Stability analysis of Caisson Cofferdam Based on Strength Reduction Method

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Abstract. The working mechanism of the caisson cofferdam depends on the self-weight of the structure and internal filling to ensure its skid resistance and overturn resistance stability. Using the strength reduction method, the safety factor of the caisson cofferdam can be obtained. The potential slide surface can be searched automatically without constraining the range of the arc center. According to the results, the slippage surface goes through the bottom of the caisson. Based on the judgement criterion of the strength reduction method, the final safety factor is about 1.65.

1. Introduction
In the coastal area, especially in the flouring area, the land shortage is more and more obvious. After several decades of construction along the coastline, there is nearly no ascendant land for the land resource. There are plenty of successful cases of artificial island and many research documents have been kept. In the Kawasaki artificial island, the cofferdam structure of the island adopts the continuous concrete wall with 2.8m thickness and 119m length, which is the greatest continuous concrete wall in the world. The sand compaction pile and the deep cement mixing methods are used to reinforce the soft ground. During the construction, massive and advanced equipment and technology of measurement and location are developed.

The gravity caisson is a retaining wall structure that utilizes its internal filling and upper structure to maintain its stability against the possible sliding and overturn. The advantages of gravity caisson include its long service durability, great bearing capacity for the wharf load, antisepticise, low cost etc. However, due to its large self-weight and upper load, the appearance of the uneven settlement and the inclination of wall body, the requirement of the foundation is relatively strict compared with other wharf structure, which is suitable for the solid seabed. The structural style on the gravity wharf depends on the structure of wall body and its construction method. It can be classified into block structure, caisson structure, buttress structure and large cylinder structure.

Considering that the initial starting of artificial island is relatively late in China and there are still many obstructions in the future, the numerical simulation about the deformation and stability of the cofferdam wall of the island is very necessary for the future design and construction. In this paper, the stability of caisson cofferdam is analyzed numerically to accumulate experience.
2. Strength reduction method

The essence of the strength reduction method is to reduce the cohesive strength and the internal frictional angle of the material gradually so that the stress of certain elements can surpass the yield surface. When the amount of such elements increases, there would be continuous slippage surface inside the ground and then the ground loses its stability. It is simple and accurate to determine the safety coefficient using strength reduction method and the possible failure position can also be automatically searched, which is the advantage of the strength reduction method. Therefore, it is widely used in the embankment, port engineering, tunnel etc. Finn and Byrne [1] carried out a series of model tests to research the influence factors of the withdrawal resistance of the suction caisson. The results showed that the withdrawal resistance mainly depends on the suction at the bottom of the caisson and the maximum of the withdrawal resistance can be fitting by assuming the classic bearing capacity problems. Bang and Cho [2] believed that the strength of the even ground is linearly increasing with the depth for the soft clay ground and the undrained horizontal bearing capacity can be solved using ultimate equilibrium method. Bye et al. [3] used the sliding surface method to analyze the bearing capacity of the suction caisson. In the calculation, the foundation can be transferred into an equivalent rectangle and its area and processional moment is the same with the circular bottom. Xue [4] discussed three failure modes and the corresponding calculation methods of the ultimate withdrawal resistances of the cylindric foundation in the clay ground. The stability of anti-overturn is also carried out according to the shallow foundation code. Deng et al. [5] gave a detailed theoretical research about the withdrawal resistance of the suction caisson foundation and compiled a finite element code for the calculation of the ultimate bearing capacity of the suction caisson. In the calculation, the modified Cam-clay model is used as the constitutive model for the soft clay and silty clay. The soil is assumed fully saturated and the flow of the pore water obeys the Darcy’s law. Zhang et al. [6] carried out the numerical simulation on the characteristics of bearing capacity of the suction caisson in the saturated sand ground and analyzed the influence of length-radius ratios on the bearing capacity under different load-displacement curve and coupled load. Erbrich [7] analyzed the withdrawal resistance of the suction caisson foundation in the dense silica sand using ABAQUS. In the calculation, it is found that the greater the loading rate is the larger the withdrawal resistance is. Sukumaran et al. [8] carried out two-dimensional and three-dimensional analysis on the horizontal bearing capacity of the suction caisson in the soft ground under undrained condition. Zdravkovic et al. [9] utilized the three-dimensional Fourier series aided with finite element method to analyze the bearing capacity of the suction caisson in the soft ground and the influence of the loading direction, length-radius ratio, cohesive strength and anisotropy of the soil is taken into consideration. Supachawarote et al. [10] used the Swipe method and displacement method to apply load on the suction caisson foundation and gave the failure enveloping surface of bearing capacity. Wang et al. [11] determined the slippage displacement and angle of rotation as the main referring parameters of the dynamic response using finite element method and dynamic analysis method when the caisson-type breakwater is subjected to the dynamic wave load. The variation tendency of the slippage displacement and the rational angle along the time history is also proposed. Wang [12], Yu [13] researched the deformation and stress under the interaction of the caisson, foundation and rear filling and analyzed the stress and settlement of the caisson using ANSYS under static condition. Liu et al. [14] carried out the non-linear dynamic effective stress analysis to explain the failure of the caisson-style wharf in the big earthquakes in Osaka and Kobe. The results show that there is significant influence of the increase of excess pore pressure inside the filling of the rear caisson and replaced sand at the bottom of the caisson on the earthquake-resistance of the caisson wharf.

