Study on the bottom resistance during sinking stage of super-sized caisson foundation

Dong Xuechao1,2,a*, Yang Tiechui3, Shen Kongjian4, Guo Mingwei1

1State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei, China
2University of Chinese Academy of Sciences, Beijing, China
3Power China Henan Electric Power Engineering Co. Ltd, Zhengzhou, Henan, China
4Jiangsu Provincial Transportation Engineering Construction Bureau, Nanjing, Jiangsu, China

*aemail: dongxuechao18@mails.ucas.ac.cn
*Corresponding author: aemail: dongxuechao18@mails.ucas.ac.cn

Abstract: Open caisson foundation sinks by overcoming the buoyancy and soil resistance by means of its own gravity and sinking auxiliary measures. Bottom resistance is a dominant variable in the sinking stage of super-sized caisson foundation. The magnitude of bottom resistance is of great importance to the safe sinking of the caisson foundation. Based on the super-sized caisson foundation of the main tower of a long-span bridge, a method is proposed for calculating the bottom resistance on the basis of the field monitoring data of earth pressure on the food blade, the bottom resistance of different zones within the bottom of the caisson foundation is calculated by the proposed method, and the distribution characteristics and variation of the bottom resistance are analyzed. The calculating results of the engineering practice show that in the process of soil sampling from the internal area to the external area within the bottom, the bottom resistance of inner bulkhead and inner partition walls decreases, while the bottom resistance of outer bulkhead and outer partition walls increases. The distribution characteristics and variation of the bottom resistance can actually reflect the global mechanical behavior of caisson foundation, which helps guide the safe sinking of the caisson.

1. Introduction

Through the earth excavation, open caisson foundation sinks by overcoming the buoyancy and soil resistance by means of its own gravity and sinking auxiliary measures[1]. During the sinking stage, bottom resistance is the key issue in the study of open caisson. As for bottom resistance, its value and distribution were analyzed through measured data analysis of caisson foundation of main tower of a certain bridge in Haikou when the cutting edge was in different soil layers[2]. By analyzing the monitoring data of South Anchor Foundation of Ma’anshan Yangtze River Bridge, the relationship between the value and distribution of bottom resistance of open caisson and the sinking depth was studied[3]. Based on the construction work of Shanghai-Nantong Yangtze River Bridge, the force condition of the bottom of this caisson during the sinking stage was calculated and compared with the measured value[4]. The spatial distribution of stress on tread and incline of cutting edge during sinking stage was analyzed through simulation test of sinking of open caisson based on the same construction.
work[5]. Through the sinking simulation of the open caisson in four different depth conditions, the earth pressure distribution on incline of the cutting edge has been studied. In the sinking stage, the scale factor of incline and tread per unit width remained the same[6].

Existing studies mostly focus on small or medium-sized caissons, but few on the bottom resistance of large or super-sized ones. The distributive properties of bottom resistance of small or medium-sized caisson (lateral friction plays a leading role in the sinking stage) are different from the ones of large or super-sized caissons. In addition, the bottom resistance of incline of cutting edge and the shape effect of cutting edge on bottom resistance are rarely studied. Therefore, studying on the bottom resistance during the sinking stage is of great engineering significance to guide the earth excavation.

In this paper, a practical method is proposed of bottom resistance based on the scale factor of earth pressure on incline and tread of cutting edge. Taking the super-sized caisson foundation of the long-span bridge, the bottom resistance during sinking stage was analyzed. The variation characteristics of bottom resistance were studied, especially the variation law of the bottom resistance with typical earth extraction processes, which guided the determination of earth excavation scheme and prediction of sinking situation of open caisson.

2. Calculation methods of bottom resistance

The sinking process of open caisson can be considered as quasi-static process if this process is steady, uniform and no sudden sinking. In this process, the open caisson is in equilibrium condition under the action of gravity, buoyancy, bottom resistance and lateral friction. The bottom resistance of the caisson is provided by the soil in the limit state around the cutting edge.

There are three main methods for calculating ultimate bearing capacity of soil under a caisson: slip line method, limit analysis method and limit equilibrium method[3]. Compared with the other two methods, the limit equilibrium method is simple in theory and convenient in calculation, which has been widely used in engineering calculation and analysis[7].

