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Stability Analysis of Cofferdam Structures on Different Reinforced Soft Foundations

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Abstract: A calculation model for large cylindrical structures is established based on quasi-static analysis on the ABAQUS platform. Through numerical simulation, the stability of large cylindrical structure with different reinforced foundations can be analyzed. The results manifest that the reinforcement effect of the cylindrical structure is not clear when the soil inside the cylinder is reinforced with different burial depths. However, the reinforcement effect of the cylindrical structure becomes obvious when the horizontal and buried depth directions of the soil outside the cylinder are reinforced simultaneously. The reinforcement effect of the large cylindrical structure is roughly the same as that of the soil outside the cylinder when both the inside and outside of the cylinder are reinforced simultaneously. Through comparative analysis, we draw some useful conclusions for practical engineering.

1. Introduction

With the expansion of port marine engineering, Chinese port areas will inevitably develop towards deep water areas in the open sea. On contrast, deep water areas in the open sea often have high waves and thick soft clay with poor shear strength. Therefore, it is of great necessity to study and analyze the stability of port and coastal engineering structures in this environment. The cylindrical structure is a new structure which is introduced and promoted in port engineering and marine engineering in recent years, and this structure is similar to the circular caisson structure without bottom or partition walls, which is more suitable for complex conditions such as deep soft clay foundation and harsh marine environment. It has advantages such as low cost, short construction period, and good durability compared with other traditional ocean structural forms and has been widely used in muddy coastal areas such as Yangtze River, the Pearl River Estuary and

Bohai Bay in China. This article uses the large general finite element software ABAQUS to establish a calculation model for large cylindrical structures based on quasi-static analysis. Through numerical simulation, it is analyzed that the stability of large cylindrical structures on soft clay foundations within different reinforcement ranges [1].

2. Finite Element Model

Finite element analysis of large-diameter cylindrical structures applied the standard module in the main solution block of ABAQUS, a universal finite element analysis software. A linear elastic constitutive model is used for the cylindrical structure, and an undrained total stress analysis method is used. The Mohr Coulomb elastoplastic constitutive model is used for the soil, and the structure and soil are discretized using a 3-dimensional 8-node reduced integral solid element. Considering the symmetry of the geometric shape and loading conditions of the structure and foundation coupling system, only half of the structure and foundation coupling system needs to be selected for finite element numerical analysis to reduce the cost of simulation calculation. As shown in Figure 1, three degrees of freedom are constrained on the bottom boundary of the finite element model, the normal and tangential degrees of freedom of nodes are constrained on the side direction, and on the symmetric boundary, only the normal degrees of freedom are constrained. And the finite element model's elevation and vertical view is shown in Figure 2. For the convenience of finite element mesh division, the selected soft clay foundation area is cylindrical, and 7.5 times the radius of the large cylindrical structure is the horizontal radius of the area. Besides, 4 times the burial depth of a large cylindrical structure is the vertical depth of the area. After verification, such an area can basically eliminate the influence of boundary effects on the numerical calculation results [2].

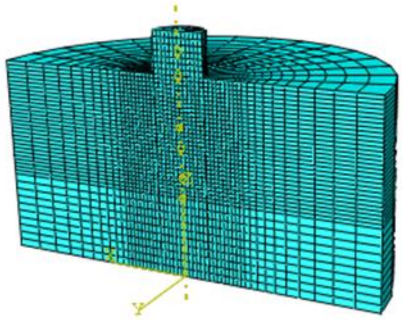
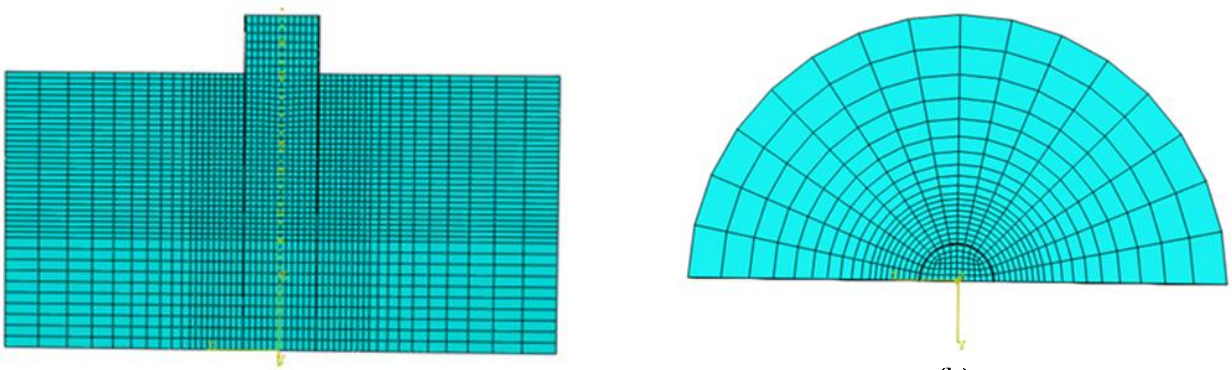


