Research and application of double-row steel sheet pile stability in soft soil foundation

Chao-xuan Huang1*, Yue Liu1, Zhi-wei Yao2, Jun-jie Li1, Yong Xia1

1Zhejiang Design Institute of Water Conservancy and Hydroelectric Power, Hangzhou 310002, China.
2Zhejiang Urban Construction Survey and Research Institute Co., Ltd, Hangzhou 311112, China.

Email: hcx8311@mail.zdwp.net, ly7088@mail.zdwp.net, zjcjkc@qq.com, ljy8903@mail.zdwp.net, xy8810@mail.zdwp.net

* Corresponding Author; Email: hcx8311@mail.zdwp.net; Phone:+86057186073122; Fax: +86057186073122

Abstract: In view of the complex stability calculation of double-row steel sheet piles in soft soil foundation, based on the theory of soil mechanics, the control analysis was carried out from the aspects of anti-uplift stability, overall anti-slip stability, anti-overturning stability, and overall sliding stability of the sheet pile. By theoretical derivation and calculation, the calculation formula of the minimum penetration depth \( L_d \) of steel sheet piles is given. Taking the double-row steel sheet pile cofferdam project of the sluice of the Oufei Reclamation Project in Zhejiang Province of China as a case, according to the formula in this paper, the recommended minimum depth of soil penetration is 17.01m, which is basically the same as the actual design value of 18.50m. Combined with the finite element soft foundation, the comparative analysis of simulation calculation results and the measured horizontal displacement monitoring data of steel sheet piles provides references for related engineering applications.

1. INTRODUCTION

Steel sheet piles were used in Europe at the beginning of the 20th century, and then made great progress in Europe and Japan. Compared with single-row steel sheet piles, double-row steel sheet piles have greater overall rigidity, safety and stability, and are more reliable. It has the advantages of small area and is widely used in the construction of cofferdams and foundation pits in such fields as docks, wharves, bridges, sluices, pumping stations, etc. in China.

Byfield, M. P, etc. [1]. R. W. Mawer, etc. [2], R.J. Crawford, etc. [3] studied the problem of reducing modulus of steel sheet pile interlocking problems. MP Doubrovsky et al. [4] carried out a numerical simulation analysis on the steel sheet pile-soil correlation. GuhaRay, A. et al. [5] studied the reliability of steel sheet piles. Rens, KL et al. [6] conducted optimization problems on the structure of steel sheet piles. Gajan, Sivapalan [7] studied the sheet pile wall structure in sand. Zhang Yucheng et al. [8] used finite element method to calculate and analyze the typical cofferdam supporting structure. The double-row pile supporting structure is explained in foundation pit code [9], but even if the design of the double-row steel sheet pile is not involved. CEN [10] explains the calculation of the sheet pile structure.
However, there is less application of double-row steel sheet piles in coastal soft soil foundations, and their engineering practice experience is also lacking, especially for wide sea reclamation silt foundations. Therefore, this article relies on a large-scale reclamation project in Zhejiang Province of China to summarize and refine the design and construction key technologies such as the depth of the double-row steel sheet pile cofferdam in the deep and soft soil foundation in the wide sea area, and provide a reference for the design and construction of similar projects.

2. ANALYSIS OF CALCULATION MODEL OF DOUBLE-ROW STEEL SHEET PILES

2.1. MODEL ANALYSIS

For the double-row steel sheet pile structure in the deep silt foundation in the wide sea area, the foundation-soil porosity ratio is large, the water content is high, and the bearing capacity is poor. At the same time, it is affected by the tide level of the sea and the action of the wave load, so the force form is complicated. Therefore, the following simplified model calculations are used (Figure 1).

![Figure 1. Schematic diagram of calculation model for double-row steel sheet piles](image)

2.2. STRUCTURAL STABILITY ANALYSIS

According to the calculation formula for the stability of the bottom for the double-row steel sheet pile:

\[
\frac{(\gamma_m L_d + \gamma_s h)N_q + c_{m2}N_c}{(\gamma_s H + \gamma_m L_d) + q_0} \geq K_b
\]

(1)

Where, \( N_q = \tan^2(45^\circ + \varphi_{m2}/2) \cdot \exp(\pi \tan \varphi_{m2}) \). \( N_c = (N_q - 1)/\tan \varphi_{m2} \), \( K_b \) is the anti-heave safety factor[10], and \( K_b \geq 1.4 \). \( \gamma_m \) is the average weight of the soil layer within the depth of the steel sheet pile into the soil (kN/m³). \( \gamma_s \) is the weight of the backfill in the double-row steel sheet pile (kN/m³). \( q_0 \) is the uniform load applied on the top surface of the double-row steel sheet pile (kPa). \( N_c \) and \( N_q \) are the bearing capacity coefficients. \( \gamma_s \) is the weight of the suppressed layer of riprap on the inner and outer sides of the double-row steel sheet pile (kN/m³).

