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Research Article

Effect Analysis of Steel Sheet Pile Supporting for Utility Tunnel Foundation Pit in Water-Rich Soft Soil

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Given the structural stability of steel sheet pile support in a water-rich soft soil area, the interaction mechanical mechanism between steel sheet pile support and soft soil was analyzed in the paper. Based on the limit equilibrium theory of soil mass and the coordinated deformation effect of retaining structure and soil, the force equation and action coefficient considering the cohesion of soil and the friction angle of steel sheet pile to soil were obtained. According to the characteristics of the soil around the foundation pit, reasonable supporting spacing ($d = 4$ m) could be obtained considering the friction angle of the steel sheet pile to soil properly without the cohesion of soil. The monitoring results show that the axial force during the support process is more reasonable considering the cohesion of soil and the friction angle of interaction with the wall and soil. The axial force of the measuring point was affected by the construction site and the layout of the utility tunnel foundation pit. The location with large deformation of the steel sheet pile and the most unfavorable range from the top of the foundation pit was 0.5–0.7 H. For the mechanical analysis of the interaction between steel sheet pile and soil, the apparent cohesion and friction angle can be taken as 0.05 rH and $\varphi/3$–$\varphi/2$, respectively. The foundation pit in the water-rich soft soil area could operate stably with a better waterproof effect by the steel sheet pile under different working conditions.

1. Introduction

The construction of the utility tunnel is conducive to the management and maintenance of various urban engineering pipelines, the coordination of underground engineering construction, and the improvement of the utilization rate of underground space. The research on the utility tunnel has attracted great interest with the rapid development, mainly involving construction technologies, treatment of waste soil, and the interaction between structure and soil [1–3]. Due to the deep and long foundation pit for the utility tunnel and the influence of surrounding soil and groundwater, the steel sheet pile support often was adopted for the foundation pit excavation. The retaining wall composed of a steel sheet pile and internal support is a simple support system used widely, which is composed of U-steel positive and negative buckles to play the role of retaining soil and water [4–6]. The steel sheet pile support system [7–12] has good waterproof performance, high strength, and resistance to the surrounding water and soil pressure. Its stability mainly was analyzed by considering the interaction between the support structure and soil. The earth pressure in the process of steel sheet pile support could be accurately used to evaluate the reliability and effect of the support. The researchers [13–20] accurately analyzed the earth pressure in the retaining process from the friction between wall and soil, soil strength parameters, and displacement in the retaining wall. Then, they established a formula for calculating the earth pressure considering the friction of wall–soil and soil cohesion. Mei et al. [21] proposed a model to predict displacement-dependent lateral earth pressure based on an earth pressure–displacement relationship commonly observed in practice. The proposed model could predict the relationship between earth pressure and retaining structure movement for any condition intermediate to the active and passive states, which were in good agreement with the test results.

The mechanical characteristics of steel sheet pile support have a great influence on the displacement mode of steel sheet piles. The researchers [5, 22, 23] analyzed the displacement model of the retaining structure under the action of earth pressure according to the mechanical principle, including the displacement mode of rotation around the top of the wall (RT), the displacement mode of rotation around the bottom of the wall (RB), or the displacement mode of wall translation (T). Fang and Ishibashi [14] and Fang et al. [22] studied the changes in earth pressure and action position caused by the wall movements of RT, RB, and T. The experimental results showed that the passive pressure distribution of the wall was linear under T mode. For the wall under RT or RB mode, the size and action point of the passive thrust were significantly affected by the wall displacement mode, and the action point of the lateral thrust was far higher than one-third of the wall bottom. Caputo et al. [23] proposed a new limit equilibrium method to calculate the maximum internal force of the anchored steel sheet pile. The interaction between support structure and soil was also studied by tests, including the distribution of lateral earth pressure, support structure deformation, and displacement at different depths [4, 5, 24–26].

According to the literature above, the mechanism of steel sheet pile support was analyzed by theoretical and experimental methods. Combined with the site environment in the water-rich soft soil area, the displacement mode of the rotation points at the top and bottom of the steel sheet pile was formed during the supporting process. Then, the influence of the apparent cohesion of the soil and the internal friction angle between the wall and soil was analyzed by the measured results.

2. Monitoring Scheme of Foundation Pit in Soft Soil Environment

2.1. Project Introduction. The utility tunnel is arranged under the sidewalk and nonmotorized vehicle lane on the east side, starting from Dongshan River in the north to Xiandai Avenue in the south, Jiaojiang District, Taizhou City, China, as shown in Figure 1. The covering soil thickness of the utility tunnel is 2.5 m, and the excavation depth of the foundation pit is about 5–8 m. According to the survey report of the site, the terrain is relatively flat with some houses, cultivated land, and planting land in the project site. The utility tunnel is located in the environment of a water-rich soft soil area. The elevation of average static water table is 2.50 m. Within the survey depth, the site foundation is divided into seven engineering geological formations from the top. It is easy to collapse during the excavation of the foundation pit, which has a great impact on the stability of the foundation pit support. The whole construction process of the foundation pit needs to be supported and monitored. The stability effect analysis of foundation pit support mainly involves the following geological formations, as shown in Table 1.

2.2. Monitoring Scheme for Supporting Structure. The stake range of steel sheet pile support was analyzed from AK2+ 780 to AK2+ 980 in the paper. The proposed utility tunnel and supporting structure were located in layer 2. The supporting was composed of IV Larsen steel sheet pile and I-shaped steel purlins (H $400 \times 400 \times 13 \times 21$ mm) and steel pipes, with the steel purlins installed on the same horizontal line. To ensure the safety of the structures around the foundation pit, monitoring the foundation pit should be carried out timely to obtain the deformation information of the supporting structure during the excavation of the foundation pit. The monitoring layout of the foundation pit supporting for utility tunnel in the paper is shown in Figure 2.

Figure 1: The location of the utility tunnel.

