Study on the Influence of Harbour Channel Excavation on the Stability of Breakwater

Yuting Zhang¹, Haichen Sui¹*, Zhouting Tan², Dianjun Zuo¹

¹ Tianjin Research Institute for Water Transport Engineering, M.O.T., Tianjin 300456, China.
² China University of Geosciences, Wuhan 430074, China.
*Corresponding author’s e-mail: sui_chs@126.com

Abstract. A large number of soft clay layers are distributed in coastal areas, which brings risks to port construction. Especially in the course of channel excavation, the construction will affect the overall stability of the outer riprap breakwater. Through numerical simulation and Geocentrifuge model test, the influence of waterway excavation on the overall anti-sliding stability of a breakwater in Tianjin harbour is studied and analyzed. The experimental results show that when the excavation boundary line is 38.9 m away from the foot of the breakwater and the excavation depth is 10 m, the overall anti-sliding stability of the breakwater is less affected. The vertical displacement of the top of the breakwater is 6 mm, and the horizontal displacement of the foot of the breakwater is 23.4 mm, all within the safety control range.

1. Introduction
In most offshore areas of China, there are soft soil layers deposited by marine or lacustrine facies, whose thickness varies from several meters to tens of meters. For example, in the Yangtze River Estuary, Pearl River Estuary, Bohai Bay and other areas, the physical and mechanical indexes of soft soil layers are poor and the bearing capacity is low. It is very important to study the stability of breakwater under severe wave conditions on soft soil foundation. Because of its simple technology, convenient construction and low cost, riprap breakwater has become a traditional gravity breakwater structure. In order to keep the whole body of the breakwater stable against sliding, riprap breakwater is often used together with plastic drainage plate, sand pile and other foundation treatment methods.

In order to improve the navigation conditions, maintain the channel size and eliminate the flow pattern which has an impact on the navigation of ships, it is generally necessary to dredge the channel after the completion of the construction of hydraulic structures in the port area, thus forming the height difference of underwater topography on both sides of the breakwater, and the elevation of the inner channel is much lower than that of the outer channel. Due to channel dredging, the law of tidal current and sediment deposition has changed, coupled with the wave cyclic load, the physical and mechanical indexes of foundation soil have changed, and the calculation conditions of building safety and stability have also changed. The inadequate study of waterway dredging in China has resulted in many accidents of rubble embankment damage. Therefore, the study on the influence of channel dredging on the safety and stability of riprap breakwater is of great significance not only for determining the design parameters such as dredging depth and scope, but also for ensuring the safety and stability of hydraulic structures such as breakwaters.
2. Research progress

The upper structure of breakwater is affected by complex wind, wave and current. Besides vertical load, its foundation is also subjected to horizontal cyclic load, which will weaken the strength of foundation soil and increase the risk of overall sliding failure. In order to solve this problem, scholars have carried out a series of research through theoretical calculation, numerical simulation and physical model test.

Based on the two-dimensional generalized Biot dynamic consolidation theory, the dynamic response model of seabed and seawall under wave action and the governing equation of finite element including acceleration term of soil skeleton are established by Gangfeng JIN. Based on the new box-and-tube foundation breakwater in Tianjin Port, the interaction between complex breakwater structure and soft foundation under wave loads is studied by means of soil centrifugal simulation technology, static and dynamic triaxial tests and finite element numerical simulation (Minmin CAI, 2010). Xiaowei FENG taking the intact soft clay of Tianjin Port as the research object, the strength softening characteristics and stability analysis methods of semi-circular caisson and cylindrical foundation under wave action are studied by means of laboratory tests. The transient responses of pore water pressure, effective stress and displacement in saturated seabed soils under random waves are solved by dynamic elastic consolidation finite element method, and the stability of ocean buildings is analyzed (She an BIE 1998).

From the research results of scholars, most of the current studies on breakwater stability are focused on the overall safety of the structure under external loads, and the factors that cause the difference between the excavation of the inner channel and the siltation of the outer beach surface are not taken into account. However, the difference of earth pressure caused by the difference of seabed beach height on both sides of the breakwater is unfavorable to the overall anti-sliding stability of the breakwater foundation. From the point of view of research means, scholars mostly adopt the combination of theoretical calculation and analysis, numerical simulation and physical model.