Although the strength reduction method has been widely used in the stability analysis of the slope, the final safety coefficient is always depended on the evaluation criterion of instability. Usually the numerical convergence is taken as the judge criterion, but the influence factors of the convergence of FEM are multiple and it is difficult to explain whether the divergency is attributed to instability or not. Now there are mainly three judge criterions for the instability: convergence of calculation, run-through of the plastic range and sudden change of characteristic position. When using strength reduction
method for the slope stability, the calculation convergence is usually used as the criterion. If the convergent solution cannot be obtained under the designated convergence judgement, the structure loses its stability. For the run-through of the plastic range, some significant shear bands have been observed during the damage of the slope. Similar regulation can be forecasted. If there is run-through plastic deformation in the slope under certain reduction coefficient, such a coefficient can be regarded as the safety coefficient. For the sudden change of characteristic position, the treatment is building the relationship between the displacement of certain point and the reduction coefficient in the FE calculation. If there is a sudden change in the curve, the slope is in a critical state. In Plaxis3D, a module called safety analysis can be used for the slope stability analysis. In the calculation, the reduction coefficient is gradually reduced and the total displacement at the toe of the structure is also monitored for each reduction coefficient. When the relationship between the reduction coefficient and the total displacement is plotted in the diagram, the safety coefficient is taken as the reduction coefficient if there is no variation even though the total displacement increases.

3. Calculation conditions

3.1. Calculation model

According to the design documents and ground survey materials, the gravity caisson structure is adopted for the cofferdam of the artificial island. The strength grade is C30. The supporting course is jackstone bedding and the sand compaction piles are installed beneath the bedding. The weight of 10~100kg block stone is thrown in the caisson. The jackstone bedding is composed of 10~500kg block stone with 6~10m width. In the rear of the caisson, the 10~100kg stone is placed. The dimension of the caisson is 28m, 15m and 18m in the length, width and height direction respectively and the weight of each caisson is 3800t. The altitude at the top of the caisson is +3.0m, on which the wave wall is casted in-situ with the altitude of +5.0m. In the front of the caisson, the block stone of 300~500kg weight is placed to protect the bedding. The skeleton map of the caisson is shown in Figure 1.

![Figure 1 Skeleton map of caisson](image_url)

3.2. Calculation parameters

The determination of the in-situ soil parameters is based on the indoor experiments, in-situ test results and drilling documents of nearby engineering. The parameters of the bedrock are determined by the uniaxial compression strength of the rock. The relative parameters of the caisson and the stone utilized in the calculation are listed in Table 2.

| Name         | Density $\rho$ (g/cm$^3$) | Triaxial test Modulus of compression | Permeable coefficient |
|--------------|----------------------------|--------------------------------------|-----------------------|
| Filling sand |                            |                                      |                       |
| 300~500kg stone |                          |                                      |                       |
| 10~100kg rock mound |                      |                                      |                       |
| 10~100kg block stone |                      |                                      |                       |

Table 1 Recommending parameters of soils for the artificial island
In order to consider the interaction between the caisson and the ground, the contact surface is set up at the side and bottom surfaces. According to the load in the practical engineering, the magnitude of the load is assumed to be 20kPa during the construction period. Considering the symmetry of the model, the normal constraints are applied on the front and rear surfaces, the fixed constraints are applied on the bottom surfaces and the free boundary is on the top surface, as shown in Figure 2.