Figure 1. Finite Element Model of Large Cylindrical Structure with Soft Foundation



(a) (b)

Figure 2. Finite Element Mesh of Large Cylindrical Structure on Soft Foundation

The contact effect between the large cylindrical body and the soil interface has a significant impact on the instability state of the structure. In previous studies, Wang, Yuanzhan and others generally assumed that the active side soil and structure behind the caisson were always in a cohesive state, without considering the impact of tensile cracks between the outer wall of the caisson and the soil on the ultimate bearing capacity. Wang Dong et al. postulated that the inner wall of the caisson and the soil inside the caisson were in a cohesive state, with no relative movement and no contact surface, while Muff et al. assumed that the suction caisson and the soil plug inside the caisson were a rigid body, without considering the impact of the soil plug inside the caisson on the horizontal bearing capacity. This article adopts the friction thin unit method proposed by Luan, Maotian, Fan, Qinglai, and others, which introduces a layer of friction thin units between the outer surface of a large cylinder and the adjacent soil, with a thickness equivalent to the thickness of the cylinder wall. Friction contact pairs are set between the inner wall, bottom surface, and adjacent soil, as shown in Figure 3. When the normal stress at the interface is tensile stress, the contact pairs undergo relative detachment, and both the normal stress and friction force disappear simultaneously. When the normal stress at the interface is compressive stress, Mohr Coulomb friction law is used to simulate the tangential friction characteristics [3-5].

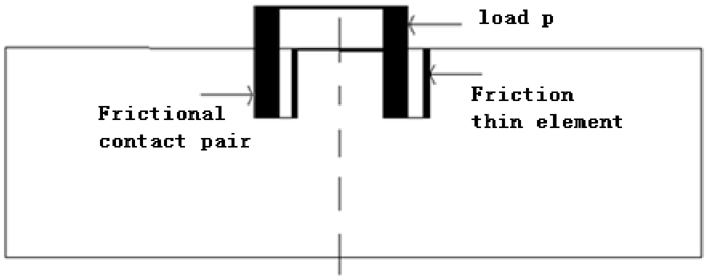


Figure 3. Interface Contact in the Finite Element Model

The large cylindrical structure uses a linear elastic model, with a deformation modulus of E=210Gpa and a Poisson's ratio of μ=0.3; The ideal elastic-plastic constitutive model based on Hill yield criterion is adopted for soft clay under undrained conditions, with a deformation modulus of E=2771200pa and a Poisson's ratio of μ=0.49; The deformation modulus of the reinforced soil is E=5400000pa, Poisson's ratio is μ=0.3, and the Mohr Coulomb plastic friction angle is 12 °.

The finite element calculation adopts a load control method, where monotonic loading is achieved by gradually applying an external load Q to determine the lateral displacement S of the large cylinder at the pile top, thereby obtaining the corresponding load-displacement relationship curve until the curvature of the curve approaches 0 [6].

3. Example analysis and comparison of variable parameters

Take the selection of relevant calculation parameters for the large cylindrical structure test section of the North Guide Dam of the Yangtze River Estuary Deepwater Channel Regulation Project as an example. The outer diameter D of the large cylindrical structure is taken as 13.5 m, the burial depth L=25 m, the distance between the point of action of the horizontal load and the mud surface is 5.73 m, and the friction coefficient is 1.