When the limit equilibrium method is used to calculate the bottom resistance, the bottom resistance is equal to sum of products of the bearing area (the projection area of the soil in contact with the the bottom of the caisson) and the ultimate bearing capacity of the soil in different zones:

\[
 R_b = \sum_{i=1}^{n} (p_i^u \times A_i) \tag{1}
\]

where, \( R_b \) is the bottom resistance, \( p_i^u \) is the ultimate bearing capacity of soil in different zones of caisson, \( A_i \) is the bearing area in corresponding zone, \( n \) is the total number of zones of a caisson.

2.1. Traditional method for calculating ultimate bearing capacity of soil

Terzaghi’s bearing capacity equation is the most general formula for calculating the ultimate bearing capacity of soil[8]. The corresponding theoretical model assumes that there is a distribution load of vertical directions on the horizontal strip foundation, ignoring scale effect of the foundation and the influence of soil shear strength on both sides of the foundation. The computational expression is

\[
 p_u = \frac{\gamma h}{2} N_i + c N_c + q N_q \tag{2}
\]

where, \( p_u \) is ultimate bearing capacity of soil; \( N_i, N_c, N_q \) are bearing capacity factors, which are determined only by internal friction angle of the soil and can be decided by checking table. Mayerhof, Hansen et al generalized the Terzaghi’s bearing capacity equation[9]. By using the shape correlation coefficient of foundation, depth correction coefficient, correction coefficient of inclined load, correction coefficient of inclined floor and correction coefficient of inclined foundation bottom, the formula can be applied to more general cases.

In addition, some researchers estimate ultimate bearing capacity by calculating the product of allowable bearing capacity of foundation soil and a safety factor above 1 or based on engineering experience[6].
2.2. Determination of bearing area

There are different methods for calculating the bearing area of the cutting edge at the end of open caisson (including the cutting edge with single incline shown in figure 1 (a) and the cutting edge with double inclines shown in figure 1 (b)). The common methods include: Taking the area of tread of the cutting edge as the bearing area; The sum of the projected area of incline of the cutting edge and the area of tread is regarded as the bearing area; The sum of the projected area of incline of multiplied by 0.5 and area of the tread is taken as bearing area. The above three calculation methods can be expressed by:

\[ A = A_t + \lambda A_b \]  

where, \( A \) is the bearing area of the cutting edge, \( A_t \) is the area of tread of the cutting edge, \( A_b \) is the projected area of incline of the cutting edge, \( \lambda \) is a scale factor.

In the process of steady sinking of open caisson, the bottom resistance is the product of ultimate bearing capacity of soil and the bearing area (Eq. 4), and it can also be expressed as the sum of the bottom resistance of incline and tread of the cutting edge(Eq. 5).

\[ R_b = p_u (A_t + \lambda A_b \sin \beta) \]  
\[ R_b = p_i A_t + p_i A_b \sin \beta \]  

Where: \( A_t \) is the area of tread of the cutting edge; \( \beta \) is the angle between incline of the cutting edge and vertical direction (as shown in figure 1); \( A_b \sin \beta \) is equal to the projected area of incline (\( A_b \)); \( p_u \) is the earth pressure on tread, which is equal to \( p_u \) when the open caisson sinks steadily; \( p_i \) is the earth pressure on incline; \( p_i A_b \sin \beta \) represents the vertical component of the resultant force of earth pressure on incline.

Eq. (6) can be obtained by combining Eq. (4) and Eq. (5).

\[ \lambda = \frac{p_i}{p_u} \]  

It can be seen from Eq. (6) that \( \lambda \) is the scale factor of earth pressure on incline and tread of the cutting edge, which is abbreviated as the scale factor.

![Schematic diagram of the cutting edge](image)

(a) The cutting edge with single incline  
(b) The cutting edge with double inclines

2.3. Calculation method of bottom resistance based on earth pressure on tread of cutting edge

In order to accurately calculate the bottom resistance of the caisson foundation, it is necessary to obtain reliable ultimate bearing capacity of soil (\( p_u^* \)) and the corresponding bearing area (\( A \)). In the existing research, the limit equilibrium method is generally used to calculate the ultimate bearing capacity of soil. This method obtains ultimate bearing capacity based on the shallow foundation model of soil mechanics, and is applied to engineering after depth and width correction. The conventional method ignores the influence of the shape of cutting edge and the spatial effect of the soil near the bottom, and the calculation results often deviates from the actual ultimate bearing capacity.

When calculating the bearing area, as described in Section 2.2, the scale factor (\( \lambda \)) is generally predetermine based on engineering experience, which has strong subjectivity.
In view of the above shortcomings, a calculation method of bottom resistance based on monitoring data of earth pressure on tread of the cutting edge is proposed. When calculating the bottom resistance, the ultimate bearing capacity of soil and the scale factor are determined by monitoring value of earth pressure, which is obviously more conform to reality.

