Numerical Analysis on Deep Foundation with Spatial Effect

Han Xu

Institute of Earthquake resistance and Disaster reduction, Beijing University of Technology, Beijing, 100124, China
e-mail: hanxu3321699@163.com

Wang Ning-wei

School of Civil Engineering, Shenyang Jianzhu University, Shenyang, Liaoning, 110168

Su Jing-yu

Institute of Earthquake resistance and Disaster reduction, Beijing University of Technology, Beijing, 100124, China
College of Architecture and Urban Planning, Beijing University of Technology, Beijing 100124, China

Wang Wei

Institute of Earthquake resistance and Disaster reduction, Beijing University of Technology, Beijing, 100124, China
College of Architecture and Urban Planning, Beijing University of Technology, Beijing 100124, China

ABSTRACT

The excavation of foundation deformation can result with spatial effect. The paper makes a numerical analysis on the deep foundation for Wanda square project by using software Midas. The numerical analysis results are verified by the data from the project. Based on analysis on the deformations, the laws of the spatial effect on the supporting structure and the surrounding soil are summarized, showing that the spatial effect can be found in most foundation projects, but the spatial effect is not obvious when the depth of the foundation is small or the excavation is not started. The factors including the depth of the foundation and the type of supporting makes clear effects on the spatial effect of the foundation. Foundation pit retaining wall deformation has some relationship with flexural rigidity and the depth of excavation, increase the excavation depth or reduce the structure stiffness can lead retaining wall to the maximum deformation position move downwards, until the pit bottom. Surface settlement around foundation pit excavation unloading is within the scope of influence of each layer of soil deformation cumulative formation, with the increase of soil depth, the settlement deformation of soil gradually decrease.

KEYWORDS: deep foundation; deformation; supporting structure; soil settlement; spatial effect

INTRODUCTION

The deformation of foundation pit engineering has a strong regional. Many scholars have put forward the deformation law of foundation pit engineering in different regions. Such as Clough and O` Rourke [1] through summarizing of steel support and anchor as supporting structure of foundation pit engineering, the three kinds of the deformation law of supporting structure. Respectively summarized as deformation of cantilever type, deformation of parabolic type, and the combination of two forms of deformation. Zhong-hua Xu[2] collects a large number of monitoring data of deformation of foundation pit engineering in southern region of China. He believes in the location of the maximum deformation of supporting structure in soft soil area is at the bottom of the foundation pit. Wei-dong Wang [3] statistics and analysis the deformation of foundation pit engineering in the south of China. He proposed the surface subsidence deformation law of the supporting structure in different stiffness, and the size of the surface subsidence range. Lee Lin [4] analyzed deformation data of the foundation pit excavation in southern China . She set up the relationship between the uplift resistant safety coefficient and the maximum horizontal displacement of retaining structure and the maximum ground settlement. Hsieh and Ou [7] regression analysis the surrounding surface subsidence deformation of. He found prediction formula of the triangle surface settlement curve and groove shape surface settlement curve, and divided the whole settlement influence scope into main influence zone and the secondary influence area. Bai-gou Xie[8] using numerical analysis techniques, to study the influential parameters of supporting structure deformation in clay soil. He adopts the method of multiple regression analysis, puts forward the simple method of evaluating the maximum deformation of the retaining structure. Jian-hang liu [9] compared and analyzed the other prediction formulas of the ground settlement around the foundation pit engineering. He put forward the predicting formula of ground settlement in soft soil area of Shanghai. The research result was elected to “Shanghai standard code for design of excavation engineering” [10].

This paper calculates the deformation of Yingkou Wanda Plaza deep excavation process. It analyzes the deformation of the surrounding soil and deformation of the supporting structure in numerical model. It summarizes laws of the spatial effect on the supporting structure and the surrounding soils are summarized; this provides reference and guidance for other projects.

