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Construction monitoring and numerical simulation of an excavation with SMW retaining structure

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ABSTRACT: The soil mixing wall (SMW) retaining structure is applied in two long strip excavations in Shanghai. Firstly, the bearing and deforming mechanism of SMW is analyzed in brief. The structural analysis method of SMW is discussed. Secondly, based on the in-situ excavating construction procedures, the construction steps of excavating and supporting are simulated in the numerical calculation with the method of Fast Lagrangian Analysis of Continua 3D. There are two cases simulated in numerical calculation, case 1 is the normal case in which the supports are installed timely, and case 2 is a case in which the supports are not installed timely because of some reasons. Then, the deformation of the retaining structure, the horizontal displacement at the top of SMW and the axial forces of steel pipe supports are analyzed and compared with the actual observation data in two cases. A good agreement can be found between the calculation results and observation data. It can be seen that in case 1 the excavation is stable and safe; the axial forces are lower than the alarm values and the displacement due to excavating is in the permissible range. In case 2, however, the excavation is in danger of instability and some measures should be taken to protect the SMW retaining structure from failure.

1 INTRODUCTION

The composite structure with H-shaped steel and deep cemented-soil piles is called SMW method. This method can be applied in cohesive soil, sandy soil and sandy gravel layers. It has been widely accepted in China, which is mainly applied to deep excavations in soft soils of eastern and southern China.

This paper studies the bearing and deforming mechanism of SMW. Based on the in-situ excavation construction procedures of the engineering example, the construction steps of excavating and supporting are simulated in the numerical simulation method with FLAC3D. Because the excavations are too long, the method of excavating is similar to tunnel excavating, which is from one side to another. And there are two cases simulated, one is the normal case in which the supports are installed timely. However, in middle of March 2007 during excavating, because of the bad weather and some other reasons, the supports were not installed timely so that the excavation was in danger of collapse. Therefore, another case is a case in which the supports are not installed timely.

Through comparing the actual observation data in-situ and the calculation results, some useful conclusions are achieved.

2 THE PROJECT GENERAL SITUATION AND MONITORING SCHEME

2.1 *The project general situation*

The underground channels project contains two long strip excavations, the eastern and western excavations, which are similar to each other. The length is both 820.5 m, and the width is 16.5 m. The excavation depth is between 6.645 m ~ 8.039 m. It is clear around the construction site.

The foundation soil layers belong to Quaternary Pleistocene-Holocene deposit, including cohesive soils, silt and sandy soils which distribute in planes. The physico-mechanical parameters of soils in site are shown on Table 1.

The φ650 SMW method is applied and steel pipe supports are installed. The SMW retaining structure is 17 m long in depth, which is inserted with $500 \times 200 \times 10 \times 16$ H-shaped steels. In order to facilitate the earthwork excavating, two steel pipe support tiers including the upper and the lower supports are installed considering the characteristic of the excavations. The upper steel supports locate 1.0 m below the ground surface. The lower steel supports locate 2.5 m above the excavation bottom. The sizes of the steel

Table 1. Physico-mechanical parameters of soils in site.

The soil layers	Depth (m)	γ (kN/m^3)	C (KPa)	φ (°)	E (MPa)	μ
Silty clay and clayey silt	3	17.8	10.0	23.0	4.38	0.3
Sandy silt	2	18.2	4.0	29.0	4.78	0.33
Silty clay	2	17.3	10.0	21.5	3.84	0.35
Sandy silt and silty clay	2	17.6	3.0	25.5	5.08	0.3
Silty clay	10	16.2	11.0	11.0	13.62	0.3
Clay	11	17.3	13.0	12.0	17.0	0.3

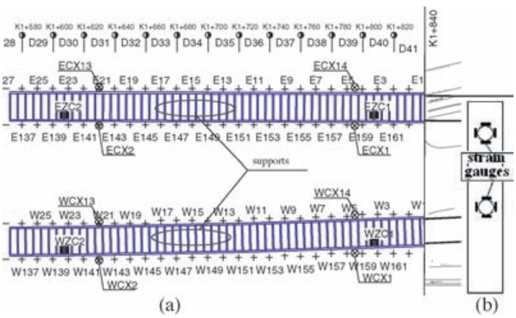


Figure 1. General layout of monitoring points: (a) The south section of the excavations; (b) The strain gauges welded around the support.

supports are all $\varphi 609 \times 12$. The distance between the adjacent supports is 5 m.