During the quasi-static process during sinking stage of caisson foundation, the sum of bottom resistance, lateral friction and buoyancy equals to the gravity of the caisson (Eq. 7).

\[ G = R_b + R_f + N_w \]  

(7)

Where, \( G \) is the gravity of open caisson, \( R_f \) is the lateral friction, \( N_w \) is the buoyancy of the caisson. If the caisson includes \( n \) regions, the expression of bottom resistance (\( R_b \)) is:

\[ R_b = \sum_{i=1}^{n} \left( p_i^u \times A_i \right) = \sum_{i=1}^{n} \left( p_i^u \times (A_i^e + \lambda_i A_i^o) \right) \]  

(8)

Eq. (9) can be obtained by combining Eq. (7) and Eq. (8).

\[ G - R_f - N_w = \sum_{i=1}^{n} \left( p_i^u \times (A_i^e + \lambda_i A_i^o) \right) \]  

(9)

The bottom resistance is directly related to whether the large caisson can sink smoothly or not. Therefore, in recent years, sinking constructions of large caissons equip earth pressure cells on treads or inclines to monitor the earth pressure of soil near the cutting edge during sinking of open caisson. The measured earth pressure at the cutting edge is the reaction force of the soil under the cutting edge in the sinking process. Compared with the conventional calculation methods, it is undoubtedly more accurate to reflect the actual value of the earth pressure.

According to the measured values of earth pressure, the quantity \( p_i^u \) in Eq. 9 belongs to the known quantities, and only scale factors (\( \lambda \)) are unknown quantities. When the number of groups of monitored data of earth pressure is greater than or equal to the number of the partitions at the end of the caisson, the scale factors can be calculated. On the basis of it, the bottom resistance of each partition can be further calculated.

3. Engineering example

3.1. Introduction

Taking the super-deep and super-large open caisson foundation of the main tower of a long-span road-rail cable-stayed bridge as an engineering example. With a total height of 72m, the plane form of the caisson foundation is rounded shape and the facade form is step shape. The lower step is 95m in length, 57.8m in width, 43m in height and 28.9m in radius of round end, while the upper step is 77m in length, 39.8m in width, 29m in height and 19.9m in radius of round end. The plane of caisson is divided into four zones: outer bulkhead, inner bulkhead, outer partition walls and inner partition walls (figure 2). The research stage is the first sinking stage of the caisson through earth excavation, and the elevation of soil in well holes before earth extraction is -30.8m. Excavating soil by region, and the specific processes are shown in Table 1.

| Process number | Process details | Process time/day | Total time/day |
|----------------|-----------------|------------------|---------------|
| 1              | Excavating soil to -31.35m in 18 well holes in the centre of caisson | 7               | 7             |
| 2              | Excavating soil to -31.85m in 18 well holes in the centre of caisson and blind area under the inner partition walls | 5               | 12            |
| 3              | Excavating soil to -32.85m in the area within 2.0m outside the inner bulkhead | 9               | 21            |
3.2. Calculation results of bottom resistance

The average values of the earth pressure of cutting edge in different regions were calculated respectively (shown in figure 3). After the first earth excavation, the cutting edge has sunk into the soil 2.15m, which was only slightly larger than the height of the cutting edge of outer bulkhead (2.0m) Therefore, the lateral friction of the caisson could be ignored in the first earth excavation process. The calculation method of bottom resistance in Section 2.3 was used to calculate the bottom resistance of each region of the super-sized caisson foundation. Figure 4 shows the distribution and variation of the bottom resistance in each region.

Before earth excavation, the bottom resistance of the outer bulkhead was 26.27 kilotons, followed by the inner partition walls, which was 18.08 kilotons. The bottom resistance of the inner bulkhead was 10.08 kilotons, and the one of the outer partition walls is the smallest, which was 8.72 kilotons. At the end of the first earth excavation, the bottom resistance of the four areas were outer bulkhead was 42.17 kilotons, 4.97 kilotons, 6.27 kilotons and 9.80 kilotons.

