WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2024.148927

ARCHIVES OF CIVIL ENGINEERING

Vol. LXX ISSUE 1 2024



**pp. 543 –555**



**Research paper**

# Method of settlement calculation for underlying layer of soft soil composite foundation based on load transfer mechanism

**Yaoting Xiao[1], Jing Wang[2]**

**Abstract:** The mechanical properties of soil in soft soil area are poor, and the settlement of the underlying layer in the composite foundation accounts for a large proportion of the total settlement. At present, most of the research focuses on the settlement of the reinforced area, and the research on the settlement of the underlying layer is of great significance for the settlement of soft soil composite foundation. The differences in load transfer modes of soil and pile are analyzed, and based on the Boussinesq solution and Mindlin solution, a calculation method for the stress and settlement of the underlying layer in flexible and rigid pile composite foundation is proposed. The relative displacement of soil and pile in flexible pile composite foundation is small, and the negative friction can be ignored, but the influence of effective pile length should be considered. The relative displacement of soil and pile in rigid pile composite foundation is large, so the negative friction should be considered. Part of soil top stress is transmitted to the pile via negative friction, and then the pile axial force is transmitted back to the soil via positive friction. In addition to effective pile length, the change of stress transfer path caused by negative friction should also be considered in settlement calculation.

**Keywords:** oft soil, composite foundation, load transfer, negative friction

[1]Associate Professor, PhD., Eng., Hubei University of Arts and Science, College of Civil Engineering and Architecture, No. 296, Longzhong Road, Xiangyang, Hubei, China, e-mail: xiaoyaoting1983@163.com, ORCID: 0000-0002-9537-8692
[2]Associate Professor, MSc., Eng., Hubei University of Arts and Science, College of Civil Engineering and Architecture, No. 296, Longzhong Road, Xiangyang, Hubei, China, e-mail: wangjing821206@163.com, ORCID: 0000-0001-7655-8850

# 1. Introduction

The settlement of composite foundation includes the settlement of reinforced area (RA) and the settlement of underlying layer (UL). At present, most of the settlement studies of composite foundation focus on the RA and less on the UL [1–3]. The traditional methods for calculating the settlement of the UL include equivalent solid method, stress diffusion method, etc. These methods are simple and easy to be mastered by engineers, but there are defects in theory due to the neglected interaction between soil and pile [4–6]. Many scholars have also studied the settlement of the UL from the perspective of pile-soil interaction [7–12], but these methods are difficult to apply to practical engineering projects because of their complicated calculation process and many assumptions. The mechanical properties of soil in soft soil area are poor, and the settlement of the UL has great influence on the total settlement. Therefore, the reasonable calculation method of the UL is of great significance for the settlement of soft soil composite foundation.

In composite foundation, the pile transmits load by tip resistance and lateral resistance, the soil transmits load via downward diffusion, and the load transfer modes of soil and pile are different [13–15]. Tip resistance and lateral resistance are the internal forces of soil, and their load effects can be solved by Mindlin solution. The force of soil between piles is surface force, and its downward diffusion stress can be solved by the Boussinesq solution. Therefore, Boussinesq solution and Mindlin solution should be combined to analyze the settlement of the UL.

On the basis of analyzing the load transfer mechanism of composite foundation, combining Boussinesq solution and Mindlin solution, the stress in flexible pile and rigid pile composite foundation is analyzed, and then the settlement calculation method for the UL of flexible pile and rigid pile composite foundation in soft soil area is proposed.

# 2. Load transfer mechanism of composite foundation

In a homogeneous foundation, the base pressure transmits stress downward in the soil, and the stress decreases as the depth increases. For the homogeneous foundation, the stress in the soil can be calculated by the Boussinesq solution [16].

Because of the action of cushion, the base pressure of the composite foundation is allocated to soil top and pile top in a certain proportion, as shown in Fig. 1a. The soil stress decreases rapidly because of the negative friction, and the reduced stress is transmitted to pile body via negative friction. That is why the pile axial force increases below the pile top, as shown in Fig. 1b. In fact, this part of the increased axial force is transmitted by the soil top stress via negative friction, and the remaining soil top load that is not passed to the pile body is transmitted downward via the soil.

The pile axial force is transmitted to the UL and pile lateral soil via tip resistance and lateral resistance. When pile length is greater than effective pile length, lateral resistance transmits vast majority of load, and the tip resistance transmits less load. The load transfer path of the composite foundation is shown in Fig. 2.

