

Research on Optimization Design of High Strength Prestressed Grooved Sheet Piles

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Abstract. Through theoretical calculations, the cracking moment, bending moment and section bending coefficient of high-strength prestressed grooved sheet piles and high-strength prestressed corrugated sheet piles were compared and analyzed; theoretically, the optimized high-strength prestressed grooved plates were obtained. And through this method we optimize the grooved sheet pile section. The optimized mechanical properties of the section have been greatly improved, making the mechanical properties of the grooved sheet piles approach or better than that of the corrugated sheet piles of the corresponding model. Combined with production experience, a series of optimization measures have been proposed for the section of the grooved sheet piles.

1. Introduction

In the construction of foundation pit excavation and support in urban underground construction of high-rise buildings, river courses, bank dikes, road abutments, and railway highway slopes, it is necessary to construct retaining structures for retaining soil. Choosing the appropriate form of support structure is the key to safe and economic construction and timely construction of the enclosure. The methods for supporting foundation pits in traditional projects include drilled cast-in-place piles, deep-mixed cement-soil retaining walls, high-pressure jet-grouting pile retaining walls, underground continuous walls, etc. All these supporting structures require the completion of concrete pouring on site. The construction cost is high and the working hours are long^[1]. In recent years, steel sheet piles have gradually been used as foundation pit support structures in some important projects, but the overall cost is high. Compared with traditional materials and construction methods and steel sheet piles, concrete sheet piles have the advantages of beautiful appearance after piled walls, good durability, reliable quality, fast construction speed, and a significant reduction in construction costs while shortening the construction period^[2]. Although the cost is higher than that of conventional masonry, the project has a long service life and it is safe and reliable. Due to the reasonable structure adopted, a large amount of materials are saved, and the materials have good corrosion resistance and no maintenance. Compared with traditional construction methods, concrete sheet piles have obvious advantages in terms of performance, economic benefits, energy saving and environmental protection.

The countries that use sheet piles abroad mainly include Japan, the Netherlands, Vietnam, and other Southeast Asian countries. In 1989 and 1993, Prof. S. Ikeda of Yokohama National University in



Japan made reports on the successful development of prestressed concrete sheet piles at different international concrete academic conferences^[3]. The Netherlands successfully applied sheet piles to various fields in construction projects. The country not only applied sheet piles to river revetments, but also successfully applied road and railroad engineering slope protection, urban building foundation pit engineering, dock engineering, municipal engineering, and bridge and culvert engineering, etc.^[4]. At present, prestressed concrete sheet piles have three types of cross sections: flat piles, U-shaped sheet piles, corrugated sheet piles, and Japan is keen to develop corrugated sheet piles^[5]. In 2009, U-shaped sheet piles were used in China and cooperated with foreign companies to optimize sheet pile technology^[6].

Guo Liting^[5] through the preparation of "sheet pile revetment components general map", explored the practical and economic rational structure of the sheet pile components, and carried out analysis and calculation, in order to improve the design of sheet piles. Zhang Jingjing^[7] proposed an economical analysis of the height of the relative compression zone of a reinforced concrete single-reinforced rectangular cross-section member by means of controlling the height of the compression zone in the cross-section to achieve optimal design. Hu Shaowei^[8] established a calculation model for the flexural bearing capacity of prestressed concrete corrugated sheet piles based on section equivalent equivalence assumptions, and obtained calculation methods for the neutral axis height and cross-section bending moment. Lou Tiejiong^[9], etc. Based on the nonlinear constitutive relation between concrete and steel, different formulas for the internal force of the section due to the movement of the neutral axis during the loading of the prestressed concrete section of the double-strand section are deduced, and a coupling between two variables into a set of nonlinear equations is established. For the U-shaped and corrugated sheet piles used in the current project, the height of the cross-section of the U-shaped and corrugated sheet piles is small, and the pile heads are easily damaged when the piles are piled up; the connection between the piles and the piles is too small, and the cracks easily occur in the piles, leading to pile position deviations and other issues. Prof. Huang Jianhua has developed a new type of prefabricated pile—high-strength prestressed concrete grooved sheet piles^[10, 11] (hereinafter referred to as grooved sheet piles). The overall section of the sheet pile is in the form of a groove, and the connector of the sheet is arranged on the left and right side webs, as shown in Figure. 1. The author compares and analyzes the mechanical properties of grooved sheet piles and corrugated sheet piles through theoretical calculations. At the same time, an optimized section of the grooved sheet piles is proposed by calculation.