3. Engineering background

The breakwater of a harbour project in Tianjin consists of East and West breakwaters, of which the East breakwater is 3694 m in length and the West Breakwater is 3701 m in length. The breakwater projects are all sloping structures. The body of the breakwater is mainly filled with large stones, and the protective structure is reinforced concrete fence. Foundation treatment methods include laying 1000mm sand cushion + laying plastic drainage plate + laying high-strength geotextile. In order to reduce the loss of sand cushion, the sand barrier is formed by throwing bags on both sides. The landform of the site is mainly coastal deposits, supplemented by continental and estuarine delta deposits. Affected by topography, it is a muddy coast. The underwater topography is gently inclined to the sea. The inner layer of the site changes slightly. The surface layer is mainly composed of silt or silt mixed with silt, and the silt layer becomes thicker gradually with the depth of the water. Table 3-1 shows the physical and mechanical indexes of foundation soil.

| Table 3-1 Foundation soil parameters of a seaport Breakwater Project in Tianjin |
| --- | --- | --- | --- | --- | --- |
| Physical properties of soil | Boundary water content | Direct shear test | Compressibility |
| $W$ | $G_s$ | $\rho$ | $\rho_d$ | $\epsilon$ | $W_i$ | $W_p$ | $I_p$ | $I_L$ | $c'$ | $\phi'$ | $a_{0.1-0.2}$ | $E_{0.1-0.2}$ |
| % | g/cm$^3$ | % | % | MPa | ° | MPa$^{-1}$ | MPa |
| 28.9 | 2.72 | 1.91 | 1.48 | 0.798 | 28.3 | 16.3 | 12.0 | 1.05 | 17.0 | 18.0 | 0.373 | 4.82 |

4. Numerical simulation of horizontal displacement of breakwater caused by channel excavation

4.1. Establishment of Finite Element Model

ABAQUS finite element software is used to establish the finite element numerical analysis model of breakwater-foundation. The influence of dredging excavation on the stability of breakwater is studied.
The stability of breakwater is analyzed. According to the previous design data, the excavation distance of the channel is 38.9 m, the excavation depth is 10 m, and the excavation time is about 3 months. The data provided in Table 3-1 are used to calculate the soil parameters.

Relying on the typical section of the engineering breakwater, a three-dimensional finite element numerical analysis model of the breakwater is established by choosing the width of a single fence plate as the calculation element. The element is meshed by eight-node hexahedron, with a total of 9857 elements. Figure 4.1 and Figure 4.2 shows as follow.

4.2. Analysis of numerical simulation results
The numerical simulation results are shown in Figure 4.3, which shows the horizontal displacement of each part of the breakwater caused by channel excavation. The maximum horizontal displacement mainly occurs at both ends of the first dike block stone material, especially in the back of the dike, reaching 88.8mm. It shows that channel dredging has little influence on the breakwater, and will not cause the sliding failure of the breakwater in the direction of the inner channel as a whole.

Figure 4.1 Model Building Material Diagram

Figure 4.2 Finite Element Modeling

Figure 4.3 Horizontal Displacement of Breakwater Section
5. Centrifuge Test on the Effect of Channel Dredging on the Stability of Breakwater
Geotechnical centrifuge model test was carried out. The main object of this test simulation is the embankment structure itself and the foundation soil within 5 m depth below it. The purpose of centrifuge test is to analyze and evaluate the influence of dredging excavation on the stability of breakwater, and verify the results of finite element numerical simulation.

5.1. Test scheme
The experiment was completed on the Geocentrifuge of the Hong Kong University of Science and Technology. The centrifugal test model of 1:100 (model: prototype) was used in the experiment. The method of releasing heavy liquid was adopted in the excavation of inner channel (Zheng et al., 2010 a; 2010 b; Hong&Ng, 2011), while the sediment deposit layer of outer channel was replaced by Fengpu sand cushion.

The depth of excavation is 10m. In centrifuge test, the stress release effect caused by channel excavation is simulated in three steps. The depth of each excavation step corresponds to the prototype size of 3m, 3M and 4m, and the time of simulation excavation corresponds to the site for 3 months. In the experiment, 20 mm sand cushion was laid to achieve the same stress effect as in-situ sediment deposit. Two times of high acceleration (100g) soil consolidation was used in the experiment. After the first consolidation, the breakwater and silt deposit were piled up. After the completion of the pile-up, the second consolidation is carried out immediately, and the excavation simulation of stress release effect is carried out after the completion of consolidation.

5.2. Test Similarity Relation
Centrifugal model test is to increase the self-weight stress of soil by centrifugal acceleration so that the stress and strain of prototype and model are equal and the deformation is similar. The scale relationship between the prototype and the model of the main physical quantities in this experiment is shown in Table 5-1.

| Physical quantities       | Scale relationship (Model/prototype) when centrifugal acceleration is ng |
|--------------------------|--------------------------------------------------------------------------|
| Acceleration a           | n                                                                        |
| Linear scale L           | 1/n                                                                      |
| Area A                   | 1/n^2                                                                    |
| Volume V                 | 1/n^3                                                                    |
| Time(consolidation/seepage) t | 1/n^2                                                                  |
| Seepage velocity v       | n                                                                        |
| Coefficient of Permeability k | n                                                                     |
| Settlement s             | n                                                                        |
| Stress σ                 | 1                                                                        |
| Strain ε                 | 1                                                                        |
| Force F                  | 1/n^2                                                                    |
| Density ρ                | 1                                                                        |
| Mass m                   | 1/n^3                                                                    |
| Bending rigidity EI      | 1/n^4                                                                    |
5.3. Test model

Figure 5.1 and 5.2 show the front and top views of the centrifuge test model design. The test soil consists of silty clay layer, rockfill material and Fengpu sand layer. The thickness of silty clay layer is 400 mm, which corresponds to 40 m in situ. The lower part of silty clay layer is a 50 mm Fengpu sand cushion, which is used to provide drainage path; the upper part is a breakwater and silt deposit layer.