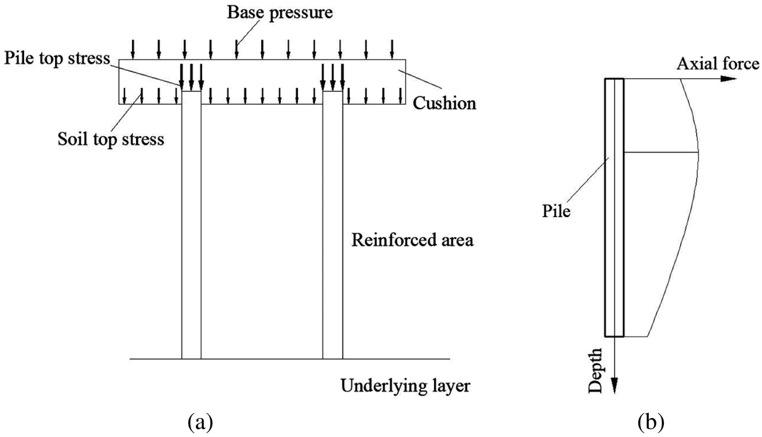


Fig. 1. Force diagram of composite foundation: a) Load distribution of base pressure, b) Axial force of pile

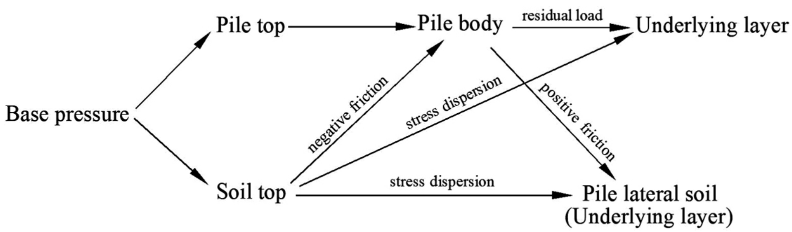


Fig. 2. Load transfer diagram of composite foundation

Boussinesq solution and Mindlin solution are commonly used to solve the stress in soil caused by load. Boussinesq solution is often used to solve the problem of soil stress under soil surface load, Mindlin solution is often used to solve the problem of soil stress under soil internal load.

Under vertical uniform load with rectangular distribution, the Boussinesq solution of vertical stress in soil below corner point is

$$\sigma_z = \alpha_c p_0 \tag{2.1}$$

where: $\sigma_z$ – vertical stress in soil below corner point, $\alpha_c$ – stress coefficient of the Boussinesq solution, $p_0$ – base pressure.

Geddes integrated the Mindlin solution and obtained the calculation formulas of the stress in soil under the action of pile tip force, uniform pile lateral force and regular triangular pile lateral force respectively, as shown in Eq. (2.2).

$$\begin{cases} \sigma_{zp} = \frac{p_p}{L^2} I_p \\ \sigma_{zs1} = \frac{p_{s1}}{L^2} I_{s1} \\ \sigma_{zs2} = \frac{p_{s2}}{L^2} I_{s2} \end{cases} \tag{2.2}$$

where: $p_p$, $p_{s1}$ and $p_{s2}$ – pile tip force, uniform pile lateral force and regular triangular pile lateral force respectively, $\sigma_{zp}$, $\sigma_{zs1}$ and $\sigma_{zs2}$ – stress in soil under the action of $p_p$, $p_{s1}$ and $p_{s2}$ respectively, $I_p$, $I_{s1}$, $I_{s2}$ – stress coefficients of Mindlin solution under the action of $p_p$, $p_{s1}$ and $p_{s2}$ respectively, $L$ – pile length

There are three types of stress transfer in Fig. 2:

The first type is the downward transfer of soil top stress. The soil top stress, that is not transmitted by negative friction, belongs to this transfer type. The stress of this transfer type can be calculated by Boussinesq solution.

The second type is that the lateral resistance transfer stress to RA and UL. For friction piles, most of the load is transmitted in this type. The lateral resistance belongs to the internal force of soil, and the transmitted stress can be calculated by Mindlin solution.

The third type is that the tip resistance transfer stress to the UL. For end bearing piles, most of the load is transmitted in this type. The tip resistance belongs to the internal force of soil, and the transmitted stress can also be calculated by the Mindlin solution.

The load transfer capacity of the above three types is different. By comparing the stress coefficients $I_{s1}$, $I_{s2}$ of pile lateral force and $I_p$ of pile tip force in Mindlin solution, it can be found that the stress coefficients $I_{s1}$ and $I_{s2}$ of lateral resistance is smaller than the stress coefficient $I_p$ of tip resistance under the same conditions. According to Eq. (2.2), the stress in Mindlin solution is inversely proportional to the square of pile length. With the increase of pile length, the stress caused by tip resistance and lateral resistance will become weaker and weaker. Therefore, when the forces are equal, the stress in soil caused by soil top force (solved by Boussinesq solution) is usually greater than the stress in soil caused by soil internal force (solved by Mindlin solution).