2.2 *The monitoring scheme*

Around the two excavations, the monitoring points for the horizontal displacement and settlement at the top of the retaining structure are located about every 10 m. And they are numbered using E and W, in which E denotes the eastern excavation, W denotes the west excavation. There are all 324 monitoring points for the top horizontal displacement and settlement of the SMW in two excavations, as shown in Figure 1(a). Because the excavations are so long that the south section is given only.

14 inclinometer tubes for lateral deformation of SMW are set in every excavation. They are located in the same distance about 100m symmetrically. The location of every monitoring point is shown in Figure 1(a), in which ECX denotes the inclinometer tube in the eastern excavation and WCX denotes the inclinometer tube in the western one.

In every excavation there are 6 pairs of monitoring points for axial forces of supports, and every pair has two points including the upper and the lower supports. As shown in Figure 1(a), for example, EZC1 includes the upper EZC1 and the lower EZC1 supports. Therefore, there are 12 monitoring points for every excavation, EZC denotes the axial force monitoring points in the eastern excavation, and WZC denotes the western one. The distance between each pair monitoring points is about 120 m. The steel strain gauges are welded around the steel pipe supports as shown in Figure 1(b).

3 BEARING AND DEFORMING MECHANISM OF SMW

The cemented soil material that is produced generally has a higher strength, lower permeability, and lower compressibility than the native soil. Therefore, the SMW method can make it possible to form water-preventing and earth-retaining walls quickly by mixing earth collected at a construction site with cement slurry. The rigidity of the earth retaining walls was further enhanced by forming a compound earth-retaining wall with H-shaped steel materials welded with studs that act as stress material arranged within the improved soil walls. And under the suitable conditions, the H-shaped steels can be recycled.

Stress-strain characteristics of SMW are extremely complex during the course of the pit excavation. The curves of H-shaped steel strain are under the linear elastic scope, but cemented-soil is nonlinear response, and the rigidity changes of composite structure mainly by the cemented-soil. It is commonly considered that the H-shaped steels bear all the lateral water and earth pressure and the cement deep mixing piles are used to prevent water. However, it is testified through experiments that cement soil can enhance the H-shaped steels to reduce the deformation. In addition, the cement soil can also have confinement effect to prevent the H-shaped steels instability. The composite flexural stiffness is 20% greater than only H-shaped steels. The stiffness enhancing coefficient can denote the degree of stiffness enhancing as follows:

$$\alpha = \frac{E_{cs} I_{cs}}{E_s I_s} \tag{1}$$

where E_{cs} and E_s are the elastic modulus of cement deep mixing pile with H-shaped steel and the elastic modulus of H-shaped steel, respectively; I_{cs} and I_s are the inertia moment of cement deep mixing pile with H-shaped steel and the inertia moment of H-shaped steel.

In this numerical calculation, the cement deep mixing pile with H-shaped steel is equivalent to diaphragm wall and the influence of stiffness enhancing coefficient α is considered. According to the principle that the stiffness is equal to each other, the equation is given by

$$E_{cs} I_{cs} = \frac{1}{12} E(W + t)h^3 \tag{2}$$

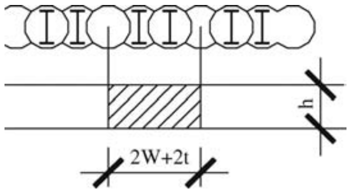


Figure 2. The stiffness equivalence between SMW and diaphragm wall.