![Figure 2 Finite element model of caisson cofferdam](image)

### Table 2 Parameters in calculation

| Material                  | Elasticity modulus (kPa) | Poisson’s ratio | Bulk Density (kN/m³) | Friction angle | Cohesive strength (kPa) |
|---------------------------|--------------------------|----------------|----------------------|----------------|-------------------------|
| Caisson                   | 3 × 10⁷                   | 0.2            | 24.0                 | -             | -                       |
| Rubble-mound foundation   | 1 × 10⁵                   | 0.3            | 15.0                 | 35°           | 5                       |
| Block stone               | 5 × 10⁵                   | 0.3            | 18.0                 | 35°           | 5                       |

4. **Calculation results**

Figure 3 demonstrates the possible slippage surface of the caisson cofferdam and the distribution of the shear strain in the ground. As can be seen in the figure, the slippage surface goes through the bottom of the caisson. Using the strength reduction method, the possible arc slippage surface can be determined automatically without designating the range of the arc center. Furthermore, the variation of the reduction coefficient against the virtual displacement is shown in Figure 4. According to the criterion of the failure, the safety factor of the caisson cofferdam is about 1.65 after the installation of the sand compaction piles.
5. Conclusions

This paper aims to analyze the engineering property of the caisson cofferdam via numerical calculation. According to the design materials and geological exploration, the finite element model and soil parameters are determined. A serial of calculation is carried out to research the detailed characteristics of the caisson and the conclusions are as follows:

(1) The working mechanism of the caisson cofferdam depends on the self-weight of the structure and internal filling to ensure its skid resistance and overturn resistance stability. Due to its great self-weight, the requirement of the bearing capacity to the ground is very strict, which make it suitable for the solid ground. If the caisson cofferdam is utilized, the ground improvement should be carried out to ensure its stability. In this case, the sand compaction piles are installed.

(2) Using the strength reduction method, the safety factor of the caisson cofferdam can be obtained. The potential slide surface can be searched automatically without constraining the range of the arc center. According to the results, the slippage surface goes through the bottom of the caisson. Based on the judgement criterion of the strength reduction method, the final safety factor is about 1.65.

(3) It should be clarified that the deformation and stability of the caisson cofferdam is close related to the strength and the replacement ratio. If the requirement of the deformation is much stricter, the cost of the ground reinforcement is inevitable to increase. In the practical design and construction, it should be considered overall.
References
[1] Firm W D L, Byrne P M. The evaluation of the breakout force for a submerged ocean platform[C]. Proceedings, Offshore Teleology Conference, Houston, Texas, OTC1064, 1972, 351-365.
[2] Bang S, Cho Y. Ultimate horizontal loading capacity of suction piles[J]. International Journal of Offshore and Polar Engineering, 2002, Vol. 12(1), 56-63.
[3] Bye A, Erbrich C, Earl K, Wright et al. Geotechnical design of bucket foundations. OTC7793, 1995: 869-883.
[4] Xue W.D., Analysis of resistance to pullout and stability against tilting for shallow water bucket foundation platform[J]. Journal of Oceanography of Huanghai and Bohai seas, 2001, Vol. 19(3), 87-92.
[5] Deng W, Cater J P. Vertical pullout behavior of suction caisson. Research Report 1999, Center for Geotechnic Research, The University of Sydney.
[6] Zhang J.L. et al., The characteristics of the bearing capacity of bucket foundation[J]. Chinese Journal of Rock Mechanics and Engineering, 2005, Vol. 24(7), 1169-1172.
[7] Erbrich, C T. Modeling of a novel foundation for offshore structure. Proceeding of the 9th UK ABAQUS User’s Conference, Oxford, English, 1994.
[8] Sukumaran B, Mccarron W O, Jeanjean P, Abouseeda H. Efficient finite element techniques for limit analysis of suction caisson under lateral loads [J]. Computers and Geotechnics, 1999, 24(2): 89-107.
[9] Zdravkovic L, Potts D M, Jardine R J. A parametric study of the pull-out capacity of bucket foundations in soft clay[J]. Geotechnique, 2001, 51(1): 55-67.
[10] Supachawarote C, Randolph M, Gourvenec S. Inclined pull-out capacity of suction caissons [A]. Proceedings of the Fourteenth International Offshore and Polar Engineering Conference [C]. 2004, 500-506.
[11] Wang J.J., Miao D., The stability analysis of caisson breakwater[J]. Port Engineering Technology, 2007, Vol.4, 19-21.
[12] Wang S., Yu Z.H., Static analysis of large-scale caisson wharf base on Anaysis[J]. China Water Transport, 2010, Vol. 1, 40-45.
[13] Wang, S., Non-linear dynamic analysis of large-scale caisson wharf[D]. Changsha Technology University, 2010.
[14] Liu H.L. et al., Caisson structure effective stress analysis seismic liquefaction residual deformation[J]. Chinese Journal of Geotechnical Engineering, 1998, Vol. 20(2), 26-30.