Structural Deformation Analysis of Double-Row PC Pile Cofferdam by Finite Element Numerical Simulation and Actual Project Monitoring

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Abstract. In coastal areas, hydraulic projects often involve deep silty soil foundations, drawing attention to the selection of cofferdam support structures at such project sites. The commonly used cofferdam structure for such sites is the double-row steel sheet pile cofferdam. However, this type of cofferdam has drawbacks such as low overall structural stiffness, difficulty in removal, and high cost. The double-row pipe combination (PC) pile cofferdam, which has a higher overall structural stiffness and advantages in reducing structural deformation and project cost, has gained widespread attention. Taking a specific cofferdam project located in a foundation with deep silty soil as an example, a double-row PC pile cofferdam was adopted. Through numerical simulation analysis, the deformation performances of the double-row PC pile cofferdam were analysed. Finally, a double-row PC pile cofferdam was successfully applied, and the deformation of the cofferdam was monitored and compared with the simulation results. The results indicate that the difference between the numerical simulation results and the monitoring data is relatively small. The horizontal displacement of the structure is within the safe range allowed by the regulations. The research findings of this paper are expected to provide valuable references for the selection of cofferdam structural forms in deep and thick silty soil.

Keywords: PC pile, cofferdam, deep silty soil foundation, structural deformation, finite element simulation, numerical simulation, deformation monitoring

A. S. B. A Rashid et al. (eds.), *Proceedings of the 2024 3rd International Conference on Applied Mechanics and Engineering Structures (AMES 2024)*, Advances in Engineering Research 34,
https://doi.org/10.2991/978-94-6463-473-0_13

1 Introduction

In the process of hydraulic engineering construction, it is common to establish temporary water- and soil-retaining cofferdam projects to create a dry construction environment and ensure the smooth progress of construction within the cofferdam[1-3]. Common cofferdam forms include earth and rock cofferdams[4], steel pipe pile cofferdams[5], reinforced concrete cofferdams, and steel sheet pile cofferdams[6]. As a common form of sheet pile cofferdam, steel sheet pile cofferdams have become prevalent in hydraulic engineering due to their high strength, fast construction speed, good water-stopping performance, ease of penetration into soil layers, and reusable nature.

Steel sheet pile cofferdams include two structural forms: single-row steel sheet pile cofferdams and double-row steel sheet pile cofferdams. During hydraulic engineering construction in coastal areas, the construction environment may involve deep and thick silty soil foundations, with the thickness of the silty soil layer sometimes exceeding 10.0 metres. But, Single-row steel sheet pile cofferdam have drawbacks, such as relatively large horizontal displacement at the top of the structure and low flexural capacity. In such projects, the double-row steel sheet pile cofferdam structure is commonly adopted.

When using a double row steel sheet pile cofferdam, the length of the steel sheet piles is usually designed to be larger to ensure infiltration into a certain depth of non cohesive soil layer, thereby ensuring the safety and stability of the cofferdam in a deep silt foundation environment. Therefore, it increases the difficulty and cost of construction. In addition, in deep silty soil, the double row steel sheet pile cofferdam is prone to bending and deformation during pile driving, posing a significant risk of collapse. And the lateral stiffness of the steel sheet pile cofferdam is low, which is not conducive to limiting the lateral deformation of the cofferdam. Excessive lateral deformation can affect the dismantling of steel sheet piles and their reuse in the next cofferdam project.

Addressing the abovementioned drawbacks when applying a double-row steel sheet pile cofferdam in deep and thick silty soil foundations, it is necessary to improve and optimize the structure and develop a suitable cofferdam support structure. This structure should limit cofferdam deformation and ensure safety while reducing project costs. The PC pile was a new type of support structure derived from improvements to steel sheet piles. It consists of steel pipe piles and steel sheet piles effectively connected by lock joints welded on both sides of the steel pipe piles. This approach establishes a continuous steel rigid sheet pile for retaining soil and preventing water. PC piles primarily rely on steel pipe piles, and compared to traditional sheet pile support structures, their pile body stiffness is greater, thereby addressing the drawbacks of low stiffness and easy deformation of Larssen steel sheet piles. Moreover, PC piles have the advantages of being lightweight, having high strength, having fast construction speed, having high structural stiffness, being reusable, and being economically efficient. As a result, they have become a good choice for excavation support structures.