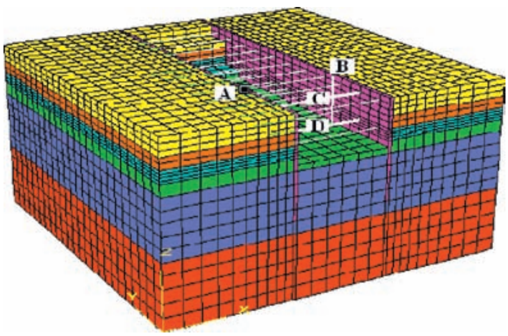


Figure 3. Elements of model in case 1.

Based on equation (1), thus

$$h = \sqrt[3]{\frac{12\alpha E_s I_s}{E(W+t)}} \tag{3}$$

Here, α is considered as 1.2. The equivalent thickness of diaphragm wall in this numerical calculation is $h = 0.65$ m and the Young modulus is $E = 12.6$ GPa.The equivalent figure from SMW with H-shaped steels to diaphragm wall in this project is shown as Figure 2 shown.

The interfaces are installed to simulate the interface characteristics between the retaining structure and the soils. In FLAC3D, Interfaces have the properties of friction, cohesion, dilation, normal and shear stiffness, and tensile and shear bond strength, which are characterized by Coulomb sliding and/or tensile and shear bonding. In this computation, the equivalent diaphragm wall is considered as elasticity.

4 CALCULATION CASE

4.1 *Case 1*

Because there are two long strip excavations and they are similar, one part of the eastern excavation is chosen to be simulated. The model size is 60 m in extent, 60 m in breadth and 30 m in height. The model is shown in Figure 3.

The earthworks soils for excavating are divided into 3 layers. The first layer is from 0.0 m to −2.0 m, the second layer is from −2.0 m to −6.5 m, the third is from −6.5 m to −8.0 m. There are upper and lower two supports installed, the upper supports are located at −1.0 m and the lower supports are at −6.5 m. And the distance between two adjacent supports in y direction is 5 m. Therefore, the length of soils excavated in every layer is 5 m in y direction in every excavating step. Because the excavation is too long, the excavating method is similar to tunnel excavating method which is from one side to another. The construction procedure of excavating and supporting is divided into lots of steps, as follows:

- The construction of SMW.
- The first layer is excavated 5 m in y direction and the first upper steel support is installed.
- The first and second layers are excavated 5 m in y direction and the second upper and the first lower supports are installed.
- All the three layers are excavated 5 m in y direction, and the third upper and the second lower supports are installed.
- Do this until the earthworks excavation is completed.

The whole procedure of excavating steps and installing supports is simulated by 3D numerical method. There are 11 excavating and supporting steps except the construction of SMW.

In this numerical simulation calculation, the mechanical soil behavior is modeled with Mohr-Column model and the supporting structures are considered as elastic model. The interfaces are installed between SMW and soils. The top of the model, at z = 30 m, is a free surface. The base of the model, at z = 0 m, is fixed in the z-direction, and roller boundaries are imposed on the sides of the model, at x = 0 m, x = 60 m, and y = 0 m, y = 60 m.

4.2 *Case 2*

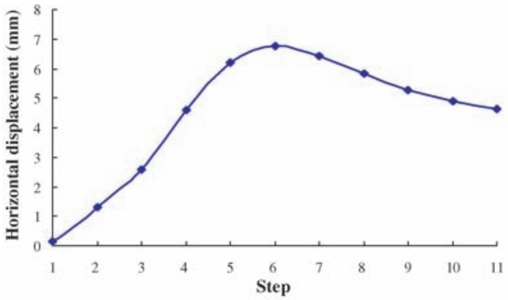
In middle of March 2007, because of the bad weather and other reasons, the steel pipe supports were not installed in time. There were about 30 m in length without supports from the excavating face to the lattermost supports for a long time. Meanwhile, according to the in-situ measurements, there was a sharp increment in horizontal displacement of the soil mixing wall. This case is simulated to analyze the influence.

In this case, the material properties and boundary conditions are same to case 1. The excavating and supporting procedures are same, too.

