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Waterproof Design and Construction Control Technology for SMW Retaining Structure

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ABSTRACT: SMW retaining structures can satisfactorily meet the waterproof requirements for shallow foundation pits. However, it is rather difficult to control seepage in retaining structures for super-deep foundation pits (excavating depth exceeding 15m) due to ground pressure, soil property, equipment performance, and construction control technology. This paper takes the Zhujianglu Station of Nanjing Metro Project as the background. Based on analysis of the cause of seepage in SMW retaining structures of super-deep foundation pits, this paper theoretically makes a design calculation of the thickness and deformation of the watertight wall, and practices seepage control technology during construction. It is shown that the mentioned technical notes of guiding are significant to some extent for design and construction of SMW retaining structures.

1 OVERVIEW

The SMW (Soil Mixing Wall) method is an underground construction technology for forming a cement soil retaining wall by mixing cut soil with cement slurry injected from the front of a special multi-axial drill which cuts and breaks soil among the original stratum, and inserting reinforced core materials according to the function of the retaining wall. Compared with other forms of retaining structures, retaining walls constructed with the method of SMW have the following features:

(1) Less influence to surrounding soil
(2) Less noise, no vibration, shorter time for completion;
(3) Less production of waste soil and basically no slurry pollution;
(4) Less land use;
(5) Larger rigidity of the retaining structure;
(6) More economical

Phase 1 Project of No. 1 Nanjing Metro Line is a national major project. Since commencement in December of 2000, the SMW method has firstly been applied in the retaining structures of the shield working shaft (excavation depth of 12.9m) and in the open cut foundation pits (maximum depth of 8.7m) in the test section. Favorable effects have been achieved. Based on the experience summary, a special study has been carried out of the SMW method. It has satisfactorily solved a series of key technical difficulties in design and construction. Such method has also been successfully adopted in the construction of stations like Zhujianglu, Zhongsheng, and Xiangxinglu where a record 18m deep excavated foundation pit with the SMW method has been created. This has accumulated invaluable experience for design and construction with such method. Taking Zhujianglu Station of Nanjing Metro Project as the background, this paper discusses mainly its waterproof design and construction control technology.

2 ANALYSIS TO CAUSES FOR SEEPAGE IN SMW RETAINING STRUCTURE

When the foundation pit is embedded shallowly, both the soil pressure and the pore water pressure are small. An effective function of water barrier and pressure retaining may be achieved depending on cement soil mixing pile wall and core materials. However, as for super large and deep foundation pits, the peripheral water and soil pressures are quite large which makes it difficult to some extent to insert mixing piles and shaped steel and easily leads to partial or large-scale seepage in the protecting wall. There are many causes for seepage in SMW retaining structures including soil conditions, insufficient design thickness or strength or improper construction control.

(1) Soil Conditions

The dimension, shape and grading of undisturbed soil and grain packing and the inherent soil structure have all influenced the permeability of SMW retaining structure. If the soil is graded evenly, especially for gravel soil whose structure forms in order, the permeability of the mixed cement soil is strong and easily leads to seepage. As for fine clayey soil with small pores, the permeability of undisturbed soil is weak. With the consolidation and filling of mixed cement soil which produces a thick combined water membrane, the pore passage for seepage becomes smaller which is good for water stoppage.

(2) Insufficient Design Thickness or Strength

If the thickness of cement soil watertight wall is too thin or its strength and rigidity are insufficient, large deformation of SMW will happen during the excavation of foundation pit due to earth pressure. Tiny cracks and some thorough cracks will appear in the wall, especially cracks between SMW core materials (such as shaped steel) and cement soil. Due to that the core material itself has been painted with antifriction agent, the combination is weak. In combination with different rigidity and inconsistent deformation, this easily leads to seepage.

(3) Construction Control

Improper construction control is the major reason for seepage of SMW. Poor quality in any procedure or process could likely lead to seepage. Too fast raising speed of slurry spray, insufficient thickness of pile joining, inclined or deviated pile position, unstable mixture ratio, unduly support for excavation and cold construction joints caused by some accidental factors such as obstacles or equipment failure will also lead to seepage of SMW. More serious is water and sand gushing from the seepage even collapse of the foundation pit.

