Innovative design of pipe piles combined both the effect of pile foundation and composite foundation for soft soil treatment

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ABSTRACT

The soft soil treatment is one of the hot issues needed to be solved in many constructions including tunnels, freeways, etc. In this paper, a prefabricated pipe pile with side openings and wrapped geotextile is first proposed aiming to realize both the effect of pile foundation and composite foundation for soft soil treatment, which could be capable of draining and increasing frictional resistance. It combines fast drainage consolidation and high bearing capacity, which could be used under different engineering conditions with different designs. Small holes on pipe pile provide the drainage channel for vacuum to accelerate the consolidation and reduce the squeezing effect. The geotextile wrapped outside reduces the friction in pile-driven process and has the anti-filtering effect to ensure the long-term stability of the drainage channel. After the consolidation, the drainage pipe pile is grouted to form a composite foundation with high bearing capacity, which has good time, economy and environmental benefits. The drainage pipe pile can be developed to some special designs for dam filling and reclamation of islands. The proposed innovative designs of pipe pile could satisfy the demand of high bearing capacity and quick consolidation on soft soil, which combine both the effect of pile foundation and composite foundation.

Keywords: soft soil, drainage pipe pile, pile foundation, foundation treatment

1 INTRODUCTION

With the deep development of the coastal cities, already soft foundation treatment methods cannot meet the needs of rapid construction and settlement control of large-scale logistics centers and factories in the deep soft soil area, which is slow to drain and consolidate with low in natural bearing capacity.

Common treatment method of soft soil foundation is to carry out drainage consolidation in advance, and then pile up in the composite foundation. However, studies (Indraratna et al., 2004; Shao et al., 2016) have shown that this treatment method can meet the needs of quick consolidation and high bearing capacity at the same time, which consumes a lot time and budget. The squeezing effect is obvious during the pile sinking process, and it is difficult to dissipate the excess pore pressure after construction.

In order to make the pile foundation have the function of drainage, many scholars made new attempts. Zhou and Mei (2014) put forward the permeable pipe pile which can promote the bearing capacity in short time. The influence area is still not clear, and the mass production is hard to realize. Wang et al. (2017, 2018) proposed a liquefaction resistant rigid-drainage pile, which slots on both sides of the square pile, then insert the plastic drainage board. This pile has good resistance to liquefaction. Tanaka et al. (1996) and Otushi et al. (2010) use the steel plate (tube) pile with small holes to dissipate the pore pressure and realize the anti-liquefaction. Wan et al. (2019) pointed out that a small number of small holes in the pile body can accelerate drainage consolidation without considering the problem that the small holes may be blocked by the soil around the pile under vacuum.

For better pursuing of both quick consolidation and high bearing capacity, this paper proposes a new type of drainage pipe pile with uniform holes and wrapped by geotextile. Small holes on pipe pile provide the drainage channel for vacuum. The geotextile wrapped outside reduces the friction in pile-driven process and has the anti-filtering effect to ensure the long-term stability of the drainage channel. After the completion of drainage, grouting machine is used to grout through holes on the pile to improve the bearing capacity of surrounding soil. The drainage pipe pile could also
control the uneven settlement and improve the lateral force resistance and pull-out resistance of the foundation, which is of great economic benefit.

2 STRUCTURE AND MECHANISM OF DRAINAGE PIPE PILE

2.1 Structure of the drainage pipe pile

The structure of the drainage pipe pile is shown in Fig. 1. The pile body has evenly distributed small holes to provide the drainage channel for vacuum and grout. The geotextile wrapped outside reduces the friction in pile-driven process and has the anti-filtering effect to ensure the long-term stability of the drainage channel. Through the pile openings the patent grouting machine, the soil can be further grouted and reinforced, which can be applied in the fields of heritage protection, sea filling and island reclamation.

Fig. 1. Structural design of the drainage pipe pile.

The construction process of drainage pipe pile (see Fig. 2) is as follows:

1. the prefabricated pipe piles covered with special geotextile are embedded into the soil to the design depth.  
2. Due to the squeezing effect, water drains to the pile penetrates into the inner pipe through the small holes and is filtered by the wrapped geotextile.  
3. After drainage and consolidation (this step can be combined with vacuum preloading to accelerate consolidation), the geotextile will be pierced, and the soil around the pile will enter the inner pipe through the small holes, which will increase the side friction of the pile and ease the soil squeezing effect.  
4. Continue to fill enough soil from the top of the prefabricated pipe pile to the design elevation.

2.2 Mechanism of drainage pipe pile

When the pile is driven, the geotextile helps to reduce the resistance of implantation; after the implantation, the filtration of the geotextile is used to separate the soil and water to ensure the drainage. When the consolidation reaches certain extend, the geotextile is punctured, and the soil extruded from the hole and the surrounding soil are compacted to provide a higher side friction, which can effectively improve the bearing capacity of the pile foundation.