According to the above analysis, when the forces are equal, the stress caused by the soil top force is the largest, followed by the stress caused by the tip resistance, and the stress caused by the lateral resistance is the least. Therefore, among the three stress transfer types, the first type has the strongest load transfer capacity, the second type has the worst load transfer capacity, and the third type is between the two.

When the pile length is long, the load is mainly transferred by lateral resistance. The lateral resistance has the worst stress transfer capacity, so the stress in the UL is small. When the pile length is short, the soil between the piles bears more stress, and the load is mainly transferred in the first type, so the stress in the UL is large.

# 3. Settlement method of flexible pile composite foundation

In flexible pile composite foundation, the penetration of pile top in cushion layer is small, the soil-pile relative displacement is small, and the negative friction force of pile body is also small. According to the analysis in Section 2, it can be found that when negative friction is ignored, the soil top stress is not transmitted to the pile body, but all is transmitted downwards to the UL. The stress transmitted to the UL can be solved by Boussinesq solution. At the same time, the friction force of the pile body is all positive, and the tip resistance and lateral resistance of the pile will also produce stress in the UL, which can be solved by Mindlin solution.

Considering that piles far away from the calculated position have little influence on the stress at calculation position, When piles are arranged in a square, the stress at the calculation position caused by tip resistance and lateral resistance only considers the influence of adjacent four piles and nearer eight piles, and the other piles far away from the calculation position can be ignored.

The deformation of flexible pile is large, so the soil-pile relative displacement is small, especially in the lower part of pile, the relative displacement is very small. Therefore, the lateral resistance can be assumed to be an inverted triangular distribution [17].

Mindlin solution assumes that the lateral resistance is a rectangular distribution and a positive triangular distribution. When the lateral resistance is inverted triangle, it is considered to be a rectangle minus a positive triangle, as shown in Fig. 3. Therefore, when the lateral resistance is inverted triangular distribution, stress coefficient is

$$I'_{s2} = 2I_{s1} - I_{s2} \tag{3.1}$$

where: $I'_{s2}$ – stress coefficient of the Mindlin solution when the lateral resistance is the inverse triangular distribution.

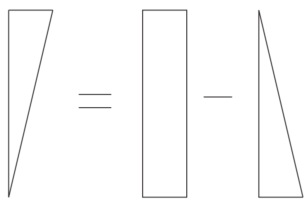

Fig. 3. Calculation diagram of lateral resistance as inverse triangular distribution

When the length of flexible pile is greater than the effective pile length, the excess pile length does not play a role in reducing the settlement. Therefore, the calculated pile length of flexible pile is taken as the effective length, and the calculated top surface of the UL is taken as the bottom of effective pile length, as shown in Fig. 4. At this time, pile tip force is 0, and pile top load is all carried by lateral resistance, so the stress in the UL is

$$\sigma_z = \alpha_c \sigma_s + \sum_{i=1}^{n} \frac{Q_p}{L_e^2} I'_{si2} \tag{3.2}$$

where: $\sigma_z$ – stress in the UL, $\sigma_s$ – soil top stress, $L_e$ – effective pile length, $Q_p$ – pile top load.

When length of the flexible pile is less than effective pile length and more than half of effective pile length, the pile tip force isn't 0, which can be calculated by the tip resistance and take $q_{pk}A_p$. After deducting pile tip force, the remaining pile top load is carried by lateral resistance. At this time, the stress in the UL is

$$\sigma_z = \alpha_c \sigma_s + \sum_{i=1}^{n} \frac{q_{pk}A_p}{L^2} I_{pi} + \sum_{i=1}^{n} \frac{Q_p - q_{pk}A_p}{L^2} I'_{si2} \tag{3.3}$$

where: $q_{pk}$ – characteristic value of the tip resistance, $A_p$ – cross section of pile.