The left side of the model box is a reserved trapezoidal trough, which is used to simulate the dredging excavation area. Its depth, bottom width and upper width are 100mm, 250mm and 450mm respectively, corresponding to the prototype size of 10m, 25m and 45m. On the right side of the model box are breakwaters and silt deposits. The distance between the levee foot and the dredging excavation point is 389 mm, corresponding to the prototype size of 38.9 M. The cross-sectional dimension of the breakwater in the model is 1/100 of the site size, the upper width, the lower width and the height are 40 mm, 222 mm and 45.5 mm, respectively. When the breakwater is built, the rockfill material with the particle size range is calculated and piled. The thickness of sand cushion outside the breakwater is 20 mm, which corresponds to the same thickness (2m) of sediment deposit in the field.

5.4. Test process

5.4.1. Construction of breakwaters and silt deposits. After the first consolidation is accelerated by centrifuge, the model is shut down and the breakwater and sand layer are piled up. Figure 5.3 shows the construction of breakwaters and silt deposits. In the test, the quality of rockfill and Fengpu sand is 2.9 kg and 3.3 kg, respectively. The calculated accumulative densities of breakwater and sediment deposits are 1.39 g/cm 3 and 1.75 g/cm 3, respectively. After the completion of the stacking, the second high acceleration consolidation is carried out.
5.4.2. Simulated excavation. After the constant displacement sensor reading is stabilized, the stress release effect caused by dredging is simulated three times, corresponding to the size of the prototype. The depth of each excavation step is 3 m, 3 m and 4 m, respectively. The total time of simulated excavation corresponds to the prototype for 3 months.

5.5. Test result

5.5.1. Comparative analysis of model images. All the test results are prototype results based on similarity relation (Table 5-1). Figure 5.4 shows the front and top views of the breakwater before and three months after excavation. It is clear from the figure that the breakwater remains stable after excavation.

5.5.2. Analysis of soil displacement field. Based on PIV technology, by comparing two images taken at different times, the displacement field of soil can be obtained in the corresponding time period. In this experiment, the digital camera was used to take the image, and the model images were taken before and after the simulated excavation. After the experiment, the displacement field of soil could be obtained by PIV software. Figure 5.5 shows the displacement field of the whole soil caused by the model test three months after excavation. The calculation of displacement vector shows that the maximum horizontal displacement of breakwater foot is 23.4 mm after channel excavation.
5.5.3. Settlement of breakwater top. In this test, the vertical displacement sensor is used to monitor the vertical displacement of the top of the breakwater. Three months after excavation, the settlement of the top of the breakwater is 6 mm.

5.5.4. Settlement at the foot of breakwater. A displacement sensor is installed at the foot of the breakwater to measure the vertical displacement of the soil. Three months after excavation, the settlement of breakwater foot is 4 mm.

5.6. Test analysis
Through centrifuge model test of breakwater, the displacement field and stress field of breakwater and foundation soil after channel excavation are analyzed. The results show that after channel excavation 38.9m away from the foot of breakwater, the settlement of top of breakwater is 6mm, the settlement of foot of breakwater is 4mm, and the maximum horizontal displacement of the foot of breakwater towards inner channel is 23.4mm. It can be seen that channel excavation has little effect on the overall stability of the breakwater.

6. Conclusion
Aimed at the engineering case of the influence of the excavated waterway on the overall stability of the outer breakwater in a Tianjin harbor, the stability of the breakwater after the excavation of the waterway is studied and analyzed by using the finite element numerical simulation and centrifuge model test method. The following conclusions are drawn:

- From the results of three-dimensional finite element numerical model of breakwater-foundation, it can be seen that the overall horizontal displacement of breakwater and foundation soil increases by about 88 mm after channel excavation, indicating that channel excavation and sediment deposition on the offshore side have little influence on the additional stress distribution of foundation soil of breakwater;

- From the centrifuge model test results of the breakwater after dredging, it can be seen that the displacement field and stress field of the breakwater and foundation soil are uniformly distributed, horizontal displacement and vertical displacement are in the order of mm, which shows that the influence of the channel excavation on the breakwater is small, which is similar to the results of the finite element method. Generally speaking, the results of the finite element displacement calculation are slightly larger than those of the centrifuge model test. It shows that the finite element numerical calculation model adopted in this paper is reasonable;
After channel excavation, ship waves will generate cyclic loads on the soil at the foot of the
breakwater and scour the foot of the breakwater to a certain extent. It is suggested that after channel
excavation, sand ribs should be laid along the width of the foot of the breakwater in order to weaken
the impact of breakwater foot scour on the overall stability of the breakwater.

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