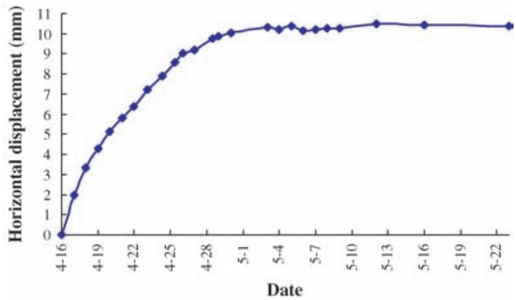
5 RESULTS

5.1 *Case 1*

In order to analyze the calculation results conveniently, some key points are set in the model, as shown in

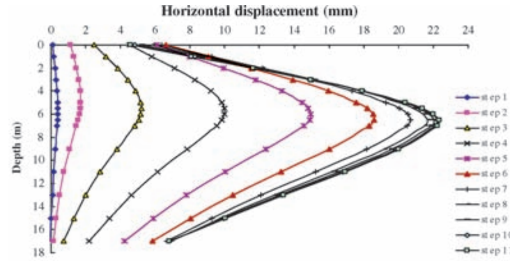


(a) The calculation results.

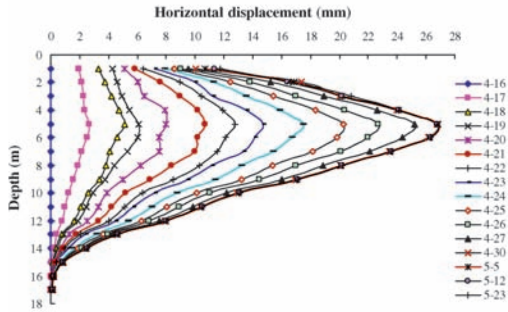


(b) The observation data.

Figure 4. The horizontal displacement at point A in case 1.



(a) The calculation results.



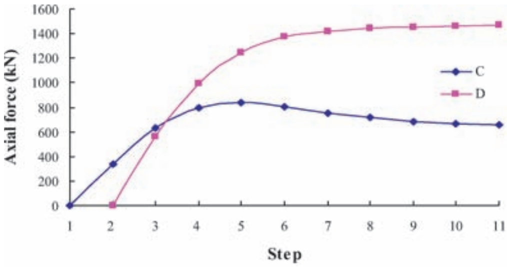
(b) The observation data.

Figure 5. The horizontal displacement of the SMW in line B in case 1.

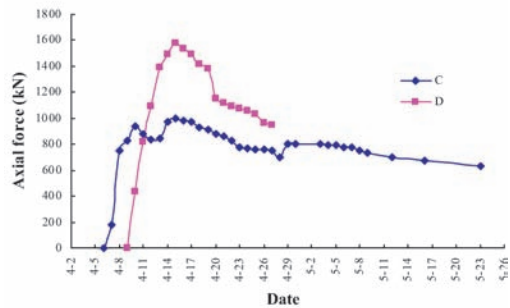
Figure 3. Firstly, the horizontal displacement at the top of SMW is analyzed. The curve of horizontal displacements at point A is shown in Figure 4(a). It can be seen that the horizontal displacement increases before step 6 but then decreases in the following steps. The maximum value is 6.76 mm at step 6 and the ultimate value is 4.63 mm. According to the excavating steps in calculation, when the excavating face exceeds point A about 15m, the value of the horizontal displacement begins to decline. The actual observation data for point A is shown in Figure 4(b). It can be seen that the actual values are bigger than the calculation results. The curve is monotone increasing by steps and tends to be constant after having reached a certain level. Its ultimate value is 10.4 mm. The calculation result of the horizontal displacement at point A is much less than the observation value.

The curves of calculation results with excavating steps and the observation data with date for the horizontal displacement of the retaining structure in line B are shown in Figure 5. According to the calculation results, its maximum horizontal displacement of the SMW occurs at the point of 6.5 m depth, and its value is 22.35 mm. As shown in Figure 5(a), when the excavating face reaches the line B at step 3, the deformation of SMW increases dramatically. When it has passed away from line B about 20 m, the deformation increases slowly. Figure 5(b) shows the observation curve of horizontal displacement of SMW in line B with the date. A rather good agreement can be found between (a) and (b). According to the observation data, the maximum horizontal displacement in line B occurred at point of 5.0 m depth and its value is 26.8 mm, which is greater than the maximum calculation value by 4.45 mm. With the excavating face advancing, the deformation increment is becoming smaller. From the actual observation data and calculation results, it can be seen that the horizontal displacement of the SMW mainly occurred during the period of excavating surface passing this line.