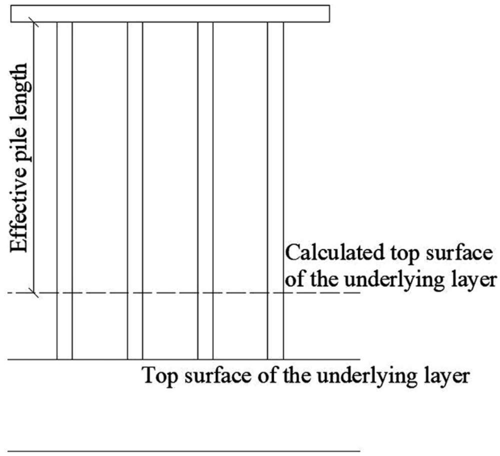


Fig. 4. Calculation model when pile length is longer than effective pile length

When length of flexible pile is less than half of effective pile length, due to the short pile length, the load transfer of the pile is not considered, only the replacement effect of the pile is considered, and the RA can be regarded as an equivalent homogeneous soil layer. Therefore, the stress in the UL is calculated from the base pressure according to Boussinesq solution.

$$\sigma_z = \alpha_c p_0 \tag{3.4}$$

Generally, when the composite foundation reaches its bearing capacity, the soil between piles also reaches its bearing capacity, but the piles do not reach their bearing capacity, and the bearing capacity coefficient is 0.7–0.9 [18–21]. Therefore, in Eqs. (3.2) and (3.3), the soil top stress $\sigma_s$ can be taken as the characteristic value of bearing capacity of the soil between piles, and the pile top load $Q_p$ can be taken as 0.7–0.9 times of the characteristic value of single pile bearing capacity.

After the stress in the UL is determined, the settlement of the UL can be calculated by the layerwise summation method, and the calculation expression of the layerwise summation method is

$$s_U = \sum_{i=1}^{n_2} \frac{\overline{\sigma}_z h_i}{E_{si}} \tag{3.5}$$

where: $s_U$ – settlement of the UL, $n_2$ – the number of soil layers in the UL, $\overline{\sigma}_z$ – average stress in the $i$-th soil layer, which can be taken as the average of the stresses at the top and bottom of the soil layer, $E_{si}$ – compressive modulus of the $i$-th soil layer; $h_i$ – thickness of the $i$-th soil layer.

The settlement of the RA can be solved by the layerwise summation method based on the composite modulus, and the expression is

$$s_R = \sum_{i=1}^{n1} \frac{p_0}{E_{spi}} \left(z_i\overline{\alpha}_i - z_{i-1}\overline{\alpha}_{i-1}\right) \tag{3.6}$$

where: $s_R$ – settlement of the RA, $n_1$ – number of soil layers in the RA, $z_i$ and $z_{i-1}$ – distances from the bottom of the $i$-th soil layer and the ($i$-1)-th soil layer to the base respectively, $\overline{\alpha}_i$ and $\overline{\alpha}_{i-1}$ – average stress coefficients in $z_i$ and $z_{i-1}$ respectively, $E_{spi}$ – composite modulus of the RA.

The sum of Eqs. (3.5) and (3.6) is the total settlement of the flexible pile composite foundation.

# 4. Settlement method of rigid pile composite foundation

The stiffness of soil and pile in rigid pile composite foundation is quite different, so there is negative friction on the pile side. Due to the effect of negative friction, part of the soil top stress will be transmitted to the pile. Fig. 5a and Fig. 5b show the load transfer diagram when piles are arranged in a square.

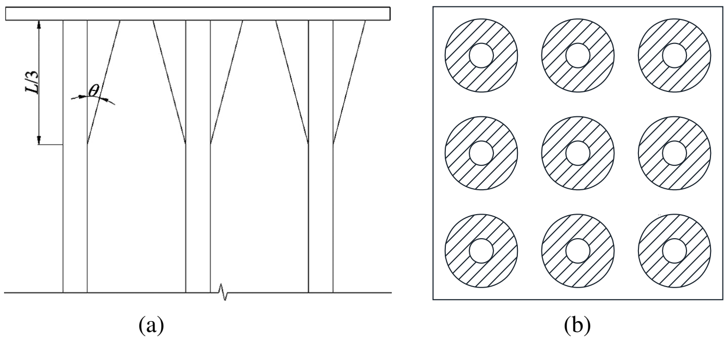


Fig. 5. Load transfer diagram of rigid pile composite foundation: a) Elevation, b) Plan

Research shows that the depth of negative friction force is generally 1/4–1/3 of the pile length [22, 23], and this paper takes 1/3 pile length. As with the pile foundation, the diffusion angle $\theta$ of negative friction can take 1/4 of the internal friction angle of soil.

In Fig. 5b, the soil top stress in shaded area is transmitted to the pile via negative friction, and The shaded area corresponding to a pile is calculated by Eq. (4.1).

$$A_{s0} = \pi \left( \frac{L}{3} \tan \frac{\varphi}{4} + \frac{D}{2} \right)^2 - \frac{\pi D^2}{4} \tag{4.1}$$

where: $A_{s0}$ – the area of soil top stress which is transferred to the pile via negative friction, $\varphi$ – the internal friction angle of soil near the pile top, $D$ – pile diameter.