SIMULATION PROCESS

Wanda Plaza deep foundation pit area of about 140000 square meters. The foundation pit is 350 meters long, 320 meters wide, and the maximum excavation depth is 12.8m. Soil parameters are shown in Table 1. The site distribution of this project is paralic sedimentary strata. The heterogeneity and variability of the soil layer were obvious.

Table 1: The basic parameters of the soil

Soil name	specific weight kN/m^3	cohesion C/MPa	Frictional angle $\varphi/^o$	Bond strength MPa
miscellaneous fill	16.6	5	8	16
Silt and silty clay	19.2	5	2.4	16
Silty clay and fine sand	18.7	20	7.06	30
fine Silt-1	18.0	0	28	20
Muddy silty clay	19.4	12.2	3.6	16
fine Silt-2	18.0	0	28	26
silty clay	18.0	0	28	50

The supporting structure of foundation pit is arranged as shown in Figure 1. On the east side of the site are double row piles and three row of cables. On the west side of the site is two rows of cables and SMW. According to the different excavation depth, the north and south sides of the site using the SMW and double row piles. Steel bracing was adopted for the abrupt change of the retaining wall.

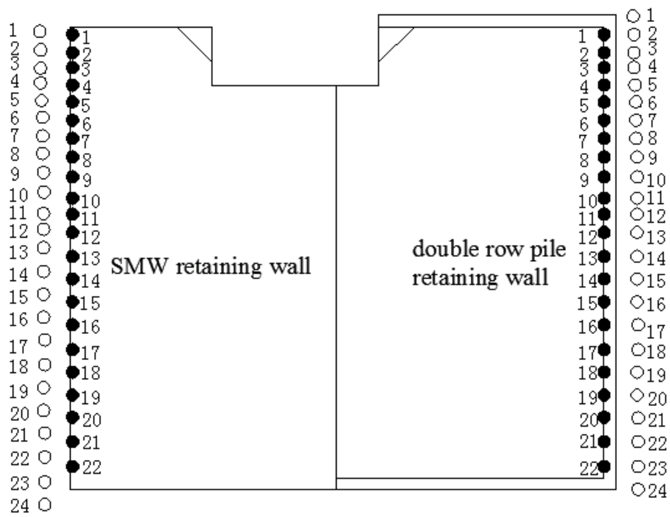

Figure 1: Arrangement of foundation pit

FINITE ELEMENT SIMULATION

In order to more accurately calculate the deformation of excavation, selecting HS model as the soil model. HS model need to enter two elastic modulus. They are the soil compression elastic modulus E and unloading corresponding elastic modulus Eur。Shanghai Jiaotong University research found that[13]: unloading elastic modulus is approximately equal to the initial compression elastic modulus 3 ~ 5 times. Compression elastic modulus is calculated using the following formula:

$$E = 5 \times E_S \quad (1)$$

$$Eur = 3 \times E \quad (2)$$

E_s–Compression modulus

E–soil Elastic modulus

Eur–Soil unloading modulus

Table 2: Elastic modulus of soil layers（MPa）

Soil name	E_S	E	Eur
miscellaneous fill	4.13	20.65	49.74
Silt and silty clay	3.86	19.3	57.9
silty clay and fine sand	5.31	26.55	79.65
fine Silt-1	9.53	47.65	142.95
Muddy silty clay	7.53	37.65	112.95
fine Silt-2	7.15	35.75	107.25
silty clay	12.26	61.3	183.9

According to design of deep excavation report shows that the supporting structure can be divided into four types as shown in Table 3. In order to facilitate the establishment of the supporting structure model, SMW and double rows piles are at equal flexural rigidity in terms of underground continuous wall. Deep excavation retaining structure model are shown in Figure 2.

