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INFLUENCE OF PVD-ENHANCING SOFT SOIL GROUND ON THE ADJACENT BRIDGE PILES – A 3D FEM ANALYSIS

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ABSTRACT

The influence of prefabricated vertical drain (PVD)-enhancing soft soil on the adjacent bridge pile foundation is not sufficiently clear. The related studies are scarce and far behind the requirement of engineering practice. Three-dimensional finite element model (3D FEM) is established to investigate this important issue. Plastic drainage boards in the PVD are modelled by a user-defined element, which considers the axial force and permeability of the plastic drainage board, whereas its weight, shear, and torsion are not considered. The elastoplastic-consolidation coupled model is used for the soils. Field measured results of pore water pressure, ground settlement, and pile cap displacement are used to validate the 3D FEM with good accuracy. A number of useful conclusions can provide guidelines for similar projects and inform designers of the adverse effects of PVD-enhancing soft soil ground on the adjacent bridge pile foundation.

KEYWORDS

PVD, Soft soil, Bridge pile foundation, FEM

INTRODUCTION

In the past three decades, with the rapid development of China, land resources for municipal and civil projects became increasingly scarce, especially in the developed coastal areas of China. However, because of the widespread distribution of soft soil in these areas, ground treatment techniques are widely used for soft soil foundation to provide a foundation that satisfies requirements of bearing capacity and strength. These techniques include the use of lightweight materials [1], stone columns [2], deep mixed (DM) columns [3], vertical drains [4], and prefabricated vertical drains (PVDs) [5-7], the latter being one of the most cost-efficient method and has been widely used in practice [8]. PVDs can greatly accelerate the consolidation and drainage process of soft soil ground and effectively increase the bearing capacity of soft soil foundation [9-13]. Recently, this technique has been widely used in the construction of urbanization in the world. Lam et al. [14] studied the performance of improved soft clay with PVDs combined with embankment preloading and vacuum preloading for the 2D FEM and field tests. Indraratna et al. [15] proposed an equivalent 2D numerical modelling to analyse PVD-assisted soft ground consolidation, and the performance of the model provided a good agreement between the numerical and analytical predictions, as well as the field measurements. Ya et al. [16] proposed a method to calculate the ground settlement and the lateral displacement induced by vacuum preloading and analysed two well-documented field cases in China. Ye et al. [8] used the field test and numerical analysis method to study the performance of PVD-reinforced soft soil with surcharge preloading and vacuum preloading.

Most of the consolidation deformation of soft soil ground can be completed in a short time owing to the PVD [17] and rapidly break the pile–soil interaction balance of the adjacent pile foundation, which result in excessive post-construction deformation of the adjacent pile foundation. This excessive post-construction deformation may lead to the collapse of the superstructure. A PVD-enhancing soft soil ground is unfavourable to an adjacent bridge pile foundation. However, if inappropriately implemented, would seriously endanger the safety of the superstructure. However, at present, the influence of the PVD-enhancing soft soil on the pile foundation of adjacent bridge is not evident. The related studies are scarce and far behind the requirement of engineering practice.

The PVD-enhancing soft soil ground is located in Guangzhou City, Guangdong Province, China. The settlement of the adjacent bridge pile foundation and the pore water pressure in soft soil ground are monitored in the site to validate the three-dimensional finite element model (3D FEM). The influence of the PVD-enhancing soft soil on the adjacent bridge pile foundation is studied systematically by using the verified 3D FEM.

PROJECT DESCRIPTION

The site of the PVD-enhancing soft soil ground is located in Guangzhou City, Guangdong Province, China. In terms of thickness, the subsoil of this site is composed of 2.4 m miscellaneous fill, 13.1 m very soft soil (also called mucky clay in China), 2.2 m medium sand, 5.7 m fine sand, 4.3 m soft silt clay, and medium sand. The groundwater level is 0.5 m below the ground surface. The typical properties along with the soil parameters are depicted in Figure 1.

