Collapse of a Deep Excavated Foundation Pit in the Soft Soils by 3-D FEM

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Abstract: In view of the collapse of a deep excavated foundation pit of the Xianghu subway underground station in Hangzhou of China, the main features of the accident are analyzed, and the induced factors of the accident are summarized. Then, a 3-D FEM analysis model is created to demonstrate the soil-support structures interaction system, and the effect of the main factors, such as the volume replacement ratio of the bottom soil reinforcing, the asymmetric ground overload, the embedded depth of the diaphragm wall, the shear strength of the bottom soils disturbed by the construction, and the excessive excavation of the bottom soil, are analyzed and compared. The results show that the ineffective original reinforcement plan for the bottom soft soil is the most prominent factor for the accident, and the disturbance effect of the deep excavation on the shear strength of the bottom soft soil is another significant factor for the accident. Meanwhile, if the reinforcement of the bottom soft soil is canceled, an appropriate extension of the diaphragm retaining walls to the under lying harder soil layer can also effectively prevent the collapse of the deep excavated foundation pit. In addition, the partly excessive excavation in the process has a great influence on the axial force of the most nearby horizontal support but few effect on the stability of the diaphragm wall. Thus, the excessive excavation of the bottom soils should not be the direct inducing factor for the accident. To the asymmetric ground overload, it should be the main factor inducing the different damage conditions of the diaphragm walls on different sides. According to the numerical modeling and actual engineering accident condition, the development process of the accident is also identified.

Key words: deep excavation; subway station; collapse process; numerical modeling; soft soil

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0 Introduction

With the rapid development of the urban modernization in China, the heavy traffic becomes severer and severer in some large cities of China, such as Shanghai, Beijing, and Guangzhou. As a result, subway system, as a convenient and quick public transport means, is a most effective method to solve this problem. However, many engineering accidents have occurred frequently during the construction processes of the subway engineering, which have caused significant losses of life and property. For example, in the early morning of July 1, 2003, the water inrush accident of metro tunnel in line No.4 of Shanghai caused large-scale pavement collapse and ground buildings inclination. On February 5, 2007, at about 6:00 am, a seepage collapse took place in a deep excavated process for a subway station in Nanjing metro line No. 2, which caused a nearby gas pipeline explosion. At around 5 am on May 4, 2007, a deep excavation collapse occurred in the excavation process of a subway station in Beijing metro line No.10. Especially, on November 15, 2008, about 3:15 pm, more serious collapse accident occurred in the deep excavated process of a subway station in Hangzhou Metro Line No.1, which killed

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21 construction workers. Accordingly, the deep excavation accident should be still a difficult scientific problem in the geotechnical engineering research field.

At present, the main research methods on this problem are the analytical method, the numerical modeling, the model test and the in-site monitoring. However, though the analytical methods have the advantage of direct rapid calculation, which cannot include the nonlinear problems, the uneven soil stratum, and other main factors under the complex environment of deep excavated pit. Moreover, the accuracy of most analytical methods also needs to be further improved and verified. For the environmental effects caused by deep excavations, in-site monitoring is the most effective and most efficient method to study this problem, which also can make effective verification on the feasibility and accuracy of the analytical methods and the numerical modeling[1-5]. However, when the foundation size is too large, the limited in-site monitoring data cannot effectively reflect the actual working state of the excavation retaining structure.

With the rapid development of computer technology, numerical calculation can be well adapted to solve complex geotechnical problems, especially the non-homogeneous and non-linear problems. Therefore, numerical modeling has been widely used in the existing researches[6-11]. The common analysis software mainly include PLAXIS, FLAC and MIDAS, but most of the previous studies applied two-dimensional plane strain analysis model, and there is still an obvious gap between the calculated results and the in-site measured results. In spite of this, the numerical modeling is still the most effective method to analyze the mechanism leading to a disaster and failure characteristics of the deep excavated foundation pit.

Accordingly, this work analyzes firstly on the collapse of the deep excavated foundation pit through the in-site photos, and then summarizes the main inducing factors by the existing studies. After this, a three-dimensional (3-D) finite element analysis model is made to simulate the whole excavation process of the foundation pit. The effects of the possible main factors on the collapse are analyzed one by one. Then, the main factors are decided, and the collapse process of the foundation pit is also initially deduced according to the numerical modeling. The relevant research methods and conclusions can provide reasonable reference and guidance in the accident prediction and risk assessment of the foundation pit excavated in soft soil.

1 Accidents Review

Xianghu Subway Station in Hangzhou is a starting station for Hangzhou Metro Line No.1. It is located on the north side of the Hangzhou Park (the 2nd stage) in the Xiaoshan District, whose location is shown as Fig.1. This subway station is a two-story island-styled structure, whose total length is about 934.5 m and the width is about 21 m. It is constructed by the open excavation method with eight small foundation pits excavated respectively, and the excavation order of each section is from the two ends to the middle. The minimum distance from the west side of the collapsed foundation pit to the changed Fengqing Avenue is about 5.8 m. This avenue is filled with heavy traffic, including some heavy trucks. Meanwhile, some municipal pipelines locate under this avenue. The collapsed foundation pit is 107.8 m long and 21.05 m wide, whose excavated depth is 15.7—16.3 m.