Table 3: The supporting structure parameters

support structure type	excavation depths/m	size/m	associated construction	thickness/m
SMW	7.7	18	steel bracing	0.6
Double row pile	12.8	22.5	steel bracing	1.2
Double row pile	12.8	22.5	anchor cable	1.2
SMW	7.7 and 6.5	18	anchor cable	0.6

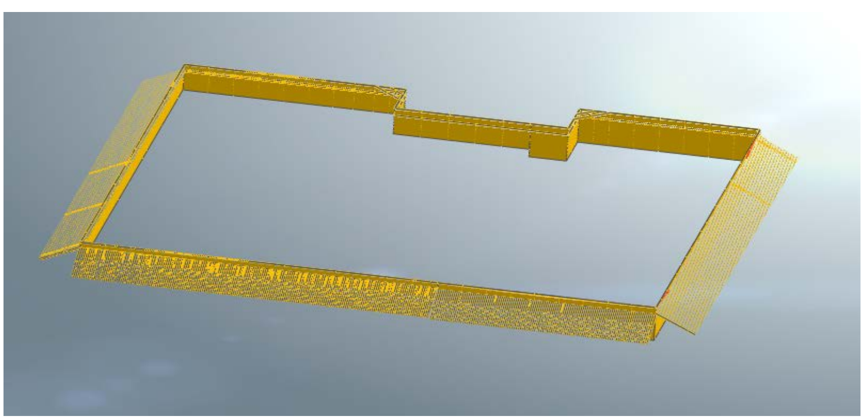

Figure 2: Structure simulation of foundation pit

Excavation model are shown in Figure 3. The length of the model is 800.0m, the width is 600.0m, and the height is 50.0m. The length of Excavation area is 350m, width is 320m, interior region is divided into three parts according to different excavation depth . First of all, depth of the right side of the excavation pit area is 12.8m. Secondly, depth of the left 6.5m dark pit area. Finally, depth of the left pit 7.7m light areas. Meshing as shown in Figure 2. Pit internal mesh size is 15.0m. Pit external mesh size is 30.0m. The whole model contains 110,327 units.

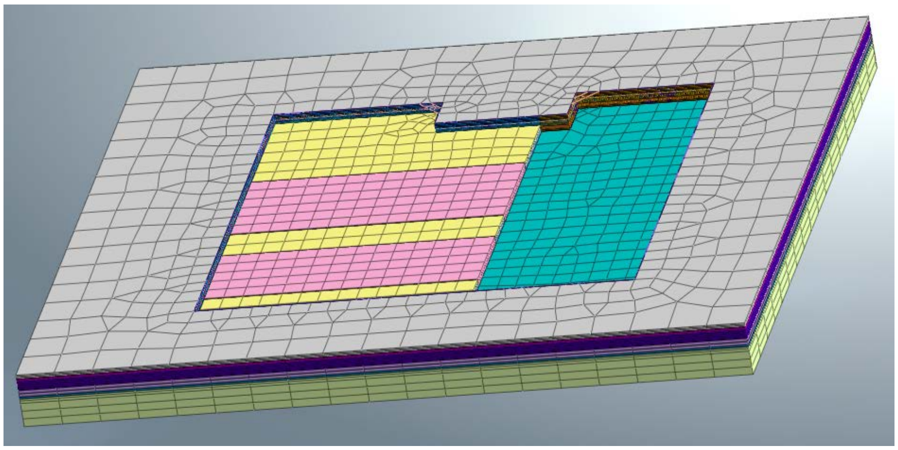

Figure 3: The excavation of foundation pit

COMPARISON OF ACCURACY

1. Use the actual deformation data to determine the results of numerical simulation is accurate or not. As shown in Figures 4 and 5, Comparing the difference between the pile displacement monitoring data and deformations of the supporting structure of Numerical model in the same position, determine the accuracy of the settlement result of the numerical simulation .

