pile. Because the development of additional compressive force in a pile (Fellenius 1998), and excessive pile settlement could cause many engineering problems, such as, foundation yield or failure, pile damage, uneven settlement of
structure etc. (Davisson 1993, Acar et al. 1994, Poulos 1997), it is important to pay attention to the problem of NSF on pile.

Since Terzaghi & Peck presented NSF in the 1930’s, many researches on NSF of pile foundation have been conducted. Shibata et al. (1982) studied on NSF of vertical piles and batter piles by model test, asphalt coating and surface load which influence the efficiency of pile groups were discussed. At last, a method of estimating the group action of NSF was derived for vertical pile groups. Toma (1989) did similar NSF model tests, in addition, he tested the settlement of layer soil by settlement plate. Based on test results, he built a formula which could prediction variation of NSF and pore water pressure with consolidation time. Mehmet & Devrim (1995) studied the relative settlement of the soil surface inside and outside the groups as the soil was compressed by air pressure, and pointed out that pile group effects were negligible at pile spacing at 5 to 6 pile widths. Recently, some centrifuge model studies have been carried out to research NSF. Leung et al. (2004) investigated the effects of axial load on the load-transfer characteristics along a pile experiencing NSF induced by consolidating clay by centrifuge model test, and the effects of pile tip condition, pile socket length and magnitude of applied load on pile were studied. Charles et al. (2008) reported the results of four centrifuge model tests which investigated the response of a single pile subjected to NSF with different pile tip location with respect to the end-bearing stratum layer and the behavior of floating piles subjected to NSF with and without shielding by sacrificing piles. Compared to conventional pile model test, the model test on NSF on pile needs to apply load on soil surface and it is difficult to simulate large surcharge load by conventional test methods except centrifuge. Besides, some researchers have conducted field tests to study the behavior of pile subject to NSF (see for example, Leung et al. 1991, Fellenius 2006). As discussed above, many studies have been carried out, and these studies were very helpful for revealing the behavior of NSF on pile and on pile groups.

However, the researches on NSF are not deep enough. The mechanism on group effect of NSF is still not well understood and existing design methods are mainly empirical in nature. Some correlative research work on group effect needs to be continued. This paper designed and conducted model tests of NSF on single pile and pile groups in sand, and the mechanism on group effect is discussed in detail.

2. Indoor model test

2.1. Test description

In order to study the NSF of pile groups, five different tests, such as a single pile, 3×3 pile group tests with pile spacing of 3D (pile diameter), 4D and 5D under surrounding load and a 3×3 pile group test with pile spacing of 5D under side load, were designed in this work.

The basic process of model test is described as follow. First, the drain valves were closed and gravel sand was put into tank. The earthwork cloth was put nearby the drain valves and on the gravel sand layer. Secondly, model piles were arranged at designed position. Thirdly, the saturated sand was pushed into the tank. The settlement plates (6mm diameters slender steel rod with 60mm diameters thin steel sheet welded on one side and displacement sensor on 10mm diameters thin steel sheet welded on the other side) were set on several soil layers inside and outside the pile groups shown in Fig. 1. After the burying process and standing for 12h, the drain valves were opened and the process of saturated sand consolidation was finished by self-weight. Then, the drain valves were closed again and 0.3m thickness dry sand with 45% compactness was put into tank as the surcharge load on soil surface. Fourthly, the down loading plate, which was prepared from 20mm thickness steel plate and opened holes for model piles and settlement plates as shown in Fig.2 and Fig. 3, was put on the dry sand surface. Then two balance beams and a small counterforce frame were fixed at tank wall. Subsequently, the up loading plate, which was prepared from 30mm thickness steel plate and welded with four legs, was put on the down loading plate. Finally, pile caps were put on the piles and bearing plate was put on the caps.

All the tests were performed in a steel tank (2000mm ×2000mm ×1400mm) with 10mm in thickness, which was large enough to reduce of the effect of the edges. The layout of model test with 3×3 pile group was showed in Fig. 1. Reinforcing bands was welded on tank side to reduce the tank deformation caused by applying surcharge load
on soil. There were 4 drain valves which pore size was 20mm on the bottom of the tank side for drained consolidation.

![Diagram of model test](image1)

**Fig. 1. Layout of model test(mm):** 1-big counterforce frame; 2-balance beam; 3-small counterforce; 4-down loading plate; 5-up loading plate; 6-settlement plate; 7-model pile; 8-sand surcharge; 9-reinforcing band; 10-sand; 11-gravel sand; 12-drain valve.

![Diagram of loading plate](image2)

**Fig. 2. Down loading plate for surrounding load.**

![Diagram of loading plate](image3)

**Fig. 3. Down loading plate for side load.**

Model piles were prepared from thin-wall steel pipes of 1.4m length, 40mm outer diameter (D) and 1.18mm thickness with strain gauges on the inner wall of the pipe piles. The length of embedment of pile (L) in sand bed was 1m. The modulus of pile was $2.1 \times 10^5$MPa. Strain gauges and wires were arranged on the inner wall of the pipe that can protect the test element not be damaged and can avoid the surrounding soil influenced by test element. Strain gauges were moisture proof by silica gel and then covered by epoxy resin coat. The bearing plate at pile cap was prepared for single pile and pile group using 10mm thick steel plate with sizes of 200mm×200mm and 520mm×520mm, respectively. The pile cap was slotted at one side so that the strain gauge wires could lead out of the pipe.