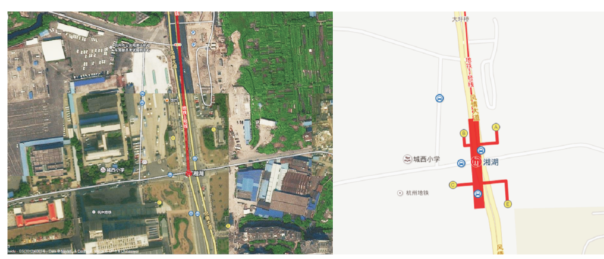

Fig.1 Location of the Xianghu subway station in Hangzhou Metro Line No.1

At about 3:15 pm on November 15, 2008, the west side of the excavated foundation pit collapsed suddenly. The west diaphragm wall of the foundation pit was broken at the connection between the foundation pit and the end working well for the shield construction, whose bottom soft soil was reinforced by the cement-soil deep mixing piles, as shown in Fig. 2. Meanwhile, the west diaphragm wall was also broken in horizontal direction, as shown in Fig.2(d), and the broken places located about 5 m under the original ground and 3m under the bottom of the foundation pit. However, the diaphragm wall on the east side of the foundation pit was not broken, but it tilted to the pit about 3.9 m. After the west wall broken, the Fengqing Avenue collapsed with 6.5 m depth of the collapse basin, 40 m width, and about 100 m long, as shown in Fig. 2(a). All the inner supports of the foundation pit failed, as shown in Fig.2(c). After the west wall broken, the outer soils of the wall slid into the foundation pit, which induced about maximal 7 m inward horizontal displacement of the west wall. Then, the bottom soil of the foundation pit was uplifted about 5.7 m, as shown in Fig. 2(d). Before the accident, the bottom plates of the foundation pit had been constructed in construction areas No.1 and No. 2, as shown in Fig. 3. The last soil layer had been excavated in construction areas No.3 and No.4, and the last internal horizontal support had been installed in construction area No. 3. The last soil layers in construction areas No.5 and No.6 were excavated before the accident.

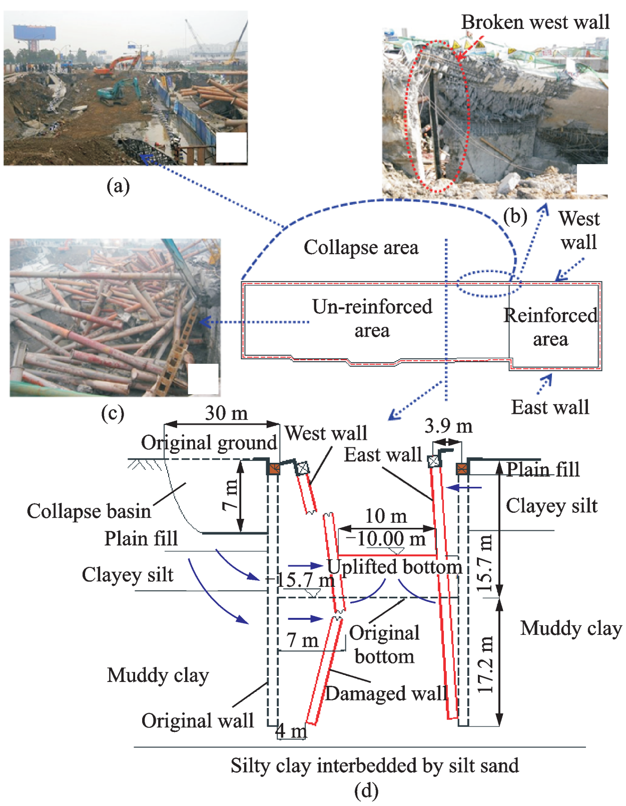

Fig. 2 Failure situation of deep foundation pit in Hangzhou Metro Line 4

This engineering accident caused serious casualties and social influence. According to the investigations given by government and some related studies on this engineering accident[12-14], the major factors may be: (1) The excessive excavation of the bottom soil without installing the horizontal support in time, as shown in Fig.3; (2) the support structures designed by using the shear strength of the soft soils without considering the disturbance by the construction; (3) the bottom soft soils without reinforced by an effective method; (4) the bottom end of the diaphragm retaining walls embedded in soft soils; and (5) the ground overload induced by the heavy traffics running on the Fengqing Avenue.

Some minor factors are also summarized as: (1) The top horizontal support should be built by the reinforced concrete; (2) the bottom plate of the foundation pit in construction areas No. 3 and No. 4 should be constructed in time after the last soils excavated; (3) the monitoring data were not effective in waring the potential collapse of the foundation pit; (4) some horizontal supports were not fixed with the diaphragm retaining wall.

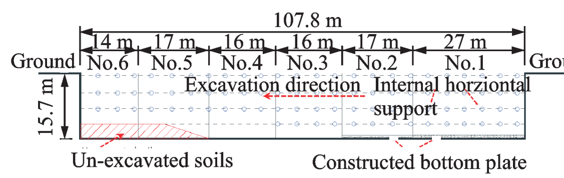

Fig.3 The last excavated condition of the foundation pit before the accident

2 FEM Numerical Model

According to the above summarization on the accident of the foundation pit for the Xianghu subway station in Hangzhou Metro Line No.1, a 3-D finite element numerical model is made to investigate the effect of the five major factors on the working state of the support structures with the soil-support structure interaction.

2.1 Geometric model and the boundary conditions

According to some related studies on the influenced area of the deep excavation, the dimension of the soil foundation cut from the half space is about 121 m × 207 m × 50.1 m, as shown in Fig.4. The retaining structure of the foundation pit is an enclosed concrete diaphragm wall with thickness of 0.8 m. According to the original engineering design, its buried depth was about 33 m. The horizontal support system of the foundation pit is made by four-story steel pipes whose diameter is 609 mm and the wall thickness is 16 mm, which are installed by 3 m horizontal distance to each other and different distances in vertical direction, as shown in Fig. 5. An array of columns made by the steel-lattice rigid frame is installed to maintain the stability of the horizontal support system, as shown in Fig.5. The transection dimensions of the support structures are shown in Table 1.