According to the overall slip stability and safety calculation formula:

\[
\frac{E_{pl} + (G - u_m B) \tan \varphi_{m2} + c_{m2} B}{E_{pl} + F_w} \geq K_{sl}
\]

(2)
Where, $K_{s1}$ is the anti-skid safety factor [9], and $K_{s1} \geq 1.2$. $E_{ak}$ and $E_{pk}$ are the active earth pressure and passive earth pressure on the equivalent gravity structure respectively. $G$ is the dead weight of the equivalent gravity structure. $u_m$ is the water pressure on the bottom surface of the equivalent gravity structure. When it is located in the aquifer, $u_m=\gamma_w(h_{wa}+h_{wp})/2$; $h_{wp}$ and $h_{wa}$ are the pressure heads inside and outside the equivalent gravity structure. $B$ is the width of the bottom surface of the structure. $F_w$ is the wave pressure under the action of the wave.

Based on the anti-overturning stability calculation:

$$E_{ak}a_p + (G - u_B)a_a \geq K_{ov}$$  \hspace{1cm} (5)

Where, $K_{ov}$ is the anti-overturning safety factor [9], and $K_{ov} \geq 1.3$; $a_a$ is the vertical distance from the reasonable point of active earth pressure outside the gravity structure to the bottom toe. $a_p$ is the passive soil inside the gravity structure the vertical distance from the reasonable point of pressure to the bottom toe. $a_a$ is the vertical distance from the point of action of the resultant force of the equivalent gravity structure and the bottom water pressure to the bottom toe. And $a_w$ is the difference between the point of action of the resultant wave pressure under the action of the wave and the painted surface.

The overall sliding stability of double-row steel sheet piles is calculated by the Swedish strip method and the total stress method:

$$K_s = \frac{\sum [W_i \cos \alpha_i \tan \phi_{mi} + c_{mi} b_i \sec \alpha_i]}{W_i \sin \alpha_i}$$  \hspace{1cm} (6)

Where: $K_s$ is the overall sliding stability safety factor. $W_i$ is the sliding arc length and weight of the soil strip (kN). $b_i$ is the width of the i-th soil strip. $c_{mi}$ is the cohesive force of the soil on the sliding surface of the soil strip. $\phi_{mi}$ is the internal friction angle on the sliding surface of the soil strip. $\alpha_i$ is the angle between the tangent line of the midpoint of the sliding surface and the horizontal line.

3. RESULTS

According to the above anti-uplift calculation formula (1), the equation about $L_d$ is solved, and the soil penetration depth of the steel sheet pile under anti-uplift stability is satisfied:

$$L_d \geq K_{s1}(\gamma H + q_a) - c_{n2}N_q - \gamma hN_w$$  \hspace{1cm} (7)

According to the above formula (2) of the overall slip stability calculation, combined with formulas (3) and (4), the one-dimensional quadratic equation deduced by mathematical theory, according to actual engineering experience, generally $B=H$ can be taken to obtain the steel sheet pile penetration depth for:

$$L_d \geq \frac{-A_i + \sqrt{A_i^2 - 4A_iA_0}}{2A_i}$$  \hspace{1cm} (8)
Where:

\begin{equation}
A_i = \left[ \frac{1}{2} \gamma_a \tan \left( 45^\circ + \varphi_a \right) - \frac{1}{2} K_s \gamma_a \tan \left( 45^\circ - \varphi_a \right) \right];
A_i = \left[ 2 \gamma_a \tan \left( 45^\circ + \varphi_a \right) + \gamma_a \tan \varphi_a + 2 K_s \gamma_a \tan \left( 45^\circ - \varphi_a \right) \right];
\end{equation}

\begin{equation}
A_i = \left( c_{m2} - u_m \tan \varphi_a \right) B + \gamma_a H \tan \varphi_a = \left( K_s F_h + \frac{2 K_s \gamma_a}{\gamma_a} \right).
\end{equation}

