Calculation of breakwater stability by strength reduction method

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Abstract. The breakwater is the first barrier to prevent sea wave for entering the port basin and vital to provide a safe environment for ships or vessels. The stability of a breakwater in North China is studied by strength reduction method. This breakwater is constructed with silt-solidified fills in bags and armoured with accropode blocks and four-pin concrete hollow blocks. Calculation result shows that the factor of safety calculated by strength reduction method is 2.52, and the breakwater is in a good stable state since the ground and breakwater have no trend to slip.

1. Introduction
The breakwater is the first barrier to prevent sea wave from entering the port basin and is used to ensure the stability and safety of ships anchored in the port. Therefore it is necessary to research its structures and construction methods. Xu et al. summarized the development of Japan's new breakwater structures into three main development divisions according to their experience of technical exchange in Japan[1]. The safety of breakwater can be checked and analyzed by numerical analysis or experiment. Xie et al. studied the stability of the cambered breakwater under the action of waves through wave tests, and also conducted a preliminary study on the hydraulic characteristics of the cambered breakwater by numerical analysis[2]; Hua and Yu established a numerical model to analyze the seabed dynamic response around the breakwater[3]; Xiao et al. analyzed the stability of the box-type foundation breakwater by using the limit equilibrium method and put forward technical requirements for stabilizing the height of the box[4]; Zhao et al. studied the stability characteristics of arc breakwater through experiments[5]; Yang and Yang solved the anti-skid property of the new submerged bucket breakwater by finite element analysis[6]; Gu and Zhang studied the wave reduction performance of the horizontal twin-plate breakwater under oblique waves[7].

Analysis of historical cases showed that the failure of caisson breakwater was mainly due to foundation instability, not wave loads acting on breakwater exceeding design standards. In this paper, the stability of a port breakwater project is analyzed by numerical method.

2. Engineering geology
According to geological and geotechnical investigation information, the breakwater is built on marine soft soil, mainly consisting of two layers, i.e. marine mud and silty clay. Since these two kinds of soft soils are featured with low strength and strong compressibility, the ground improvement is necessary.
In the design scheme, the soil ground is improved by C-type band drains with a spacing of 1 m is used under the breakwater. The engineering geological information is as follows:

I-1 layer, mud (Q 4m): discovered by 0.40 m to 10.70 m in depth, gray, saturated, and fluid plastic. The soil quality is uniform and fine, with local silt and silty thin layers and lumps. The distribution of this layer is stable and exposed, with a bottom elevation of -12.37 m to -0.44 m; the exposed thickness is 0.40 m to 10.70 m.

The main physical and mechanical indexes of this layer are listed as follows: water content $w=70.8\%$, natural density $\rho=1.59$ g/cm$^3$, natural void ratio $e=1.949$, plasticity index $IP=25.0$, liquid index $Il=1.92$, compression coefficient at (0.1-to-0.2) MPa=1.92 MPa$^{-1}$, compression modulus $E_s=1.66$ MPa, quick shear cohesion $c=6$ kPa, internal friction angle $\phi=0$, consolidation quick shear cohesion $C_g=12$ kPa, internal friction angle $\phi_g=10.9\degree$, triaxial unconsolidated undrained shear cohesion $C_{uu}=17$ kPa and $\phi_{uu}=0.98\degree$.

This layer has stable distribution, high water content, large void ratio, low mechanical strength, and bad engineering geological characteristics such as rheology, creep, high sensitivity and high compressibility. Its allowable bearing capacity $f=25$ kPa.

II-2 layer, silty clay (Q 4m): discovered by 1.50 m in depth, light gray and fluid plastic. The soil quality is uneven, with thin layers of silty soil and silty sand mixed locally. This layer is exposed only through Borehole K2 with a thickness of 1.50 m.

This layer has medium compressibility and its allowable bearing capacity $f=100$ kPa.

3. Calculation and result

3.1 Breakwater section

The highest section of the breakwater surface is chosen for analysis as shown in Figure 1. The breakwater is constructed with silt-solidified fills in bags, armoured with modified concrete block structures at the top, four-pin hollow blocks and accropode blocks at both sides. The 150- to 300-kg and 300- to 500-kg boulders are also set at the shoulders on both sides. The breakwater is located about 350 m north of the wharf and has a total length of about 200 m. It was constructed with silt-solidified fills in bags.

![Figure 1. The design scheme of breakwater.](image)

The breakwater is designed with an extreme highest water level of 6.7 m whereas the top elevation of the breakwater is 5.0 m. It seems reasonable to assess the breakwater stability under this extreme design condition. However it is recommended to assess its stability under a design lowest water level of 0.45 m.

