Stability analysis of temporary cofferdam of a ship lock construction project in coastal area

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Abstract. The determination of the structural type and location of the cofferdam is the key to the design, and the stability of the cofferdam is the premise to ensure the subsequent construction. Based on the actual project, the stability of the existing cofferdam during the foundation pit dewatering is tested and studied on site, the safety coefficient of the cofferdam is given by using the foundation calculation software of port engineering, and the specific position of the potential slip surface of the foundation is determined, finally, the optimal design and stability analysis of the current cofferdam structure are carried out, the results show that: the cofferdam has the problem of leakage, so the corresponding water isolation measures should be taken, and the foundation pit dewatering causes large horizontal displacement of the foundation, the sliding failure surface occurs in the muddy clay layer; the cofferdam has instability and leakage problems, in order to meet the safety of later construction, the structure of the cofferdam should be optimized; combined with the distribution law of the failure surface of foundation slip, the optimization scheme of driving steel sheet pile in the inner side of cofferdam core soil is put forward; it is verified that the steel sheet pile cofferdam can meet the stability needs of foundation pit during dewatering and after excavation, which is a reasonable and effective support scheme.

1. Introduction

Cofferdams are indispensable structures for port nearshore engineering, traditional cofferdams are mainly divided into light-duty and heavy types. The main types of heavy cofferdams are sloping dike[1], straight wall dike[2] and mixed dike, sloping dike is the main type of port engineering.

In the structural design of cofferdam[3], its stability must be verified first[4,5], the most common engineering problem of slope dike is the overall sliding failure, because the geological conditions of landslide are quite complex, and the action factors are many and uncertain, at present, the occurrence mechanism of landslide can not be fully grasped, and the evolution process of slope deformation can not be quantitatively grasped, therefore, the prevention and control of landslide disaster[6,7] is still a very arduous task, it is of great theoretical significance and application value to deeply analyze and study the stability of temporary cofferdam in waterway engineering.

Based on a ship lock construction project, according to the geological characteristics of the project and the existing cofferdam structure, this paper analyzes the stability of the existing cofferdam structure in the dewatering period and foundation pit excavation construction period by using the field test[8] and port foundation calculation system (2008 version), so as to provide effective reference for
the later construction and similar cofferdam support project design.

2. Project overview
In this project, the slope dike cofferdam structure is adopted to block the surrounding of the foundation pit from the domestic and overseas, the top elevation of the cofferdam is 3.0 m, the top elevation of the wave wall is 3.5 m, and the road width is 6.0 m. The plain soil dike core is used as the dike core, and the slope ratio is 1:2. The 3.0 m wide shoulder is set on the offshore side, which is composed of building debris, and the offshore side slope ratio is 1:2; the 3.0 m wide shoulder is set on the foundation pit side, which is composed of building debris, and the top elevation is 2.0 m, the slope ratio is 1:2. 250 mm thick film bag concrete is used as the temporary cofferdam cover, under which a layer of waterproof geotextile is set, and 300 mm thick bag gravel is used as the inner cover. The section of the temporary cofferdam is shown in Figure 1.

Figure 1. Section of temporary cofferdam.

3. General situation of engineering geology
The geological distribution of the site from top to bottom is as follows:
   ① artificial filling layer, it is distributed all over the site, with a thickness of 1.10m-7.90m, it is loose and mainly composed of block stones with gravel and sand, uneven distribution.
   ② fine sand layer, 1.10m-6.90m thick, slightly dense-medium dense state, no bedding, belongs to low compressibility soil. It is mainly composed of manual hydraulic reclamation sand bag.
   ③ mucky clay, 0.60m-2.50m thick, in flow plastic-soft plastic state, with bedding and shell, belongs to high compressibility soil.
   ④ silty clay, 9.40m-15.50m thick, in flow plastic-soft plastic state, with bedding and shell, belongs to medium compressible soil. The soil is more uniform horizontally and its distribution is more stable.
   ⑤ clay, 2.00m-3.70m thick, plastic, no bedding, low compressibility soil.

4. Cofferdam stability analysis

4.1. Field test

4.1.1. Design of test scheme
In order to understand the development trend of the deep horizontal displacement of the slope during the precipitation period, so as to grasp the position and distribution law of the slip surface in time, the field test research on the stability of the cofferdam is carried out as follows:
   1) The deep horizontal displacement monitoring points are arranged along the foundation pit side of the cofferdam, with a buried depth of 20m, the layout of the monitoring points is shown in Figure 2.
   2) After the layout of monitoring points is completed, a fixed number of pumps are used to continuously dewatering the foundation pit, combined with the water level drop in the foundation pit, monitor the development law of deep horizontal displacement of cofferdam in time.
   3) Inspect whether there are cracks on the cofferdam, record the cracks location and development law.
   4) According to the distribution law of horizontal displacement curve in deep layer and the characteristics of crack development, comprehensively analyze the cofferdam stability.
4.1.2. Analysis of test results

(1) Analysis of water level variation

| Precipitation time (d) | 1d | 2d | 3d | 4d | 5d | 6d | 7d |
|------------------------|----|----|----|----|----|----|----|
| Water level elevation (m) | 1.53 | 1.26 | 1.03 | 0.83 | 0.68 | 0.59 | 0.55 |

It can be seen from Table 1 that the decline rate of the water level is slowing down in a week, and the water level basically does not change after 6 days of continuous precipitation, indicating that there are leakage points in the existing cofferdam structure, in order to ensure the stability of the cofferdam and subsequent construction, the problem of cofferdam leakage should be solved first.

(2) Analysis of cofferdam crack development law

Figure 2 shows the layout plan of deep horizontal displacement monitoring points. Figure 3 shows the distribution of cofferdam cracks.

