Study of the Construction Technology of Caisson Under Complex Geological Conditions

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Abstract. Taking a project in southwest China as an example, this paper analyses the design and construction of pipe jacking caisson under the complicated geological conditions, discusses the problems with suspension of construction and waterproofing, optimises the construction technology of the undrained underwater concrete bottom seal in the caisson. The construction quality of the project conforms to the standard of inspection and evaluation, the methods of calculation can be used for reference in similar projects.

1. Introduction
For the pipe jacking construction process, caisson technology is very mature in China, and the technology reduces the influence of large area slotted pipe, especially in areas rich in groundwater. As long as the subsidence conditions are reasonable, the technology can be adapted to almost any soil [1-3], and withstand horizontal thrust to a large degree, which can be widely used in the operation of no slotted pipe jacking. At the same time, due to the application of unscientific calculation methods and schemes used in the design and construction process [4-5], there may have been cracks in the shaft lining concrete, segmented joints, inadequate treatment of the construction joints, water seepage, and so on. Moreover, due to the complex geological conditions, the construction is more difficult.

In this paper, the construction of pipe jacking caisson under the geological condition of quicksand is taken as an example, the design is improved in terms of the aspects of the nodal subsidence height, the bottom thickness of the underwater concrete, and so on. The technical measures taken to strengthen the construction quality are also proposed.

2. Project profile
Deal with domestic sewage in the area is the main task of the project, and the quantities are as follows: 1 sewerage plant; 2 lifting pump station; main pipe network along lake for 17.1km; channel branch line for 19.6km; 18 full-line pipe jacking well(6.5m×3.5m, φ6.5m); 18 receiving wells(5.0m×3.5m, φ5.0m); 31 riding well(φ1.6m), caliber is d600~1000mm, and the buried depth is 3.6m-10m. All of the working wells are constructed by caisson and segmented. C30P6 concrete is used in shaft lining, and the size of concrete iron is C12mm and C16mm, the bottom concrete use undersea C35P6.

Due to the project is near the sea area, so the groundwater is porous diving. The maximum high-water is 1966.0m. According to the survey data, the physical and mechanical properties of each soil layer are shown in Table 1.
Table 1. Physical and mechanical properties of each soil layer.

| No. | Solum     | Depth | Natural Density $r$ (kN/m$^3$) | Natural Moisture Content $w$ (%) | Natural Void Ratio $e$ | Liquidity Factor $I_L$ | Poisson ratio $\mu$ | Bearing capacity eigenvalue $f_{ak}$ (kPa) | Average indoor permeability coefficient $K$ (cm/s) |
|-----|-----------|-------|---------------------------------|---------------------------------|-----------------------|-----------------------|-------------------|--------------------------------------------|-----------------------------------------------|
| 1   | Mool      | 3.8m  | 14.0                            | /                               | /                     | /                     | /                 | /                                          | /                                             |
| 2   | Silty clay| 1.7m  | 18.7                            | 33.3                            | 0.957                 | 0.41                  | 0.35              | 110                                        | $34.00 \times 10^{-6}$                      |
| 3   | Silt      | 4.5m  | 18.4                            | 22.3                            | 1.004                 | /                     | 0.28              | 125                                        | $576.50 \times 10^{-6}$                      |

3. Calculation and analyses of sinking process

The height of the sinking is up to 10m. To ensure the stability of caisson and reduce the thickness of concrete cushion under the edge of caisson, the caisson is made in two sections, sink for twice, the height of Section 1 is 6.0m and the height of Section 2 is 4.0m.

3.1 Checking calculation of sinking in sections of caisson

Before the sinking of the caisson, check the settlement of the drawn sunk well. The following formula is used to calculate the subsidence coefficient:

$$ K = \frac{Q - S}{T + R} $$

In this formula: $K$ is sinking safety factor which is generally greater than 1. 15-1. 25; $Q$ is the weight of caisson and additional load(kN); $S$ is the amount of water discharged by the shaft wall(kN), $S$ is equal to 0 if drainage is taken to sink; $T$ is the friction force between caisson and soil(kN); $R$ is the blade reaction force(kN), $R$ is equal to 0 if the earth on the bottom and slope of the blade is hollowed.

The size of caisson is 6500mm×3500mm, drainage works are used and earthwork on the bottom of the blade and the slope surface is hollowed out in the sinking project. So $Q_1=2056.32$ kN, $Q_2=1370.88$ kN; $S=R=0$; $T=1780.8$ kN. Sinking of caisson in section 1 is $K_1=2056.32/1780.8=1.15\geq 1.15$, and sinking of caisson in section 2 and 3 is $K_2=(2056.32+1370.88)/1780.8=1.92\geq 1.25$, which are qualified with the requirement of sinking.

In conclusion, the height of Section 1 is 6.0m and the height of Section 2 is 4.0m.