2. Sheet pile calculation section simplified

The section of a single pile of grooved sheet piles is shown in Figure. 2. In engineering applications, a single sheet pile is connected to each other through a groove (ie, a groove on one side and a tongue on the opposite side) to form an integral sheet pile wall, as shown in Figure.3. In order to simplify the calculation in theoretical force calculation analysis, the chamfer and other details in the groove have little effect on the calculation of the overall mechanical properties of the grooved sheet piles. In the calculation, neglecting the chamfer and interface misalignment visual misalignment grooves are adopted. The section is equivalent to two regular rectangular spliced T-section, as shown in Figure 4. The cross-sectional dimensions are: flange width L , flange height t_1 , web height t_0 , and web width b .



Figure 1 High-strength prestressed concrete grooved sheet pile

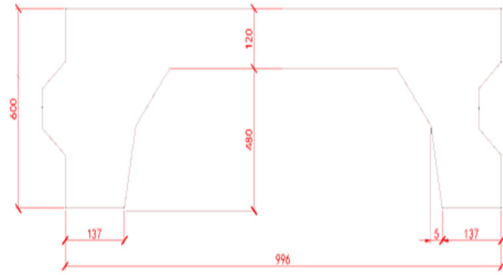


Figure.2 Single component section of pre-stressed sheet pile

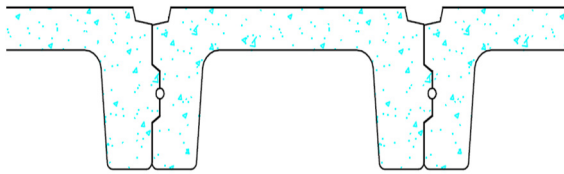


Figure.3 Sheet pile connection diagram

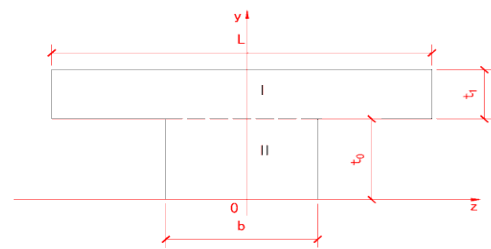


Figure.4 T-section Calculation diagram of prestressed sheet piles

3. Method for calculating the mechanical properties of sheet piles

3.1. Grooved sheet pile crack resistance bending moment calculation method

$$A_p = n \times S_p \quad (1)$$

$$A'_p = n' \times S'_p \quad (2)$$

A_p 、 A'_p —The total nominal area of the prestressed steel bars in the tension zone and compression zone.

n 、 n' —Prestressed steel bar reinforcement in tension zone and compression zone.

S_p 、 S'_p —Prestressed steel bar nominal area of tension zone and compression zone.

Loss of prestress caused by stress relaxation of prestressed steel bars σ_{l4} ,

$$\sigma_{l4} = 0.125 \left(\frac{\sigma_{con}}{f_{ptk}} - 0.5 \right) \sigma_{con} \quad (3)$$

$$\sigma_{con} = 0.70 f_{ptk} \quad (4)$$

σ_{con} —Steel tension control stress.