When the drainage pipe pile is vacuumed, it can be initially consolidated in 30 days, and the shear strength of the soil increases to about 3.5 times of the previous value. Compared with the pile without hole, the stiffness reduction of the pile with hole is not obvious. The bearing capacity of group pile is twice as high as that of conventional pile foundation treatment, which mainly comes from the greatly increased strength of soil between piles.

As shown in Figure 3, the consolidation of several soft soil treatments is compared. Compared with other treatment methods, the consolidation time of drainage pipe pile is the shortest which means the drainage pile has a significant improvement on the consolidation of the foundation.

Fig. 3. Comparison of consolidation effect of different piles.

Pore pressure dissipation of drainage pipe pile foundation is investigated by numerical method, as shown in Figure 4 (Tang et al., 2019). The results show that the higher the frequency of dynamic load is, the faster the pore pressure accumulates. The load frequency affects the amplitude of initial pore pressure but does not affect the decay rate of pore pressure oscillation. It proves that the composite foundation of drainage pipe pile has strong anti-liquefaction ability under earthquake load.
3 APPLICATION OF THE DRAINAGE PIPE PILE WITH DIFFERENT DESIGNS

The drainage pipe pile could make the soil and water around the pile separate and compact the pile and the surrounding soil. When the soil is soft with high moisture content, the pile is driven. After the vacuum pre-pressure drainage is completed, the friction of the soil around the pile increases, and the bearing capacity of the pile foundation of the friction pile is improved correspondingly, which achieves both the effect of the pile foundation and the composite foundation. Drainage pipe piles are further developed based on their "soft piling and compact using" engineering characteristics, which can be applied to various construction conditions with different designs in soft soil areas.

3.1 Application of the drainage pipe pile in dam filling

During the filling process of dams in coastal areas, large lateral displacement will occur at the bottom of soft soil, which will adversely affect the construction of pile foundations. At present, the method of soil replacement, drainage consolidation and retaining walls are often used to reduce the lateral displacement of the soil caused by dam filling, which all have certain limitations. The method of soil replacement can only deal with soft soil with a certain depth, of which the settlement and lateral displacement of underlying stratum are large and cannot be ignored (Li et al., 2011; Liu et al., 2012; Jahid, 2013). The drainage consolidation method has a long construction period and may cause non-uniform deformation (Zhang and Li, 2011; Kim et al., 2018). Retaining walls cannot provide enough reaction force for the soft soil foundation and will have an overall displacement with the soil. The implantation of the retaining wall will lead to the soil compaction and further increase the lateral displacement (Skinner and Rowe, 2005; Chen et al., 2012).

This paper introduces a floating pipe pile and its construction method to be used in dam filling. The design of the pipe pile consists of a groutable drainage pipe pile and a retaining structure to reduce the lateral displacement of the soft soil foundation of the dam more effectively. Each groutable drainage pipe pile is connected with two diagonal anchor cables and a horizontal anchor cable as shown in Fig. 5. The diagonal anchor cables are anchored in the bedrock of the soft soil foundation. The horizontal anchor cables extend horizontally to the embankment and are anchored to the anchors of the embankment. For the retaining structure, the groutable drainage pipe pile and the steel sheet pile are connected to each other and are divided into a middle section and two ends of the middle section. The middle section is mainly composed of groutable drainage pipe piles and steel sheet piles, which are arranged in a row parallel to the embankment. At the two ends of the middle section, the arrangement of piles is changed to two branches extending to the embankment (see in Fig. 6).
the dam filling is completed and the settlement tends to be stable, steel sheet piles are pulled out by the vibration method, which can be reused.

Numerical analysis is carried out based on a bridge project in the coastal channel of Zhoushan Sea by Plaxis 3D. In Fig. 7, the left side is the center dyke, the right is the east bank perpendicular to the center dyke, and the shadow part is the reinforced soil by gravel piles. The bridge pile number is 1 # to 8 #. The nearest bridge pile 7 # and 8 # are affected by the embankment filling in the reclamation area of the east bank. If the pile foundation construction is carried out immediately after the construction of the cofferdam is completed, the lateral displacement of the pile foundation along the bridge increases by 17 %. The cofferdam will affect the stability of bridge. Using the pile foundation mentioned above, a three-dimensional model is established to study the lateral displacement, of which the retaining structure is located at the pile 6 # and 7 #. Figure 8 shows the comparison of the lateral displacement curve of the pile 7 # before and after the retaining structure is entered. It can be seen that the negative displacement of the top of the pile 7 # is slightly larger than that of the original, and the displacement of the other parts of the pile is significantly reduced compared with the original, where the maximum node displacement is reduced by approximately 75 %.

Fig. 7. Construction schematic diagram of the bridge project in the coastal channel of Zhoushan Sea.

Fig. 8. Comparison of the lateral displacement of the pile 7 #.

The design of the drainage pipe pile and the retaining structure transmits a part of loads to the foundation through the anchor cables, of which the stability of the retaining structure is enhanced to prevent the overturning of the retaining structure. The spatial position of pipe piles after construction is fixed, which can effectively reduce the influence of the lateral displacement on the bridge pile foundation during the dam filling process.

