Stability and Bearing Capacity Analysis of Breakwater with Cylindrical Jacket & Pile Foundations

Lian Li Zhang1*, Xiao Chang Ni1, Wen Wen Zhang1 and Yu Feng Tian2

1 Department of Architectural Engineering, Tianjin University Renai College, Tianjin, 301636, China
2 Tianjin Key Laboratory of Harbor & Ocean Engineering, Tianjin University, Tianjin, 300072, China
*Corresponding author’s e-mail: zhanglianli1984@tjrac.edu.cn

Abstract. In view of deep water and soft soil foundation, a new type of breakwater with cylindrical jacket and pile foundations is proposed. According to the hydrological and geological conditions of Tianjin Port, the stability and bearing capacity of breakwater are numerically simulated by ABAQUS software. The results show that when the pile is an elastic model, the failure of soil is the main cause of structural instability. In the limit state, the structure is unstable in rotation in addition to arc sliding, and its turning point is below the bottom of the cylindrical jacket and deviates from the structural axis near the front-pile side. When the pile is a damage plastic model, the loss of bearing capacity is the cause of structural instability. The safety coefficient is greater than 1, but it is obviously smaller than the one of elastic model. The research results provide a reference for structural design and stability study of the breakwater with cylindrical jacket and pile foundations.

1. Introduction
The new breakwater project has developed to deep water and soft clay coast, which has a great impact on the construction. Therefore, it is necessary to study new types of breakwater[1]. This paper puts forward a new type of breakwater with cylindrical jacket & pile foundations, which has high integrity and relatively convenient construction. However, analysis on stability and bearing capacity of the structure has not been carried out. Numerical simulation is an effective method to study the new structure. The section stability of semi-circular breakwater is studied by literature[2-3]. In reference[4-5], the stability of large cylinder structure is studied by loading coefficient method and strength reduction method respectively. Numerical simulation is carried out on the variation of horizontal displacement and rotation angle with loading of bucket foundation breakwater in paper[6-7]. The stability of the inverse T type breakwater with jackets and pile foundations is analyzed by ABAQUS software in paper[8], and the simplified calculation of the structure stability is carried out by using the limit balance method.

According to the hydrological and geological conditions in Tianjin Port, the stability and bearing capacity of breakwater with cylindrical jacket & pile foundations are numerically simulated by ABAQUS software. The displacement distribution of structure, plastic deformation of soil and stress distribution of each component are studied by 3D numerical model, which provides a reference for structure design.
2. Engineering profile

2.1. Breakwater structure

A new type of breakwater suitable for deep water and soft clay foundation is proposed, which is breakwater with cylindrical jacket & pile foundations, as shown in figure 1. The breakwater consists of cylindrical jacket and piles, in which the cylindrical jacket consists of cylindrical outer plate, auxiliary bunker outer plate, transverse partition plate, longitudinal partition plate and conduit. The cylindrical outer plate is mainly used to withstand wave and block sand. The auxiliary bunker outer plate is used to connect the cylindrical jackets, and the auxiliary silo can improve stability, which is formed by cylindrical outer plate and auxiliary bunker outer plate. Adding transverse and longitudinal plate can enhance the integrity and reduce the internal force. Conduits are arranged at junctions between the cylindrical outer plate and partition plate, the main function of which is to provide guidance for the pile to enter the seabed accurately. The pile passes through the conduit into the seabed to form pile foundation, and the concrete is poured in the gap between pile and conduit, so that the cylindrical jacket and the pile form a whole. In summary, the new breakwater has good integrity and simple structure type. The construction is convenient and the construction period is short. The structure can effectively enhance the bearing capacity and stability, so it is suitable for deep water and soft soil foundation.