The monitoring displacement at the top of the steel sheet pile support includes horizontal and vertical displacement. Through connection measure of stable elevation for datum points, a fixed level line was established to calculate the elevation of each monitoring point. The axial force of the support structure was monitored by the axial force sensor, the water table outside the foundation pit was measured by the water level gauge, and the displacement of the deep soil was measured by the inclinometer. The locations of the measuring points on the construction site are shown in Figure 3.

During the construction of steel sheet piles for supporting the foundation pit, monitoring should be conducted once a day. The monitoring evaluation requirements for foundation pit support are shown in Table 2.

3. Effect Analysis of Supporting Method

3.1. Axial Force Analysis of Steel Sheet Pipe. In the supporting process of the steel sheet pile was located in the water-rich soft soil area, the interaction between the steel sheet pile and soil was relatively complex with its force and displacement related to the characteristics of the soil. The characteristics and parameters of each layer of soil are shown in Table 3 within the scope of relevant soil layers of the utility tunnel. The supporting process mainly was reflected by the active earth pressure and steel sheet pile displacement related to the characteristics of the soil.

When the depth of the foundation pit was less than 6.4 m, a support structure, N_I, should be used. Otherwise, two support structures, N_I and N_{II}, should be staggered. As the supporting top of the foundation pit was supported by steel pipe, the steel sheet pile rotated around the top and

Table 1: Geological characteristics of foundation pit.

Layer	Soil description	Composition properties	Mechanical characteristics	Thickness (m)
1-0	Mixed fill soil	Loose or slightly dense state, cohesive soil mixed with rubble and sand	—	0.2–4.5
1	Silty clay	Soft-plastic or plastic state, smooth and shiny soil section, no shaking response	High toughness and dry strength, high compressibility	0.7–2.8
2	Silt	Plastic-flow state, smooth with grease luster soil section, no shaking response		9.4–21.3
3-1	Clay	Plastic state with soft-plastic part, smooth and shiny soil section, no shaking response	High toughness and dry strength, medium compressibility	0.6–14.7
3-2	Clay	Soft-plastic state with the plastic part, smooth with grease luster soil section, no shaking response	High toughness and dry strength, high compressibility	3.1–16.6

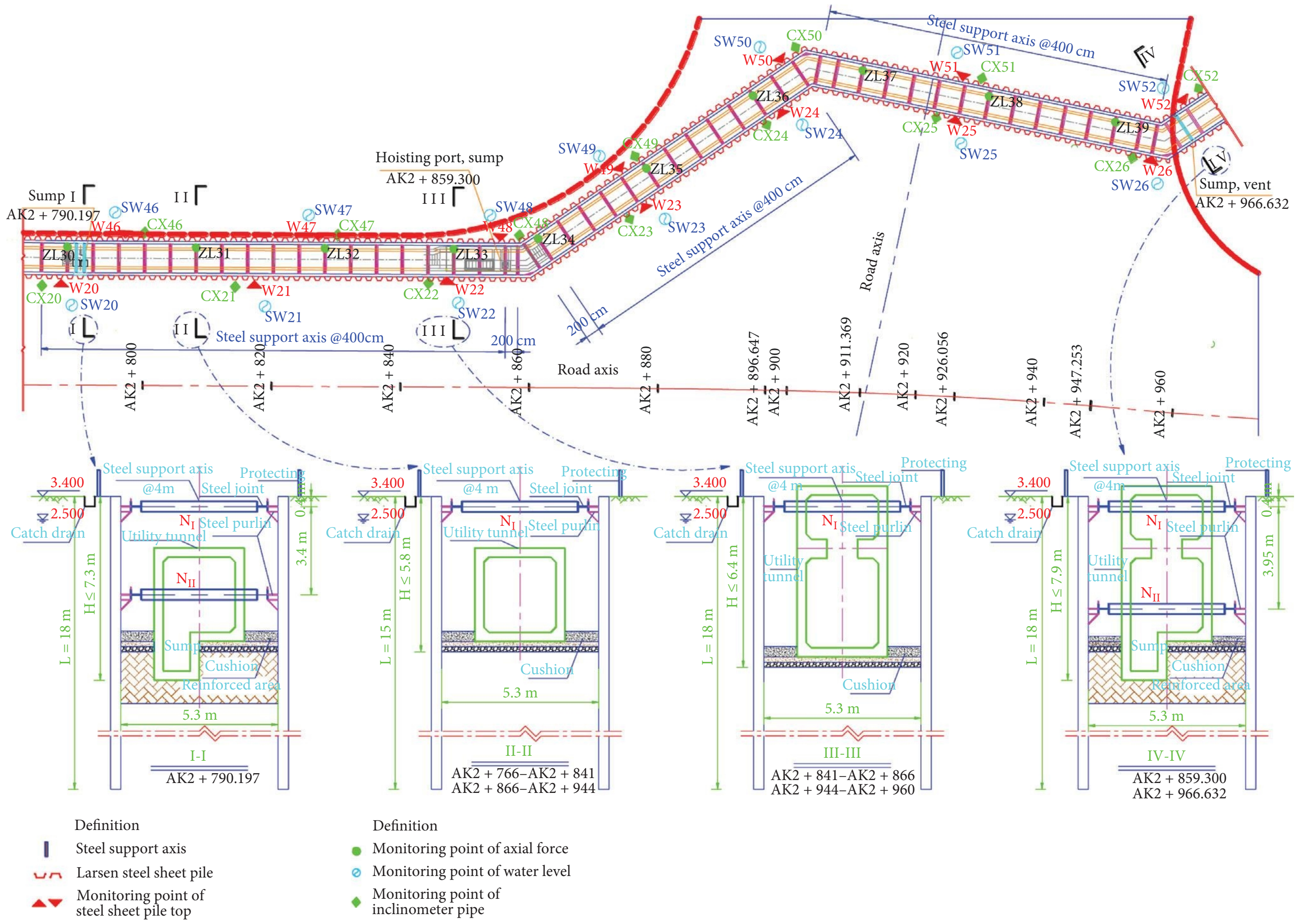

Figure 2: Monitoring layout plan and section of the steel sheet pile support.

bottom of the supporting structure at the same time under the action of earth pressure.

