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Study on characteristics of pile–net composite foundation at 500 kV substation in China

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The overall requirements of substation engineering are very high, and the differential settlement control of substation engineering is relatively strict. On the soft foundation of the tidal flats at the Zhenhai 500 kV substation in China, a field test was carried out to study the working characteristics of the pile–net composite foundation during the soil filling and consolidation stage. Variation laws of the settlement, earth pressure, pile–soil stress ratio, geogrid tension and axial force of pile were obtained and analysed. When the height of the filled soil increased to 2 m, a plane of the equal settlement was formed. Because of the soil arch effect, the earth pressure on the pile top was always higher than that between the adjacent piles. The pile–soil stress ratio rapidly increased from 1.2 at the stage of soil filling to 6.0 at the initial stage of consolidation. The ability of the geogrid to transfer the load was limited, and the soil arch effect was the main reason that the load was transferred to the pile top. Due to the lateral negative friction resistance of the pile in the shallow soil, the axial force of the pile first increased and then decreased along the depth.

Notation

c_u	undrained shear strength
e_0	void ratio
k_h	horizontal permeability coefficient
k_v	vertical permeability coefficient
w_l	water content of the liquid limit
w_n	natural water content
w_p	water content of the plastic limit
γ	gravity density

Introduction

With the rapid development of social economy, demands for power in coastal areas are increasing. A large number of substations have been built in coastal areas, where deep structural clay is widely distributed. Deep structural clay is characterised by a high water content, a large pore ratio, poor permeability, high compressibility, a low bearing capacity and other unfavourable engineering characteristics. Substations are sensitive to long-term settlement and differential settlement. Therefore, the settlement of the substations on deep structural clay must be strictly controlled.

A pile–net composite foundation is a geosynthetic-reinforced and pile-supported earth platform over soft soil. As a new, economical and effective treatment technology, the pile–net composite foundation is widely used in soft soil foundation due to its advantages of small settlement deformation, easily controlled

post-construction settlement, short stabilisation time, convenient construction and relatively low cost (Liu and Zhao, 2016; Zheng *et al.*, 2012). In a recent report (Chen *et al.*, 2004), the pile–net composite foundation has been applied to the foundation treatment of deep soft soil of highways, high-speed railways, airports and so on. The typical cross-section of the pile–net composite foundation is shown in Figure 1. Piles with pile caps bear the upper load, while the reinforced cushion can efficiently adjust the pile–soil stress ratio. The piles, reinforced cushion, embankment filler and foundation soil, which interact with each other, constitute the mechanical system to bear the upper load jointly (Zheng *et al.*, 2012). The soil between piles contributes to the so-called soil arch effect and tensioned membrane effect to transfer the weight of such soil directly to piles; thus, settlement deformation of the filled soil can usually be reduced (Yapage and Liyanapathirana, 2018; Zheng *et al.*, 2012).

In recent years, many researchers have studied the pile–net composite foundation from the aspects of the characteristics and actions of the reinforced cushion, soil arch effect and so on. Based on theoretical derivation, Sun *et al.* (2011), Lu and Miao (2015) and Qian *et al.* (2017) analysed the influence of the reinforced cushion on the pile–soil stress ratio. Ariyaratne *et al.* (2013), Rowe and Liu (2015) and Cao *et al.* (2017) studied the influence of the reinforced cushion on the load-transfer characteristics of the pile–net composite foundation through

Figure 1. Application of the pile–net composite foundation in engineering

numerical simulations. Blanc *et al.* (2014) performed a centrifuge test to study the deformation characteristics of the reinforced cushion under different loads. Xu *et al.* (2016) developed a set of equipment to study the stress characteristics of the grid at different positions and proposed a three-dimensional (3D) calculation method for geogrid tension. Zhang *et al.* (2016) assumed the geogrid deflection distribution as a parabolic form to simplify the calculation of the tensioned membrane effect. Hewlett and Randolph (1988) performed a bench-scale experiment to verify the soil arch effect and further analysed the 3D soil arch effect using the elastic–plastic theory and limit state theory. Chen *et al.* (2004) improved Hewlett’s limit state analysis method by considering the non-limit state. Cheng and Zhang (2013) studied the subgrade stress distribution of the pile–net composite structure of the Beijing–Shanghai high-speed railway using numerical simulation. Chen *et al.* (2015) studied the cumulative settlement of the pile–net composite subgrade under long-term train load based on a laboratory model test. Lü *et al.* (2017) carried out a physical model test to analyse the structure of the pile–net composite subgrade under a long-term cyclic dynamic load and obtained the variation laws of the subgrade settlement, pile–soil stress ratio and axial force distribution of piles. The works of Ong *et al.* (2003, 2015) presented the bending moment along the piles due to excavation-induced soil movement.