Prestressed loss of concrete shrinkage and creep σ_{l5} ,

$$\sigma_{l5} = \frac{60 + 340 \frac{\sigma_{pc}}{f'_{cu}}}{1 + 15\rho} \quad (5)$$

$$\rho = \frac{A_p + A'_p}{A_0} \quad (6)$$

$$A_0 = \frac{E_p}{E_c} (A_p + A'_p) + A \quad (7)$$

$$\sigma_{pc} = \frac{N_p}{A_0} \pm \frac{N_p e_{p0}}{I_0} y_0 \quad (8)$$

$$N_p = (\sigma_{con} - \sigma_{l4}) A_p + (\sigma'_{con} - \sigma'_{l4}) A'_p \quad (9)$$

$$e_{p0} = \frac{(\sigma_{con} - \sigma_{l4}) A_p y_p + (\sigma'_{con} - \sigma'_{l4}) A'_p y'_p}{N_p} \quad (10)$$

$$\sigma_{pc} = \frac{N_p}{A_0} \pm \frac{N_p e_{p0}}{I_0} y_0 \quad (11)$$

A_0 —The sum of the cross-sectional area of the concrete and the total cross-sectional area of the prestressed steel bars and the non-prestressed bars in the concrete.

N_p —Combined force of prestressed steel bars and non-prestressed steel bars.

e_{p0} —Convert section center of gravity to distance between prestressed and non-prestressed reinforcements.

W —Sectional bending coefficient.

σ_{pc} —The normal compressive stress of the concrete at the respective resultant point of the prestressed steel bars in the tension zone.

y_p, y'_p —The distance from the resultant point of the longitudinal prestressed steel bars of the tension zone and compression zone to the center of gravity of the net section (assuming that the thickness of the protective layer of the prestressed steel bars is 50mm, y_p, y'_p Representing the distance from the edge of the tension zone and the compression zone to the centroid minus the thickness of the protective layer.

$\sigma_{con}, \sigma'_{con}$ —Tensile stress control of prestressed steel bars in tension zone and compression zone.

f'_{cu} —Concrete compressive strength standard value.

$$\sigma_{p0} = (\sigma_{con} - \sigma_{l4} - \sigma_{l5}) \quad (12)$$

$$\sigma_{pcII} = \frac{(\sigma_{con} - \sigma_{l4} - \sigma_{l5}) A_p}{A_0} \quad (13)$$

σ_{p0} —Effective prestress of prestressed tendon in tension zone.

σ_{pcII} —Concrete prestressing after the completion of the second stage of prestress loss.

Calculating the moment of inertia of transition section of prestressed reinforcement.

$$I_g = A_p (h_0 - X)^2 \frac{E_p}{E_c} \quad (14)$$

Calculate section bending coefficient.

$$W = \frac{I_0 + I_g}{y_c} \quad (15)$$

$$X = \frac{E_p A_p}{E_c b} \left(\sqrt{1 + \frac{2b h_0 E_c}{E_p A_p}} - 1 \right) \quad (16)$$

I_g —Reinforced steel section inertia moment.

h_0 —The effective height of the section.

X —The relative compression zone height of the section.

Considering the plasticity of the concrete in the tension zone, the cross-section resisting moment shaping factor of the concrete component is introduced.

$$\gamma = \left(0.7 + \frac{120}{h} \right) \gamma_m \quad (17)$$

Cross-section bending moment.

$$M_{cr2} = (\sigma_{pcII} + \gamma f_{tk}) W \quad (18)$$

3.2. Calculating method of normal section ultimate bending moment for grooved piles

$$\alpha_1 f_c b x = f_{pt} A_p + (\sigma'_{p0} - f_{pc}) A'_p \quad (19)$$

x —Concrete pressure zone height.

σ'_{p0} —Effective prestress of prestressed tendons in compression zone.

f_c —C60 concrete compressive strength design value.

f_{pt} —Prestressed steel tensile strength design value.

f_{pc} —Prestressed steel compressive strength design value.

$$M_u = \alpha_1 f_c b x \left(h_0 - \frac{x}{2} \right) - (\sigma'_{p0} - f_{pc}) A'_p (h_0 - a'_p) \quad (20)$$

h_0 —Effective section height, equal to the height of the section minus the thickness of the prestressed steel protective layer.

a'_p —The distance from the resultant force point of the prestressed tendon to the edge of the compression zone of the section.