It is assumed that the earth pressure of the steel sheet pile is generated by the sliding wedge of the soil behind the wall in the limit equilibrium state. The horizontal differential element is taken vertically on the sliding wedge, and the force and moment equilibrium conditions on the element can be analyzed. The steel sheet pile is in a vertical or oblique state with horizontal ground. The mechanical analysis can be carried out under the support for the foundation pit, and the interaction of wall–soil can be analyzed without considering the supporting force, as shown in Figure 4.

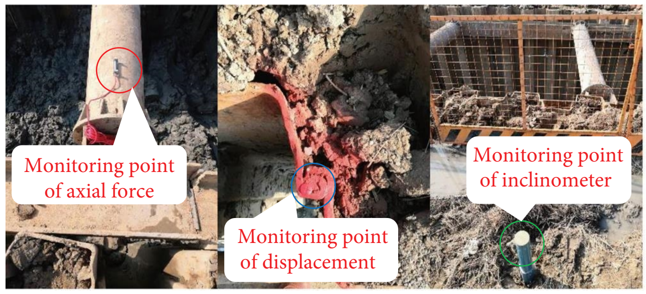

Figure 3: The locations of the measuring points on the construction site.

Table 2: The monitoring evaluation requirements for foundation pit support [27].

No.	Monitoring items	Change rate of warning value (mm/d)	Early warning of cumulative value (mm)	Monitoring frequency (1/d)
1	Horizontal displacement of the support structure at the top	4	40 or 0.5% H	1
2	Vertical displacement of the support structure at the top	3	30 or 0.5% H	1
3	Displacement of the deep soil outside the foundation pit	5	60 or 0.6% H	1
4	Water table outside the foundation pit	500	1,000	1
5	The axial force of the support structure	Warning value (kN) 750		1

Table 3: Parameters of each layer of soil within the scope of the steel sheet pile.

Layer	Soil description	Bulk density γ (kN/m^3)	Effective cohesion c' (kPa)	Internal friction angle φ (°)
1-0	Mixed fill soil	18.5	10	10
1	Silty clay	18.07	27.7	14.1
2	Silt	16.51	14.6	10.4
3-1	Clay	18.82	34.4	15.7
3-2	Clay	18.15	28	14.4

3.1.1. Analysis of Static Earth Pressure.

$$Ea = \frac{1}{2}\gamma H^2 dK0, \tag{1}$$

where H is the depth of the foundation pit, $K0$ is the stand-still coefficient of earth pressure, $K0 = 1 - \sin\varphi$ is the active earth pressure, and d is the horizontal supporting spacing.

3.1.2. Effect Analysis of the Soil Shear Strength on Steel Sheet Piles. According to the interaction analysis between the steel sheet pile and soil, as shown in Figure 4(a), it can be found that [28]:

$$Ea = \frac{1}{2}\gamma H^2 d \frac{\sin(\theta-\varphi)\cos\theta - \frac{2c}{\gamma H}\cos\varphi}{\cos(\theta-\varphi-\delta)\sin\theta}, \tag{2}$$

where θ is the angle (°) between the sliding surface of soil behind the steel sheet piles and the horizontal plane, φ is the internal friction angle (°) of the sliding mass, c is the apparent cohesion (kPa) of the interaction between steel sheet pile and soil, and δ is the internal friction angle (°) between steel sheet pile and soil.

According to the relationship between the active earth pressure and the angle of the sliding surface (i.e., $dEa/d\theta = 0$), the following formula can be obtained.

$$Ea = \frac{1}{2}\gamma H^2 dKa, \tag{3}$$

$$Ka = \frac{\left[\sqrt{\gamma H \cos\delta \sin(\varphi+\delta) + 2c\cos\varphi} - \sin(\varphi+\delta)\sqrt{\gamma H \sin\varphi + 2c\cos\varphi}\right]^2}{\gamma H \sin(\varphi+\delta)\cos^2(\varphi+\delta)} - \frac{2c\cos\varphi}{\gamma H \sin(\varphi+\delta)}, \tag{4}$$

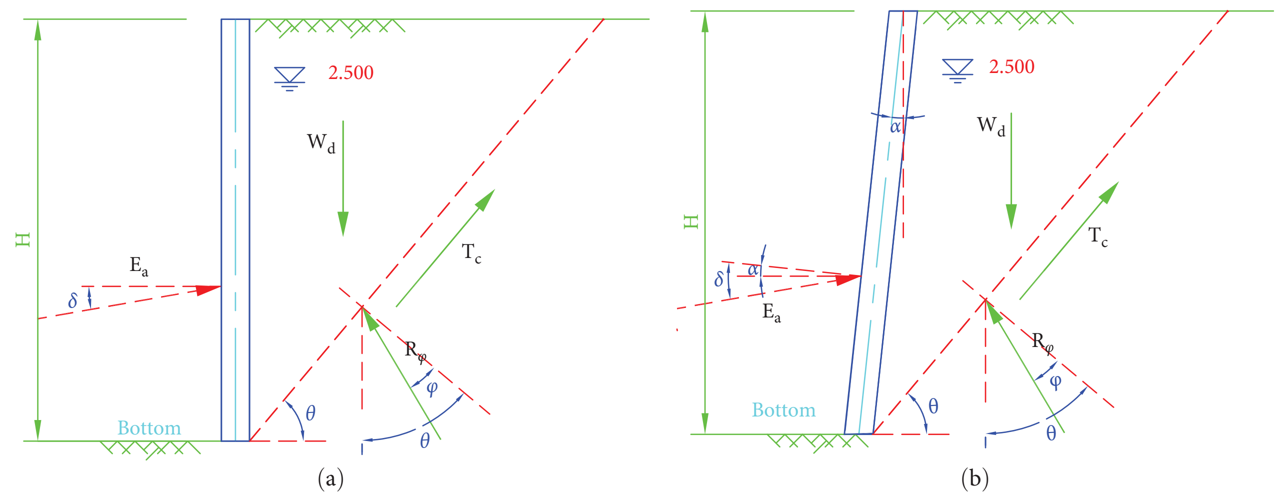

FIGURE 4: The wall–soil interaction analysis of steel sheet piles: (a) vertical state; (b) oblique state.