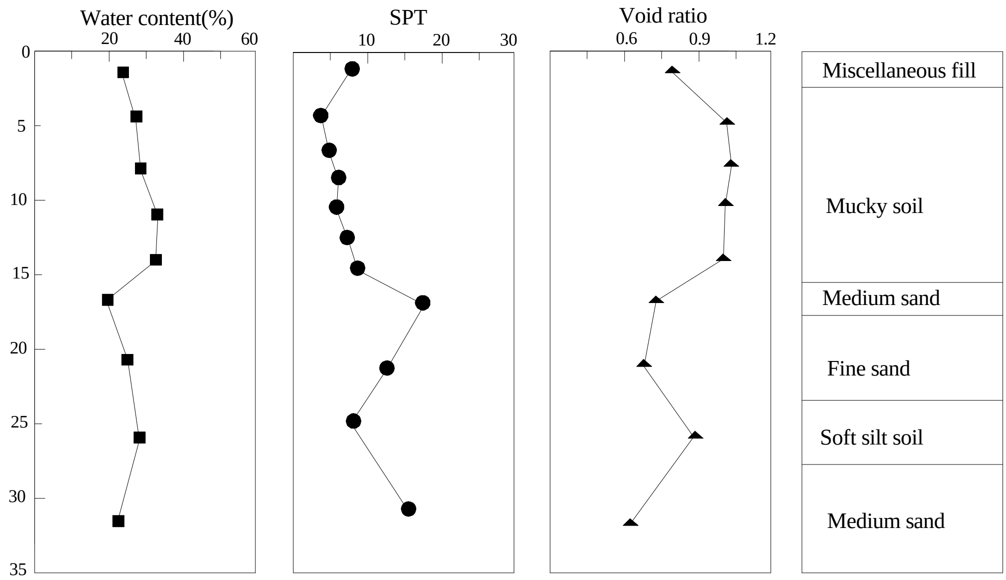


Fig. 1 – Soil profile and properties at the site

The site of PVD-enhancing soft soil ground is an irregular quadrangle, 106.59-m long, 91.62-m wide, and an area of 8555 m2. A highway bridge pile foundation exists at approximately 43 m away from the site. The plane view of the site is shown in Figure 2. The settlement, pore water pressure of the PVD-enhancing soft soil ground, and the deformation of the adjacent pile foundation are monitored synchronously in the process of construction. The location of the monitoring components is also shown in Figure 2. The pore water pressure monitoring point is located in the very soft soil layer at 8 m below the T1 and T2 monitoring points; XS-186 pore water pressure gauge is used to measure the pore water pressure. The settlement and deformation monitoring points are designated at the T1–T2 and T3–T4 monitoring points (i.e., two corners of the bridge pile cap) by using a high-precision monitoring station. The plastic drainage boards with an area of 0.007 m2 and a length of 16 m are punched through the very soft soil layer and embedded in the middle sand layer at a spacing of 1 m. Gravelly soils with the height of 2 m are used as surcharge fill material for 56 d.

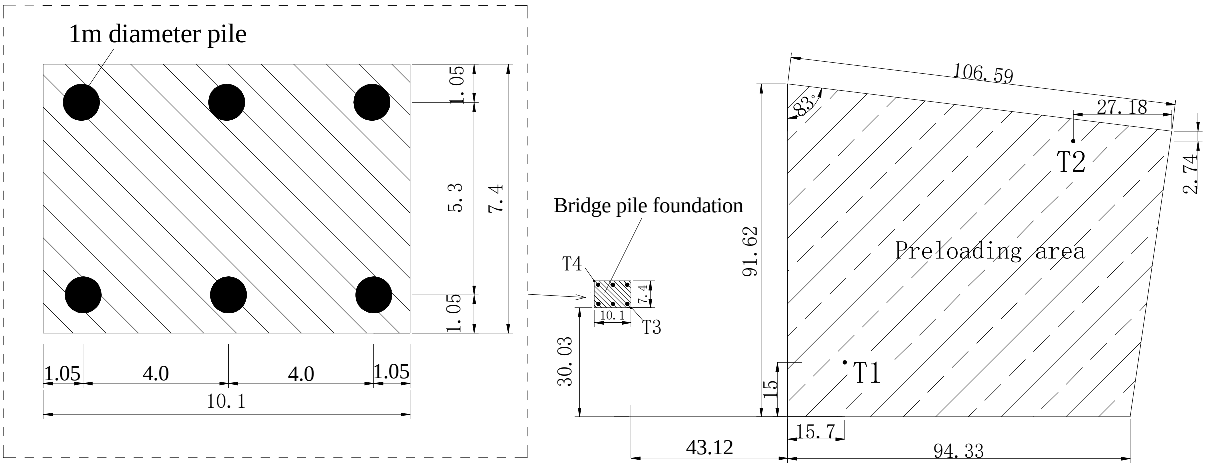
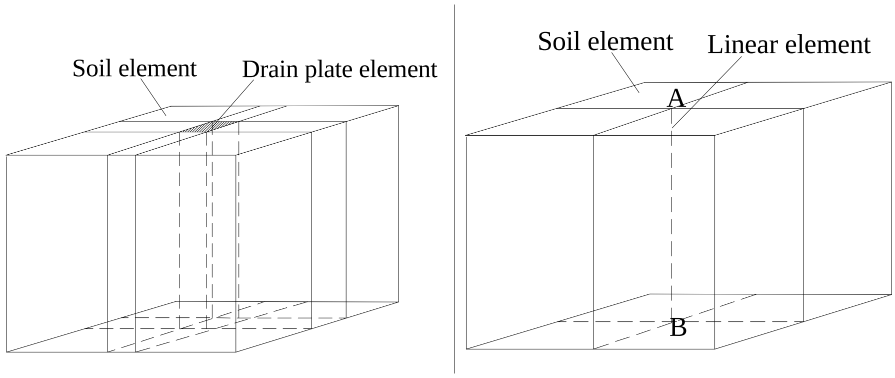