The model piles were embedded in 1m thick homogeneous saturated sand bed. In order to ensure the consistency of sand bed in each test, the sand was filled into the tank with the compactness controlled at 45% by weighing and compaction, and its compression test result was shown in Fig. 4. The parameters of saturated sand for test are listed in Table 1. Gravel sand was used as bearing stratum and drainage layer on the bottom of the tank, which thickness was 50mm and pore size was about 5mm.
Table 1. Parameters of sand for tests.

| Internal friction angle (°) | Specific gravity | Natural water content (%) | Wet density (g/cm³) | Minimum dry density (g/cm³) | Maximum dry density (g/cm³) | Permeability coefficient (10⁻⁶cm/s) |
|-----------------------------|------------------|---------------------------|---------------------|----------------------------|-----------------------------|----------------------------------|
| 34.52                       | 2.68             | 15.77                     | 1.649               | 1.249                      | 1.682                       | 934.57                           |

2.2. Loading method

The model pile was step-loaded every 15min by using weight (for the single pile) or hydraulic jack (for the 3×3 pile groups), and the total load on each pile was 250N. After pile head loaded, the surcharge load on soil surface was created by dry sand and the jack which used down and up loading plate to ensure the surface load uniform. The surcharge load for single pile test and pile group test was step-loaded to 120kPa and 80kPa respectively. When the soil settlement rate was less than 0.01mm/10min, the next surcharge load grade was applied. Pile stress, pile top displacement and layered settlement of soil were tested under different surcharge load.

3. Results and discussion

3.1. Result of the single pile test

The result of the single pile under surrounding load is shown in Fig. 5. As shown in Fig. 5(a), the settlement of pile top is 0.17mm after pile load was applied. When the surrounding load was applied and increased to 120kPa, the settlement of pile top increases and reaches 1.78 mm at last. Because the dragload is bigger than pile head load in the test, the settlement induced by dragload is bigger than that induced by pile head load. Fig. 5(b) shows that the layered settlement of soil increases with the increase of surrounding load, but the increment decreases. The intersection point between layered soil settlement curve and pile settlement curve (settlement at pile top equals settlement at pile bottom because of the less compression of pile in the test) is the neutral plane, which depth increases with the increase of surrounding load. The axial force of pile indicates that the neutral plane varies from 0.8L to 0.95L and dragload varies from 0.77kN to 2.64kN shown in Fig. 5(c), which arrives at the same conclusion deduced from settlement. Due to the great stiffness of pile-end soil in this test, the neutral plane is near to pile bottom. And the increment of soil is larger than that of pile when the surrounding load increases, which cause neutral plane to shift down. In addition, effective stress coefficient of NSF calculated by back calculation is between 0.38-0.19 which decreases with the increase of surrounding load.

The result of single pile under side load is shown in Fig. 6. As shown in Fig. 6(a), the settlement of pile top is 0.15mm after pile load was applied. When the side load was applied and increased to 120kPa, the settlement of pile top increases and reaches 1.47 mm at last. Fig. 6(b) also shows that the layered settlement of soil increases with the increase of side load. The axial force of pile indicates that the neutral plane varies from 0.8L to 0.95L and dragload varies from 0.47kN to 2.12kN shown in Fig. 6(c).
Fig. 5. The test result of single pile under surrounding load: (a) The relationship between pile settlement and load; (b) The layered settlement of soil and the single pile settlement; (c) The relationship between axial force of pile and surrounding load on soil surface.

Fig. 6. The test result of the single pile under side load: (a) The relationship between pile settlement and load; (b) The layered settlement of soil and the single pile settlement; (c) The relationship between axial force of pile and side load on soil surface.

Compared with the test results of surrounding load, settlement of the single pile under side load is smaller. The axial force of the pile under side load is about 0.75 times of that of the pile under surrounding load. NSF due to side load were smaller than that due to surcharge loads, while the location of neutral plane was higher. There are two main reasons for this result. One is the smaller effective stress around the pile under side load. The other is more soil around the pile under surrounding loads motivated to produce NSF.

### 3.2. Results of pile group tests

For the case of surrounding load, the results of pile group test are listed in Table 2, which the group effect coefficient of NSF is be defined as the ratio of dragload of a pile in pile group to that of a single pile. The position of pile has significant influence on the group effect of pile groups under NSF, and the group effect coefficient which increases sequentially in order of interior pile, perimeter pile and corner pile. The results show that group effect coefficient and neutral plane depth increase with the increase of pile spacing because of the less interaction of piles. Furthermore, group effect coefficient and neutral plane depth increase with the increase of surrounding load. When pile spacing reaches 5D, the group effect coefficient of corner pile is 0.93 while that of perimeter pile and interior pile are 0.83 and 0.78 respectively. The influence of pile position on dragload is small, which shows group effect is not obvious in this instance.