The soil top load transmitted to pile body via negative friction is

$$N_{s0} = \sigma_s A_{s0} \tag{4.2}$$

The remaining soil top load transmitted downward is

$$N_s' = \sigma_s \left( A_s - A_{s0} \right) \tag{4.3}$$

where: $A_s$ – the area of soil between piles corresponding to a pile.

The remaining soil top load is converted based on the area of the soil between the piles, and the converted soil top stress transmitted directly downward can be obtained.

$$\sigma_s' = \frac{N_s'}{A_s} = \sigma_s \left(1 - \frac{A_{s0}}{A_s}\right) \tag{4.4}$$

The effect of converted soil top stress on the UL can be calculated by the Boussinesq solution.

For the pile, in addition to bearing pile top load, but also bear load transmitted by negative friction, that is, the maximum pile axial force is

$$Q_{\max} = Q_p + N_{s0} = Q_p + \sigma_s A_{s0} \tag{4.5}$$

Because the stiffness of rigid pile is greater, the soil-pile relative displacement and lateral resistance are greater than that of flexible pile. Therefore, the positive lateral resistance can be assumed to be a rectangular distribution, and the effect of lateral resistance on the UL can be calculated by Mindlin solution.

When the length of rigid pile is greater than the effective length of pile, the tip resistance is 0, and the pile is only subjected to lateral resistance. At this time, the calculated top surface of the UL is taken as the effective pile length depth.

As shown in Fig. 6a, rigid piles only have positive lateral resistance at the lower 2/3 of the pile length, which is different from the positive lateral resistance at the entire pile length shown in Fig. 6b. Therefore, when calculating with the Mindlin solution, Fig. 6a should be converted to Fig. 6b.

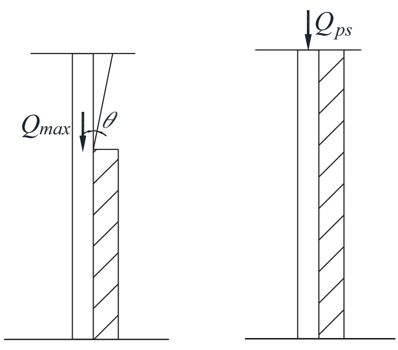


Fig. 6. Diagram of calculation model transformation: a) Before conversion, b) After conversion

Since the lateral resistance is assumed to have a rectangular distribution, in order to ensure the same lateral resistance in Fig. 6a and Fig. 6b, the pile top load $Q_{ps}$ in Fig. 6b should be 1.5 times of the maximum axial force $Q_{\max}$ in Fig. 6a, that is

$$Q_{ps} = 1.5 Q_{\max} \tag{4.6}$$

When the length of rigid pile is greater than effective pile length, the pile tip force is 0, and the pile top load is all carried by the lateral resistance. According to Eqs. (4.4) and (4.6), the stress in the UL can be expressed as

$$\sigma_z = \alpha_c \sigma_s' + \sum_{i=1}^{n} \frac{Q_{ps}}{L_e^2} I_{si1} \tag{4.7}$$

where: $\sigma_s'$ – converted soil top stress transmitted directly downward, calculated by Eq. (4.4), $Q_{ps}$ – lateral friction force after conversion, when length of pile is longer than effective pile length, it can be calculated by Eq. (4.6).

When the length of rigid pile is less than effective pile length, pile tip force isn't 0, which can be calculated by the tip resistance, as shown in Eq. (4.8). The remaining pile top load is carried by the lateral resistance, which is a rectangular distribution. The load carried by the lateral resistance should be converted when the Mindlin solution is used, and the conversion is Eq. (4.9).

$$Q_{pb} = q_{pk} A_p \tag{4.8}$$

$$Q_{ps} = 1.5 \left( Q_{\max} - Q_{pb} \right) \tag{4.9}$$

Thus, the stress in the UL can be expressed as

$$\sigma_z = \alpha_c \sigma_s' + \sum_{i=1}^{n} \frac{Q_{pb}}{L^2} I_{pi} + \sum_{i=1}^{n} \frac{Q_{ps}}{L^2} I_{si1} \tag{4.10}$$

where: $Q_{pb}$ – pile tip force, $Q_{ps}$ – lateral friction force after conversion, when length of pile is less than effective pile length, it can be calculated by Eq. (4.9).

Similar to the flexible pile composite foundation, the stress at the calculation position caused by tip resistance and lateral resistance only considers the influence of adjacent four piles and nearer eight piles, and the other piles far away from the calculation position can be ignored. The settlement of the RA and the UL of rigid pile composite foundation can be calculated by Eqs. (3.6) and (3.5) respectively.