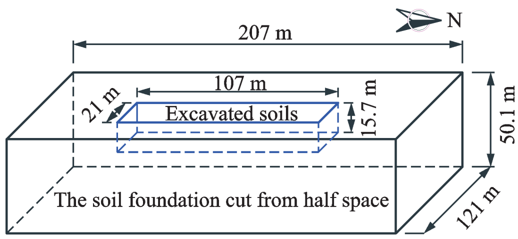

Fig.4 Dimensions of soil foundation cut from the half space

In the numerical model, the soil foundation is meshed by 8-nodes solid elements. The diaphragm wall is meshed by 4-nodes shell elements. The internal support structures are all meshed by 2-nodes beam elements. The contact between the soils and the diaphragm wall is modeled by the Goodman elements. The lateral boundary of the soil foundation is constrained in horizontal direction and free in vertical direction, and the bottom boundary of soil foundation is constrained wholly. The overall finite element meshing is shown in Fig.6. It should be noted that the internal supports are fixed on the diaphragm wall. The main methods used in this FEM numerical model have been verified by comparing with the

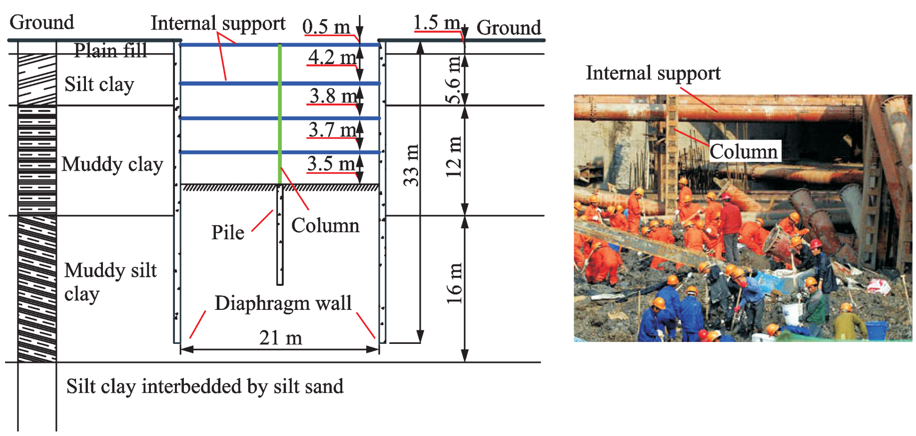

Fig.5 Cross-section of the foundation pit

Table 1 Sizes of structure and mechanics parameters of the materials

Structure	Material	υ	$\gamma/(\mathrm{kN \cdot m^{-3}})$	E/GPa
Diaphragm wall	C30	0.2	24	30
Concrete bracing	C30	0.2	24	30
Steel bracing	Q235-B	0.26	78.5	200
Pile of column	C30	0.2	24	30

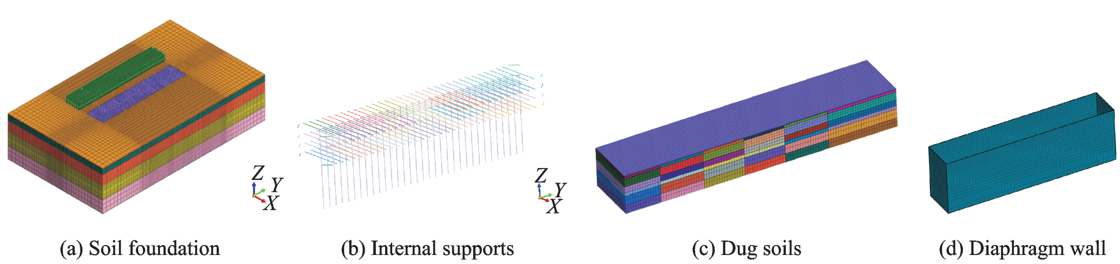

Fig.6 Overall finite element meshing plan for the numerical modeling

field measured results[15].

2.2 Constitutive models for the materials

The mechanics properties of soil are modeled by the Mohr-Coulomb model.

According to the original engineering design, the soft soils under the bottom of the foundation pit should be reinforced by the cement-soil deep mixing piles. To model the reinforcement effect on the soft soils, the reinforced soil foundation is equal to be a homogeneous foundation[16]. As a result, the mechanics properties of the equivalent materials in reinforced soil foundation can be calculated by

$$E_{sp}=mE_p+(1-m)E_s, \gamma_{sp}=m\gamma_p+(1-m)\gamma_s,$$
$$\upsilon_{sp}=m\upsilon_p+(1-m)\upsilon_s,$$
$$c_{sp}=mc_p+(1-m)c_s, \varphi_{sp}=m\varphi_p+(1-m)\varphi_s \quad (1)$$

where $E_p, \gamma_p, \upsilon_p, c_p$, and φ_p are the compression modulus, unit weight, Poisson's ratio, cohesion, and internal friction angle of the reinforced soil, respectively; $E_s, \gamma_s, \upsilon_s, c_s$, and φ_s are the corresponding parameters of the natural soft soil, and m is the volume reinforced replacement ratio of the soil foundation.

According to the original engineering design, the elastic modulus of the cement-soil mixture was about 189 MPa. By Eq.(1), the mechanical parameters of the equivalent materials in reinforced soil foundation are given in Table 2 for different volume replacement ratios of the soil foundation. The mechanical parameters of other soils are given in Table 3.

Table 2 Mechanical parameters of the reinforced soils

m	υ_{sp}	γ_{sp}/(kN·m^{-3})	c_{sp}/kPa	φ_{sp}/(°)	E_{sp}/MPa
0.1	0.35	17.9	14	8.2	37.8
0.2	0.36	18.2	18	11.8	54.6
0.3	0.39	18.4	22	15.3	71.4
0.6	0.43	19.1	34	25.9	121.8
1.0	0.49	20	50	40	189

The diaphragm walls and piles are made by concrete No. C30 and steel No. Q235-B, and the columns and the horizontal support are also made by steel No. Q235-B. The concrete and steel are modeled by the linear elastic model, whose mechanics parameters are given in Table 3. By the original engineering design, the designed moment capacity of the diaphragm wall is about 1 423 kN·m per unit horizontal width, and the designed axial load capacity of the horizontal support is about 5 764 kN. The contact between soil and concrete is modeled by Goodman element, which mechanics parameters of the contact between soil and concrete are given in Table 4.