![Figure 1. Diagram of the new breakwater.](image1)

![Figure 2. FEM domain.](image2)

2.2. Hydrological and geological conditions

Because there is no practical engineering application of breakwater with cylindrical jacket & pile foundations, therefore, this paper studies the structural stability and bearing capacity of the breakwater based on the hydrological and geological conditions of Tianjin port. The hydrological conditions are shown in Table 1, and the soil parameters of the sea area are shown in Table 2.

| Table 1. Hydrological conditions (designed high water level). |
|---------------------------------------------------------------|
| Water depth (m) | Wave height (m) | Wave length (m) | Period (s) |
|-----------------|-----------------|-----------------|------------|
| 10              | 5               | 72              | 8.1        |

| Table 2. Main parameters of soil layers (consolidation quick shear). |
|---------------------------------------------------------------------|
| Soil Depth (m) | Floating weight (kN/m³) | Compression modulus (MPa) | Cohesion (kPa) | Internal friction angle (°) |
|----------------|--------------------------|---------------------------|----------------|---------------------------|
| ① 0~10         | 6.13                     | 1.94                      | 9.25           | 12.68                     |
| ② 10~13        | 7.31                     | 2.28                      | 14.76          | 16.03                     |
| ③ 13~19        | 8.47                     | 4.07                      | 17.97          | 21.54                     |
| ④ 19~24        | 9.26                     | 5.87                      | 12.99          | 33.74                     |
| ⑤ ——           | 8.87                     | 5.87                      | 2.50           | 34.00                     |
3. Numerical analysis model

3.1. Domain of finite element model (FEM domain)
According to the conditions of Tianjin Port and the relevant specifications of port engineering, the size of the new breakwater is determined. The diameter of the cylindrical jacket is 10 m. The thickness of the plate such as cylinder outer plate, the transverse or longitudinal partition plate is 0.3 m. The total width of the jacket is 12 m, and the total height is 17.5 m (4 m below the mud surface). The depth of the pile into the soil is 16 m. Because of obvious force characteristics and complex action with soil foundation, the stability of breakwater under wave force is simulated by integral 3D modeling. In this paper, a single breakwater member (including sand and stone filled in the cylinder) and a certain range of soil are taken as the FEM domain, as shown in figure 2. In order to simplify the numerical model properly for grid division, the stability of auxiliary silo is not considered, and the auxiliary bunker outer plate is simplified into a flat plate. The depth of soil foundation should be at least 3 times of the depth of pile into the soil, such as 60 m. The width of the soil is taken as the width of a single structure, and the length on both sides is 5 times of the cylinder diameter, that is, the total length is 110 m. The surface of the soil foundation takes the free boundary and the bottom surface takes the fixed boundary. Furthermore, the left and right sides adopt the symmetrical boundary, the front and behind sides adopt the lateral limit boundary.

3.2. Material and constitutive model
Each member of the new breakwater is made of reinforced concrete, whose strength and stiffness are much larger than that of soft soil foundation. So the whole breakwater is modeled by using the linear elastic constitutive, and the soil selects Mohr-Coulomb constitutive model. In order to simulate the phenomenon of slip and detachment between different materials, the contact surface elements are set up between the jacket & piles with soil foundation. Hard contact model is used in normal direction and the Coulomb friction model is used in tangential direction.

3.3. Stability analysis method
In this paper, the loading coefficient method is used to research stability of breakwater under wave load. Based on the idea of hierarchical loading, the loading coefficient is defined as the ratio of actual load to design load, that is, \( \alpha = \frac{P}{P_D} \). The loading coefficient increases gradually until structure unstable under the ultimate state. The wave load at this moment is defined as ultimate bearing capacity \( P_U \), and the stability safety coefficient is defined as the ratio \( P_U \) to \( P_D \). In the limit state, the loading coefficient \( \alpha \) is equal to the safety coefficient \( K \).

4. Numerical analysis result

4.1. Displacement distribution
The displacement distribution of breakwater in the ultimate state is shown in figure 3. It can be seen that the displacement of the breakwater increases gradually from bottom to top, the isoline is close to the concentric circle, and the center of the circle is roughly located below the bottom of the cylindrical jacket and deviates from the cylinder axis near the front-pile side.