4. Examples of calculation of mechanical properties of grooved sheet piles

4.1. Groove sheet pile parameters

In order to compare with corrugated sheet piles with more specificity, we chose the grooved sheet piles with the same section size as the corrugated sheet piles. The specific dimensions of the grooved sheet piles are shown in Table 1.

Table.1 Size of grooved sheet piles

Section height h /mm	Flange width l /mm	Flange height t_f /mm	Web height t_w /mm	Web thickness b /mm	Area A /mm ²	Sectional moment of inertia I_0 /mm ⁴	Cross section Centroid y_c /mm
450	996	100	350	222.63	177520	3091673760	301.24
600	996	120	480	273.77	250930	8299728820	382.89

The prefabricated steel bars of the same kind and quantity are arranged on the grooved sheet piles and the corrugated sheet piles. The difference is that the corrugated sheet piles are asymmetrical in cross section. Therefore, the calculation model using six prestressed steel bars are arranged in the

compression zone, and six prestressed steel bars are arranged in the tension zone. The prestressed steel parameters used are shown in Table 2. Both types of sheet piles are made of concrete with a strength grade of C60. According to the "Code for Design of Concrete Structures" (GB50010-2010) ^[12], the mechanical properties of concrete are shown in Table 3.

Table.2 Information table of prestressed reinforcement

Section height h/mm	Number of prestressed steel bars	Rebar specifications n/mm	Steel nominal area S/mm^2	Pressure zone prestressed bars nominal area A_p/mm^2	Tensile zone prestressed bars nominal area A_p'/mm^2	Tensile strength standard value f_{ptk}/MPa	Tensile strength design value f_{pt}/MPa	Compressive strength design value f_{pc}/MPa
450	12	15.2	140	840	840	≥ 1860	1320	390
600	12	15.2	140	840	840	≥ 1860	1320	390

Table.3 Concrete parameters of strength and elastic modulus

Concrete strength grade	Compressive strength standard value $f_{ck}/\text{N/mm}^2$	Compressive strength design value $f_c/\text{N/mm}^2$	Tensile strength standard value $f_{tk}/\text{N/mm}^2$	Tensile strength design value $f_t/\text{N/mm}^2$	Elastic Modulus $E_c/\text{N/mm}^2$
C60	38.50	27.50	2.85	2.04	3.60×10^4

4.2. Calculation of Crack-resisting Moment for 450mm grooved Sheet Piles

$$A_p = 840\text{mm}^2, A_p' = 840\text{mm}^2 \quad (21)$$

$$\sigma_{con} = 0.70f_{ptk} = 1860 \times 0.7 = 1302 \text{ N/mm}^2 \quad (22)$$

$$\sigma_{l4} = 0.125 \left(\frac{\sigma_{con}}{f_{ptk}} - 0.5 \right) \sigma_{con} = 0.125 \times (0.7 - 0.5) \times 1302 = 32.55 \text{ N/mm}^2 \quad (23)$$

$$\rho = \frac{A_p + A_p'}{A_0} = \frac{1680}{186860.8} = 0.00899 \quad (24)$$

$$A_0 = \frac{E_p}{E_c} (A_p + A_p') + A = 9340.8 + 177520 = 186860.8\text{mm}^2 \quad (25)$$

$$\sigma_{pc} = \frac{N_p}{A_0} \pm \frac{N_p e_{p0}}{I_0} y_0 \quad (26)$$

$$N_p = (\sigma_{con} - \sigma_{l4}) A_p + (\sigma'_{con} - \sigma'_{l4}) A_p' \quad (27)$$

$$= (1302 - 32.55) \times 840 + (1302 - 32.55) \times 840 = 2132676 \text{ N}$$

$$e_{p0} = \frac{(\sigma_{con} - \sigma_{l4}) A_p y_p + (\sigma'_{con} - \sigma'_{l4}) A_p' y_p'}{N_p} \quad (28)$$