2.3 Numerical modeling on the excavation process

According to the construction process of the foundation pit, the soils in the foundation pit are parted into four layers in vertical direction and dug out from the top to the bottom. In horizontal direction, the ladder type excavation method is adopted,

Table 3 Mechanical and physical parameters of the natural soils in site

Soil	Thickness/m	υ_s	γ_s/(kN·m^{-3})	c_s/kPa	φ_s/(°)	E_s/MPa	Permeability coefficient
Plain fill	1.5	0.2	18	10	10	4.5	1.04×10^{-4}
Silt clay	5.6	0.35	19	10.2	31.8	21	1.75×10^{-4}
Mucky clay	12	0.4	17.7	10	4.7	15	4.29×10^{-7}
Mucky silt clay	16	0.33	16.9	17.3	12.6	21	4.00×10^{-7}
Silt clay interbedded by silt sand	15	0.3	18.5	24	15.1	25.2	4.00×10^{-4}

Table 4 Mechanics parameters of the contact interface between soil and concrete

Name	Normal stiffness/(GPa·m^{-1})	Tangential stiffness/(MPa·m^{-1})	Cohesive strength/kPa	Internal friction angle/(°)
Interface	10	6	50	20

as shown in Fig.7. The detailed numerical modeling steps in the soil excavation process of the foundation pit are shown in Fig.8.

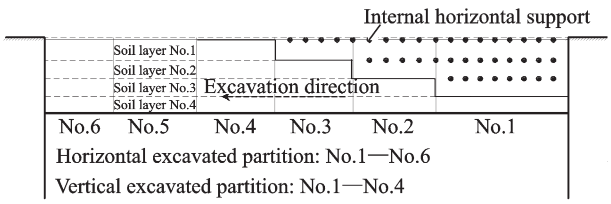

Fig.7 Soil excavation manner of the foundation pit

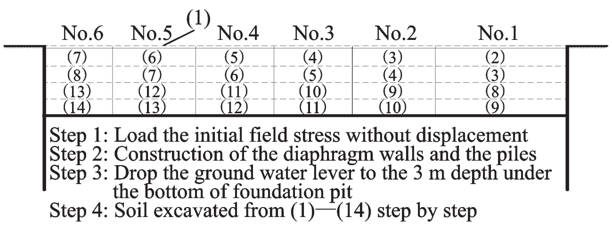

Fig.8 Numerical modeling on soil excavation process of the foundation pit

3 Influence of Different Factors

To express the working state of the support system, the axial force of the horizontal support, the bending moment, and the lateral displacement of the diaphragm wall are analyzed by the numerical modeling results. It should be explained that the positive displacement denotes the diaphragm wall moving inward to the foundation pit. On the contrary, the diaphragm wall moves outward to the foundation pit. Meanwhile, the positive moment of the diaphragm wall denotes that it is compressed on the side to the foundation pit and the negative one denotes compressed on the side to the back soils. The positive axial force of the horizontal support denotes that the support is compressed and the negative one denotes the support stretched.

3.1 Influence of reinforcement replacement ratio

According to the original engineering design of the foundation pit, the soft soils under the bottom of the foundation pit should be reinforced by the cement-soil mixed piles, as shown in Fig.9(a). However, the construction organization did not use the original reinforcement method. Instead, the alternative consolidation method was used by dropping the underwater lever to 3 m depth under the bottom of the excavated pit. However, the consolidation method by dropping the underwater lever is not effective to reinforce a clay layer in short time by the existing engineering experiments. According to the accident conditions, the construction well at the right end of the foundation pit has not been damaged in the accident for its bottom soft soils reinforced by the cement-soil mixed piles, as shown in Fig. 9(b), which proves that the reinforcement method by the cement-soil mixed piles is more effective than the consolidation method for this engineering. Accordingly, the influences of the volume reinforcement replacement ratio (m) on the working state of the support structures are analyzed in this section. By the numerical modeling, Fig. 10 shows the lateral displacement distribution curves of the collapsed diaphragm wall and the relationship curves between m and the maximal lateral displacement of the diaphragm wall. In general, the maximal lateral displacement of the diaphragm wall decreases with the larger m, and the location of the maximal displacement also slightly moves upward. According to the related codes, the design allowable to the maximal displacement for the diaphragm wall should be 60.8 mm (about 3%H, H is the length of the diaphragm wall in vertical direction). Compared with the design allowable, the maximal displacements of the diaphragm wall are all larger than 60.8 mm when m is less than 30%. When the bottom of the foundation pit is not reinforced, the maximal displacement is about