In this study, a specific cofferdam project located in a foundation with deep silty soil was taken as an example, and the cofferdam adopted a double-row PC pile cofferdam. Through numerical simulation analysis, the horizontal deformation performance of the cofferdam was analysed. Then, the cofferdam scheme was successfully implemented in the cofferdam project, and the horizontal deformation of the cofferdam was monitored and compared with the simulation results. Therefore, three-dimensional finite element analysis can be carried out on the most dangerous section of the double-row PC pile cofferdam design scheme; simulate and analyse the load, deformation law and overall stability of the steel sheet pile and tie rod under successful implementation of the cofferdam structure under all working conditions; and strengthen monitoring of the key position of the stability of the cofferdam structure. The research findings of this paper are expected to provide valuable references for the selection of cofferdam structural forms in deep and thick silty soil.

2 Project Overview and the Two Cofferdam Schemes

2.1 Project Overview

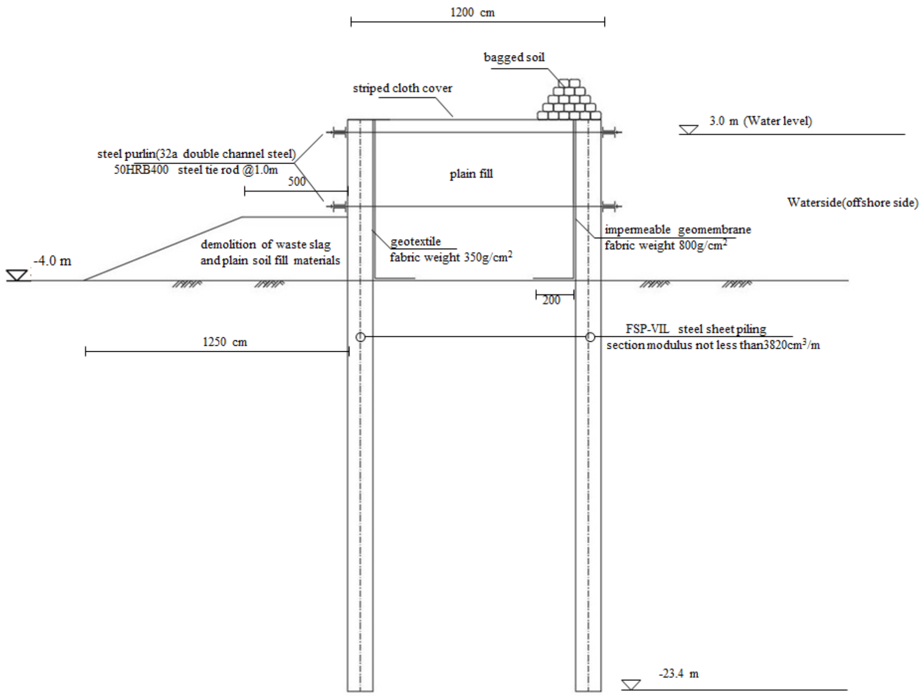
The cofferdam project was located in a river channel connected to the open sea, with significant sedimentation in the downstream riverbed. The riverbed consists of deep and thick silty soil, with the maximum depth of the silty soil layer reaching 16.4 metres. The soil types and mechanical properties of each layer below the bottom of the river channel are detailed in Table 1.