Fig. 2 – Plane view of the test site and location of the monitoring components

NUMERICAL MODELLING

At present, the conventional numerical modelling for PVD-enhancing soft soil ground are simplified to axisymmetric single well or plane strain [18-20]. Axisymmetric single well can effectively model one type of sand, but they cannot analyse ground lateral deformation and load distribution. In the plane strain method, the equivalent transformation is required to convert the three-dimensional PVD-enhancing soft soil ground into the two-dimensional drainage plate wall for plane strain modelling. However, after the equivalent transformation, the geometric position of each point of the ground cannot correspond to the prototype one by one. Thus, the method is evidently unsuitable for complex engineering problems, such as those similar to this study. The ideal method is to use 3D FEM. However, if the plastic drainage plate is divided as a solid element, then the computing scale of the numerical model becomes extremely large.

Increasing the permeability of the soil is the main function of the plastic drainage board, while improving the corresponding mechanical properties is only secondary. We used a user-defined element (called UEL subroutine in ABAQUS), a one-dimensional two-node linear element proposed by Fei [21], to model the plastic drainage board. If the drain plate is considered a solid element, then its mesh is rough (Figure 3a). If the drain plate element is a line element and shares nodes A and B (Figure 3b) with the soil element, then the number of elements and nodes are reduced to avoid inaccurate simulation results caused by the difference between the size of the drainage plate element and the surrounding soil element. The weight, shear, and torsion properties of the plastic drain board are not considered in the simulation, only the axial force and its influence on overall permeability.



(a) Mesh of drainage plate with solid element *(b) Mesh of drainage plate with linear element*

Fig. 3 – Schematic of the drainage plate element

Then, we used the ABAQUS software to establish a 3D FEM of the PVD-enhancing soft soil ground, as shown in Figure 4. The transverse, longitudinal and vertical directions of the model are 400, 200, and 96 m. The pile foundation of the adjacent bridge is composed of 3×2 concrete cast-in-place piles with 1.0 m diameter. The thicknesses of the pile length, longitudinal pile spacing, transverse pile spacing, and pile cap are 32, 4, 5.3, and 1.5 m, respectively. The elastoplastic-consolidation coupled model is used for the soils, and the model parameters of each soil layer are shown in Table 1. The elastic model is applied to the bridge pile foundation. The density, elastic modulus, and Poisson's ratio of the pile foundation are 2500 kg/m^3, 32 GPa, and 0.17, respectively. The plastic drainage boards are modelled by the UEL element with the elastic modulus of 1.5 GPa and the permeability coefficient of 1×10^{-2} m/s. The contact element is arranged on the pile–soil interface and the pile cap-soil interface, in which the Coulomb friction model is used for the pile-side interface. The non-friction hard contact model is used for the pile-bottom soil and the pile cap-soil interface. The friction coefficient of the pile-side interface μ can be calculated by the internal friction angle φ, written as $\mu = \tan 0.75\varphi$. The eight-node hexahedron pore pressure element (called C3D8P in ABAQUS) is used for the soils, and the eight-node hexahedron element (C3D8) is used for the piles. In the 3D FEM, the horizontal direction of the side surface and the vertical displacement of the bottom surface are fixed, and the top surface is set to drainage boundary. The PVD surcharge load is equal to 40 kPa that lasts for 56 d. The total load on the bridge pile foundation is 13287 kN.