In the process of earth excavation in central well holes of the caisson (process 1), the bottom resistance of the inner partition walls decreased by 6.60 kilotons, the ones of the outer partition walls and the inner bulkhead increased slightly, and the one of the outer bulkhead increased significantly (about 4.78 kilotons). In the earth excavation process of the central well holes and blind area under the inner bulkhead (process 2), the bottom resistance of the inner partition walls was reduced by 3.31
kilotons, and the one of the inner bulkhead was reduced by 2.57 kilotons. The bottom resistance of the outer bulkhead was increased by 3.22 kilotons; The bottom resistance of the outer partition walls was increased by 2.66 kilotons. During the process of earth excavation from the surrounding well holes and the blind area under the inner bulkhead (process 3), the bottom resistance of outer bulkhead first increased significantly and then decreased slightly, reaching a peak value of 43.53 kilotons, the bottom resistance of outer partition walls decreased by 3.22 kilotons, and the ones of inner bulkhead and the inner partition walls area fluctuated around 6.0 kilotons.

According to the time travel curve of bottom resistance changing with earth excavation processes, the bottom resistance of the inner bulkhead and the inner partition walls decreased gradually with the earth excavation in central well holes (process 1 & process 2), while the ones of the outer bulkhead and the outer partition walls gradually increased. During these processes, the bottom resistance transferred to surrounding area from the central area of the caisson. In the process of soil excavation in the surrounding well holes (process 3), the bottom resistance of the outer partition walls decreased, while the one of the outer bulkhead continued to increase, and the bottom resistance of the caisson was mainly concentrated in the outer bulkhead.

4. Conclusions

By using the proposed method in this paper, the variation characteristics of bottom resistance were studied, which guided the determination of earth excavation scheme and ensured the smooth sinking of the caisson foundation. The main conclusions are as follows:

(1) Based on field monitoring earth pressure on the cutting edge, a practical method was proposed considering the scale factor between the earth pressure on incline and tread of the cutting edge and the bottom resistance can be reasonably determined. Moreover, the distribution characteristics and variation of bottom resistance during earth excavation were analyzed, which has important engineering significance to guide the sinking of caisson.

(2) During the sinking stage of the caisson foundation, the bottom resistance of the inner partition walls and the inner bulkhead decreased gradually, while the one of the outer bulkhead area increased gradually. The bottom resistance of outer partition walls increased slowly in the processes of earth excavation from central well holes and blind area under the inner bulkhead but decreased in the process of earth excavation from surrounding well holes.

(3) With the earth excavation, the bottom resistance was gradually concentrated in the outer bulkhead. Once the soil under the cutting edge of the outer bulkhead reached the limit state, the caisson appeared obvious subsidence.

(4) It is suggested that the earth pressure of the cutting edge in outer bulkhead and the outer partition walls should be paid special attention during the sinking stage of the caisson. The ultimate bearing capacity of the soil should be reasonably determined in the further study.

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Reference

[1] Zhang, Z., Deng, Y., Zheng, F., Wang, J. (2020) Analysis on sudden sinking behaviors of massive open caisson in deep-thick soft clay area. Chinese Journal of Underground Space and Engineering, 16: 933-943.

[2] Chen, X., Qian, P., Zhang, Z. (2005) Study on penetration resistance distribution characteristic of sunk shaft foundation. Chinese Journal of Geotechnical Engineering, 27: 148-152.

[3] Mu, B., Wang, Y., Zhu, J., Gong, W., Ouyang Z. (2012) Analysis of large caisson sinking measured resistance. Journal of Civil, Architectural & Environmental Engineering, 34: 107-115.
[4] Zhou, H., Ma, J., Li, J., Zhang, K., Yang, B. (2019) Field monitoring of sinking resistance of large and deep caisson. Journal of Highway and Transportation Research and Development, 36: 81-89.

[5] Jiang, B., Ma, J., Li, M., Chu, J. (2019) Experiments on spatial stress of foot blade during caisson sinking in water. Rock and Soil Mechanics, 40: 1693-1703.

[6] Zhou, H., Ma, J., Zhang, K., Luo, C., Yang, B. (2019) Study of sinking resistance of large and deep caisson based on centrifugal model test. Rock and Soil Mechanics, 40: 3969-3976.

[7] Shi, Z., Li, S., Yang, S., Feng, C. (2019) Study on the characteristics of friction resistance and the mechanism of sudden sinking in the middle and late sinking stages of super large caisson foundation. Chinese Journal of Geotechnical Engineering, 38: 3894-3904.

[8] Yan, F., Shi, G. (2013) Analysis of limiting soil resistance beneath cutting curb during sinking of open caisson. Rock and Soil Mechanics, 34: 80-87.

[9] Li, G., Zhang, B., Yu, Y. (2013) Soil Mechanics. Beijing: Tsinghua University Press, Beijing.