3 ANTI-SEEPAGE DESIGN FOR SMW RETAINING STRUCTURE

For the purpose of ensuring the anti-seepage performance of SMW retaining structure to comply with requirements of excavation during excavating foundation pit, the following controls on thickness of retaining wall, strength of cement soil, density of inserted shaped steel and deformation control shall be strengthened.

3.1 Strength of Cement Soil

For deep foundation pits with SMW retaining structure, it mainly depends on the core material (such as H-shaped steel) in the retaining structure to bearing the earth pressure. Cement soil mainly acts to prevent seepage. Therefore, the requirement on strength of cement soil is quite low. However, if the strength of it is too much lower, the tiny deformation during excavation will lead to cracks in the cement soil and as a result, the cement soil will fail in prevention of seepage. So, the strength of cement soil must be ensured as required. Main factors influencing the strength of cement soil include: cement consumption, cement grade, water and cement ratio, sand percentage in soil and soil age.

Takeo Suzuki et al (siragan: “et al” means “and others” while “etc.” means “and so on”) (1994) have made indoor tests to properties of materials for underground cement soil wall, which shows that if the slurry amount for cement soil is the same, the less the water and cement ratio is and the larger the sand percentage is, the larger the unconfined compressive strength is, which may be expressed by the following empirical formula:

$$q_{n28} = \frac{k}{m} \times s + n \tag{1}$$

where, q_{n28} means the unconfined compressive strength of 28 days; m refers to water and cement ratio; s refers to sand percentage; n refers to q_{n28} when the sand percentage is 0%; k is the coefficient.

For super deep (over 15m) foundation pits, high grade cement shall be used as possible. It is shown by studies that when the cement grade increases by 100#, the unconfined compressive strength of cement soil increases about 20~30%. In addition, proper addition in cement consumption will help to increase the strength of cement soil. Such addition shall be controlled within 15~20%. As a result, the strength of cement soil may reach over 1.2Mpa.

3.2 Thickness and Core Material Density of Cement Soil Mixing Pile

The determination of the thickness of cement soil shall mainly take into consideration of peripheral water and earth pressure, strength of cement soil and the row spacing of H-shaped steel. As for super deep strata, too thin cement soil retaining wall will most likely lead to shear failure and result in seepage. To avoid this, the design shall control well the arrangement density of H-shaped steel and the thickness of cement soil mixing pile. They two have an inverse relation, i.e.

$$a \times \sigma \leq 2[\tau]b \tag{2}$$

where, a is the row spacing of H-shaped steel; σ is the ground pressure; [τ] is the shear strength of cement soil and b is the thickness of cement soil.

3.3 Layer Spacing of SMW Retaining Structure without Support

Excessive deformation in SMW will accelerate the growth of cracks in cement soil mixing piles and lead to large-scale seepage. This will make it difficult to excavate foundation pits and most likely cause foundation pit instability. So, the layer spacing of supports shall be properly determined based on calculation and forecast of lateral displacement of the foundation pit and actual construction control.

Under ideal conditions, the H-shaped steel and the cement soil form a composite structure and deform in the same way. It may be deemed as a fully combined action. However, in practice, due to different rigidity, it is impossible to be a fully combined action. This paper takes partly combined action as a model to calculate the deformation of SMW. For the simply-supported beam in Figure 1, a uniform load q is added. The origin of coordinate locates in the middle of the beam span. The following hypotheses are made:

(1) The deflection of two materials for the loaded composite beam keeps the same, i.e. $Wc = Ws = Wi$;

(2) Two materials distribute evenly along the beam, and the shear on the contact surface τ(x) in elastic phase and the relative slippage u (x) have a linear relation, i.e.

$$\tau(x) = G \cdot u(x) \tag{3}$$

where, G is the cohesive shear rigidity in the unit of MPa, determined through test; u(x) is the longitudinal linear shear of unit slippage in the unit of N/mm.