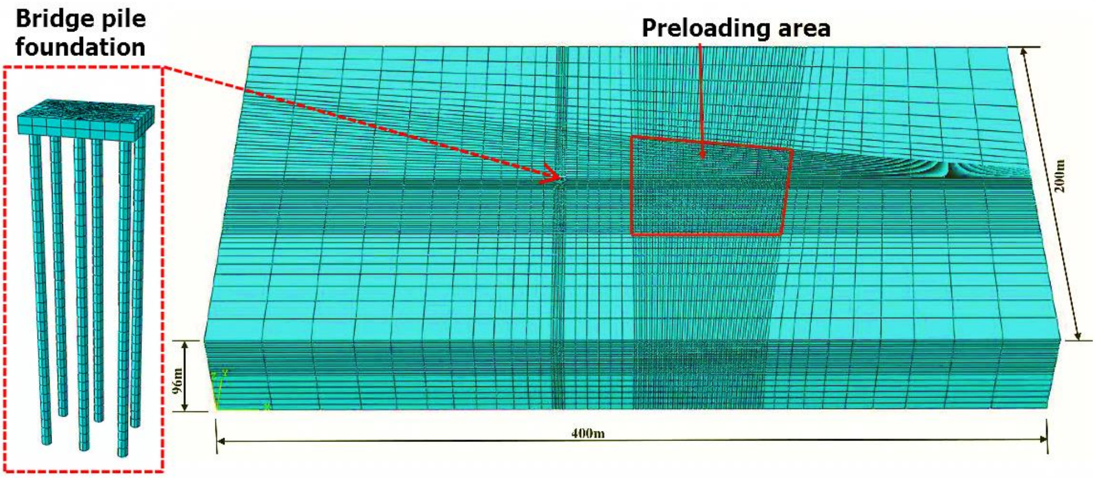


Fig. 4 – 3D FEM of preloading

Tab. 1 - Parameters of soil physical mechanics

Soil Layer	Thickness /m	Density /(g/cm^3)	Young modulus /MPa	Permeability coefficient /(cm/s)	Cohesion /kPa	Internal friction angle /°	Void ratio
Miscellaneous fill	2.4	1.8	6.2	6e-5	14.2	15.8	0.82
Mucky clay	13.1	1.68	3.7	1.54e-6	8.4	6	1.03
Medium sand	2.2	1.95	36.2	6e-4	0.1	21.4	0.72
Fine sand	5.7	1.8	22.1	3.4e-4	0.1	12.9	0.68
Soft silt clay	4.3	1.75	7.8	1.3e-5	12.4	7.8	0.92
Medium sand	5.4	1.9	61.8	7.8e-4	0.1	23.7	0.66

DISCUSSION OF RESULTS

Figure 5 presents the field measured pore water pressure along with the calculated results from the numerical analysis in the mucky clay layer of 8 m below monitoring points T1 and T2. The calculated results of pore water pressure in soft soil ground are close to the measured results. The pore water pressure increased rapidly in the early stage (0–0.5 d) of PVD-enhancing soft soil ground, and then decreased slowly with time. The process of pore water pressure dissipation is completed on the 56th day.

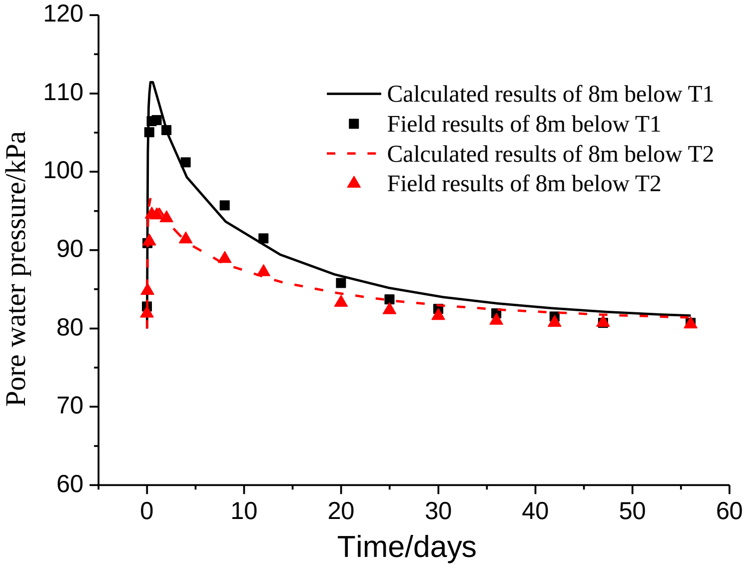


Fig. 5 – Calculated and measured pore water pressure in the mucky clay layer of 8 m below T1 and T2

Figure 6 shows the field measured ground settlement along with the calculated results from numerical analyses at monitoring points T1 and T2. The calculated ground settlement is close to the measured result. Most of the ground consolidation settlement is completed in a short time given that the plastic drainage plate accelerated the dissipation of pore water pressure in the soil. The ground settlement has gradually become stable after 56 d, which indicates that the soft soil ground has been strengthened.