The previous studies on the pile–net composite foundation were usually completed with numerical simulations, theoretical models and bench-scale experiments and were mainly aimed at the treatment of the subgrade under general geological conditions. The study of the pile–net composite foundation under the geological conditions of super-large deep soft soil is still very rare. Generally, the stress level of bench-scale experiments is much smaller than that of field tests. Thus, the applicability of conclusions obtained from bench-scale experiments to the actual deformation and mechanism of the pile–net composite foundation is unreliable. Meanwhile, the soil samples used in bench-scale experiments are inevitably disturbed, and the soil structure is destroyed, particularly for soft soil with high sensitivity. The results of field tests are more reliable and can also verify the results of numerical methods and evaluate the experimental data. Based on a field test of the pile–net composite foundation on the extremely soft foundation of the Zhenhai 500 kV substation in China, this paper studies the variation laws of the pile–net composite foundation settlement, earth pressure, pile–soil stress ratio, geogrid tension and axial force of the pile at the soil filling and consolidation stage.

Project overview and measuring point layout

The 50 V substation of Zhenhai is located in the inside of the intersection of the Qiantang River and the Yongjiang River in China, which is a backwater deposition area. The shallow soil layer of the site is mainly sludge and clayey silt of Quaternary coastal facies. Muddy–silty clay and sandy silt of continental alluvial–diluvial facies are in the middle soil layer. The lower layer is silty clay of shallow marine facies, and the bottom layer is mainly composed of fine-grained sand. The pile–net composite foundation was used in the test section. The stratum parameters of the test section are given in Figure 2.

Figure 3 presents the pile–net composite foundation profile in the test section. The filling height of the subgrade was 3.25 m, and the slope rate was 1 vertical to 2 horizontal. Prestressed high-strength concrete pipe piles were used with a pile diameter of 0.5 m, a pile spacing of 3 m, a square pile layout and a pile cap

Figure 2. Stratum parameters of the test section

Figure 3. Profile of the pile-net composite foundation in the test section

size of $1.8 \text{ m} \times 1.8 \text{ m}$. Two layers of geogrid were laid on the top of the pile caps, and the designed tensile strength of the geogrid was greater than 30 kN/m .

The arrangement of the measuring points of the pile-net composite foundation in the test section is shown in Figure 4. Six settlement plates were arranged at piles A and B (see Figure 5 for details). Ten earth pressure cells were arranged at pile C (refer to Figure 6 for details). Seven flexible displacement meters were arranged on the geogrid above the pile cap of pile D (refer to Figure 7 for details). Eight steel stress meters were fixed on a steel bar, which was lodged in concrete in the centre of pile A. The steel stress meters were arranged along the depth of pile A and located about 0, 4.2, 8.4, 12.6, 17.6, 23.3, 28.0 and 35.4 m below the pile cap (refer to Figure 8 for details).

Figure 4. Layout of the measuring points of the pile-net composite foundation in the test section

Figure 5. Layout of the settlement plates

Figure 6. Schematic diagram of the layout of earth pressure cells

Figure 7. Layout of the flexible displacement meters

Figure 8. Layout of the steel stress meters

Results and discussion

Settlement analyses

The layout of the settlement plates is shown in Figure 5. Six settlement plates (S1–S6) were arranged above piles A and B. Four of them were 0 or 2 m above the piles and at the centre of pile A or B, and the other two were above the soil between piles A and B. In the process of soil filling and consolidation, the cumulative settlement curve of the pile-net composite foundation with time is plotted in Figures 9 and 10. It is shown that the differential settlement between S2 (above the soil between the piles) and S1 and S3 (above the piles) was small at the early stage of soil filling.

Figure 9. Cumulative settlement-time curve of the settlement plates on the top of the piles in the test section

With the increase in the filling height and consolidation time, the settlement of S2 greatly increased, and the settlements of S1 and S3 were almost unchanged. The settlement of S2 reached 34 mm after 220 days; meanwhile, the settlements of S1 and S3 were only 2 and 8 mm, respectively. After the completion of soil filling, the settlements of S4, S5 and S6 at 2 m above the top of the piles increased with the consolidation time, and the settlement of the three plates was all stable at about 68 mm after 220 days.