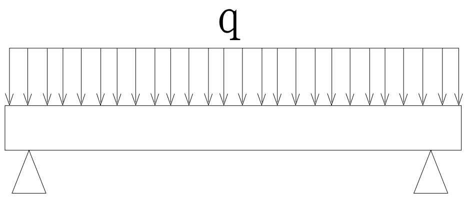

Fig.1. Deformation of Cement Soil Mixing Pile Wall

The equilibrium condition is:

$$\begin{cases} Vs + Vc = q_x \\ \dfrac{dMc}{dx} + \dfrac{dMs}{dx} + Vc + Vs = 0 \\ \dfrac{d^2Mc}{dx^2} + \dfrac{d^2Ms}{dx} = q \\ \tau = -\dfrac{dN}{dx} \end{cases} \tag{4}$$

The boundary condition is, at $x = \pm \frac{L}{2}$, $f = 0, \frac{d^2 f}{dx^2} = 0, \frac{du_c}{dx} = 0, \frac{du_s}{dx} = 0$

For the cement soil corresponding to any point in the contact surface, the displacements of H-shaped steel are respectively:

$$\begin{cases} u_c' = u_c - y_c \dfrac{df}{dx} \\ u_s' = u_s - y_s \dfrac{df}{dx} \end{cases} \tag{5}$$

where, $y_{c,}y_s$ means the coordinate of neutral axis for the cement soil and H-shaped steel respectively.

The deformations of the cement soil and H-shaped steel corresponding to any point in the contact surface are respectively:

$$\begin{cases} \varepsilon_c = \dfrac{du_c'}{dx} = \dfrac{du_c}{dx} - y_c \dfrac{d^2 f}{dx^2} \\ \varepsilon_s = \dfrac{du_s'}{dx} = \dfrac{du_s}{d_s} - y_s \dfrac{d^2 f}{dx^2} \end{cases} \tag{6}$$

The relative slippage of any point in the contact surface is:

$$u = u_c' - u_s' \tag{7}$$

If substitute (5) and (7) into (3), we will get

$$\tau = G(u_c - u_s - d_0 \frac{df}{dx}) \tag{8}$$

Based on hypothesis (1), we get

$$\frac{d^2 f}{dx^2} = \frac{M_c}{E_c I_c} = \frac{M_s}{E_s I_s} \tag{9}$$

The axial force is:

$$N = -E_c A_c \frac{du_c}{dx} = E_s A_s \frac{du_s}{ds} \tag{10}$$

If substitute (9) and (10) into (4), we get:

$$\begin{cases} (E_c I_c + E_s I_s) \dfrac{d^4 f}{dx^4} = q \\ E_c A_c \dfrac{d^2 u_c}{dx^2} - G(u_c - u_s) = 0 \end{cases} \tag{11}$$

If integral (11) and substitute the boundary condition, we get the deflection of the beam as follow:

$$f = \alpha_1 chpx + (\frac{qQ}{24 p^2}) x^4 + (\frac{\alpha_{2Q}}{2p^2} + \frac{qQ}{p^4} - \frac{R}{2p^2}) x^2 \tag{12}$$

where,

$$\begin{aligned} \alpha_1 &= -\frac{1}{p^2 ch \frac{pL}{2}} (\frac{Qq}{p^4} - \frac{R}{p^2}) \\ \alpha_2 &= -\frac{q}{8} L^2 \\ p^2 &= G(\frac{1}{E_c A_c} + \frac{1}{E_s A_a}) \\ Q &= \frac{G}{E_c I_c + E_s I_s} (\frac{1}{E_c A_c} + \frac{1}{E_s A_s}) \\ R &= \frac{q}{E_c I_c + E_s I_s} \end{aligned} \tag{13}$$

$$f_{\max} = \alpha_1 = -\frac{1}{p^2 ch \frac{pL}{2}} (\frac{Qq}{p^4} - \frac{R}{p^2}) \tag{14}$$

During the construction, proper row spacing of supports shall be selected relying on steel support or other supports. The maximum horizontal displacement of SMW f_{max} shall be controlled within 3~4cm.

4 SMW ANTI-SEEPAGE CONSTRUCTION CONTROL TECHNOLOGY

There are so many reasons inducing leakage of retaining structure. During construction, control shall be implemented in the aspects of material selection, program design, construction process, and emergency anti-seepage technology with principle of "combination of prevention and block as well as integrated governance".