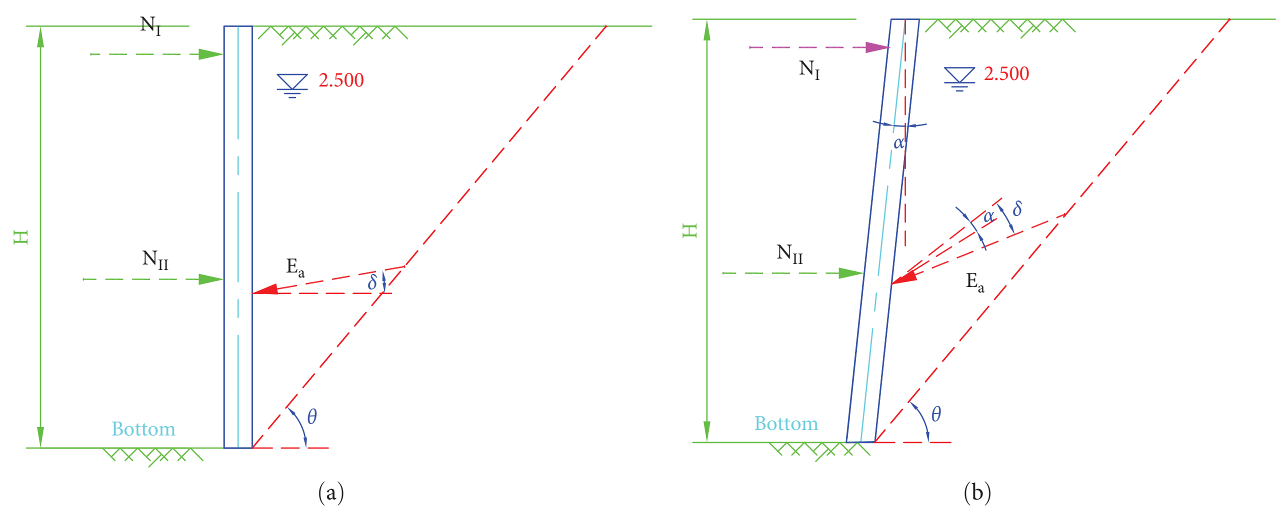

FIGURE 5: Force analysis of steel sheet pile support: (a) vertical sheet piles; (b) oblique sheet piles.

where Ka is the active earth pressure ($Ka \geq 0$). It is assumed that the cohesion between steel sheet piles and soil is not considered, i.e., $c = 0$, it can be found that:

$$Ka = \left[\frac{\sqrt{\cos\delta} - \sqrt{\sin\varphi \sin(\varphi + \delta)}}{\cos(\varphi + \delta)} \right]^2 . \tag{5}$$

It is assumed that the effect of soil shear strength on steel sheet piles is not considered, i.e., $c = 0$, $\delta = 0$, it can be found that:

$$Ka = \frac{1 - \sin\varphi}{1 + \sin\varphi} . \tag{6}$$

3.1.3. Supporting Effect of Inclined Steel Sheet Piles. Under the supporting action of steel sheet piles, the small displacement occurs at the supporting end of steel sheet piles with a large displacement occurring at the lower part of the foundation pit. According to the analysis, as shown in Figure 4(b), the interaction analysis between steel sheet pile and soil can be obtained and it can be found that:

$$Ka = \frac{\left[\sqrt{\gamma H \cos\delta \sin(\varphi + \delta - \alpha) + 2c\cos\varphi} - \sin(\varphi + \delta - \alpha)\sqrt{\gamma H \sin\varphi + 2c\cos\varphi}\right]^2}{\gamma H \sin(\varphi + \delta - \alpha)\cos^2(\varphi + \delta - \alpha)} - \frac{2c\cos\varphi}{\gamma H \sin(\varphi + \delta - \alpha)} . \tag{7}$$

Table 4: The horizontal spacing of steel pipe supports.

Working conditions	$K0$	$c \neq 0$, $\delta \neq 0$	$c \neq 0$, $\delta = 0$	$c = 0$, $\delta \neq 0$	$c = 0$, $\delta = 0$
Supporting spacing (m)	3.18	5.66	5.24	4.21	3.91