Figure 3 shows the development and distribution of cofferdam cracks during foundation pit dewatering, it can be seen that the cracks are generated at the outer boundary of the embankment core soil; the cracks are distributed around the dike, with a width of about 100 mm, therefore, the existing cofferdam can not meet the stability requirements of foundation pit during dewatering, and the starting point of foundation sliding surface is the outer boundary of embankment core soil.

(3) Analysis on the variation law of deep horizontal displacement

Figure 4 shows the distribution curve of typical deep horizontal displacement, it can be seen that dewatering makes the cofferdam and foundation produce large displacement, in the initial stage of dewatering, the horizontal displacement mainly appears in the surface soil, with the increase of dewatering depth, the displacement continues to grow, on the 6th and 8th day of dewatering, the displacement increases sharply, and the range of the sharp increase is in elevation -4m—-6m (mucky clay layer), the reason is that the decrease of water level is equivalent to the unloading of foundation pit, with the decrease of water level, there is a large water level difference inside and outside the foundation pit, and the cofferdam is not provided with anti-seepage treatment, the seepage has a certain effect on the cofferdam, which aggravates the cofferdam sliding failure in mucky clay layer.
4.2. Simulation calculation of cofferdam stability

4.2.1. The establishment of the model

The safety factor and stability of cofferdam in foundation pit dewatering period are analyzed by using "port engineering foundation calculation system". The calculation model is a given engineering section, which is divided into several blocks according to the design size, and the calculation parameters of each block are determined according to the geological survey data. The calculation model is shown in Figure 5, and the calculation parameters of the model are shown in Table 2.

| Name                | Density (kN/m³) | Buoyant density (kN/m³) | Cohesion (kPa) | Friction angle φ(°) |
|---------------------|-----------------|-------------------------|----------------|---------------------|
| Dike body           |                 |                         |                |                     |
| Block retaining wall| 21              | 13                      | 100            | 45                  |
| Membrane bag        | 19              | 11                      | 0              | 32                  |
| Concrete            |                 |                         |                |                     |
| Macadam pavement    | 19              | 11                      | 0              | 32                  |
| Plain soil dike core| 16              | 8                       | 6.0            | 1.6                 |
| Miscellaneous fill  | 18.5            | 11.5                    | 6.0            | 16                  |
| Foundation          |                 |                         |                |                     |
| Fine sand           | 17              | 9                       | 4              | 33                  |
| Muddy clay          | 16              | 8                       | 5.8            | 0.6                 |
| Silty clay          | 17              | 9                       | 11.4           | 18                  |

4.2.2. Analysis of calculation results

Figure 5. Engineering calculation model.

Figure 6. Section of stability calculation.
Figure 6 shows the calculation results of the stability of the temporary cofferdam, it can be seen that the most dangerous sliding surface occurs in the muddy clay layer during the dewatering period; the minimum safety factor of the cofferdam section is 0.821, which is less than the minimum safety factor of the landslide engineering limit state (1.1-1.3)\cite{9}. Therefore, the dewatering of the foundation pit inside the cofferdam is very easy to cause slope sliding. In conclusion, the current cofferdam form cannot meet the safety and stability requirements during foundation pit dewatering, in order to meet the subsequent construction, the existing cofferdam structure should be improved.

5. Optimization design of cofferdam structure

5.1. Optimization design scheme
The improvement of cofferdam structure and the selection of materials should take into account the distribution of soil layer, the existing structure type, precipitation conditions and cost. The existing cofferdam structure has the problem of leakage, so the corresponding waterproof measures should be taken, the improved cofferdam structure is steel sheet pile cofferdam. Because the cofferdam is unstable in circular sliding mode during dewatering, and the starting position of the sliding surface is the outer boundary of the embankment core soil, Therefore, in order to meet the construction requirements and minimize the sliding of the cofferdam to the inside of the foundation pit, the driving position of the steel sheet pile is set at the inner boundary of the plain soil embankment core, and the bottom of the steel sheet pile should pass through the muddy clay layer with a length of 12m.

5.2. Stability analysis of improved cofferdam

Figure 7 shows the stability calculation results of the optimized cofferdam section, it can be seen that during the dewatering period and after the excavation, the minimum safety factors of the cofferdam section are 1.441 and 1.320 respectively, which are greater than the safety factors of the landslide engineering limit state (1.1-1.3). Therefore, the steel sheet pile cofferdam structure can effectively ensure the safety and stability requirements during foundation pit dewatering and excavation.

6. Conclusion
(1) The existing cofferdam has the problem of leakage, so the corresponding waterproof measures should be taken, and the dewatering inside the foundation pit is very easy to cause the foundation soil sliding, and the starting position of the sliding surface is the outer boundary of the embankment core soil.
(2) The existing cofferdam structure does not meet the stability requirements during foundation pit dewatering, with the increase of dewatering depth, the deep horizontal displacement of the cofferdam continues to develop to the side of the foundation pit, and the most dangerous sliding surface of cofferdam instability occurs at the elevation of -4m ~ -6m of muddy clay layer.
(3) The existing cofferdams have some problems such as instability and leakage, considering the construction conditions, progress, cost and other factors, the supporting structure of steel sheet pile cofferdams is proposed, according to the distribution law of the sliding failure surface of cofferdams,
the embedding position of steel sheet piles is given.

(4) The minimum safety factors of steel sheet pile cofferdam section are 1.441 and 1.270 respectively, which are greater than the limit state safety factors of Landslide Engineering (1.1-1.3), which verify the rationality and effectiveness of steel sheet pile cofferdam structure.

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