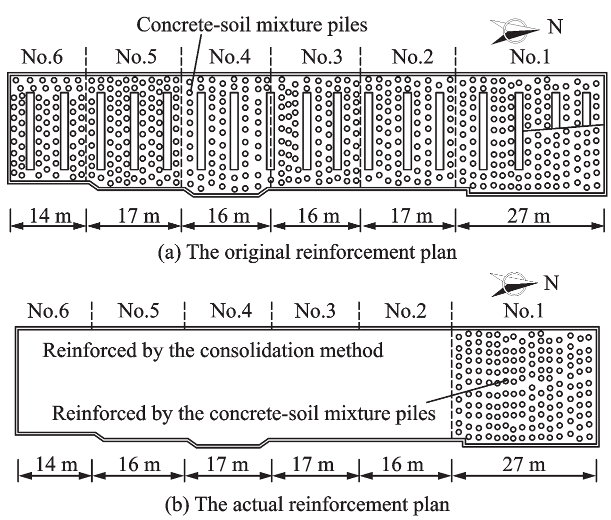

Fig.9 Reinforcement method of the soft soils under the bottom of foundation pit

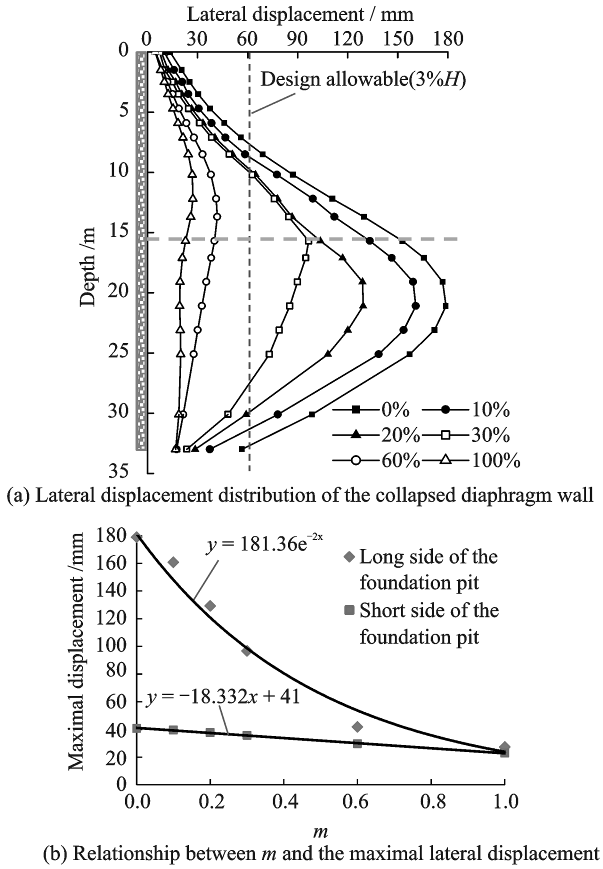

Fig. 10 Lateral displacements of the collapsed diaphragm wall

3 times of the design allowable. According to the Fig.10 (b), when m is larger than 50%, the maximal displacements of the diaphragm wall is less than the design allowable, and the influence of m weakens obviously. Generally, the influence of m on the maximal lateral displacements of the diaphragm wall in short edge of the foundation pit is not obvious. However, it should be noted that the large horizontal diplacement at the end of diaphragm wall should induced by the soft soil layer which has not penetrated by the wall.

Fig.11 shows the bending moments of the diaphragm wall and the axial forces of the internal horizontal support under different m. By Fig. 11 (a), when the bottom of the foundation pit is not reinforced, the maximal moment of the diaphragm wall is about 3 000 kN·m, which is about 2.23 times of the design allowable. By the interpolation method, when m increases to 45%, the maximal moment of the diaphragm wall decreases to the design allowable. In general, m mainly influences the maximal moment of the diaphragm wall in two places, which are at 7 m under the ground and 4—4.5 m under the bottom of the foundation pit, and are also very close to the broken points of the diaphragm wall in the accident. Meanwhile, the bending moment at 4—4.5 m under the bottom of the foundation pit is about 2 times that of at 7 m under the ground. By the above analysis, the diaphragm wall should be broken under the bottom of the foundation pit while it could not be broken at the place close to the ground. However, the diaphragm wall close to the ground has been broken in the accident, which should be damaged by the increasing bending moment after the break of the under diaphragm wall.

According to Fig.11(b), m mainly influences the axial forces of the lowest two layer internal supports, especially the last layer supports. When the bottom of the foundation pit is not reinforced, the axial force of the lowest horizontal support is about 1.42 times of its limiting value. However, the axial force of another three layer supports are all smaller than the limiting value. In general, with m increas-

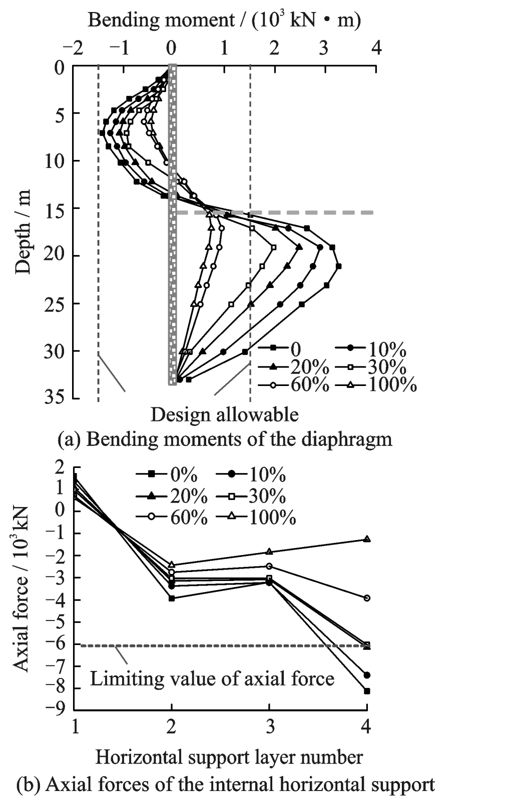

Fig.11 Internal force of the support structures under the different m

ing, the axial forces of the horizontal supports become smaller, especially the lowest layer supports. According to the accident, the horizontal supports have no obvious damages on the steel tubes, and the connection between the horizontal support and the diaphragm wall is damaged severely.

3.2 Influence of excessive excavation

Zhang et al.[13] believe that the 3.5 m excessive excavation of the last soil layers in excavated areas No.2 and No.3 should be the main factor for the collapse of the foundation pit. To investigate the influence of this factor, the internal forces and deformations of the support structures are compared to those without excessive excavation.

Fig. 12 shows the lateral displacements of the wall on the cross-section where the last soil layer is excessively excavated. In general, the lateral deformations of the wall with excessive excavation are larger than those without excessive excavation. Fig.13 shows the internal forces of the support structures compared. As a result, the excessive excavation has little influence on the bending moment of the wall. However, it has great effect on the axial force of the nearest third layer horizontal supports, making it slightly larger than the limiting value. According to the above analysis, the excessive excavation should not been the main reason for the accident.