The results show that with the increase in the differential settlement between S2 and S1 and S3, the ‘soil arch effect’ and ‘tensioned membrane effect’ continuously increased, which leads to the transfer of part of the weight of the upper filled soil between the piles to the filled soil on top of the piles. The differential settlement of S4, S5 and S6 at 2 m above the top of the piles basically disappeared, and a plane of the equal settlement was formed. Furthermore, the total settlement of the filled soil on piles consists of two parts: the deformation of the filled soil itself and the settlement of the pile top, where the latter accounts only for a small part. Due to the soil arch effect and tensioned membrane effect, the deformation of the filled soil between the piles was smaller than that of the filled soil on top of the piles. This shows that in the construction of the pile-net composite foundation of the tidal flat in which the foundation is extremely soft, the filled soil has a greater influence on the settlement characteristics. For projects with strict settlement requirements, well-graded filled soil should be used and the compactness of the filled soil should be strictly controlled.

Earth pressure in filled soil and pile-soil stress ratio

Figure 6 shows the layout of the earth pressure cells in the test section. P5 and P6 were located at the upper geogrid (0.2 m above pile C), P7 and P8 were located 1 m above pile C and P9 and P10 were located 2 m above pile C. The distribution of the earth pressure on the top of pile C or between piles C and D is shown in Figure 11. As shown, the earth pressure (P1, P2, P3) on top of

Figure 10. Cumulative settlement-time curve of the settlement plates at 2 m above the pile top in the test section

Figure 11. Earth pressure-time curve on the pile top and between the adjacent piles

the pile rapidly increased with the filling height during the whole soil-filling stage. The earth pressure (P4) between the piles increased with the filling height at the early stage of the soil filling and decreased after the filling height reached 2.7 m. During the consolidation, the earth pressure on the top of the pile slightly increased and tended to be stable, while the earth pressure between the piles slightly decreased and tended to be stable. The

results indicate that the differential settlement had a greater influence on the soil arch effect during the filling stage. With the continuous increase in the differential settlement, the soil arch effect generated in the filled soil became obvious, and the filling load was continuously transferred to the piles. The soil between the piles shared only 45% of the load at most. With the increase in the consolidation time, the total settlement and differential settlement of piles and soil developed, and the soil arch effect reached the limit state. The effect of the differential settlement on the soil arch effect weakened, and the earth pressure on the top of the pile and between the piles tended to be stable.

P2, P5, P7 and P9 are taken as the earth pressure at the top of the pile. Meanwhile, P4, P6, P8 and P10 are taken as the earth pressure between the piles. The distribution curves of earth pressure along the filling height at different times are plotted in Figure 12. For the convenience of analysis, the weight of the filled soil is also plotted in the figure. With reference to Figure 11, it can be seen that the difference between the earth pressure at the top of the pile and the earth pressure between the piles was small at the early stage of the soil filling and gradually increased with the filling height and consolidation time. However, the comparison between Figures 12(e) and 12(f) shows that the earth pressure at the top of the pile slightly decreased and the earth pressure between the piles slightly increased when the consolidation time continued to increase. This characteristic is

Figure 12. Distribution curves of the earth pressure along the depth of the filled soil: (a) filling height of 1.5 m; (b) filling height of 2.4 m; (c) filling height of 3.25 m; (d) 8 days of consolidation; (e) 49 days of consolidation; (f) 164 days of consolidation

consistent with the results by Iglesia and Einstein (2015) for a centrifugal model test and the results by Han *et al.* (2017) for a scaled model test that the soil arch effect increases with the differential settlement at the initial stage of filling and consolidation, whereas with the progress of the consolidation, the differential settlement gradually increases, and the soil arch effect gradually weakens with the increase in the differential settlement.

According to the monitoring results of the earth pressure at different positions on the top of pile C, the evolving pile-soil stress ratio throughout the construction process was obtained and is plotted in Figure 13. At the stage of the soil filling, the pile-soil stress ratio rapidly increased from 1.2 to 3.0 and reached a peak of 6.0 within 8 days after the completion of soil filling. With the increase in the consolidation time, the pile-soil stress ratio tended to be stable at about 5.0. The analysis shows that the differential settlement of the piles and soil at the stage of the soil filling was small, and the soil arch effect was not obvious. The soil between the piles shared part of the load and generated a large compression. While the differential settlement increased, the upper load was transferred to the piles by the soil arch effect, and the pile-soil stress ratio immediately increased. Finally, the pile-soil stress ratio at 184 days was 5.0.