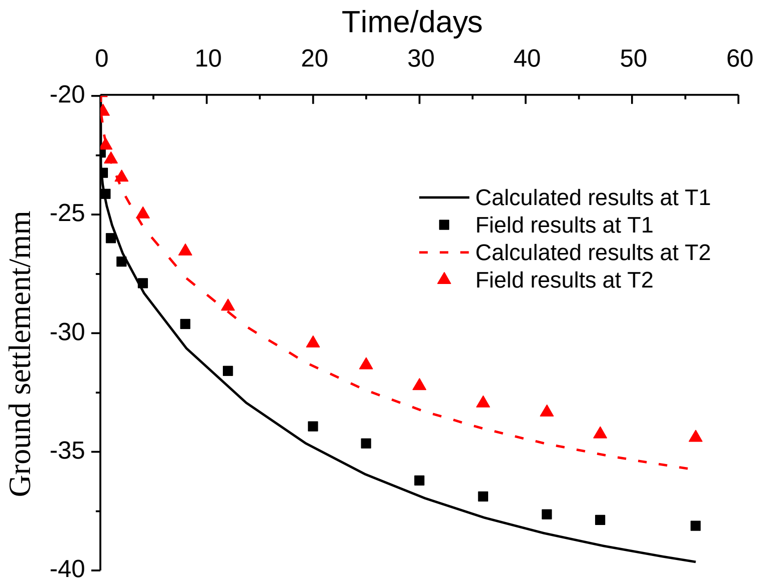
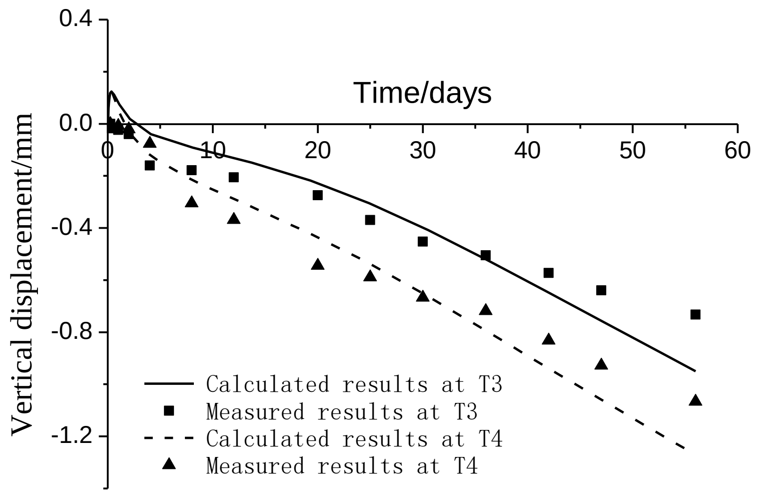


Fig. 6 – Calculated and measured ground settlement at T1 and T2

Figure 7 presents the measured vertical displacement and horizontal displacement along with the FEM results at monitoring points T3 and T4 on the pile cap corner of the adjacent bridge. The calculated vertical displacement and horizontal displacement are close to the measured results. Figure 7(a) shows that in the early stage (0–3 d), the lateral displacement occurs in the upper soil under the PVD-enhancing soft soil ground, which squeezed the adjacent pile foundation and caused the pile cap to appear slightly uplifted. The pile cap is restored to its initial position and gradually subsided with the dissipation of pore water pressure. Figure 7(b) shows that under the influence of PVD-enhancing soft soil ground, a large horizontal displacement appears in the pile cap, and the maximum is up to 18.5 mm at the initial stage. The horizontal displacement of the pile cap gradually decreased with the dissipation of pore water pressure and is approximately 9.3 mm.