4.2. Plastic deformation distribution
The plastic deformation distribution of soil in limit state is obtained by numerical analysis as shown in figure 4. It can be seen that the plastic deformation area of soil is mainly concentrated around the cylindrical jacket and the front pile. Because the upper soil foundation is soft clay, whose bearing capacity is low, the plastic deformation area of the soil around the jacket expands continuously along the bottom of the jacket, resulting in the formation of arc sliding surface. In addition, the plastic deformation area of the soil under jacket bottom expands downward along the pile, but does not extend to the bottom of the pile because that the depth of the soft soil is limited.
4.3. Stability safety coefficient

For obtaining the stability safety coefficient of breakwater with cylindrical jacket and pile foundations, it is necessary to draw the load-displacement curve (P-S curve). This paper selects point A and B in Figure 3 as the characteristic points to draw the loading coefficient $\alpha$ - horizontal displacement $U_h$ curve which analyze the anti-slide stability, and draw the loading coefficient $\alpha$ - rotation angle $\theta = \arcsin[(U_F - U_B)/L]$ curve which analyze the anti-rotate stability, as shown in Figure 5. When the load is small, P-S curve is linear. With the increase of load, the plastic deformation of soil appears, and the curve appears obvious nonlinear inflection point. Until the soil capacity reaches the limit, the slope of the curve tends to zero. In this paper, the ultimate bearing state is taken as the criterion of instability. When the slope of the curve approaches 0, the safety coefficient of anti-slide and anti-rotate stability is obtained. It can be seen that the safety coefficient of anti-rotate and anti-slide stability is 1.40, which meets the stability requirements.

4.4. Stress distribution of structure

The stress distribution based on Mises yield criterion is shown in Figure 6. It can be seen that the structural stress is concentrated on the pile, and its value is much larger than that of cylindrical jacket. The stress distribution of cylindrical jacket is uneven, which is mainly concentrated at the junction of cylindrical jacket and pile at the bottom of the jacket. Considering that the stress value is not very large, the plate thickness can be increased or local strengthening can be considered in structural design. Due to the constraint of the jacket and the soil of the bearing layer, the stress of the pile passing through the jacket and reaching the bearing layer is very small, while the stress of the pile in the soft soil area is very large.
4.5. Stability analysis based on damage plastic model

When the stability of breakwater analyzed by linear elastic constitutive model, the main reason of structural instability is that the soil reaches the bearing limit, but the influence of structural strength on the stability is not considered. Therefore, the damage plastic constitutive model of concrete is chosen to establish the numerical analysis model, and the stability of breakwater is analyzed. The P-S curve based on damage plasticity model is shown in figure 7.

![Figure 6. Stress distribution of breakwater.](image)

When the load is small, the curve of damage plastic model coincides with the one of elastic model. The nonlinearity of the curve is due to the plastic deformation of soil, and the structure mainly shows elastic deformation. As the load increases, P-S curve of damage plastic model no longer coincides with the elastic one, and the nonlinear characteristic of the structure plays an important role. According to the principle of limit bearing instability, the stability safety coefficient of breakwater based on damage plasticity model is close to 1.1, which meets the requirement of more than 1, but the value is obviously lower than that of elastic model.

4.6. Structural instability mode

According to the stability analysis of elastic model and damage plasticity model, the instability mode of breakwater with cylindrical jacket & pile foundations is determined. If the structure size and reinforcement meet the requirements of structural strength, the elastic model can be used. The main reason for the instability is the plastic failure of the soil. In addition to arc sliding, the breakwater is unstable in rotation in the limit state, and the rotation point is located below the bottom of the jacket and deviates from the structure axis near the front pile. When the size of the structure is relatively small or the reinforcement is unreasonable, the structure is destroyed before the soil, and insufficient strength of the structure is the main reason for instability.
5. Conclusion
In order to adapt to deep-water and soft soil foundation, this paper presents a new type of breakwater with cylindrical jacket & pile foundations. According to the hydrological and geological conditions of Tianjin Port, the stability and bearing capacity of the new breakwater are simulated by ABAQUS software. The results show that when the breakwater is an elastic model, the plastic failure of soil foundation is the main reason for instability. In the limit state, the structure is unstable in rotation in addition to arc sliding, and the safety coefficient is 1.4. When the structure is damaged plastic model, the safety coefficient is 1.1, which less than that of elastic model. In this case, insufficient strength of the structure is the main reason for instability.

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