Table 1. Mechanical parameters of the soil layers below the river bottom

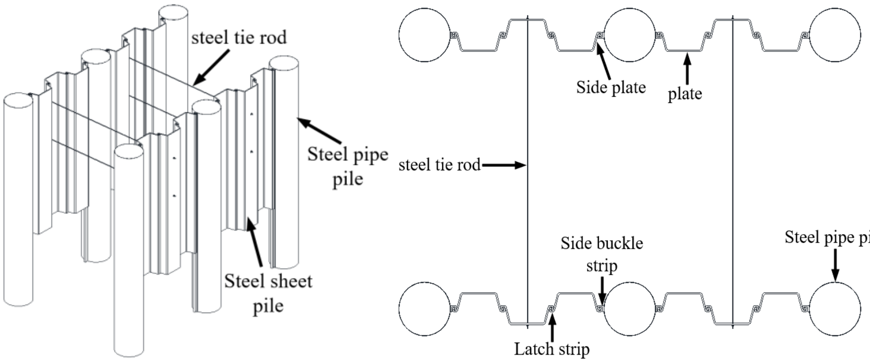
Soil Layer	Soil Layer description	Layer thickness	Specific Gravity	Cohesive Strength（kPa）	Internal Friction Angle	Wet density（g/cm^3）	Compression Coefficient	Compression Modulus（MPa）
①	Silty Soil	5.1~9.1 m	2.78	6.0	2.9	1.72	0.986	2.49
②	Silty Soil	4.5~7.6 m	2.78	9.0	4.3	1.74	0.977	2.45
③	Silty Soil	4.3~6.2 m	2.78	14.6	5.7	1.79	0.875	2.57
④	Sandy loam soil	2.4~3.5 m	2.70	5.4	23.6	2.05	0.093	7.20
⑤	Sandy loam soil	Over 20 m	2.70	7.2	25.8	2.02	0.128	12.83

2.2 The Cofferdam Scheme

Due to the location of this project in a river connected to the open sea, the riverbed is composed of deep silt, with a maximum depth of 16.4 meters in the silt layer. The top horizontal displacement of the single row steel sheet pile cofferdam structure is relatively large, and the bending bearing capacity is low. Moreover, in deep silty foundations, there is a significant risk of collapse for double row steel sheet pile cofferdams, and there is a risk of bending deformation during pile driving. Taking all factors into consideration, the cofferdam of this project uses double row PC piles, which is a new type of support structure improved from steel sheet piles. It consists of steel pipe piles and steel sheet piles, which are effectively connected by locking joints welded to both sides of the steel pipe piles. This approach establishes a continuous steel rigid sheet pile, in which PC piles mainly rely on steel pipe piles, which have increased pile stiffness compared to traditional sheet pile-supported structures. Figure 1 shows the longitudinal cross-sectional diagram of the double-row PC pile cofferdam scheme. The riverbed elevation is -4.0 m, and the external river water level is 3.0 m. The longitudinal cross-sectional size of the steel pipe pile portion was 27.0 m, while the longitudinal cross-sectional sizes of the steel sheet pile portion were different, with a longitudinal length of 18.0 m. Figure 1(b) shows the spatial schematic diagram of the double-row PC pile, and Figure 1(c) shows the plan schematic of the double-row PC pile.



(a)Longitudinal cross-sectional diagram



(b) Spatial schematic diagram (c) Plane schematic

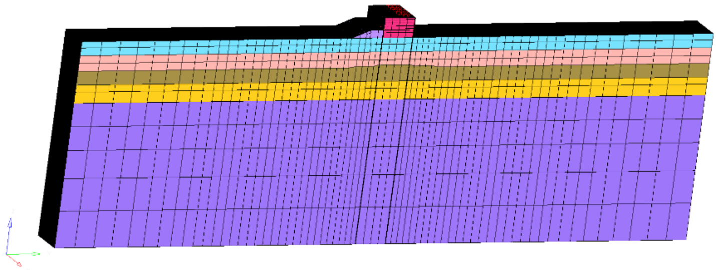
Fig. 1. Double-row PC pile cofferdam scheme