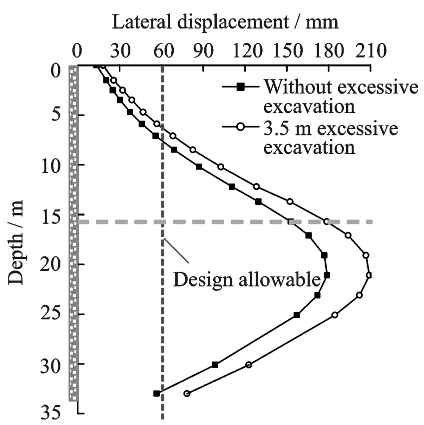

Fig.12 Horizontal displacement curves of the wall at the collapse side of the foundation pit

3.3 Influence of disturbed soils

By Fig.5 and Table 3, there are about 28 m

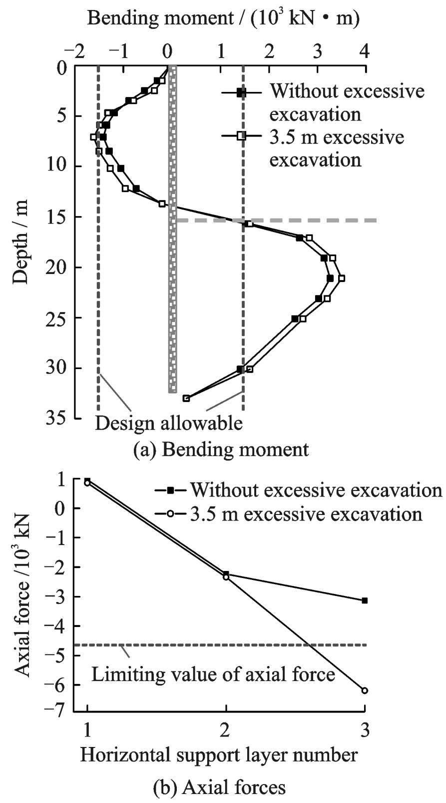

Fig.13 Inner forces of the support structures with and without excessive excavation

thickness soft soils at the lateral foundation and the under foundation of the foundation pit. According to the original geotechnical investigation report before the accident, the shear strength parameters of the mucky silt clay are shown in Table 2. However, by the geotechnical investigation after the accident, the shear strength of the mucky silt clay near the bottom of the foundation pit is only about 30% of the original shear strength, and about 70% of the original strength for the soils close to the end of the diaphragm wall. It proves that the diaphragm wall has disturbed the nearby soft soils seriously[14]. According to the new geotechnical reinvestigation report, the cohesion and the inner friction angle of the disturbed soils near the bottom of the foundation pit are about 10 kPa and 4.7°, respectively. To investigate the influence of the disturbed soft soils, the internal forces and deformations of the support structures are compared in this section.

Fig.14 shows the lateral displacements of the diaphragm wall. It proves that the maximal displacement of the diaphragm wall is severely affected by the disturbed soil. When the original shear strength

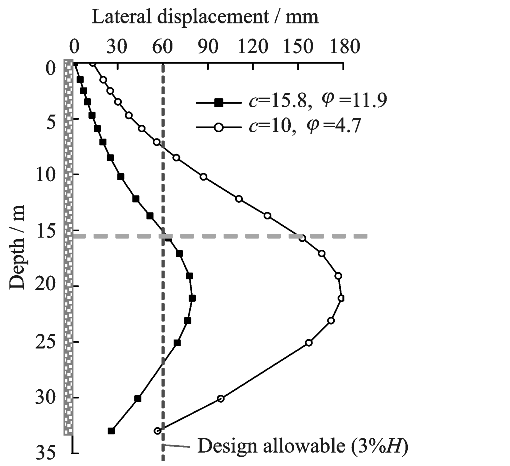

Fig.14 The lateral displacements of the diaphragm wall under different shear strengths of the soft soils

parameters are used in numerical modeling, the maximal displacement of the wall is very near the design allowable. However, the maximal displacement calculated by the shear strength parameters of the disturbed soil is about 2.3 times of the design allowable.

Fig. 15 shows the internal forces of the support structures compared, and also shows that the disturbed soils have great effect on the bending moment of the diaphragm wall and the axial forces of the lowest layer horizontal support. According to the above analysis, if the original shear strength parameters are used, the inner forces and the deformations of the support structures are all smaller than the limiting value, which proves that the support system of the foundation pit should be safe even if the soft soil at the bottom of the foundation pit wasn't reinforced. This may be the reason why the construction organization cancelled the original reinforcement design according to the original shear strength of the soft soils under the bottom of the foundation pit.

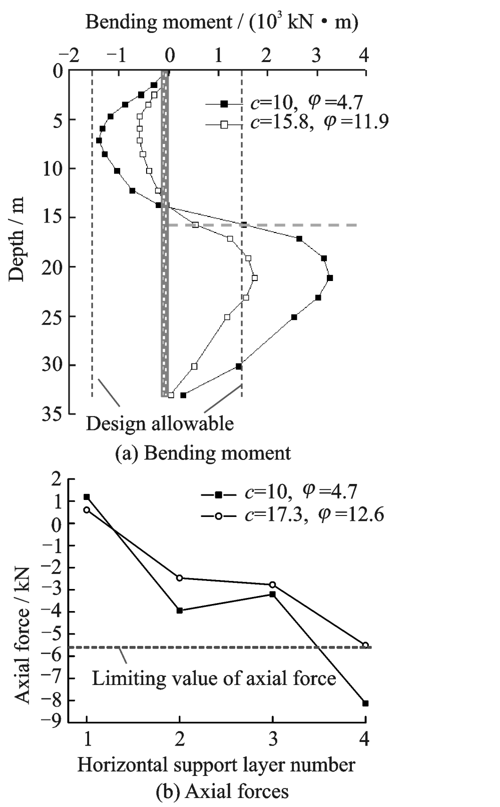

Fig.15 Internal forces of the support structures under different shear strengths of the soft soils

3.4 Influence of embedded depth of the diaphragm wall

According to the original design of the diaphragm wall, its vertical length is 33 m, which means that its bottom end does not penetrate the soft muddy silt clay layer, as shown in Fig.5. However, it has been suggested in the Engineering Geology Manual of China that the enclosing structures of the foundation pit should be embedded in the relative harder soils with an enough length[17]. As a result, the diaphragm wall in this engineering should be embedded into the silt clay layer by the existing engineering experience. Accordingly, the vertical length of the diaphragm wall is extended to 40 m to investigate its effect on the support system.