Geogrid tension and axial force of the pile

Figure 14 plots geogrid tension distribution near pile D at different times. It can be seen from the figure that the geogrid tension at the edge of the pile cap was relatively large, while the geogrid tension between the piles was relatively small. The geogrid tension was distributed in an inverted triangle, which was consistent with the results presented by van Eekelen *et al.* (2012) and Wang *et al.* (2018). The geogrid tension increased with the filling height, and the maximum geogrid tension was about 4 kN/m, which was approximately 13% of the designed tensile strength (30 kN/m).

Figure 13. Pile-soil stress ratio curve with time

Overall, the ability of the geogrid to transfer the load was very limited, and the soil arch effect was the main reason that the load was transferred to the pile top.

Figure 15 shows the curve of the axial force of pile A along the depth at different times. It is shown that the lateral friction resistance of the pile presented two distinct sections – namely, the negative friction resistance zone and the positive friction resistance zone. The axial force of the pile firstly increased and then decreased along the depth, and the axial force distribution of the pile was that the middle section was large and both ends were small. With the increase in the filling height, the position of the neutral point basically did not change, and the axial force of the pile at each depth gradually increased. After the completion of the soil filling, the neutral point gradually moved upwards from the depth of 8.4–4.2 m, and the axial

Figure 14. Distribution curve of the geogrid tension near pile D

Figure 15. Axial force curve of pile A along the depth

force of the pile below the neutral point slightly decreased, and the axial force of the pile above the neutral point firstly increased and then basically remained unchanged. This phenomenon indicates that at the initial stage of the soil filling, the settlement of the shallow soil was greater than that of the pile, and negative friction was generated along the pile. Hence, the axial force of the pile increased along the depth in this shallow soil area (i.e. the negative friction resistance zone). At the later stage of the soil filling and the early stage of the consolidation, the negative friction zone existed in the sludge, clayey silt and a small part of muddy–silty clay. While the soil arch effect continuously transferred the load to the pile, the pile deformation gradually increased. Meanwhile, the negative friction zone gradually reduced, and the negative friction zone existed only in the sludge and clayey silt at the later stage of consolidation.

Conclusions

Based on the test section of the pile–net composite foundation on the extremely soft foundation of the Zhenhai 500 kV substation, a field test study on the working characteristics of the pile–net composite foundation during the filling and consolidation stage was conducted, and the following conclusions were obtained.

- The settlement of the filled soil on the piles consists of the deformation of the filled soil and the settlement of the pile top, and the settlement of the pile top accounts only for a small part. Due to the soil arch effect and tensioned membrane effect, the deformation of the filled soil between the piles is smaller than that of the filled soil on top of the piles. While the filling height was increased to 2 m, the differential settlement basically disappeared, and a plane of the equal settlement was formed.
- During the filling and consolidation periods, the earth pressure on the top of the pile gradually increased and then tended to be stable. Meanwhile, the earth pressure between the piles increased with the filling height at the early stage of the filling and decreased after the filling height reached 2.7 m and then tended to be stable. The earth pressure on the pile top was always greater than that between the piles. In the later stage of consolidation, the earth pressure on top of the pile slightly decreased and the earth pressure between the piles slightly increased.
- At the stage of soil filling, the pile–soil stress ratio rapidly increased from 1.2 to 3.0 and reached a peak of 6.0 within 8 days after the completion of soil filling. With the increase in the consolidation time, the pile–soil stress ratio tended to be stable at about 5.0.
- The geogrid tension increased with the filling height, and the maximum geogrid tension was about 4 kN/m, which was approximately 13% of the designed tensile strength (30 kN/m). The ability of the geogrid to transfer the load is very limited, and the soil arch effect is the main reason that the load is transferred to the pile top.
- Due to the lateral negative friction resistance of the pile in the shallow soil, the axial force of the pile firstly increased and then decreased along the depth. With the increase in the filling

height, the position of the neutral point basically did not change, and the axial force of the pile at each depth gradually increased. During the consolidation stage of filling soil, the neutral point moved upwards from the depth of 8.4–4.2 m, and the axial force of the pile below the neutral point slightly decreased, and the axial force of the pile above the neutral point firstly increased and then basically remained unchanged.

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