$$= \frac{1269.45 \times 840 \times 88.76 - 1269.45 \times 840 \times 241.24}{2132676} = -76.24 \text{ mm}$$

$$\sigma_{pc} = \frac{N_p}{A_0} \pm \frac{N_p e_{p0}}{I_0} y_0 \quad (29)$$

$$= \frac{2132676}{186860.8} + \frac{2132676 \times 76.24 \times 301.24}{3091673760} = 27.26 \text{ N/mm}^2$$

$$\sigma_{l5} = \frac{60 + 340 \frac{\sigma_{pc}}{f'_{cu}}}{1 + 15\rho} = \frac{60 + 340 \times \frac{27.26}{38.5}}{1 + 15 \times 0.00899} = 265.00 \text{ N/mm}^2 \quad (30)$$

$$\sigma_{p0} = (\sigma_{con} - \sigma_{l4} - \sigma_{l5}) = (1302 - 32.55 - 265.00) = 1004.45 \text{ N/mm}^2 \quad (31)$$

$$\sigma_{pcII} = \frac{(\sigma_{con} - \sigma_{l4} - \sigma_{l5}) A_p}{A_0} = \frac{(1302 - 32.55 - 265.00) \times 840}{186860.8} = 4.52 \text{ N/mm}^2 \quad (32)$$

$$W = \frac{I_0 + I_g}{y_c} \quad (33)$$

$$I_g = A_p (h_0 - x)^2 \frac{E_p}{E_c} \quad (34)$$

$$X = \frac{E_p A_p}{E_c b} \left(\sqrt{1 + \frac{2bh_0 E_c}{E_p A_p}} - 1 \right) = \frac{5.42 \times 840}{222.63} \times \left(\sqrt{1 + \frac{2 \times 222.63 \times 390}{5.42 \times 840}} - 1 \right) = 126.30 \text{ mm} \quad (35)$$

$$I_g = A_p (h_0 - X)^2 \frac{E_p}{E_c} = 840 \times (390 - 126.30)^2 \times 5.42 = 316591195 \text{ mm}^4 \quad (36)$$

$$W = \frac{I_0 + I_g}{y_c} = \frac{3091673760 + 316591195}{301.24} = 11314118.16 \text{ mm}^3 \quad (37)$$

$$\gamma = \left(0.7 + \frac{120}{h} \right) \gamma_m = (0.7 + 0.267) \times 1.4 = 1.3538 \quad (38)$$

$$M_{cr2} = (\sigma_{pcII} + \gamma f_{tk}) W = (4.52 + 2.85 \times 1.3538) \times 11314118.16 = 94.79 \text{ kN} \cdot \text{m} \quad (39)$$

4.3. Calculation of Flexural Capacity of Normal Section of 450mm Sheet Pile

$$\alpha_1 f_c b x = f_{pt} A_p + (\sigma'_{p0} - f_{pc}) A'_p \quad (40)$$

$$0.98 \times 27.5 \times 222.63 x = 1320 \times 840 + (1004.37 - 390) \times 840$$

Solutions have to $x = 270.82$

In this case, the tensile zone and the compression zone have the same reinforcement, so $\sigma'_{p0} = \sigma_{p0}$

$$\begin{aligned} M_u &= \alpha_1 f_c b x \left(h_0 - \frac{x}{2} \right) - (\sigma'_{p0} - f_{pc}) A'_p (h_0 - a'_p) \\ &= 0.98 \times 27.5 \times 222.63 \times 270.82 \times \left(450 - 60 - \frac{270.82}{2} \right) - (1004.45 - 390) \times 840 \times 330 \\ &= 243.37 \text{ kN} \cdot \text{m} \end{aligned} \quad (41)$$

After calculation of the same working conditions and methods, we obtained that the high-strength prestressed ecological sheet piles with a section height of 600 mm had a crack-resisting bending moment of $M_{cr2} = 167.57 \text{ kN} \cdot \text{m}$, and an ultimate bending moment of $M_u = 439.90 \text{ kN} \cdot \text{m}$.