Using the CAE module of ABAQUS to establish a finite element calculation model, the entire calculation area is divided into three parts: the large cylinder, the soil layer outside the cylinder, and the soil layer inside the cylinder. All three parts take 3-dimensional 8-node reduced integral solid element. The reinforcement of soft clay foundation can be divided into three situations:

reinforcement of soil inside the cylinder, reinforcement of soil outside the cylinder, and reinforcement of soil inside and outside the cylinder [7].

3.1 Replacement and reinforcement of soil inside the cylinder

In ABAQUS, the viscoplastic algorithm was selected to replace and reinforce the soil inside the cylinder. The reinforcement depth (i.e. axial) was from the top of the pile to L/3, L/2, and 2L/3 (L is the burial depth of the large cylinder), with a deformation modulus of E=5400000pa and a Poisson's ratio of μ=0.3. As shown in Figure 4, by gradually loading the finite element simulation calculation, the horizontal load lateral displacement curve of the pile top was obtained, and it was compared with the original situation where no reinforcement measures were taken. And in Figure 5, it can be seen that the soil reinforcement measures within a certain range have almost no effect on the stability of large cylindrical structures, which is the same as the original situation where no reinforcement measures were taken [8].

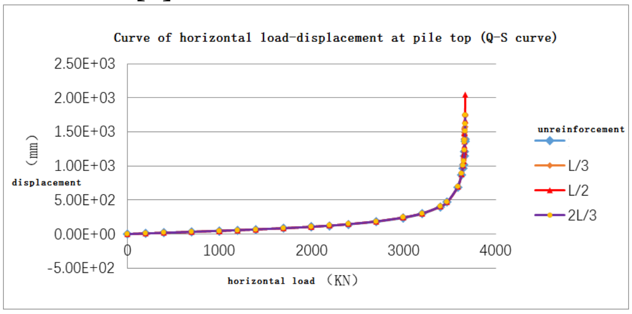
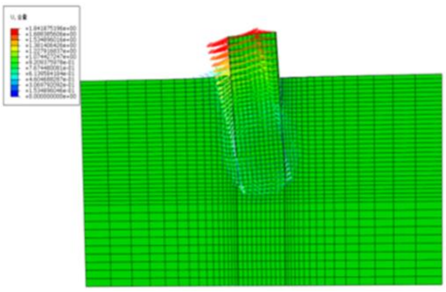
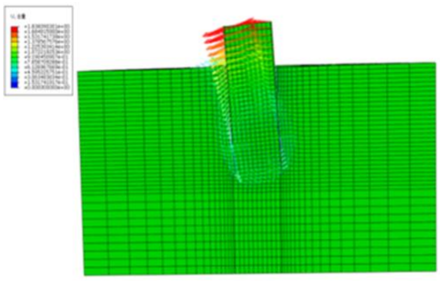


Figure 4. Horizontal Load Pile Side Displacement Relationship Curve (Soil Reinforcement in the cylinder)



(a) No reinforcement previously



(b) Soil reinforcement inside the cylinder (2L/3)

Figure 5. Deformation Diagram of Large Cylindrical Structure Obtained from Finite Element Calculation

3.2 Replacement and reinforcement of soil outside the cylinder

In ABAQUS, the viscoplastic algorithm is selected to replace and reinforce the horizontal (i.e. radial) 0.5R, R, 1.5R, and vertical (i.e. axial) L/3, L/2 (L is the burial depth of the large cylinder) combination of the soil outside the cylinder. The deformation modulus E=5400000pa, Poisson's ratio μ=0.3, and the horizontal load-pile lateral displacement relationship curve can be obtained through step-by-step loading finite element calculation, A comparison was made with the original large cylindrical structure without any reinforcement measures, as shown in Figure 6. It can be seen that strengthening the soil outside the cylinder to a certain extent significantly reduces the pile side displacement of the large cylindrical structure. Compared with the original large cylindrical structure without any reinforcement measures and the soil inside the cylinder, the effect is significant, as shown in Figure 7.