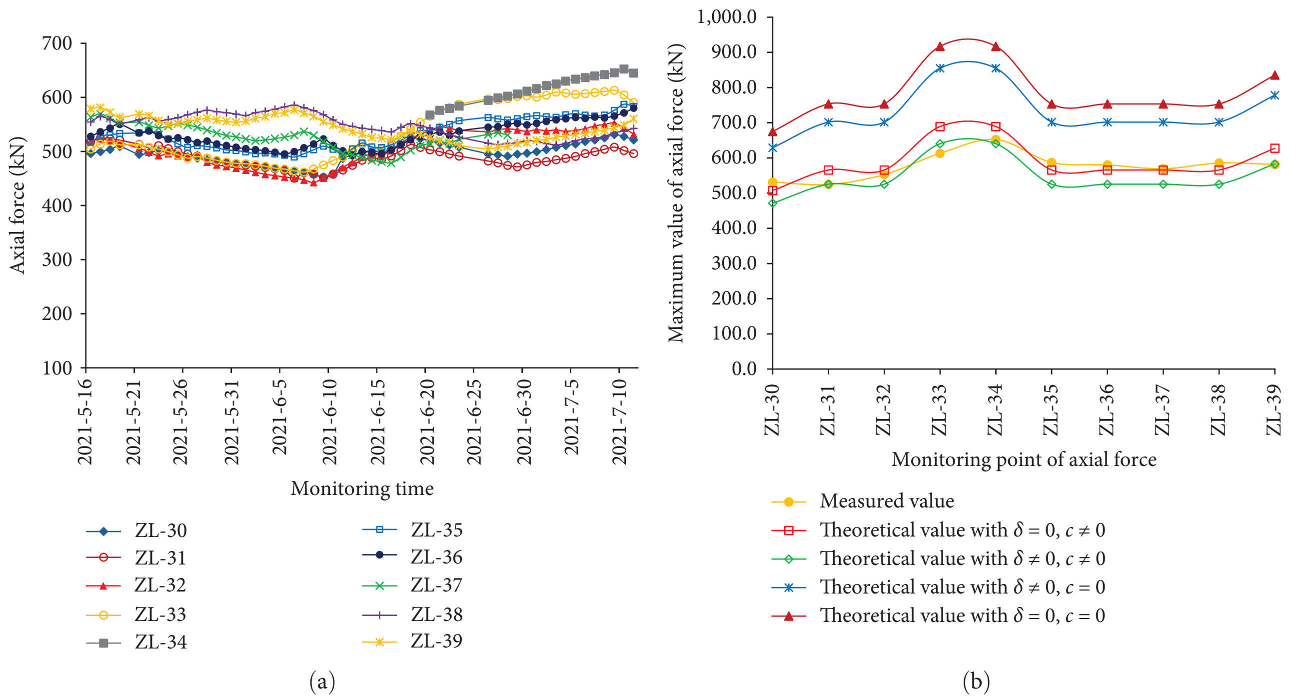

Figure 6: Changes of axial force at different monitoring points: (a) axial force at measuring points; (b) maximum axial force at different monitoring points.

Assuming that the active earth pressure above the pit bottom was all shared by the supporting shaft, the steel sheet pile and the soil mass were taken for analysis in one unit length of foundation pit. With the vertical or oblique steel sheet piles, the supporting mechanical analysis of the foundation pit was carried out. According to one supporting for the steel sheet pile, N_I, it can be found as follows:

$$NI = Ea \cos \delta. \tag{8}$$

Assuming that all soil pressure acts on the steel sheet pile with two support structures staggered, N_I and N_{II}, as shown in Figure 5, it can be found that:

$$\begin{cases} NII = \dfrac{2H - 3h}{3a} Ea \cos \delta \\ NI = \dfrac{3a + 3h - 2H}{3a} Ea \cos \delta, \end{cases} \tag{9}$$

where a is the spacing between N_I and N_{II} and h is the spacing from N_I to the top of the steel sheet pile.

Whether the parameters, c, δ, were considered under the interaction between the steel sheet pile and soil, the horizontal spacing of steel pipe supports was calculated according to Equations (1) and (2), respectively. Based on the working conditions, $c = 0.05\,\mathrm{r}H_d$ (H_d is the thickness of the soil layer) and $\delta = \varphi/2$ [14, 19], the calculation results are shown in Table 4.

As shown in Table 4, the horizontal support spacing is 3.2–5.7 m under different working conditions of steel sheet piles and soil. The horizontal support spacing obtained under the condition of static earth pressure is the minimum, and it is the maximum considering the cohesion of soil and the friction angle between the steel sheet pile and soil. The proper parameters should be taken in the water-rich soft soil area ($c = 0$, $\delta = 0$). Therefore, it is reasonable that the horizontal support spacing was selected to 4 m. According to the monitoring results of the axial force of the steel pipe support, the axial force values at different stages are shown in Figure 6.

As shown in Figure 6, the maximum axial force measured is 652.4 kN for ZL-34, and the minimum is 442.6 kN for ZL-32. The variation range of daily axial force is −14 to 14 kN, which is mainly affected by the construction load and changing water table. The axial force calculated is closer to the measured value of the measuring point according to the method of considering soil cohesion. Considering the soil cohesion and the wall–soil friction angle, the axial force of the measuring point is the minimum. The calculation results of ZL-30–ZL-34 and ZL-39 are closer to the measured values considering the soil cohesion and wall–soil friction angle. The calculation results of ZL-35–ZL-38 are closer to the measured values considering the soil cohesion without wall–soil friction angle because of the influence of the construction site. Therefore, it is more reasonable to calculate