Fig.16 shows the lateral displacements of the diaphragm wall compared. As a result, with the vertical length of the wall extending from 33 m to 40 m, its maximal lateral displacement decreases about 50% and is very close to the design allowable. Fig. 17 also

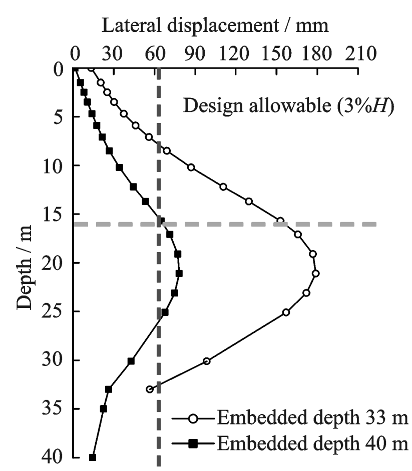

Fig.16 Lateral displacements of the diaphragm wall under its different embedded depths

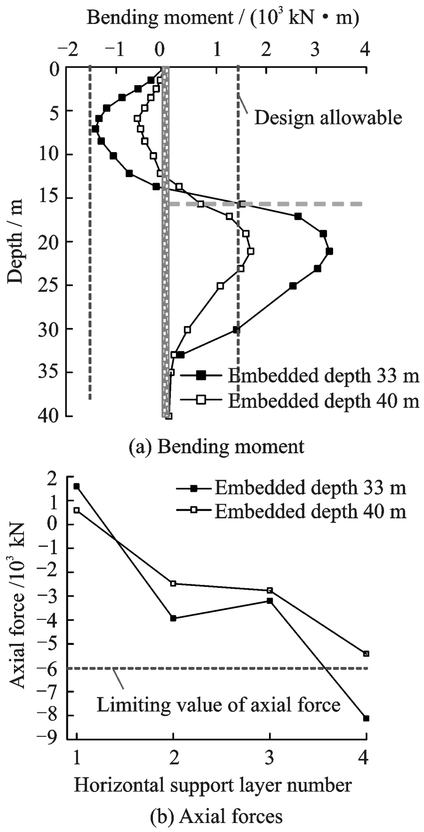

Fig. 17 Internal forces of the support structures under the different embedded depths

shows the internal forces of the support structures compared. In general, the embedded depth of the diaphragm wall has great influence on its bending moment and the axial forces of the lowest horizontal supports. When the embedded depth of the wall extends to the under harder silt clay layer, the support system may be safe even if the soft soils under the bottom of the foundation pit have not been effectively reinforced.

3.5 Influence of asymmetric ground overload

During the excavation of the foundation pit, there were many overloading vehicles running on the Fengqing Avenue, which is very close to the collapsed side of the foundation pit, as shown in Fig. 3. As a result, the ground overloads on both long sides of the foundation pit is asymmetric. According to the original design, the ground overloads on all sides of the foundation pit is 20 kPa. By the actual traffic situation, the ground overload should be 40 kPa for the heavy-duty truck or the concrete pump truck on the Fengqing Avenue. To investigate the influence of the asymmetric ground overload, some numerical modeling analyses are carried out with the ground overloads being 0, 20, and 40 kPa, respectively.

Fig. 18 shows the lateral displacements of the diaphragm wall compared. With the ground overload on the west side increasing, the lateral displacements of the west side diaphragm wall increases obviously, but it induces the lateral displacements of the opposite side diaphragm wall decreasing at the same time. Fig. 19 shows the bending moment of the diaphragm wall compared. Consequently, with the ground overload on the west side increasing, the bending moments of the west side diaphragm wall also increases obviously, which also induces the bending moments of the opposite side diaphragm wall decreasing at the same time. However, by Fig. 20, the asymmetric ground overload has little

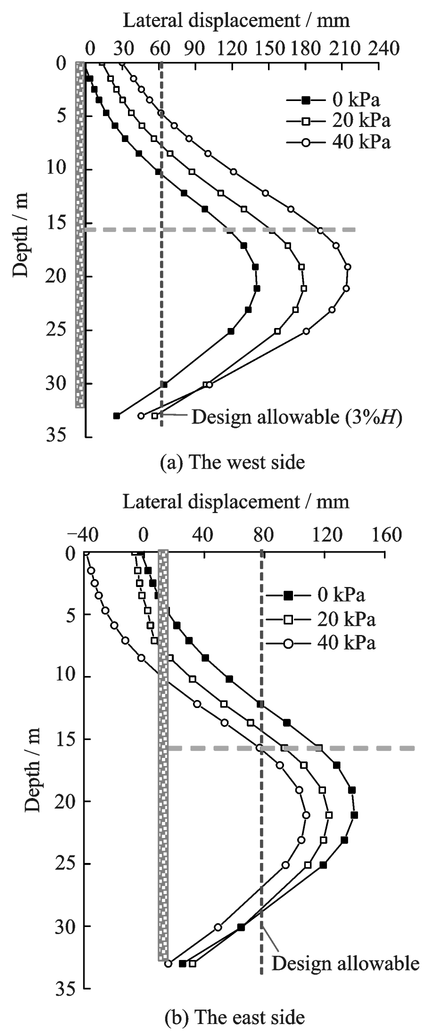

Fig. 18 Lateral displacements of the diaphragm wall under the different ground overloads