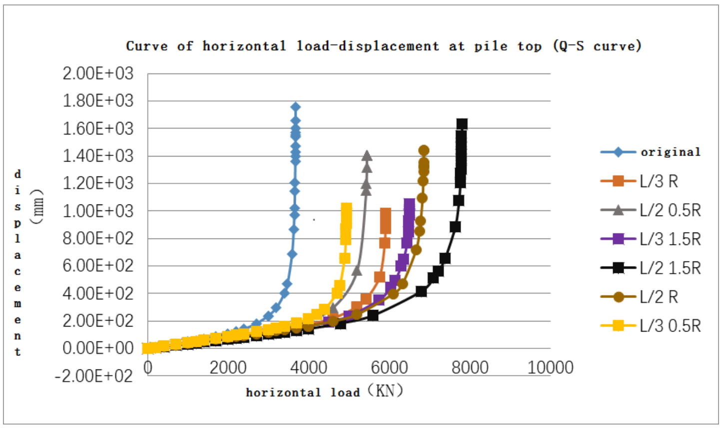
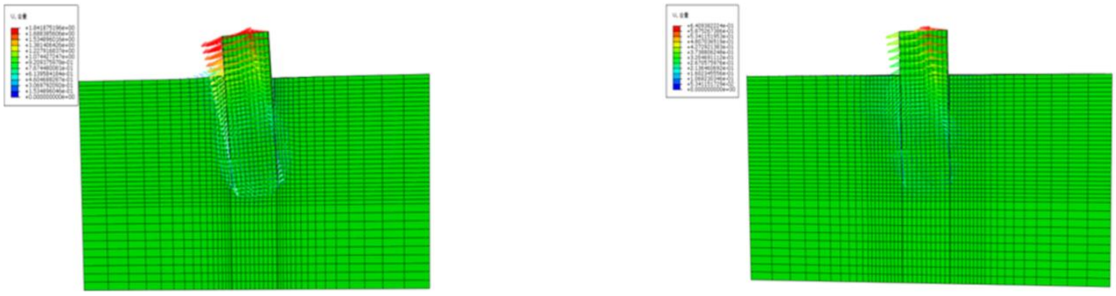


Figure 6. Horizontal Load Pile Side Displacement Relationship Curve (External Soil Reinforcement)



(a) No reinforcement previously (b) Soil reinforcement outside the cylinder(2L/3 1.5R)

Figure 7. Deformation Diagram of Large Cylinder Structure Obtained from Finite Element Calculation

3.3 Replacement and reinforcement of soil inside and outside the cylinder

In ABAQUS, the viscoplastic algorithm is selected to replace and reinforce the soil inside the tube with a combination of L/3 (L represents the burial depth of the large cylindrical structure) and R, 1.5R of the horizontal direction (i.e. radial) and L/3 of the vertical direction (i.e. axial) of the soil outside the cylinder. The deformation modulus E is 5400000pa, and the Poisson's ratio μ=0.3. As shown in Figure 8, the horizontal load-pile lateral displacement relationship curve can be obtained through step-by-step loading finite element calculation, A comparison was made with the original large cylindrical structure without any reinforcement measures. And then, a comparison between this and the original large cylindrical structure without any reinforcement measures was drawn. Thus, when reinforcing the soil inside and outside the cylinder within a certain range, the cylinder side displacement of the large cylindrical structure is significantly reduced. As shown in Figure 9, the pile side displacement is more obvious when compared with the original large cylindrical structure without any reinforcement measures [9, 10].

Moreover, the effect of simultaneously reinforcing the soil inside and outside the cylinder is the same as that of reinforcing the soil outside the cylinder [11].