(a) Vertical displacement

Fig. 7 – Calculated and measured vertical displacement and horizontal displacement at T3 and T4

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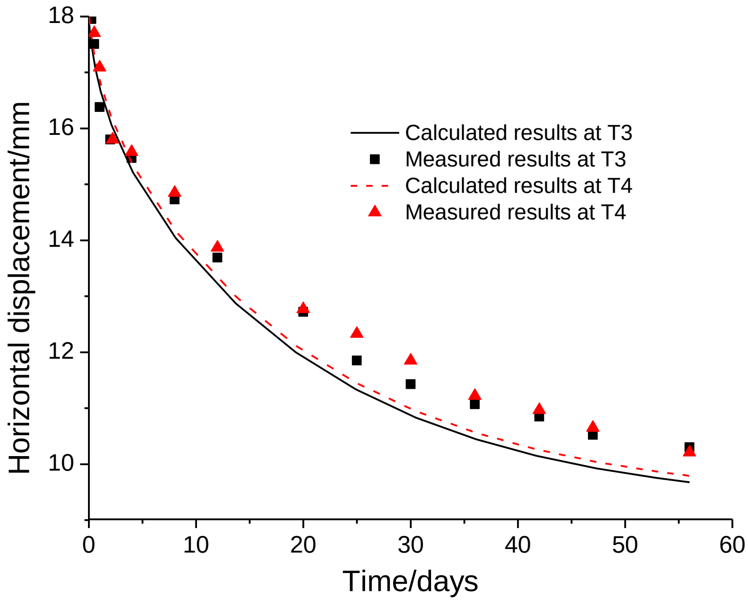

(b) Horizontal displacement

Fig. 7 – Calculated and measured vertical displacement and horizontal displacement at T3 and T4

Figure 8 presents the horizontal displacement of the pile shaft at different PVD preloading times calculated by numerical simulation. The horizontal displacement of the pile shaft decreased with the dissipation of pore water pressure. The pile horizontal displacement decreased along the pile depth at the early stage and increased at the later stage because the pore water in the deep soil has gradually discharged along the plastic drainage board. Moreover, the effective stress of the deep soil increased gradually, which resulted in the increase in passive earth pressure on the pile side. As a result, the horizontal displacement of the bottom section of the pile widened increasingly.

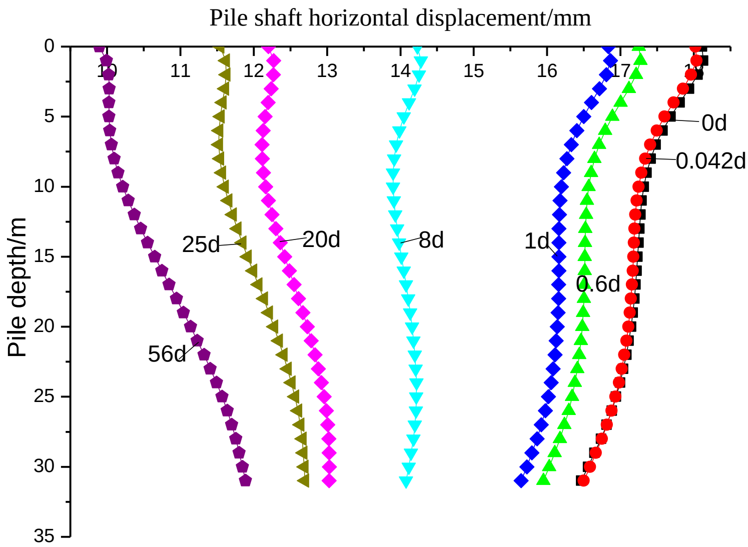

Fig. 8 – Calculated horizontal displacement of the pile shaft at different PVD preloading times

Figure 9 shows the calculated passive earth pressure on the pile side at different PVD preloading times, where the negative value indicates that the passive earth pressure comes from

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the opposite side of the surcharge and the positive value comes from the same side of the surcharge. The passive earth pressure gradually decreased with time, and the distribution of the passive earth pressure along the pile shaft tends to be increasingly uniform with the dissipation of pore water pressure. Thus, the adverse effect of PVD-enhancing soft soil ground on the adjacent pile foundation mainly occurs in the early stage, when the passive earth pressure on the pile side is the largest.