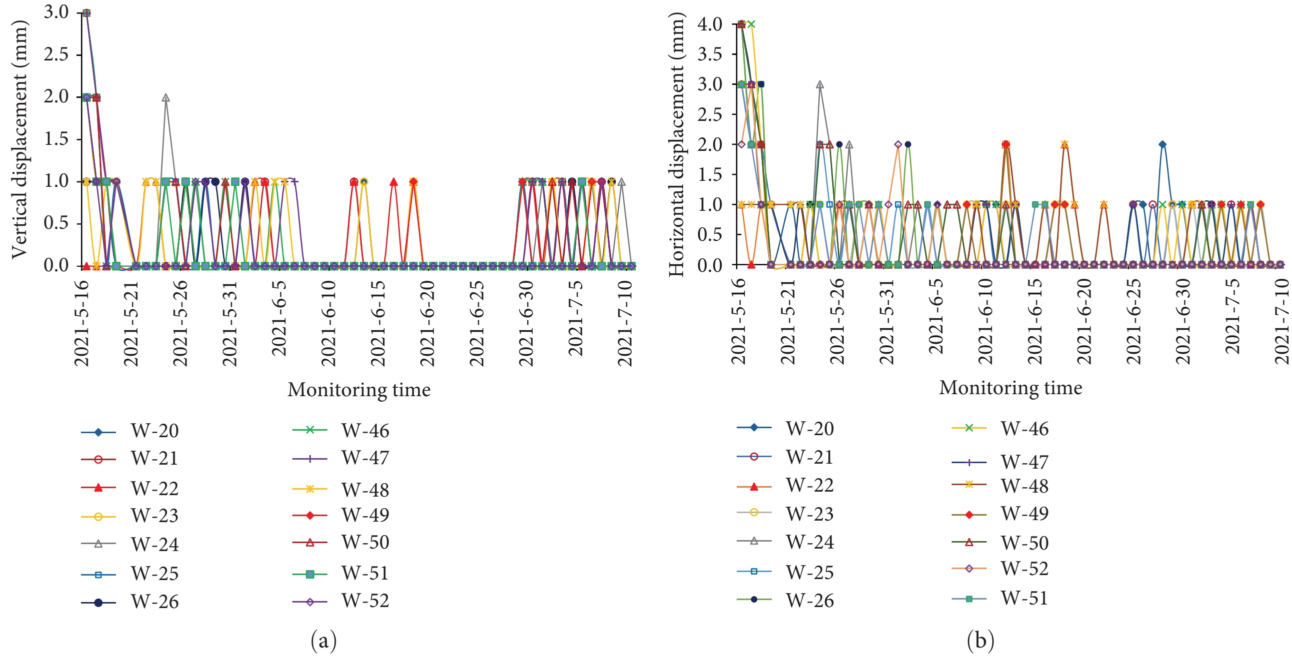

Figure 7: Displacement of steel sheet pile top: (a) vertical displacement; (b) horizontal displacement.

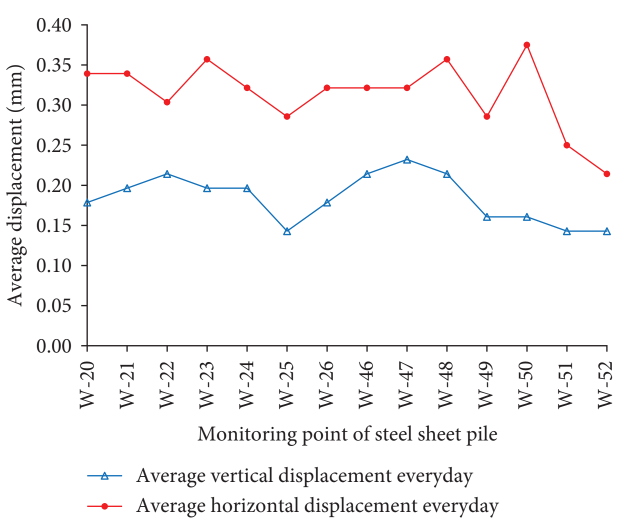

Figure 8: Average displacement of each measuring point during the support process.

the axial force of the measuring point considering the soil cohesion and wall–soil friction angle.

3.2. Displacement Analysis of Steel Sheet Pile. During the process of the steel sheet pile supporting the foundation pit, the steel sheet pile would produce vertical and horizontal displacement due to the effect of soil pressure. Under the different construction stages of the utility tunnel, the displacement at the top of the steel sheet pile is shown in Figure 7.

As shown in Figure 7, the vertical and horizontal displacement at the top of the steel sheet pile changes little. The vertical and horizontal displacement of the supporting structures along the foundation pit is mainly affected by the

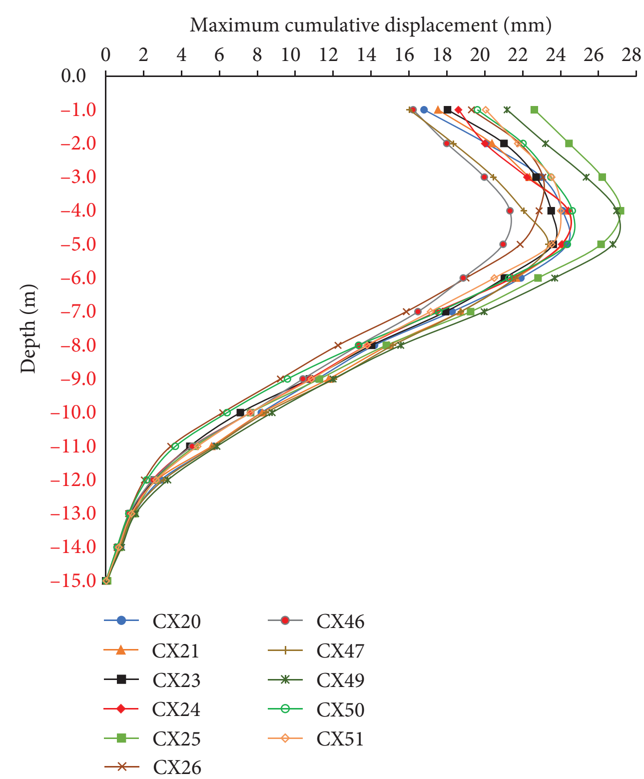

Figure 9: Maximum cumulative displacement of deep soil at each measuring point.

excavation of the foundation pit. The maximum vertical cumulative displacement is 13 mm, and the maximum horizontal cumulative displacement is 21 mm. The displacement along the east side is slightly larger because of subgrade construction along the west side. During the action of the

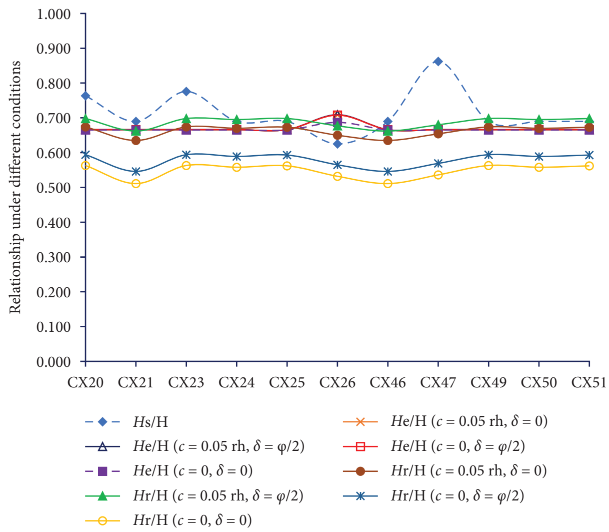

Figure 10: The position of earth pressure and maximum displacement under different conditions.