When piles are not arranged in a square, it can be transformed into a square arrangement with the same pile diameter and the same displacement rate, and then the settlement is calculated according to the relevant methods in this section.

## 5. Examples

Case 1:

The plane size of a six-story frame building is $16.4 \times 35.2$ m, and the foundation is treated with powder spray pile (flexible pile). Piles are arranged in a square, pile length is 9.4 m, pile spacing is 1m, pile diameter is 0.5 m, replacement rate is 18.7%, and the characteristic value of single pile bearing capacity is 130 kN. The buried depth of the foundation is 0.5 m, the size of the foundation is $2.4 \times 2.4$ m, the characteristic value of soil bearing capacity is 90 kPa and the characteristic value of soil bearing capacity after treatment is required to be 150 kPa. Parameters of soil in different layers are shown in Table 1.

When the base pressure is 150 kPa, the top stress of soil between piles can approximate the characteristic value of soil bearing capacity of 90 kPa. Based on the layerwise summation method, the settlement of the RA is 20 mm, and the settlement of the UL caused by the soil top stress is 5.6 mm.

Table 1. Parameters of soil in different layers

| No. | Category | Average thickness, m | Compression modulus, MPa | Lateral resistance, kPa | Tip resistance, kPa | Characteristic value of soil bearing capacity, kPa |
|---|---|---|---|---|---|---|
| 1 | filled soil | 3.9 | 2 | | | 90 |
| 2 | clay | 2.6 | 3.2 | 20 | 760 | 120 |
| 3 | Silty clay | 3.2 | 2.6 | 12 | 500 | BODY 87 |
| 4 | Silty clay | 2.8 | 4.0 | 25 | 1100 | 180 |
| 5 | Silty clay | 2.2 | 4.5 | 30 | 1150 | 220 |
| 6 | Silty clay | 9.6 | 5.5 | 35 | 1180 | 250 |

According to literature [24], the calculated effective pile length is about 10 m, which is close to the actual pile length. It can be considered that tip resistance has no influence on the stress of UL. When bearing capacity coefficient of pile is 0.7, the pile top load is 91 kN. The calculation position is taken as the center of the adjacent four piles in the bottom surface of RA, and only the influence of adjacent four piles and nearer eight piles on the calculation position is considered. It is calculated that the settlement of UL caused by lateral resistance is 6.7 mm. Therefore, the total settlement is 32.3 mm, which is close to the measured settlement of 28 mm.

Case 2:

The length and width of a coal yard in Dalian, China are 72 m and 45 m respectively, and the characteristic value of soil bearing capacity is 72 kPa. CFG piles (rigid pile) are used for foundation treatment and the characteristic value of soil bearing capacity after treatment is required to be 150 kPa. Piles are arranged in a square, pile length is 20.7 m, pile spacing is 2.6 m, pile diameter is 0.5 m, and the characteristic value of single pile bearing capacity is 689 kN. Parameters of soil in different layers are shown in Table 2.

Since the pile spacing is 2.6 m, it can be solved that the area $A_s$ of soil between piles corresponding to a pile is 6.56 m$^2$. The friction angle of the plain fill is 20°, and according to Eq. (4.1), the area $A_{s0}$ of soil top stress which is transferred to the pile via negative friction can be calculated as 2.1 m$^2$.

According to Eq. (4.2), the soil top load $N_{s0}$ transmitted to the pile body via negative friction can be calculated as 151 kN; according to Eq. (4.4), the converted soil top stress

Table 2. Parameters of soil in different layers

| No. | Category | Average thickness, m | Compression modulus, MPa | Lateral resistance, kPa | Tip resistance, kPa | Characteristic value of soil bearing capacity, kPa |
|---|---|---|---|---|---|---|
| 1 | plain fill | 1 | 2.6 | 16 | | 72 |
| 2 | Silty clay | 1.1 | 3.7 | 19 | | 80 |
| 3 | mucky soil | 17.4 | 2.0 | 10 | | 40 |
| 4 | Silty clay | 1.2 | 6.0 | 28 | | 130 |
| 5–1 | clay | 0.9 | 7.5 | 34 | 1600 | 179 |
| 5–2 | Silty clay | 0.7 | 7.3 | 33 | 1600 | 175 |
| 5–3 | Silty clay | 0.6 | 8 | 34 | 1600 | 179 |
| 6 | Silt | 6.0 | 18 | 55 | 2000 | 220 |

$\sigma_s'$ transmitted directly downward can be calculated as 49 kPa; and according to Eq. (4.5), the maximum pile axial force $Q_{\max}$ is $0.8 \cdot 689 + 151 = 702$ kN (0.8 is the bearing capacity coefficient of pile).