3.2 Application of drainage pipe pile in reclamation of the island

At present, the construction methods for reclamation of the island mainly include three methods: sand filling, pile foundation and composite foundation. The method of sand filling has disadvantages of low bearing capacity and long consolidation time (Wang et al., 2007). For the pile foundation and composite foundation, the drainage and bearing capacity cannot be realized at the same time (Guan and Yu, 2008; Liu et al., 2009). The improvement of ground treatment methods above is limited, which is impossible to meet various requirements such as bearing capacity, anti-pulling and the control of uneven settlement to adapt to complex engineering conditions.

A drainage pipe pile with grouting machine is designed to accelerate soil drainage consolidation and simultaneously improve the bearing capacity of the filled soil for reclamation of the island. The special design of the drainage pipe pile comprises a prefabricated pipe pile and a grouting machine. The pile has side openings, the outer side is wrapped with geotextile for drainage, and the angle of grouting from the opening to the outside of the hole is different for different functions. The grouting machine has two states of contraction and expansion (see Fig. 9). When the grouting machine contracts, it sinks synchronously with the pipe pile. When the grouting machine expands, it pierces the geotextile wrapped on the outside of the pipe pile and grouts the outer side at different angles to reinforce the surrounding soil.

Fig. 9. Contraction (left) and expansion (right) state of the grout machine in the drainage pipe pile.

The construction process steps of the drainage pipe pile for reclamation of the island are as follows: (1) The drainage pipe pile with the contracted grouting machine
is partially implanted into the seabed soil to ensure its stability. (2) The filling is carried out in an alternating manner between the sand and soft soil. The operation is repeated until the completion of the filling. (3) After the soil layer is drained and consolidated, the grouting machine expands. The geotextile on the pile is wrapped, and the soil around the pile is grouted. (4) Adjust the injection angle of the grouting port according to the requirements of different engineering profiles. Grouting upwards to form an upward reinforcement zone, which can improve foundation bearing capacity and control foundation settlement (see in Fig. 10a). Downward grouting forms a downward reinforcement zone, which can improve the pull-out resistance of the pile foundation and resist the uplift of the foundation such as the rise of the water level (see in Fig. 10b). Annular grouting forms a conical reinforcement zone, which can enhance the lateral resistance caused by sea tides (see in Fig. 10c).

Fig. 10. Reinforcement zones of drainage pipe pile: (a) upward reinforcement zone; (b) downward reinforcement zone; (c) conical reinforcement zone.

Numerical analysis by Plaxis 2D is used to calculate the settlement of common single pile and drainage pipe pile mentioned above in soft soil. Under the vertical load, the maximum settlement is reduced by about 20 %, which means an improvement of bearing capacity (see in Fig. 11). Under the buoyancy force, the maximum upward displacement of drainage pipe with downward grouting due to negative friction is shortened by 30 %, which improves the anti-pulling resistance of the foundation (see in Fig. 12). Under the lateral force, the maximum lateral displacement of drainage pipe with annular grouting is reduced by 35%, which indicates the improvement of foundation against lateral force (see in Fig. 13).

Fig. 11. Maximum settlement displacement of: (a) common single pipe pile; (b) drainage pipe pile with upward grouting.

Fig. 12. Maximum upward displacement of: (a) common single pipe pile; (b) drainage pipe pile with downward grouting.

Fig. 13. Maximum lateral displacement of: (a) common single pipe pile; (b) drainage pipe pile with annular grouting.
The numerical results under three conditions show that the special design of drainage pipe piles with different grouting angles can improve the bearing capacity, anti-pulling resistance and side resistance of the pile foundation for different situations. The drainage pipe pile could adjust the uneven settlement of the foundation by controlling the rate of drainage. The special design of drainage pipe pile is very suitable for reclamation of the island with multi-islands and complex constructive conditions.

4 CONCLUSIONS

This paper proposed a drainage pipe pile with side openings on the pile and geotextile wrapped outside. When the soil is soft, the pile is driven, and then the soil around the pile is drained and consolidated under vacuum negative pressure. The consolidation time is shortened, and the bearing capacity of the foundation is improved, of which the advantages of the pile foundation and the composite foundation are combined. Under variable load, the pore pressure dissipates faster to have certain ability to resist liquefaction.

The drainage pipe pile could be designed in different forms for various applications. A groutable drainage pipe pile with the retaining structure is introduced for the dam filling, which can effectively reduce the influence of the lateral displacement on the bridge pile foundation. A drainage pipe pile with grout machine that can grout at different angles is introduced for the reclamation of the island, which can improve the bearing capacity, anti-pulling resistance and side resistance of the pile foundation for different situations.

The drainage pipe pile and its special designs could improve the bearing capacity and adjust the uneven settlement of the foundation by controlling the rate of drainage, which are suitable for complex construction conditions. This kind of innovative design of pipe piles is of great economic value.

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