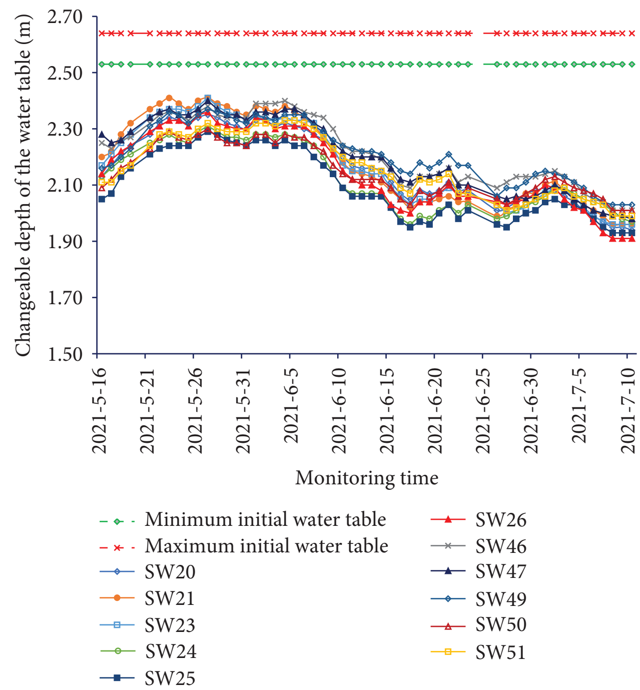

Figure 11: The changeable depth of the water table at each measuring point.

steel sheet pile, the average vertical displacement change of the support along the foundation pit is the same. However, the average horizontal displacements of W51 and W52 are small because of subgrade construction on both sides of the foundation pit.

From the beginning to the end of the steel sheet pile support, the average displacement of each measuring point during the supporting period is shown in Figure 8. As shown in Figure 8, the average vertical displacement change of the support along the foundation pit is the same. However, the average horizontal displacements of W51 and W52 are small because of subgrade construction on both sides of the foundation pit.

To master the deep deformation of steel sheet pile support, an inclinometer was set near the outside of the steel sheet pile to monitor the deep displacement of the soil. The support structure displacement was deduced by the deep horizontal displacement of the soil. The maximum cumulative displacement at different depths of each measuring point can be obtained according to the displacement of deep soil at different times, as shown in Figure 9.

As shown in Figure 9, the cumulative displacement of deep soil at the east measuring point is larger than that at the west, mainly due to the influence of subgrade construction. The maximum cumulative displacement of each measuring point is located at the 4–5 m depth, which is about 0.3L–L/3, close to two-thirds of the depth of the foundation pit. According to the measured results and theoretical calculation of the interaction between steel sheet pile and soil, the relationship between the resultant earth pressure of foundation pit support, the maximum displacement position of deep soil, and the depth of the foundation pit can be obtained under different working conditions, as shown in Figure 10.

Hs is the depth at the maximum displacement position of the deep soil, *He* is the position of the resultant earth pressure, and *Hr* is the position of the resultant earth pressure calculated through monitoring, as shown in Figure 10. It can be seen that the maximum displacement location is 0.50–0.70 H and 0.66–0.71 H according to the actual measurement and the theoretical analysis, respectively. The actual measurement location would be closer to the top of the foundation pit than that of the theoretical analysis, mainly due to the influence of the support position. Therefore, the most unfavorable range of the steel sheet pile from the top of the foundation pit is 0.5–0.7 H with large deformation considering the interaction of wall–soil, close to the position of the resultant earth pressure.

3.3. Water Table Analysis. The water table outside the foundation pit was monitored by a water level gauge. The buried depth and change of the water table at each measuring point are shown in Figure 11.

As shown in Figure 11, the change in the water table outside the foundation pit can be divided into three stages, namely the initial water table, the stable water table under the foundation pit support structure, and the falling stage of the water table. At the initial stage, the water table depth would rise again and stabilize at 2.25–2.4 m after the water table on both sides was lowered. The water table would be stable for about 15 days under the foundation pit support structure. The water table depth in the later stage would be mainly affected by the climate. The water table depth would gradually drop to a stable value of 1.9 m because of the high temperature and without rainfall since mid-June. The change of water table depth along the west side of the foundation pit (SW20, SW21, SW22, SW23, SW24, SW25, SW26) was greater than that along the east side (SW46, SW47, SW48, SW49, SW50, SW51, SW52). The change of water table depth along the east side of the foundation pit was small, mainly due to the influence of subgrade construction load on

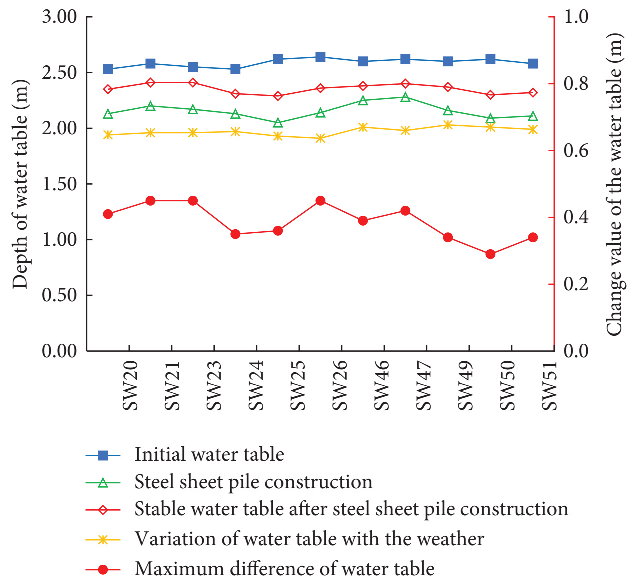

Figure 12: The depth of the water table of each measuring point at different construction stages.