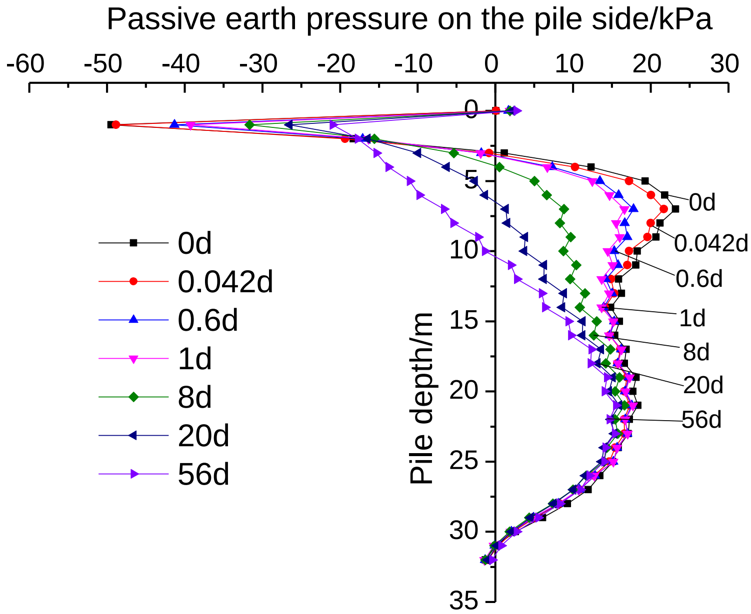

Fig. 9 – Calculated passive earth pressure on the pile side at different PVD preloading times

Figure 10 presents the calculated bending moment of the pile shaft at different PVD preloading times. All the maximum bending moments of the pile shaft at different times are located at the interface between the pile top and the pile cap, where the maximum is 247.3 kN.m at the beginning. After PVD preloading for 56 d, the maximum bending moment of the pile shaft decreased to 190.9 kN.m.

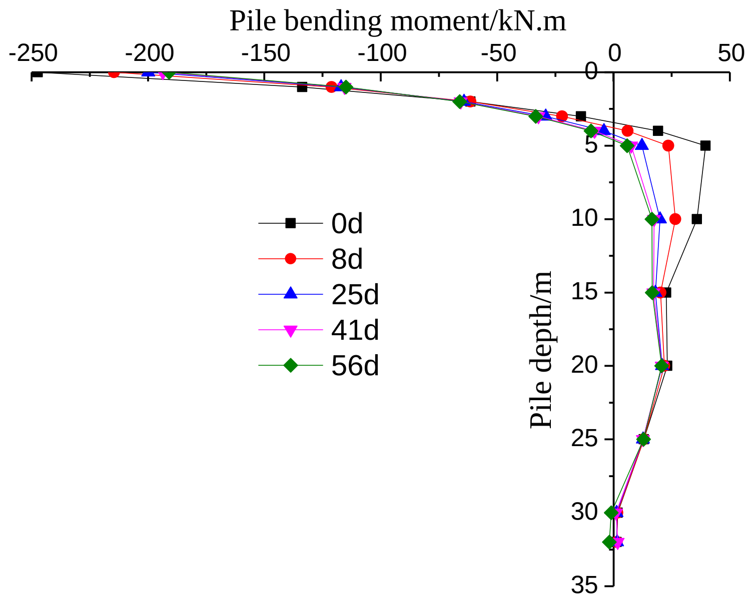

Fig. 10 – Calculated bending moment of the pile shaft at different preloading times

We studied the influence of the PVD fill surcharge distance on the adjacent bridge pile foundation by using 3D FEM. The PVD fill surcharge distance of 2B, 3B, 4.3B, 6B, and 10B are used in the 3D FEM, where B is the width of the pile cap of the adjacent pile foundation (B = 10.1 m) and 4.3B is the actual distance. Figure 11 presents the relationship between the maximum horizontal displacement of the pile shaft and the PVD fill surcharge distance at 56 d. Figure 12 depicts the relationship between the maximum bending moment of the pile shaft and the PVD fill surcharge distance at 56 d. The maximum horizontal displacement and bending moment of the pile shaft decreased sharply with the increase in the PVD fill surcharge distance. When the PVD fill surcharge distance is 2B, the maximum horizontal displacement and bending moment are 29.28 mm and 592 kN.m, respectively. This PVD fill surcharge distance greatly harms the adjacent pile foundation. When the PVD fill surcharge distance reached 10B, the maximum horizontal displacement and bending moment are 0.58 mm and 13.8 kN.m, respectively. The influence of this PVD fill surcharge distance on the adjacent pile foundation can be neglected.