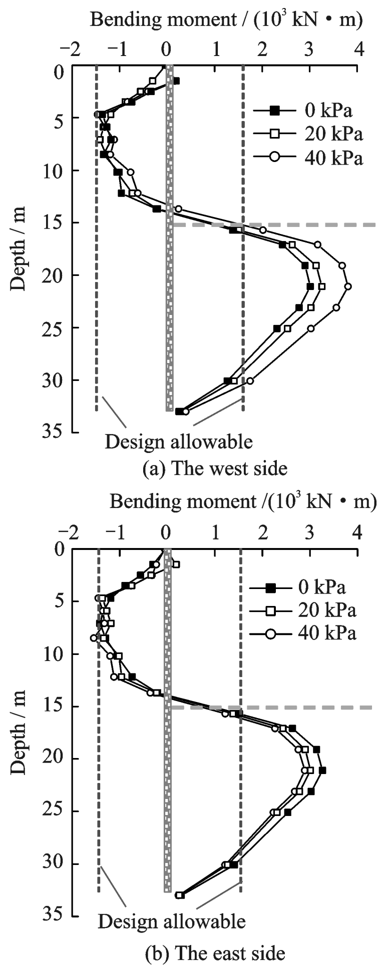

Fig.19 The maximum bending moments of the diaphragm wall under the different ground overloads

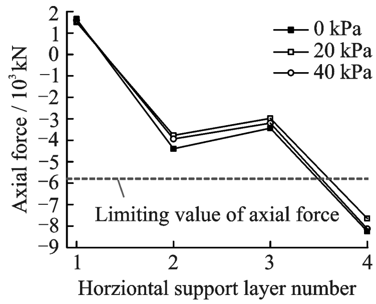

Fig.20 The maximum support axial forces of the horizontal support under the different ground overloads

influence on the axial forces of the internal horizontal support. According to the above analysis, it also proves that the asymmetric ground overload should be the main factor inducing different damage conditions of the diaphragm walls in two different long sides of the foundation pit.

4 Development Process of the Accident

According to the numerical modeling and the investigation on the accident, the development process of the accident can be deduced firstly, shown as Fig.21. The direct factor inducing the collapse of the excavation pit should cancel the foundation treatment on the soft soils under the excavation pit, which induced the axial forces of the lowest horizontal inner supports and the moment of the diaphragm wall are all exceed its limiting values. As a result, the lowest horizontal inner supports lost its balance and then the diaphragm wall under the bottom of the

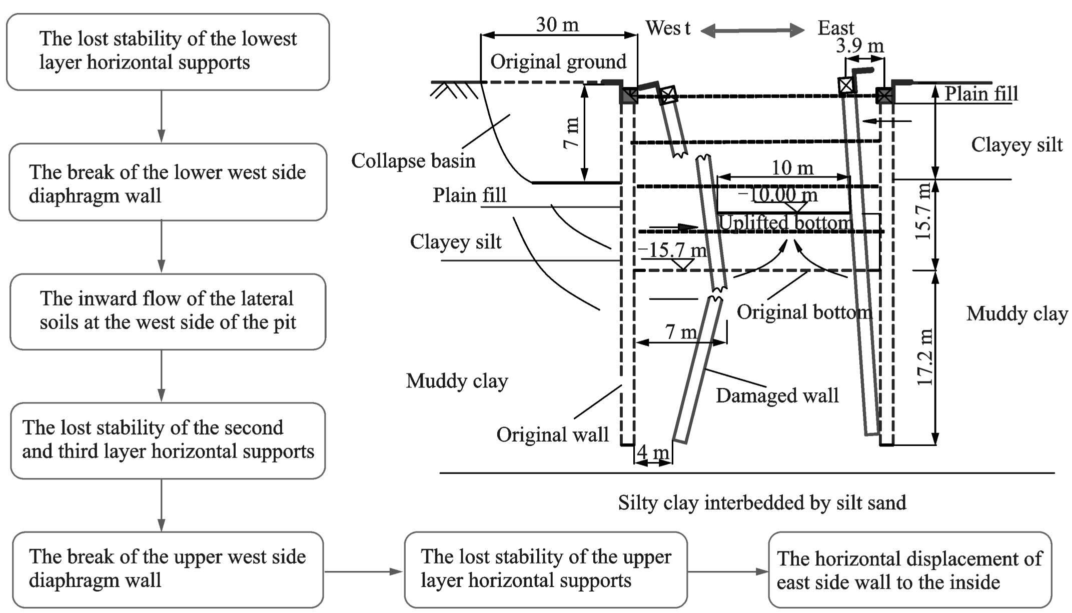

Fig.21 Development process of the accident by the numerical modeling and the investigation

pit is broken quickly. Then the supports on the second and third layers lost its balance instantaneously, which induced the upper diaphragm wall is also broken quickly, and then the soils behind the diaphragm wall flow into the pit quickly, and the bottom of the pit is lifted about six meters.

However, why the east-side diaphragm wall has not been broken in the accident? The main reason should be the overloading vehicles running on the west side of the foundation pit, which induced the west-side wall broken firstly, and then the uplifted bottom of the foundation pit should protect the east-side diaphragm wall from being broken.

5 Conclusions

Based on the collected references and data about the collapse of the deep excavated foundation pit for the Xianghu subway station in Hangzhou of China, the major factors inducing this accident are summarized firstly. Then, a 3-D finite element analysis model is made to model the soil-retaining structure interaction system, and the influence of the major impact factors on the support system are analyzed and compared with the accident site condition. The main conclusions are drawn as follows:

(1) According to the actual construction of the foundation pit, the internal forces and deformation of the support structure are all much larger than its limited allowable values when the soft soils under the bottom of the foundation pit are not reinforced effectively, which should be the direct factor of the accident.

(2) The construction influence on the shear strength of the soft soils under the bottom of the foundation pit should be effectively considered in the design of this foundation pit. Without this kind of influence, the support system may be safe by the numerical modeling even though the bottom soft soils have not been reinforced.

(3) The embedded depth of the diaphragm wall should be extended to silt clay under which has a higher shear strength. According to the numerical modeling, the support system may be safe with the diaphragm wall embedded in the under silt clay even though the bottom soft soils have not been reinforced.

(4) The asymmetric ground overload induced by the heavy trucks running on the collapsed side of the foundation pit should be the main factor inducing different damage conditions of the diaphragm walls on different long sides.

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