The curves of axial forces of the steel pipe supports C and D with excavating steps are shown in Figure 6(a). The final axial force of the upper support C is 657.60 kN, and the lower support D is 1467.7 kN in calculation results. As shown in Figure 6(b), the observation data is greater than the calculation results. The maximum axial force of the upper support C is 995.83 kN, and the lower support D is 1575.7 kN. Both C and D have an ascending firstly and then declining process with lapse of time in actual observation. This is because the foundation mat bore a part of soil pressure with its pouring and strengthening. However, the procedure of pouring and strengthening of foundation mat is not simulated in numerical calculation. So there



(a) The calculation results.



(b) The observation data.

Figure 6. The axial force of supports C and D in case 1.

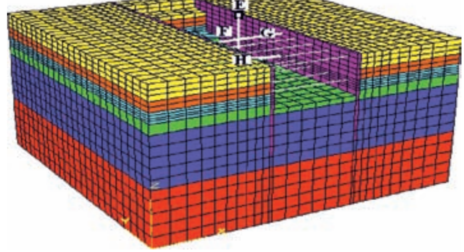


Figure 7. Elements of model in case 2.

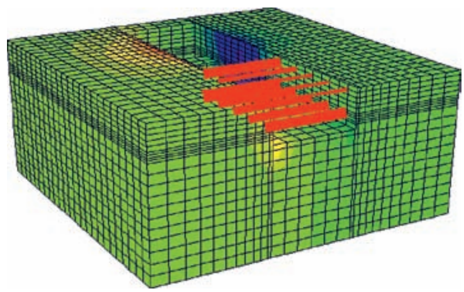


Figure 8. The horizontal displacement and the axial forces of steel pipe supports in case 2.

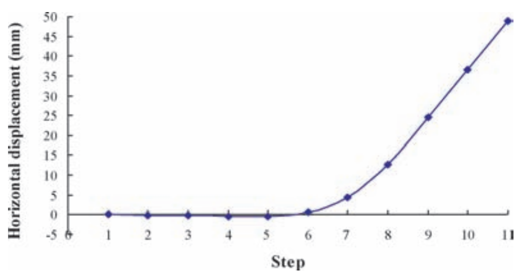


Figure 9. The horizontal displacement of point E in case 2.

is no declining trend of axial forces. But in the early stage, the trend and shape of calculation results curve with excavating steps and observation data curve with date is agreed generally. As shown in Figure 6(b), on 28 April the lower support D was removed, therefore, the axial force of the upper support C had a significant rise by 102.5 kN. However, in calculation this procedure is not simulated.

Through analysis, it can be seen the values of observation data are greater than the calculation results universally. The main discrepancy between calculation and measure can be explained that the physico-mechanical parameters of soils are not accurate enough. However, in reality, this area was less stiff than initially planned. According to the numerical simulation and the actual observation data, the excavation is stable if the steel pipe supports can be installed in time. The numerical results and actual data of axial forces are lower than the alarm values. The displacement due to excavating is in the permissible range.

5.2 *Case 2*

In case 2, the numerical calculation model is shown in Figure 7. Figure 8 shows the horizontal displacement of the model and the axial forces of steel pipe supports at last step. It can be seen the maximum horizontal displacement at the top of SMW occurs at point E with 48.96 mm, as shown in Figure 7. The curve of horizontal displacements at point E when excavating from step 1 to step 11 is shown in Figure 9. It can be seen the displacement at point E is nearly zero before step 6 until the excavating face passes point E. With the excavating face advancing after step 6, the displacement increases significantly. According to calculation results, the maximum horizontal displacement of SMW occurs at the point of 3 m depth, which is in line F, and its value is 50.44 mm. As shown in Figure 10, the horizontal displacement of SMW in line F develops slightly until the excavating face passes this line at step 6. Because the supports are not installed near this line, the deformation of SMW develops more rapidly. In actual observation, there are three points of which horizontal displacements in line F are greater than the alarm value with 50 mm. The axial forces