5. Groove sheet pile section optimization

5.1. Corrugated sheet pile parameters

The cross-section of a traditional corrugated sheet pile is shown in Figure. 5^[8]. The corrugated sheet piles with the same cross-sectional area as the grooved sheet piles are used. The cross-sectional dimensions are shown in Table 4, and the mechanical performance parameters are shown in Table 5.

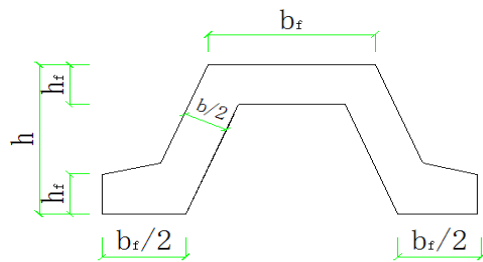


Figure.5 Dimension of corrugated sheet pile

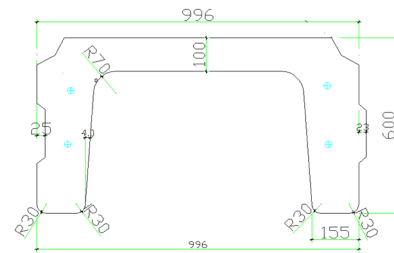


Figure.6 optimized 600mm height grooved sheet pile

Table.4 Section size and reinforcement of corrugated sheet pile

Section height h/mm	Thickness b/mm	Section width l/mm	Flange height h_f/mm	Bottom length b_f/mm	Web thickness b/mm	Area A/mm^2	Number of prestressed steel bars	Rebar specifications $/\text{mm}$	Rebar type
450	120	1000	120	440	240	177520	12	15.2	Strand
600	150	1000	150	440	300	250930	12	15.2	Strand

Table.5 Mechanical properties of corrugated sheet pile

Section height h/mm	Thickness b/mm	Section width l/mm	Sectional bending coefficient W/mm^3	Crack resistance $M_{cr}/\text{kN.m}$	Ultimate bending moment $M_u/\text{kN.m}$
450	120	1000	15402611	215.7	392.7
600	150	1000	27097200	307.2	547.9

5.2. Compare with corrugated sheet piles

The principle of optimum design of grooved sheet piles is that the grooved sheet piles in each model have the same cross-sectional area as the current corrugated sheet piles. By redesign the cross-section, calculation optimization. Improve the mechanical properties of the grooved sheet piles. The results of the initial design of the sheet pile section are compared with the corrugated sheet piles. The detailed comparisons are shown in Table 6.

Table.6 Bending moment comparison of two kinds of piles

Section height h/mm	Model	Total area of section $/\text{mm}^2$	Crack resistance $M_{cr2}/\text{kN.m}$	Ultimate bending moment $M_u/\text{kN.m}$	Bending coefficient W/mm^3
450	corrugated	177520	215.70	392.70	15402611
	grooved	177520	94.79	243.37	11314118
600	corrugated	250930	307.20	547.90	27097200
	grooved	250930	167.57	439.90	23635406

The comparative analysis of the mechanical properties of the two types of sheet piles results in the following results: In the case of the same cross-sectional area and similar section dimensions, the initial design of the grooved sheet piles is smaller than the corrugated sheet piles in terms of cracking

bending moment, ultimate bending moment, and section bending resistance. On the basis of ensuring the innovative design of the slot-grooved sheet piles, it is necessary to further adjust and optimize the cross-section dimensions of the new grooved sheet piles.