Table 2. The group effect coefficient and neutral plane depth of pile groups.

| Surrounding load (kPa) | 3D Interior | 3D Perimeter | 3D Corner | 4D Interior | 4D Perimeter | 4D Corner | 5D Interior | 5D Perimeter | 5D Corner |
|------------------------|-------------|-------------|-----------|-------------|-------------|-----------|-------------|-------------|-----------|
| 20                     | 0.30        | 0.26        | 0.47      | 0.64        | 0.61        | 0.81      | 0.80        | 0.77        | 0.84      |
| 40                     | 0.31        | 0.41        | 0.43      | 0.72        | 0.62        | 0.69      | 0.78        | 0.83        | 1         |
| 60                     | 0.34        | 0.44        | 0.45      | 0.59        | 0.67        | 0.74      | 0.78        | 0.77        | 0.89      |
| 80                     | 0.49        | 0.62        | 0.68      | 0.65        | 0.74        | 0.82      | 0.80        | 0.83        | 0.93      |
| Neutral plane(L)       | 0.4-0.8     | 0.6-0.8     | 0.7-0.9   | 0.6-0.8     | 0.7-0.9     | 0.7-0.9   | 0.7-0.9     | 0.7-0.9     | 0.8-0.9   |
Table 3. The summary of neutral plane depth, drag force and NSF.

| Group          | Side load (kPa) | 20  | 40  | 60  | 80  |
|----------------|----------------|-----|-----|-----|-----|
| Interior       | Neutral plane (L) | 0.7 | 0.7 | 0.8 | 0.8 |
|                | Dragload (kN)     | 0.19| 0.29| 0.40| 0.43|
|                | NSF (kPa)         | 2.19| 3.32| 3.95| 4.28|
| Interior-perimeter | Neutral plane (L) | 0.7 | 0.7 | 0.8 | 0.8 |
| Corner-perimeter | Dragload (kN)     | 0.23| 0.37| 0.51| 0.56|
| Corner         | NSF (kPa)         | 2.56| 4.22| 5.06| 5.60|
| Corner-perimeter | Neutral plane (L) | 0.8 | 0.8 | 0.8 | 0.9 |
| Corner         | Dragload (kN)     | 0.31| 0.63| 0.77| 0.90|
| Corner         | NSF (kPa)         | 3.11| 6.28| 7.69| 7.97|
| Corner         | Neutral plane (L) | 0.8 | 0.8 | 0.9 | 0.9 |
| Corner         | Dragload (kN)     | 0.45| 0.83| 1.03| 1.33|
| Corner         | NSF (kPa)         | 4.48| 8.31| 9.11|11.72|

Fig. 7. The position of pile in the pile group under side load.

For the pile group under side load, neutral plane depth, drag force and unit negative friction are shown in table 3. The position of the pile in pile group is named as shown in fig.7. According to the test results, NSF and neutral plane depth of corner pile are close to those of a single pile when the pile spacing reaches 5D. The effect of pile position in pile group on NSF and neutral plane depth is significantly. NSF and neutral plane depth increase sequentially in order of interior pile, interior-perimeter pile, corner-perimeter pile and corner pile. Compared with the test results of surrounding loads, NSF and neutral plane depth of the pile group under side load are smaller. Furthermore, the difference of NSF between corner pile and interior pile is more obvious.

Based on the study on test results of pile groups, it is conservatively believed that group effect can be ignored and dragload on a single pile equals that on the pile in groups under surrounding load when pile spacing reaches 5D. Along with the increase of surrounding load, neutral plane depth is close to that of a single pile. However, the effective stress on a single pile is larger than that on a pile in groups because of interaction between piles. As a result, the dragload on a single pile is larger while their neutral plane depth is similar. In addition, the average effective stress coefficient obtained by back calculation is 0.16, 0.18 and 0.21 at 3D, 4D and 5D pile spacing respectively when surrounding load is 80kPa. Due to the effective stress reduced by interaction between piles, those average effective stress coefficients are smaller than 0.24 (single pile), but they increase with pile spacing.

4. Conclusion

(1) When the surrounding load increases from 20kPa to 120kPa, the neutral plane of the single pile varies from 0.8L to 0.95L in the model test. The effective stress coefficient of single pile is between 0.38-0.19 in sand which decreases with the increase of surrounding load.

(2) Axial force of the pile under side load is about 0.75 times of that of the pile under surrounding load. The pile settlement and negative skin friction under side load were smaller compared with the results of surcharge load, while the location of neutral plane was higher.
(3) NSF and neutral plane depth increase sequentially in order of interior pile, interior-perimeter pile, corner-perimeter pile and corner pile for the pile group under side load. Compared with the test results of surrounding load, NSF and neutral plane depth of the pile group under side load are smaller, and the difference of NSF between corner pile and interior pile is more obvious.

(4) Based on test results, the group effect of NSF on pile group under surrounding load is not obvious when pile spacing reaches 5D. The average effective stress coefficient is 0.16, 0.18 and 0.21 at 3D, 4D and 5D pile spacing respectively when surrounding load is 80kPa.

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