In Figure 1, it also shows that the soil ground under the breakwater contains two layers, i.e. marine mud(I) and silty clay(II). The top elevation of natural marine mud ranges 1.33 m to 1.39 m, and the
bottom elevation ranges -14.1 m to -5.32 m. Below this mud is the silty clay which is exposed according to borehole log K1, with a layer elevation of -12.37 m to -15.22 m.

3.2 Calculation model and parameters

According to the breakwater section in Figure 1, we could establish a geometric model by using Flac3D software. Obviously it is a plane strain problem. In the model, the mud thickness is 15 m in thickness, and the silty clay 3 m. The dimensions of the geometric model are identical to those of the designed breakwater.

![Image of Flac3D software](image)

Figure 2. The geometric model in Flac3D software.

According to JTS 154-1 -2011 Code for Design and Construction of Breakwater, the mass of concrete protective layer per 100 m² for 5-t accropode blocks is 105 t, and the volume of 2.8-t square hollow blocks is 53m³. Therefore their average distribution loads are 24.15 kN/m² and 12.19 kN/m², respectively, calculated on a basis of a concrete density of 2300 kg/m³. The average distribution loads are 15.90 kN/m² and 18.55 kN/m² when the density of the boulders is taken as 2650 kg/m³ and the void ratios of and are estimated at 0.4 for 150- to 300-kg boulders, and 0.3 for 300- to 500-kg ones, respectively. The modified concrete square blocks at the top of the breakwater is estimated as 1.2 m high. Now we can obtain the breakwater loads as shown in Table 1.

| Type                     | Load (kN/m²) |
|--------------------------|--------------|
| 5-t accropode            | 24.15        |
| 2.8-t four corner        | 12.19        |
| 300- to 500-kg boulder   | 15.90        |
| 150- to 300-kg boulder   | 18.55        |
| Modified concrete square | 23.00        |

In the calculation, Mohr-Coulomb elastic-plastic model is adopted for the soft soils. According to the engineering geological survey report, the soil compression modules of these two soils (under 100 kPa to 200 kPa) are 1.66 MPa and 9.75 MPa, respectively, and the elastic modulus and shear modulus are calculated according to poisson’s ratios of 0.35 and 0.25, respectively, as shown in Table 2.

| Soil layer | Shear modulus(MPa) | Bulk modulus(MPa) | Effective cohesion(kPa) | Effective friction angle | Dry density(g/cm³) | Saturated density(g/cm³) |
|------------|--------------------|-------------------|-------------------------|-------------------------|-------------------|--------------------------|
| I-1        | 0.38               | 1.15              | 12.0                    | 10.9                    | 0.94              | 1.59                     |
| II-2       | 3.25               | 5.42              | 36.0                    | 8.6                     | 1.33              | 1.83                     |

Although the quick shear and consolidation quick shear test indexes of mud and quick shear indexes of silty clay are provided in the survey report, the effective stress indexes of these soils are not provided. In this paper we take values of the calculation parameters according to their quick shear indexes of mud and the quick shear indexes of silty clay in the survey report as shown in Table 2.

The core material of breakwater is silt-solidified fills in bags. In the absence of relevant mechanical data, shear modulus and bulk modulus of the fills are taken as 5 times those of mud.

The concrete slope protection layer contains large granular bodies with the functions of weakening waves and slope protection. It is not easy to consider its overall deformation or movement in the calculation. For the sake of simplicity, their shear modulus and bulk modulus are taken to be consistent with those of silt-solidified fills (for a purpose of freeing deformation of silt-solidified fill), but their cohesions and internal friction angles are taken to be 10 GPa and 45°, assuming they act in an elastic state in calculation.
Moreover, the design lowest water level of 0.45 m is considered as the unfavourable working condition. The bottom boundaries of the analysis model are restricted in vertical displacement, the left and right boundary in horizontal displacement, and the entire breakwater longitudinal displacement.

3.3 Calculation result

Figure 3 shows the contour of the calculated maximum shear strain increment as well as the safety factor. It can be seen that under given calculation parameters, the factor of safety calculated by strength reduction method is 2.52, and the breakwater is in a good stable state since the ground and breakwater have no trend to slip.

![FLAC3D 5.00](image)

Figure 3. Calculated maximum shear strain increment and factor of safety.

4. Conclusions

By using strength reduction method, a breakwater is assessed on its stability. The design lowest water level is considered as the unfavourable condition. The calculation result shows that, the factor of safety calculated by strength reduction method is 2.52, and the breakwater is in a good stable state since the ground and breakwater have no trend to slip.

References

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