According to the above anti-overturning stability calculation formula (5), it can be seen that combining formulas (4) and (5), through mathematical theory derivation, it is solved by the one-dimensional cubic equation Katang formula. And the above equation can be solved to meet the anti-overturning stability of steel sheet piles. The depth of entry meets:

\begin{equation}
L_d \geq \eta \cos \theta - \frac{D_3}{3 D_4},
\end{equation}

Where:

\begin{equation}
\eta = \left( -\frac{A_i}{3} \right)^{1/3}; \theta = \frac{1}{3} \arccos \left[ \frac{\beta_2}{\beta_3} \left( \frac{\beta_3}{\beta_2} \right)^{1/3} \right], \quad \beta_2 = \frac{D_4}{D_3} \left( \frac{D_2}{D_3} \right)^2; \quad \beta_3 = \frac{D_4}{D_3} \frac{D_2}{D_3} \left( \frac{D_4}{D_3} \right)^2 + \frac{2}{27} \left( \frac{D_2}{D_4} \right)^3,
\end{equation}

\begin{equation}
D_1 = \frac{1}{6} K_s \gamma_a \tan \left( 45^\circ - \varphi_a \right) h_{m2}^2 - K_s F_h a_n x, \quad D_2 = \frac{1}{6} \gamma_a \tan \left( 45^\circ + \varphi_a \right) h_{m2}^2 - K_s F_h x,
\end{equation}

\begin{equation}
D_3 = \frac{1}{6} \gamma_a \tan \left( 45^\circ + \varphi_a \right) h_{m2}^2 + K_s \gamma_a \tan \left( 45^\circ - \varphi_a \right) h_{m2}^2 - K_s F_h x,
\end{equation}

\begin{equation}
D_4 = \gamma_a \tan \left( 45^\circ + \varphi_a \right) h_{m2}^2 - K_s \gamma_a \tan \left( 45^\circ - \varphi_a \right) h_{m2}^2 - K_s F_h x,
\end{equation}

and

\begin{equation}
h_{m2} = \frac{2 \gamma_a}{\gamma_a \tan \left( 45^\circ - \varphi_a \right)}.
\end{equation}

Based on the above analysis, the initial design value of the depth \( L_d \) of the double-row steel sheet pile structure can be selected to meet the maximum value of the calculated values of anti-uplift stability, overall anti-slip stability and anti-tilt stability:

\begin{equation}
L_d \geq \max \left\{ \frac{-A_i + \sqrt{A_i^2 - 4 A_i A_} A_2}{2 A_2}; \frac{K_s \left( \gamma H + q_0 \right) - c_{m2} N_c}{\left( \gamma H + q_0 \right) - c_{m2} \gamma_a}; \frac{K_s \left( \gamma H + q_0 \right) - c_{m2} N_c}{\eta \cos \theta - \frac{D_3}{3 D_4}} \right\}.
\end{equation}

The parameters are the same as above.

4. DISCUSSION

The Oufei Reclamation Project in Wenzhou City, Zhejiang Province of China[11] is located between the mouths of the Oujiang River and Feiyun River in Wenzhou City. The total reclamation area is 88.5 km². The building level is level 1. The North Gate is located in the northern part of the reclamation area. The size of the gate is 10 holes×8m+6 holes×8m+navigation hole 16m. A ring-shaped cofferdam is arranged outside the foundation pit, and a certain land-making area is formed on the sea through the ring-shaped cofferdam, which creates conditions for the later sluice foundation treatment and dryland construction.