3.2 Settlement stability checking calculation

When the caisson sinks in soft soil, sudden sinking may occur, so it is necessary to check the stability of sinking caisson. The calculation formulas are as follows:

![Figure 1. Caisson size and geological profile.](image)
\[ K' = \frac{G - S}{R_1 + R_2 + R_3} \]  

\[ R_1 = 2\left(B_0 + L_0\right)\times \left(C + \frac{n}{2}\right) f_u \]  

\[ R_2 = A_1 f_u \]

\( K' \) is the sinking stability factor of the caisson, which should be less than 1; \( G \) is the gravity of caisson; \( S \) is groundwater buoyancy, it’s equal to 0 if drainage sinking, and equal to 70% of total buoyancy when undrained; \( R_1 \) is the summation of effective friction on the outer wall of caisson; \( R_2 \) is the supporting force of the soil under the blade foot surface and the inclined surface; \( B_0 \) is the average length of caisson and \( L_0 \) is the width of caisson; \( C \) is the width of blade tread (m); \( n \) is the horizontal projection width of the interface between the slope of the edge foot and the soil in the well(m); \( R_2 \) is the supporting force of inner partition wall and soil under bottom beam in caisson; \( f_u \) is the design value of bearing capacity of bearing layer(kN/m²), \( f_u = 125 kN/m^2 \); \( A_1 \) is the total supporting area of partition wall and bottom beam and it’s equal to 0.

\[ R_f = 2\times(6.5+3.5)\times(16\times3.8+19\times1.7+17\times4.5) = 3392 \text{ kN}; \quad R_1 = 2\times(7.1+4.1)\times(0.3+0.3/2)125 = 1260 \text{ kN}; \]

\[ K'=(2056.32 \text{ kN}+1370.88 \text{ kN})/(3392 \text{ kN} +1260 \text{ kN})=0.74<1.0. \] The caisson can be stabilized under self-weight.

4. Strengthening technical measures in construction

4.1 High pressure rotary grouting pile construction

Because the caisson works through the strong permeable layer, a single heavy pipe high pressure rotary jet grouting pile is set up around the caisson as a waterproof curtain. The pile diameter is 600mm, distance between piles is 400mm, occlusal distance is 200mm.

4.1.1 Construction technology. Pile position lofting; rig in position to adjust perpendicularity (using horizontal ruler); open hole inspection; drilling hole; test spray inspection; high spray operation; observation of high spray parameters; fill in a record form; finish.

4.1.2 Construction measures. According to the design pile position, the pile driver accurately positioned to make horizontal correction [7], and the deviation rate of hole formation is not greater than 1%. If the location of the pile machine is not accurate, it will lead to insufficient distance between piles and occlusal distance. The water cement ratio is 0.8–1.5. Immediately stop the operation and readjust the size when the specific gravity of the slurry exceeds 0.1. The cement content of high pressure rotary jet pile reach 210 kg/m³. The grouting pressure of rotary jet grouting pile is 15–20MPa, the grouting volume is 60–70 L/ min and speed is 5–16R/min, at the same time, the speed of lifting is 7–20cm/min; In construction, low speed and slow lifting are adopted to achieve the effect of full mixing and mixing of cement and soil. After cementing, the strength of the pile is \( f_{cu} \geq 2.0 \text{MPa}, \) the shear strength is more than 0.2\( f_{cu} \) and the tensile strength is more than 0.06\( f_{cu} \).

4.1.3 Problems easily occurred in construction. When the high-pressure pump is installed on the spot, the distance from the nozzle to the high-pressure pump should be less than 20 m.[8]

In the process of rotary jet grouting, if the amount of grouting is more than 20% of the amount of grouting, or no grouting at all, and so on. Immediately upon analysis of the situation on the spot to find out the cause, there may be special geological environments such as quicksand or karst cave. The supply of slurry, gas and water must be continuous to ensure the integrity of the pile. [9]However, in case of interruption, the jet pipe must be sunk to 0.5m below the stop point when the supply is
resumed. If stop for more than 2 hours, avoid clogging, pump body and slurry pipe should be cleaned properly.

4.2 Well foundation

4.2.1 Instrumentation control. Check the existing positioning piles and elevation points, After the confirmation is correct, set the corresponding points of the control pile on the four sides of the shaft wall. At four corners, red paint is used to make the ruler, with a distance of 500 mm, so that the sinking process of the caisson is monitored in both ways. According to the scale that has been made as the horizontal observation point, using the level every 1 hour omnidirectional observation, correct the deviation in time; In addition, the midline is marked on the shaft wall, and the plane position is strictly controlled according to the design requirements.

4.2.2 Measure control. According to the unique geological conditions and site construction environment of the project, various problems are easy to occur, and countermeasures should be taken according to the specific conditions. When the depth is shallow, artificial excavation on the high side of the blade foot and proper sand filling on the lower side of the edge foot are used to correct the deviation.