According to literature [24], the calculated effective pile length is greater than the actual length, so pile tip force isn't 0. According to Eq. (4.8), the pile top load carried by the tip resistance can be calculated as 314 kN, and the pile top load carried by the lateral resistance is 388 kN. According to Eq. (4.9), the converted lateral friction force is 582 kN.

Based on the layerwise summation method, the settlement of the RA is 94 mm, the settlement of the UL caused by the downward diffusion of the soil top stress is 1.8 mm, the settlement of the UL caused by the pile lateral force is 7.5 mm, the settlement of the UL caused by the pile tip force is 7.2 mm, and the total settlement is 110.5 mm. The measured settlement value of this project is 102 mm, and it is very close to the calculated value.

# 6. Conclusions

1. There are three types of stress transfer in soft soil composite foundation. The first type is the downward transfer of soil top stress, the second type is that the lateral resistance transfer stress to reinforced area and underlying layer, and the third type is that the tip resistance transfer stress to the underlying layer. Among the three types of stress transfer, the first type has the strongest load transfer capacity, the second type has the worst load transfer capacity, and the third type is between the two.
2. The soil-pile relative displacement in flexible pile composite foundation is small, and the influence of negative friction can be ignored. The settlement of the underlying layer can be solved by assuming that the lateral resistance is an inverted triangle distribution, but the effect of effective pile length should be considered.

3. The soil-pile relative displacement in rigid pile composite foundation is large, and the influence of negative friction cannot be ignored. The decrease of soil top stress caused by negative friction should be considered, and the settlement of underlying layer should be solved by assuming that the lateral resistance is rectangular distribution.
4. When piles are not arranged in a square, it can be transformed into a square arrangement with the same pile diameter and the same displacement rate.

## References

[1] Y.F. Li, J.H. Zhao, Y. Xiong, and Q.H. Wang, "Experimental and theoretical research on large-diameter rock-socketed pile embedded depth", *Archives of Civil Engineering*, vol. 67, no. 2, pp. 537–550, 2021, doi: 10.24425/ace.2021.137184.

[2] R.Q. Lang, C.H. Ma, L.Q. Sun, S. Lin, S. W. Yan, Z.L. Huo, and W.C. Yang, "Three-dimensional modeling on load-transferring mechanism of rigid pile-net composite foundation", *International Journal of Geomechanics*, vol. 22, no. 7, art. no. 4022097, 2022, doi: 10.1061/(ASCE)GM.1943-5622.0002441.

[3] Q.H. Fu and L.X. Li, "Vertical load transfer behavior of composite foundation and its responses to adjacent excavation: centrifuge model test", *Geotechnical Testing Journal*, vol. 44, no. 1, pp. 191–204, 2021, doi: 10.1520/GTJ20180237.

[4] S.G. Wang, Z.L. Zhang, and Y.L. Yuan, "The calculation method combined with Mindlin's solution and Boussinesq's analytical solutions to calculate composite foundation settlement", *Journal of Xi'an University of Architecture and Technology (Natural Science Edition)*, vol. 50, no. 6, pp. 820–825, 2018, doi: 10.15986/j.1006-7930.2018.06.009.

[5] J.J. Xu, X. Xu, and W.J. Yao, "New calculation method for the settlement of long-short-pile composite foundation based on virtual soil-pile model", *Arabian Journal of Geosciences*, vol. 15, art. no. 870, 2022, doi: 10.1007/s12517-022-10028-2.

[6] Z.F. Wang, W.C. Cheng, Y.Q. Wang, and J.Q. Du, "Simple method to predict settlement of composite foundation under embankment", *International Journal of Geomechanics*, vol. 18, no. 12, art. no. 4018158, 2018, doi: 10.1061/(ASCE)GM.1943-5622.0001293.

[7] C. Zhang, S. Liu, D. Zhang, F. Lai, T. Lu, and Y. Liu, "A modified equal-strain solution for consolidation behavior of composite foundation reinforced by precast concrete piles improved with cement-treated soil", *Computers and Geotechnics*, vol. 150, art. no. 104905, 2022, doi: 10.1016/j.compgeo.2022.104905.

[8] M.M. Lu, Q. Zhang, H.W. Jing, Y.X. Wang, and C.X. Li, "Analytical solutions for consolidation of composite ground improved by composite columns with circular and non-circular cross sections", *European Journal of Environmental and Civil Engineering*, vol. 26, no. 7, pp. 2780–2796, 2022, doi: 10.1080/19648189.2020.1767698.