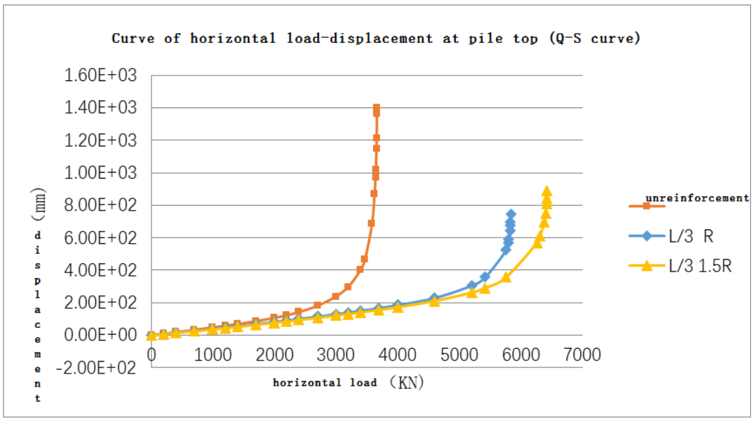
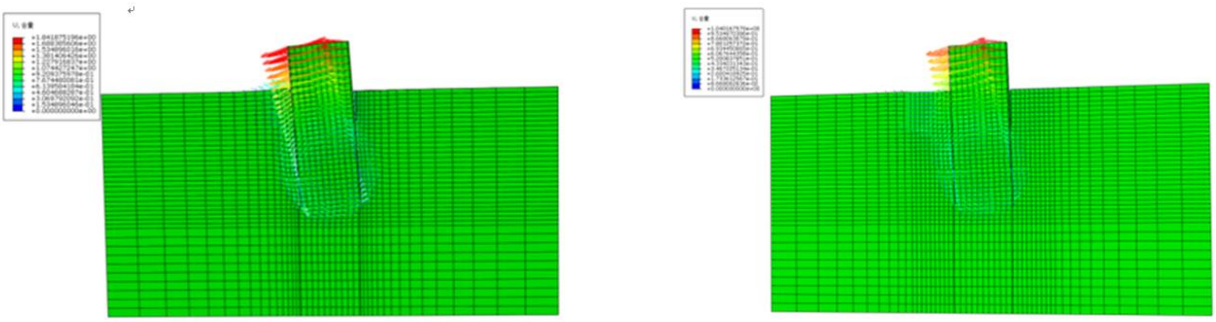


Figure 8. Horizontal load-pile lateral displacement relationship curve (soil reinforcement inside and outside of the cylinder)



(a) No reinforcement previously (b) Soil reinforcement inside the tube (2L/3 1.5R)

Figure 9. Deformation Diagram of Large Cylindrical structure Obtained from Finite Element Calculation

4. Conclusion

A finite element numerical simulation analysis and replacement and reinforcement of soil with soft clay foundation was conducted on the large cylindrical structure of the North Guide Dam test section of the Yangtze River Estuary Deepwater Channel Regulation Second Phase project. And there are something below that can be discovered through comparative analysis of variable parameters:

(1) When the large cylindrical structure is reinforced with a certain range of soil inside, it turns out that the deformation of the large cylindrical structure is the same as that of the original situation where no reinforcement measures were taken for the large cylindrical structure, and its lateral displacement of the pile is relatively large, and the effect is not obvious. When the large cylindrical structure is reinforced with a certain range of soil outside, it demonstrates that the deformation and the lateral displacement of the large cylindrical structure reduce significantly, and its effect becomes clearly. However, the deformation of the large cylindrical structure is relatively small when the soil inside and outside the cylinder is reinforced simultaneously, but the effect is the same compared to the situation where only the soil outside the cylinder is reinforced.

(2) On the reinforced soft clay foundation, the impact on the lateral displacement of the pile top varies with different reinforcement areas. When the reinforcement depth (i.e. axial) is the same, the larger the reinforcement area in the horizontal direction (i.e. radial), the smaller the lateral displacement of the pile top; when the horizontal reinforcement area is the same, the greater the

reinforcement depth, the smaller the lateral displacement of the pile top; Overall, the range of soil reinforcement is more effective in the vertical direction than in the horizontal direction.

(3) It can be seen that only replacing and reinforcing the soil outside the large cylinder has a significant effect on the deformation of the large cylindrical structure, and compared to simultaneously reinforcing the soil inside and outside the cylinder, it is more economically reasonable. The method proposed in this article provides a reference basis for the practical engineering application of large cylindrical structures.

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