The silt soil with a depth of more than 30m is distributed in the cofferdam construction area, which has the characteristics of saturation, flow plasticity and high compressibility. The structure of the foundation soil layer mainly includes ①ⅢⅢ, flowing mud, with a layer thickness of 0.30m~0.50m; ②ⅢⅢ0 layer of silt, layer thickness 2.00m~2.50m; ③ⅢⅢ1 layer of silt mixed with silt and silt, layer thickness of 5.00m~6.50m; ④ⅢⅢ2 layer of silt, layer thickness of 14.00m~16.00m; ⑤ⅢⅢ3 layer of silt, layer thickness of 3.00m~5.00 m; ⑥ⅣⅣ layer of silty clay with a layer thickness of 3.00m~7.00m. The main physical and mechanical properties of each soil layer are shown in Table 1.
The cofferdam is arranged in an overall ring shape, with a total design axis length of 1533m, and the area of the foundation pit in the cofferdam is 145,000 m². The plane layout of the cofferdam is shown in Figure 2. Two 60m long rigid composite foundation (PHC piles of Φ80cm) riprap cofferdam sections (artificial islands) are arranged at both ends of the cofferdam, and double-row steel sheet pile cofferdams are used for the remaining sections. Between the two rows of steel sheet piles in the double-row steel sheet pile cofferdam section, 44 transverse steel sheet piles are set up, and the spacing between the two rows of steel sheet piles is about 35m. The inner and outer rows of steel sheet piles are divided into 44 compartments to improve the overall rigidity of the double-row steel sheet piles. The top width of the cofferdam is 11.00m, and the design top elevation is 5.50m. The steel sheet pile adopts U-shaped cold-formed steel sheet pile with a single length of 27m and a section modulus of 3200cm³/m. The tie rods are made of Φ70cm steel tie rods with a distance of 1.4m. The typical section of the cofferdam is shown in Figure 3. The construction site drawing of steel sheet piles is shown in Figure 4.
According to geological data, design basic parameters $\gamma_2=19 \text{kN/m}^3$, $H=8.5 \text{m}$, $q_0=10 \text{kPa}$, $c_m=7.7 \text{kPa}$, $\varphi_m=5.8^{\circ}$, $\gamma_3=18 \text{kN/m}^3$, $h=2.5 \text{m}$. The section size of the steel sheet pile on the open sea side is $210 \text{mm} \times 600 \text{mm}$ in width and height, and the section size of the steel sheet pile on the cofferdam side is $290 \text{mm} \times 700 \text{mm}$ in width and height.

According to the formula (10) in this paper, calculate the recommended value of the minimum penetration depth of steel sheet piles. The penetration depth of the steel sheet pile under the condition of anti-heavy stability is as follows:

$$
N_q=1.685, \quad N_c=(N_q-1)/\tan \varphi_m=6.746; \quad L_d \geq 15.16 \text{m}.
$$

The penetration depth of the steel sheet pile under the overall anti-slip stability is:

$$
A_0=-61.564, \quad L_d \geq 8.63 \text{m}.
$$

Satisfy the soil depth of steel sheet pile under anti-overturning stability:

$$
D_3=0.155, \quad D_2=1.279, \quad D_1=-56.86, \quad D_0=-167.52; \quad \beta_1=-388.84, \quad \beta_2=-31.79, \quad \eta=22.77, \quad \theta=0.52(\text{rad}), \quad L_d \geq 17.01 \text{m}.
$$

Based on the above analysis, the initial design value of the depth $L_d$ of the double-row steel sheet pile structure can be selected to meet the maximum value of the calculated values of anti-uplift stability, overall anti-slip stability and anti-tilt stability: $L_d \geq \max \{15.16 \text{m}; \quad 8.63 \text{m}; \quad 17.01 \text{m}\}$.

The actual design pile length of the double-row steel sheet pile in this project is $18.5 \text{m}$, which is slightly larger than the theoretical calculation value.

The overall sliding stability of the double-row steel sheet pile cofferdam is calculated using the Swedish strip method. The arc radius is $37.57 \text{m}$ and the safety factor $K_S=1.21>1.20$ is obtained through trial calculations, which meets the requirements of overall sliding stability.

In order to verify the reliability of the calculated structure, the numerical simulation results of soil displacement were compared with the on-site monitoring results. The comparison results are shown in Figure 5.

From the comparison of the soil displacement inside and outside the cofferdam, it can be seen that the measured maximum horizontal displacement value is $187 \text{mm}$, while the finite element calculation value is $139 \text{mm}$. The actual measured value is slightly larger than the finite element calculation. The main reason is that the tide level rises during the actual operation of the project. It is caused by the impact of the falling reciprocating load, but its horizontal displacement meets the requirements of engineering operation, so the design of the double-row steel sheet pile structure is stable and reliable.
5. CONCLUSIONS
This article discusses, summarizes and analyzes the safety and stability of the double-row steel sheet pile structure, and verifies it through practical engineering cases. The main conclusions are as follows:

(1) Derived and calculated by mathematical theory, the formula for calculating the minimum penetration depth $L_d$ of steel sheet piles is given.

(2) Taking the double-row steel sheet pile cofferdam project of the sluice of the Oufei Reclamation Project in Zhejiang Province of China as a case, according to the calculation formula for the minimum penetration depth $L_d$ of steel sheet piles proposed in the article, the recommended minimum penetration depth is 17.01m, which is consistent with the actual project. The design value of 18.50m is basically the same, and it is considered that the calculation formula basically meets the design requirements.

(3) Through numerical simulation calculation and analysis, and comparative analysis with the actual horizontal displacement monitoring data of steel sheet piles, it is believed that the double-row steel sheet pile cofferdam structure design is safe and reliable, and provides a reference for related engineering applications.

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