5.3. Grooved sheet piles optimized section

Based on the above calculation method of cross-section bending coefficient, the calculation can be drawn: In the same sheet pile area, increasing the web height t_0 has more influence on the section bending coefficient than increasing the web width b , increasing the web width b has more influence on the section bending coefficient than increasing the Flange height t_1 . The relationship between the three is $t_0 > b > t_1$. Therefore, under the same cross-sectional area, the web height is the size that has the greatest influence on the cross-section bending coefficient. According to the results obtained, the cross-section dimensions of the grooved sheet piles are optimized. At the same time, when the prefabricated grooved sheet piles are prefabricated, air will accumulate at the edges and corners during the pouring process, and the piled surface will have pit problems after forming. In the inner side of the sheet pile, a round design is made to remove the outer edges and corners of the sheet pile. This design has three advantages: 1) Solve the problem of air accumulation when pouring into piles; 2) Effectively remove the stress concentration at the edges and corners of sheet piles; 3) Reduce the amount of concrete used. The optimized 600mm height grooved sheet pile design cross section is shown in Figure. 6. After the optimized cross section, the high strength prestressed grooved sheet pile cross section dimensions are shown in Table 7.

Table.7 Size modified of grooved sheet pile

Section height h/mm	Flange width a/mm	Flange height t_1/mm	Web height t_0/mm	Web thickness b/mm	Area A/mm^2	Sectional bending coefficient W/mm^3
600	996	100	500	155.84	177520	14913534
770	996	120	650	202.17	250930	30158396

Optimized high-strength prestressed grooved sheet piles, original-sized grooved sheet piles and corrugated sheet piles, the three mechanical parameters such as shown in Table 8.

Table.8 Bending moment comparison of three kinds of piles

Section height h/mm	Model	Total area of section S/mm^2	Crack resistance $M_{cr}/\text{KN.m}$	Ultimate bending moment $M_u/\text{KN.m}$	Bending coefficient W/mm^3
450/600	grooved	177520	215.70	392.70	15402611.0
	corrugated	177520	94.79	243.37	11314118.0
	grooved (optimization)	177520	119.48	321.48	14913534.6
600/770	grooved	250930	307.20	547.90	27097200.0
	corrugated	250930	167.57	439.90	23635406.8
	grooved (optimization)	250930	308.66	562.08	30158396.8

Compared with the original 450 mm high-profile grooved sheet piles, the optimized high-strength prestressed grooved sheet piles have a 26%, 32%, and 32% increase in cracking moment, ultimate bending moment, and bending resistance, mechanical properties are still worse than corrugated sheet piles. Compared with the original 600 mm high-profile grooved sheet piles, the optimized high-strength prestressed grooved sheet piles have 84%, 28%, and 28% increase in cracking moment, ultimate bending moment, and bending resistance, stronger mechanical properties than corrugated sheet piles. From this, it is deduced that with the successive increase of the height of each type of sheet

pile, the mechanical properties of each type of groove-shaped sheet piles over 600 mm are better than the existing corrugated sheet piles.

6. Conclusion

(1) The method for calculating the mechanical properties of the sheet piles is reasonable and feasible. After the optimization, The width of the the mouthpieces increased, and the mouthpieces are arranged on both sides of the web. Pile sinking is not prone to damage, and the guidance of the webs on both sides is conducive to the guidance during the pile driving, so that the pile position is not easy to be displaced, and the connection between the pile and the pile is tighter.

(2) In the inner side of the sheet pile, a round design is made to remove the outer edges and corners of the sheet pile, and a misalignment visual misalignment groove design is made for the interface. The design can solve the problem of air accumulation when pouring piles and effectively remove the stress concentration at the corners of sheet piles. It can not only reduce the amount of concrete but also improve the mechanical properties of sheet piles.

(3) By increasing the web height and reducing the width of the web, the cross section optimization scheme can effectively ensure that the section bending coefficient is increased under the same cross-sectional area. Thereby, the bending moment and cracking moment of the section are improved, and the mechanical properties of the sheet pile are improved, which provides a basis for the optimization design of other types of grooved sheet piles.

Acknowledgments

Fund program: Supported by the National Natural Science Foundation of China (51678153); Supported by the Science and Technology Planning Project of Fuzhou (No. 2017-G-69); Supported by the Industry Cooperative Development Fund Project of Fujian University of Technology (GY-Z17145).

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