4.1 Construction Parameters for SWM Retaining Structure of Zhujianglu Station

The Nanjing Metro Zhujianglu Station was constructed with PAS-200VAR tri-axial mixer made in Japan. H-shaped steel is adopted as core material. According to special condition of stratum and evacuation depth, main construction parameters are shown in Table 1.According to stress need insertion method of shaped steel is 1 into 1, 1 into 2 and 2 into 3 shown in Figure 2. The results of the sample inspection show that unconfined compressive strength of mixing pile with 28 days was more than 1.2Mpa. Horizontal impervious parameter was less than 10^{-7}cm/s. During excavation of foundation pit, the wall did not leak so that integral impermeability and stability were good, fully meeting the above requirements.

Table 1 Construction Parameters of Mixing Pile

Construction Parameters	Value	Remarks
Cement admixing ratio	15-20%	
Water: cement	1.6~2.0:1	
Proportion of cement slurry	1.29~1.37	
Cement slurry per cubic meter soil	0.78~0.84m^3	
Pumping pressure	1.5~2.5Mpa	
Settling speed	<1m/min	
Lifting speed	<2m/min	
Unconfined compressive strength with 28 days	>1.2Mpa	

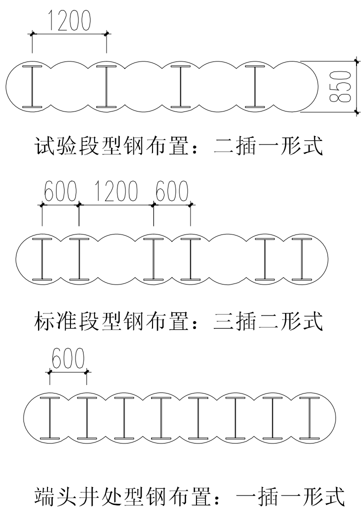

Fig.2. Insertion of Shaped Steel in SMW Method

4.2 Control of Deformation of SMW Retaining Structure at Nanjing Metro Zhujianglu Station

Figure 3 shows the results of integral finite element calculated as per formula (10-12) at Zhujianglu Station.

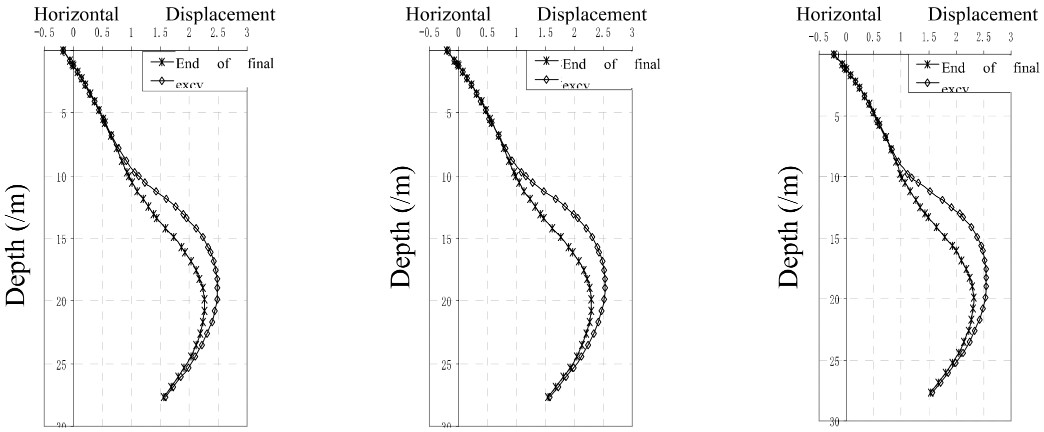

Fig.3. Depth Curve of Pile Horizontal Displacement under Every Operation Mode

In order to verify rationality of design and ensure safety of the foundation pit, typical section of each work point shall be selected under construction supervision and structural stress testing during construction. Figure 4 and Figure 5 show the supervision results of foundation pit level displacement and ground surface falling in a standard section of Zhujianglu Station. Supervision results show that foundation level displacement and ground surface falling basically meet designed calculation values.

4.3 Seepage Control during SMW Retaining Wall Construction at Zhujianglu Station of Nanjing Metro

During SMW construction at Zhujianglu Station, control of the quality of mixing pile was the key ensuring the retaining structure to meet anti-seepage requirements. Full control was conducted on construction precision of drilling, drilling and lifting speed, and mud jacking and cold joint treatment.