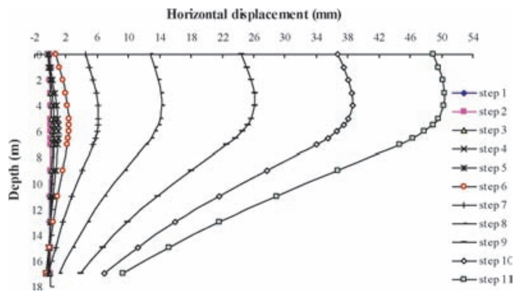


Figure 10. The horizontal displacement of the SMW in line F in case 2.

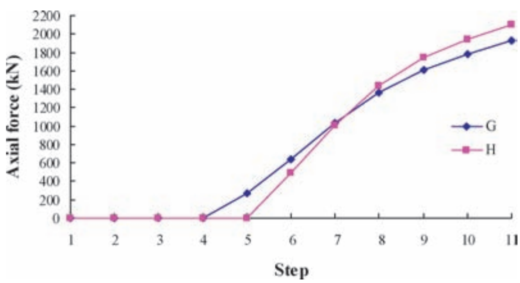


Figure 11. The axial forces of supports G and H in case 2.

of lastly installed supports G and H are much larger because of without installation of subsequent supports. The axial force of support G is 1924.50 kN, and H is 2095.60 kN. The curves of the axial forces of supports G and H with the excavating steps are shown in Figure 11. According to calculation results, the axial forces of G and H are much greater than the adjacent supports by 903.75 kN for upper support and 546.00 kN for lower support. Compared with Figure 6(a), the magnitude is much greater. The axial force of G exceeds the alarm value with the upper supports for 1500kN and H exceeds the alarm value of lower supports for 2000 kN.

There are two inclinometer tubes ECX2 and ECX13 for lateral deformation of SMW around this site. According to the observation data of 19 March and 20 March, the velocity of horizontal displacement exceeded the alarm value of 3 mm/d for two days between the depth of 5 m ~ 8 m at ECX13. The velocity values were 4.18 mm/d, 3.97 mm/d, 3.64 mm/d and 3.20 mm/d when the depths are 5 m, 6 m, 7 m and 8 m respectively on 19 March. Moreover, the velocity values were 5.18 mm/d, 5.66 mm/d, 4.98 mm/d and 3.44 mm/d in the next day. Meanwhile, the velocities of horizontal displacement were greater than 3 mm/d in the depth from 1 m to 12 m at ECX2 on 19 March, which were over 10 mm/d within 3 m from the top of SMW.

According to the results of numerical simulation and actual observation data, it was possible to collapse for this excavation because the supports were not installed in time. The risk was existent so the corresponding measures should be taken. After being alarmed, the construction team stopped excavating and installed the supports speedily. It's turned out that the measures are very effective according to the subsequent observed data.

6 CONCLUSIONS

In this paper, firstly, the bearing and deforming mechanism of SMW is analyzed in brief; secondly, the construction monitoring scheme is introduced; thirdly, a 3D numerical simulation of this long stripe excavation is described, including all the components of the project (the SMW construction, stepped excavation and supports installation); then the numerical results are compared with the actual data in-situ observation.

- The 3D numerical method can simulate the whole excavation construction very well. A good agreement can be found between the numerical results and the actual observation data except for some small deviations.
- The excavation is stable and the displacement due to excavating is in the permissible range if the steel pipe supports are stalled timely. However, because of bad weather and other reasons the steel pipe supports are not installed in time and without supports for a long time, such as case 2, the excavation is in danger of collapse.
- According to the in-situ observation data, the construction team can take corresponding measures to protect the excavation away from some undesirable events and risks.

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