3 Numerical Analysis and Monitoring Analysis

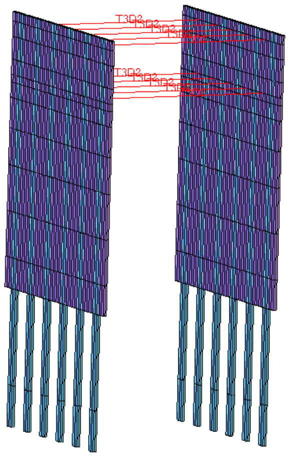
3.1 Numerical Simulation Analysis

Given that the three-dimensional elastic–plastic finite element method[7, 8] can simulate the construction process of a cofferdam, this method is used to numerically simulate the deformation and failure behavior of materials. The finite element analysis principle is used in combination with the material constitutive relation and the plastic flow theory to simulate the elastic behavior of the material and the plastic deformation and stress redistribution during the loading process. In addition, this method relies on finite element software and can solve static and dynamic problems by setting a material model, element mode, and load and boundary conditions, especially when solving linear problems; moreover, this method has good applicability to geotechnical engineering. This paper conducts three-dimensional numerical simulation analyses for the cofferdam scheme. In the finite element analysis, the following assumptions were made: (1) the soil is treated as an isotropic and homogeneous material and modelled using the ideal elastic–plastic Mohr–Coulomb constitutive model; (2) for simplification of analysis, it is assumed that before the construction of the cofferdam, the soil has already undergone consolidation under its own weight; and (3) considering that steel pipe piles and steel sheet piles are the main components subjected to bending, the equivalent stiffness principle is employed to calculate them as equivalent sheet piles with the same thickness.

Considering the distribution of soil layers and the actual arrangement of the design scheme, the analysis was performed on the cross section at the deepest part of the riverbed, extending 120 m upstream and downstream and 80 m vertically downwards. Subsequently, numerical analysis calculations are conducted. Taking the double-row steel sheet pile cofferdam scheme as an example, the model consists of a total of 25,564 three-dimensional solid elements and multiple one-dimensional rod elements. The soil, steel sheet piles, and steel pipe piles all use three-dimensional solid elements (C3D8), while the anchor tie rods use rod elements (T3D2). Figure 2 shows the three-dimensional finite element model of the overall structure and supporting structure of the double-row PC pile scheme.



(a)the overall finite element model

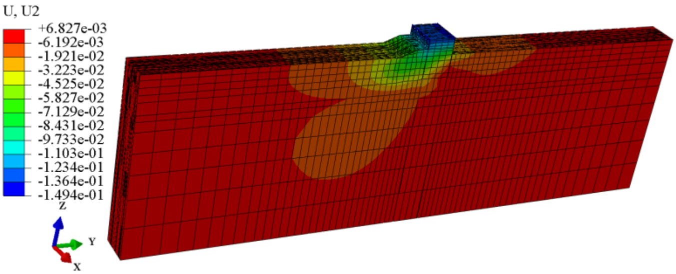


(b)Finite element model of the double-row PC pile

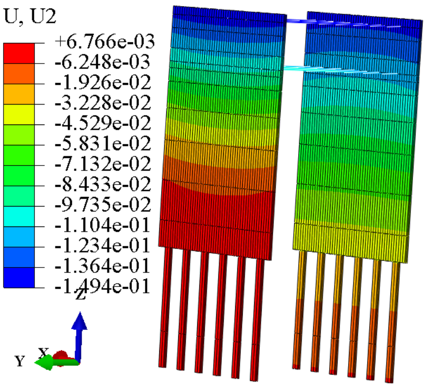
Fig. 2. Finite element model of the original double-row PC pile cofferdam

The soil was simulated using the ideal elastic–plastic Mohr–Coulomb constitutive model[9, 10], with the parameters for each soil layer shown in Table 1. The steel sheet piles, steel pipe piles, and steel tie rods were simulated using a linear elastic model. To account for the contact and potential separation between the steel sheet pile, steel pipe pile and adjacent soil layers, contact conditions were established between the piles and soil. The tangential direction of the contact surface was controlled by the penalty function Coulomb friction model, with the friction angle of the contact surface set to the corresponding internal friction angle of the respective soil layer. The normal direction of the contact surface employs a hard contact approach.

Figure 3 shows the horizontal displacements of the whole model and the double-row PC pile. The U-2 direction is the displacement along the river. The maximum horizontal displacement for the original double-row steel sheet pile cofferdam scheme is 14.94 cm, with the top displacement of the supporting structure being the largest. As the elevation decreases, the horizontal displacement of the supporting structure gradually decreases. The horizontal displacement of the PC pile on the water side changes slowly, while the horizontal displacement of the PC pile on the foundation pit side changes rapidly, mainly because the PC pile on the water side will be subjected to lateral water pressure.