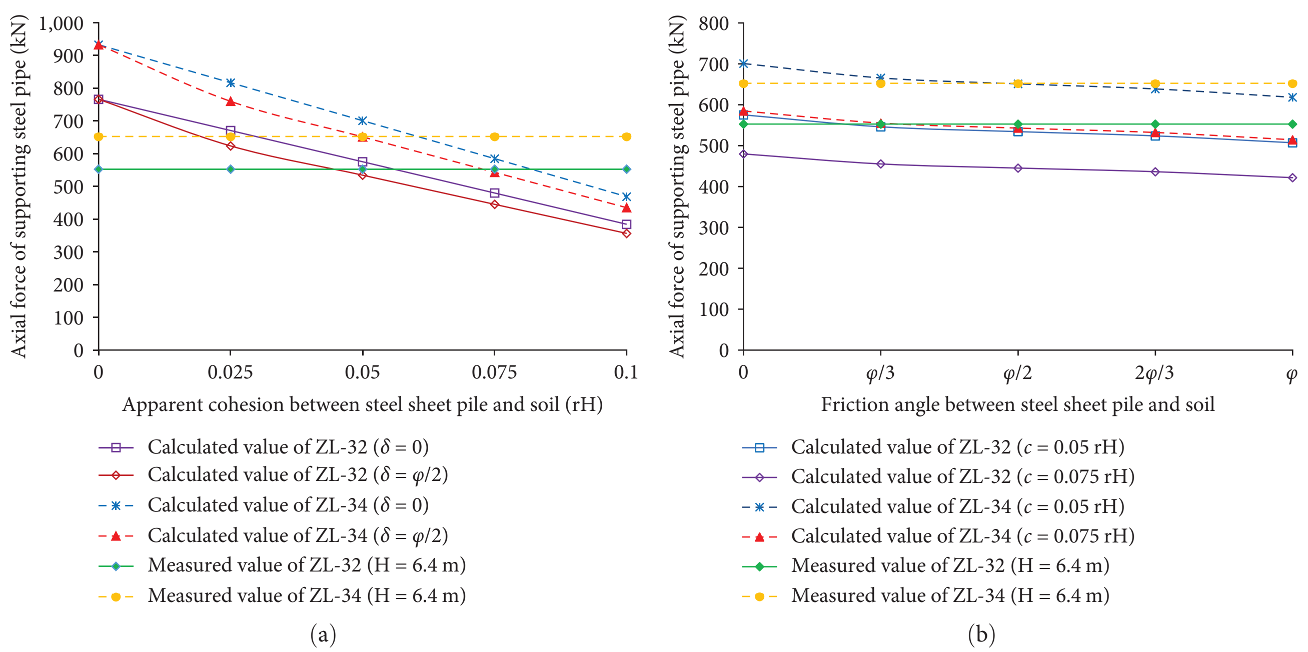

Figure 13: Calculated and measured axial force values of ZL-32 and ZL-34 varying with the parameters: (a) apparent cohesion; (b) internal friction angle.

the west side and the natural site on the east side, respectively. The maximum change value of the water table of each measuring point on the west side during the support process is relatively stable, and the change rate of the water table at different measuring points is the same.

The depth of the water table of each measuring point is shown in Figure 12 at different construction stages.

As shown in Figure 12, the water table of each measuring point along the foundation pit is constant at the same stage, the maximum change value of the water table on the west side is relatively stable during the support process, and the change rate of the water table at different measuring points is the same. Therefore, the waterproof effect of the interlock of the steel sheet pile can be predicted by monitoring the water table change. The stability and waterproof effect of the steel sheet piles support structure in the water-rich soft soil area are quite good.

4. Parameter Influence Analysis between Steel Sheet Pile and Soil

The interaction between the steel sheet pile and soil was affected by apparent cohesion and friction angle. According to the analysis in the literature [14, 19], the apparent cohesion of steel sheet pile and soil was related to the bulk density and the depth of the foundation pit, which was set as 0, 0.025, 0.05, 0.075, and 0.1 rH, respectively. The friction angle between the steel sheet pile and soil was related to the internal friction angle of the soil, which was set as 0, $\varphi/3$, $\varphi/2$, $2\varphi/3$, and φ, respectively. Therefore, the calculated axial force and measured results of measuring points, ZL-32 and ZL-34, could be obtained with the change of apparent cohesion, as shown in Figure 13(a). Similarly, the calculated axial force and measured results of measuring points, ZL-32 and ZL-34, could be obtained with the change of friction angle between the steel sheet pile and soil, as shown in Figure 13(b).

Figure 13 shows that the theoretically calculated values are different to the measured values considering the different environmental parameters of the steel sheet pile and soil. As shown in Figure 13(a), the apparent cohesion between the steel sheet pile and soil was taken as 0.05 rH, the calculated axial force was closer to the measured value. Similarly, the friction angle between the steel sheet pile and soil was taken as $\varphi/3$–$\varphi/2$, the calculated axial force was closer to the measured value.

5. Conclusions

Considering the effect of soil shear strength on steel sheet piles, the active earth pressure and the axial force of support structure were derived. The displacement, axial force, and water table of each measuring point were affected by the construction load during the supporting process in the water-rich soft soil environment, especially the working conditions on both sides of the foundation pit.

The theoretical calculation of the axial force was more reasonable according to the consideration of soil cohesion and the internal friction angle of the soil. The measured axial force was affected by the construction site and the layout of the foundation pit. According to the analysis of the supporting axial force under different conditions, the support spacing calculated was more reasonable considering the friction angle between the support structure and soil without considering the soil cohesion.

Through theory analysis and actual monitoring, the relationship between the resultant force position of earth pressure, the maximum displacement position of deep soil, and the depth of the foundation pit was obtained under different working conditions of the foundation pit. The most unfavorable deformation position of the steel sheet pile from the top was located at 0.5–0.7 H. Through mechanical analysis of the interaction between steel sheet pile and soil, the apparent cohesion and friction angle could be taken as 0.05 rH and $\varphi/3$–$\varphi/2$, respectively.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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