[9] R. Lang and A. Yang, "A quasi-equal strain solution for the consolidation of a rigid pile composite foundation under embankment loading condition", *Computers and Geotechnics*, vol. 117, art. no. 103232, 2020, doi: 10.1016/j.compgeo.2019.103232.

[10] J. Zhang, X.Z. Cui, D. Huang, Q. Jin, J. Lou, and W. Tang, "Numerical simulation of consolidation settlement of pervious concrete pile composite foundation under road embankment", *International Journal of Geomechanics*, vol. 16, no. 1, art. no. 4015006, 2016, doi: 10.1061/(ASCE)GM.1943-5622.0000542.

[11] M. Xu, P. Ni, G. Mei, and Y. Zhao, "Time effects on settlement of rigid pile composite foundation: simplified models", *International Journal of Computational Methods*, vol. 15, no. 7, art. no. 1850065, 2018, doi: 10.1142/S0219876218500664.

[12] L. Wang, A. Zhou, Y. Xu, and X. Xia, "Consolidation of unsaturated composite ground reinforced by permeable columns", *Computers and Geotechnics*, vol. 125, art. no. 103706, 2020, doi: 10.1016/j.compgeo.2020.103706.

[13] W.F. Kabeta, "Effects of full displacement pile installation on the stress and deformation state of surrounding soil: review", *Archives of Civil Engineering*, vol. 68, no. 4, pp. 445–466, 2022, doi: 10.24425/ace.2022.143048.

[14] Q. Luo and Q.Y. Lu, "Settlement calculation of rigid pile conposite foundation considering pile-soil relative slip under embankment load", *China Journal of Highway and Transport*, vol. 31, no. 1, pp. 20–30, 2018, doi: 10.19721/j.cnki.1001-7372.2018.01.003.

[15] J.J. Zheng, Y. Liu, Y.T. Pan, and J. Hu, "Statistical evaluation of the load-settlement response of a multicolumn composite foundation", *International Journal of Geomechanics*, vol. 18, no. 4, art. no. 04018015, 2018, doi: 10.1061/(ASCE)GM.1943-5622.0001124.

[16] GB50007-2011 Code for design of building foundation. Ministry of Housing and Urban-Rural Development of the People's Republic of China, China Architecture & Building Press, Beijing, 2011.

[17] K. Zhu, "Research on performances of composite foundation with rigid-flexible piles", PhD thesis, Zhejiang University, China, 2006.

[18] M.H. Zhao, J. Long, L. Zhang, B.H. Ma, and L.P. He, "Comparative analysis of model tests on different types of composite foundations", *Chinese Journal of Geotechnical Engineering*, vol. 35, no. 4, pp. 611–618, 2013.

[19] P. Liu, G.H. Yang, Z. Fang, H.K. Liu, and Y.C. Zhang, "Experimental study on scale effect of rigid pile composite foundation", *Chinese Journal of Rock Mechanics and Engineering*, vol. 35, no. 1, pp. 187–200, 2016, doi: 10.13722/j.cnki.jrme.2014.1257.

[20] C. Wang, Y. F. Xu, J. G. Pang, and Z. T. Kuai, "Application of concrete-cored DCM piles in soft subgrade improvement of expressways", *Chinese Journal of Geotechnical Engineering*, vol. 35, no. 5, pp. 974–979, 2013.

[21] Y.F. Ma, D.H. Zhou, Z.H. Zhang, and L.Q. Cao, "In-situ test and simulation of CFG-pile composite foundation in a large petrochemical project", *Periodical of Ocean University of China*, vol. 46, no. 1, pp. 86–92, 2016, doi: 10.16441/j.cnki.hdxb.20140343.

[22] C.F. Wu, W.C. Guo, Y.N. Li, and R. Tie, "Calculation of neutral surface depth and pile-soil stress ratio of rigid pile composite foundation considering influence of negative friction", *Chinese Journal of Geotechnical Engineering*, vol. 38, no. 2, pp. 278-287, 2016.

[23] W.Y. Jiang and Y. Liu, "Determination of neutral plane depth and pile-soil stress ratio of the rigid pile composite foundation", *Rock and Soil Mechanics*, vol. 39, no. 12, pp. 4554–4560, 2018, doi: 10.16285/j.rsm.2017.0812.

[24] Y.T. Xiao, "Study on load transfer mechanism and optimization design theory of composite foundation under rigid base", PhD thesis, Xi'an University of technology, China, 2019.

Received: 2023-07-12, Revised: 2023-10-24