(a) Horizontal displacement of the whole model (unit: m)



(b) Horizontal displacement of the double-row PC pile (unit: m)

Fig. 3. Horizontal displacement of the double-row PC pile cofferdam

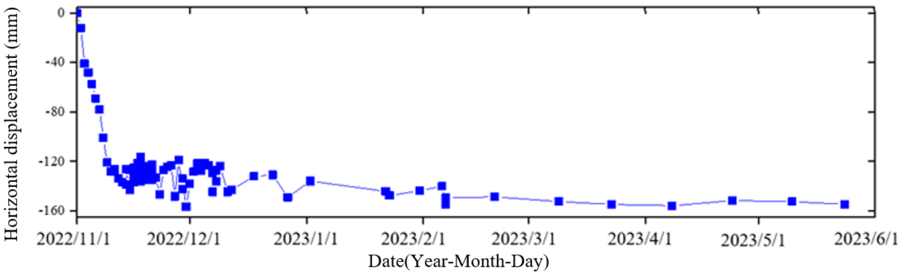
3.2 Monitoring Analysis

To comprehend the structural intricacies of double-row PC pile cofferdams and ensure project safety, it is imperative to conduct construction monitoring on cofferdam. Concurrently, a meticulous comparative analysis between the observed deformations during monitoring and the theoretical calculation results must be performed. This evaluation is designed to assess the structural performance and safety of the double-row PC method pile cofferdam. Figure 4 shows an actual diagram of the double-row PC pile cofferdam and the measured horizontal displacement of the double-row PC pile. The figure shows that the displacement of the double rows of PC piles first occurred rapidly, with the maximum displacement reaching 16 cm, and then began to exhibit stable oscillations at approximately 15 cm. Specifically, after the construction of the double-row PC pile cofferdam structure, the water pressure gradually increases, causing the displacement to deform rapidly. When the water pressure reaches a stable level, the displacement begins to shake smoothly.

By comparing the numerical simulation results of the horizontal displacement for the double-row PC method pile with the monitoring data, the maximum horizontal displacement of the double-row PC piles is 14.96 cm, and the measured maximum horizontal displacement of the double-row PC piles is approximately 15 cm.

The difference between the numerical simulation results and the monitored data was relatively small. The horizontal displacement of the structure is within the safety range allowed by the specifications. This also validates the effectiveness of finite element numerical simulation in simulating cofferdam engineering.

(a) The actual double-row PC pile cofferdam



(b) Measured horizontal displacement of the double-row PC pile (unit: mm)

Fig. 4. An actual diagram of the double-row PC pile cofferdam and the measured horizontal displacement of the double-row PC pile.

4 Conclusion

A cofferdam project, which is situated in a river connected to the sea and features a riverbed composed of deep and thick silty soil, with the maximum depth of the silty layer reaching 16.4 m, was taken as an example in this study. The cofferdam adopted a double-row PC cofferdam scheme. Utilizing the elastic–plastic finite element method, a thorough numerical simulation analysis was performed on the cofferdam, coupled with deformation monitoring that specifically focused on the horizontal displacement of the double-row PC method piles. The results reveal that, in comparison to the monitored data, the numerical simulation results exhibit a relatively minor variance. The horizontal displacement of the structure falls within the safety range stipulated by the specifications, thereby affirming the efficacy of finite element numerical simulation under replicating cofferdam engineering conditions. The successful deployment of the double-row PC method for pile cofferdam holds paramount importance in elevating project safety and efficiency, The use of double-row PC cofferdam scheme provides data support for the deep silty soil layer in coastal areas. Furthermore, the numerical model established by finite element software can provide a reference for similar numerical models. It also serves as a valuable reference for the promotion of similar deep and thick soil layer structure engineering projects. In the future, in order to achieve better stability and safety of the double-row PC method piles, it is necessary to study the frictional force between the locking buckles of the double row PC method piles.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (Grant Nos. 52179128, 52079120, 51579085), and the Yangzhou Green Yang Jinfeng project (No. 137012705), the Scientific Research Project of Tianjin Municipal Education Commission (No. 2022KJ018).

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