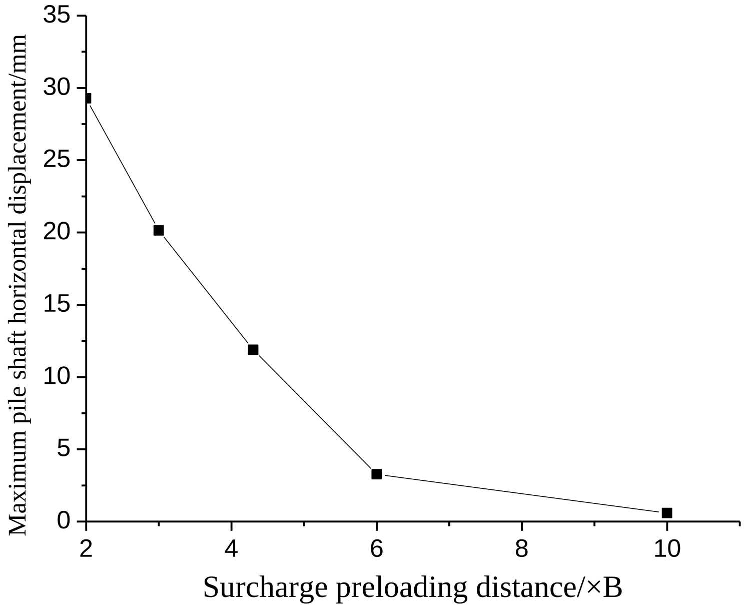

Fig. 11 – Relation between the maximum pile horizontal displacement and the fill surcharge distance at 56 d

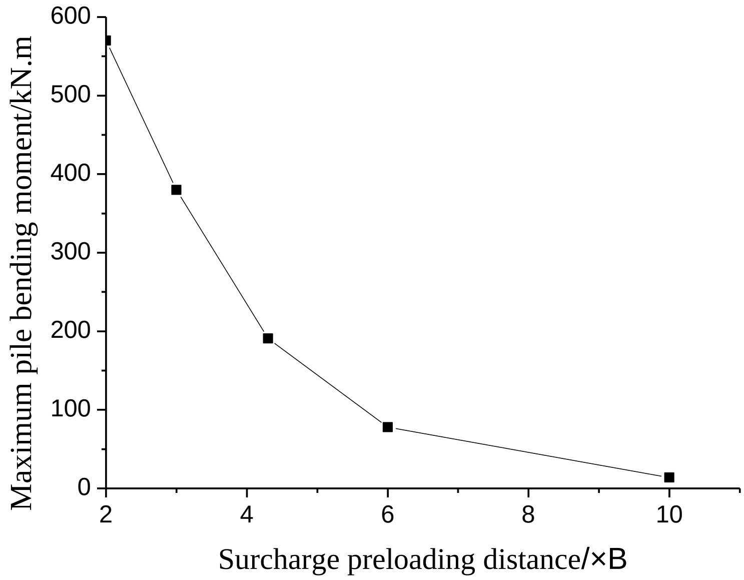

Fig. 12 – Relation between the maximum pile bending moment and the fill surcharge distance at 56 d

CONCLUSION

Field tests and numerical analyses are conducted to evaluate the influence of PVD-enhancing soft soil on the adjacent bridge pile foundation. The following conclusions can be drawn:

(1) The 3D FEM established in this study can accurately simulate the influence of PVD-enhancing soft soil ground on the adjacent bridge pile foundation. A good match exists between the calculated and measured pore water pressure, ground settlement, and pile cap displacement.

(2) The pore water pressure increased sharply in the early stage of PVD fill surcharge, then decreased with time, and the pore water pressure dissipated rapidly in the early stage and decreased gradually in the later stage.

(3) Under the influence of the PVD fill surcharge, the deformation of the adjacent pile foundation is mainly horizontal, and the vertical displacement is small. The pile horizontal displacement decreased gradually with time with the dissipation of pore water pressure.

(4) The adverse effects of PVD-enhancing soft soil ground on the adjacent pile foundation mainly occur in the early stage of PVD fill surcharge when the passive earth pressure on the pile side and pile bending moment, which are located at the top of the pile, are the largest. With the dissipation of pore water pressure, the passive earth pressure and bending moment gradually decreased with time.

(5) The maximum horizontal displacement and bending moment of the pile decreased sharply with the increase in the PVD fill surcharge distance. Therefore, the appropriate PVD fill surcharge distance should be maintained to ensure the safety of the adjacent bridge pile foundation. The safe PVD fill surcharge distance should also be comprehensively assessed on the basis of the actual situation of the site, and the relevant assessment methods should be further studied.

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