1) Control of drilling precision. This includes control of verticality and pile central distance, which directly influence continuity between piles and waterproof property. Generally, the error of hole location shall be less than 2 cm. Verticality of the pile shall not be less than 1/200.

2) Drilling speed. Speed for different strata varies: for the clay stratum it is controlled within 0.5~1.0m/min; As for sandy soil, drilling speed could be increased a little, generally within 1.0~1.5m/min. Speed of lifting mixing shall not be too quick, generally within 1~2 m/min, this could avoid vacuum suction pressure and landslip of hole wall inside the hole influencing solidity of the soil-cement and the water-stop effect of pile.

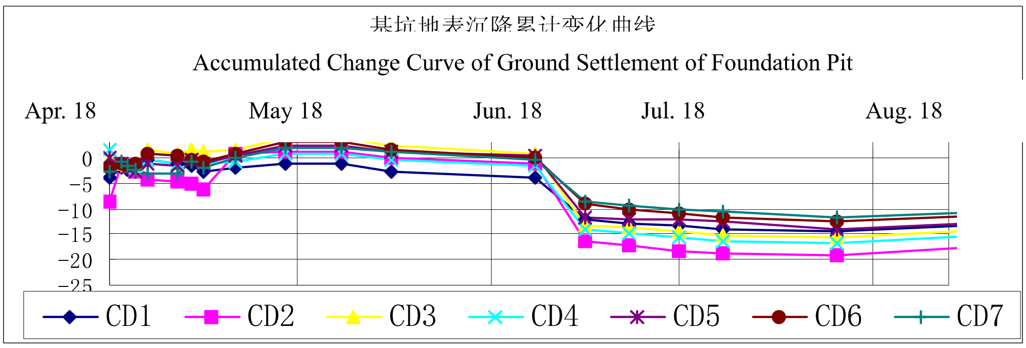

Fig.4 Curve of Ground Settlement of Foundation Pit in Zhujianglu Station

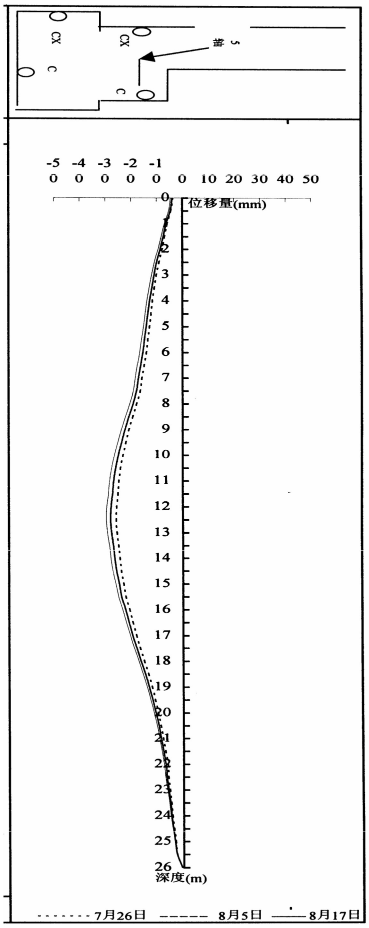

Fig.5 Level Displacement Curve of Foundation pit in Zhujianglu Station

3) Control on mud jacking. Cement slurry shall be continuously pressed and poured during drilling and mixing. Injected cement slurry during drilling is generally 70~80% of rated cement slurry. Injected cement slurry during lifting is 20~30% of rated cement slurry to prevent breaking pile.

4) Cold joint treatment. During construction, construction cold joint may occur and partial leaks due to long construction interval of the wall caused by pile drill problems or construction pauses resulting from blockage during drilling. Once there is a construction cold joint, it shall be properly strengthened with 1~2 lines plain piles outside and be closely jointed to main retaining structure piles.

5 CONCLUSION

The study shows design and construction should be controlled for seepage control of SMW retaining structures in extra-deep foundation pits. During design, density of H-shaped steel and support spacing parameters shall be properly chosen according to different geological conditions and on the basis of effective thickness of cement soil. In addition, properly increased cement strength could help to improve the anti-seepage property of mixing cement. During construction, supervision shall be intensified on the basis of proper construction parameters including drilling speed, pressure of cement slurry, and flow. Wall leakage of SMW construction shall be controlled with technologies of prevention, blockage, and control.

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