When the depth is deep, we may consider correcting the deviation by injecting water out of the well and removing soil from the inner side of the well. If the effect is not good, take the drainage method to carry on the construction. First, the higher side of the blade foot is gradually rectified, and in the process of correcting the deviation, the caisson is inclined in the direction of deviation. Until the central axis of the bottom surface of the caisson is coincident with the design axis, and then the subsidence continues to correct the deviation along the inclined direction, so that it can be adjusted to the allowable range.

4.2.3 Underwater bottom sealing. Due to the high underground water level outside the well, undrained caisson sinking is used to seal the bottom of underwater concrete to avoid the phenomenon of flowing sand under a certain head pressure[10]. The concrete pump is used to pump into the collecting hopper to fill the caisson with commercial concrete through the conduit.

The construction process is as follows: leveling of the bottom of the underwater pot; placement catheter; storing; pouring; lifting catheter; end of pouring; measurement and acceptance.

The calculation and analyses are as follows: The roof of the caisson is set up with pouring working platform to ensure the supernatural surface is 2.5m, catheter diameter is 250mm, the diffusion radius of the duct is 2.5 m and the buried depth of the nozzle is not less than 0.5 m, the following formula shall be used to calculate:

\[ V_c \geq \frac{\pi d^2 h_1}{4} + \frac{k \pi r^2 h_2}{3} \]  \hspace{1cm} (5)

\[ h_1 \geq \frac{(h - h_b) \gamma_w}{r_c} \]  \hspace{1cm} (6)

\( V_c \) is the initial pouring of concrete(m³); \( h \) is the depth from the water level to the base, the value is 7.94m; \( h_1 \) is the height required for balancing the concrete column between the conduit and the slurry column outside the pipe(m); \( h_2 \) is diffusion height of concrete outside conduit after initial grouting, the value is 1.34m; \( d \) is the ductal diameter, the value is 0.25m; \( r \) is the diffusion radius, the value is 2.5m; \( k \) is the filling coefficient, the value is 1.3; \( \gamma_w \) is the severe of water, the value is 9.8kN/m³; \( \gamma_c \) is the severe of concrete, its value is 24kN/m³. So:
\[
V_c \geq \frac{\pi d^2 h_c}{4} + \frac{k\pi r^2 h_i}{3} \\
= \frac{\pi \times 0.25^2 \times 2.7}{4} + \frac{1.3 \times \pi \times 2.5^2 \times 1.34}{3} \\
= 11.5 \text{m}^3 \\
h_i \geq \frac{(h - h_c)\gamma_c}{\gamma_w} = \frac{(7.94 - 1.34) \times 9.8}{24} \\
= 2.7 \text{m}
\]  

(7)

(8)

In the design of concrete mix ratio, the initial setting time is guaranteed to be 4 h. The rising speed of concrete surface is \( V = \frac{H}{t} = \frac{1.5}{4} = 0.38 \text{m/h} \).

Strengthening construction technical measures: The underwater C35P6 plain concrete is poured by the method of conduit, and the caisson is divided into two case, symmetrical and one-off pouring per case. During the whole process of pouring, the rise of underwater concrete surface is continuously measured by measuring rope. At the same time, according to the scale on the conduit and the water depth measured by the rope, the elevation of the lower end of the conduit is calculated, ensure the buried depth of the conduit is not less than 0.5 m.

4.2.4 Construction joint. The technical measures of strengthen the construction quality are carried out to prevent the phenomenon of water seepage at the side wall joint. The concrete horizontal construction joint practices are as follows: Firstly, the top surface groove is reserved by hardwood strip before the first caisson is made; Secondly, the hardwood strips are removed to locate the sealing strips in the trench after the concrete is coagulated. Then the WJ interface binder, which has remarkable bond ability to the old concrete interface, is used to bond the water stop strip well in the form of adhesive paste, and finally the cement nail is used to reinforce the watertight strip. The water swelling part of the exposed groove surface is less than 150mm.

5. Conclusion

During the construction of the caisson under complicated geological conditions, the safety and reliability of the sinking process are verified and analysed by using the criteria and empirical estimation formula provided in the Concise Construction Manual. The analysis provides reference for the design and construction of the caisson in quicksand layers or under other bad geological conditions.

Based on the analysis of the standard formula, concrete proportion design, and site construction arrangement, this paper proposes construction measures to implement by using undrained underwater concrete to seal the bottom of the strong permeable layer to avoid the occurrence of quicksand. This not only prevents the caisson from sinking too much, but also effectively prevents the surrounding structures from inclining and cracking due to soil collapse, and greatly reduces the drainage cost.

For the waterproof engineering, some technical measures are adopted to reduce the influence of the groundwater level, such as applying a high pressure rotary jet pile around the well body and setting a water expansion stop belt at the horizontal construction joint of the sidewall.

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