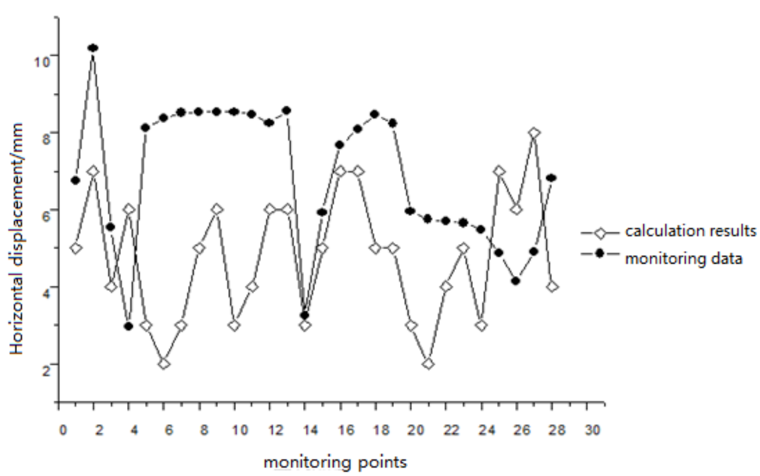

Figure 4: Analysis of horizontal displacement of pile top contrast

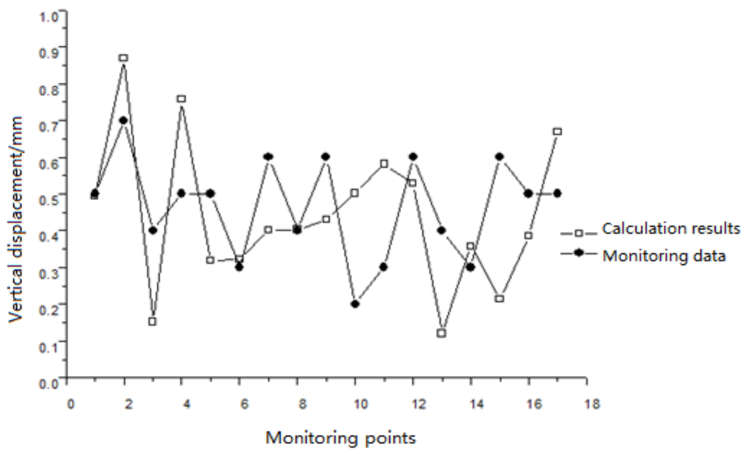

Figure 5: Analysis of vertical displacement of pile top contrast

It shows the change of displacement curve in Figure 4 and 5 . It Summarize and analyze the data as shown in Table 4.

Table 4: Analysis on deformation law of contrast

data	number of selected point	average error	maximal error
horizontal displacement	29	<30%	45%
vertical displacement	17	<25%	40%

After analysis the data in Table 4 , it can be considered that the deformation of the supporting structure is reliable.

2. By comparing deformation law of foundation pit in other soft soil regions, the accuracy of numerical simulation is analyzed.

Table 5: Analysis on deformation law of contrast

researcher	area	engineering quantity	$S_{H\max}$
Ou	Taiwan	10	$=(0.2\sim0.5)\%H$
Xing-wang Liu	Shanghai	15	$=(0.2\sim0.9)\%H$
Moormann	Soft area in other country	530	$>1\%H(27\%)$ $=(0.5\sim1)\%H\ (40\%)$ $<0.5\%H(33\%)$
Zhong-hua Xu	shanghai	20	$=(0.25\sim0.55)\%H$
Yoo	korea	62	$=(0.13\sim0.15)\%H$

This paper	liaoning	1	$= 0.21\%H$

The maximum horizontal displacement of supporting structure obtained by numerical simulation occurs in the eastern side of the deep pit, located in the middle of the double row pile retaining wall. The maximum horizontal displacement of supporting structure is about 27.0mm, and the depth of the excavation is 12.0m. Comparison of the result of numerical simulation and the deformation of other excavation in soft land . The result is consistent with the deformation law in Taiwan, Shanghai, Hangzhou and other areas. It can be confirmed that the displacement resulting by numerical simulation is reasonable.

SIMULATION RESULTS ANALYSIS

Using numerical simulation we calculated the deformation of supporting structure and the deformation of the surrounding soil. The location of deformation monitoring points is shown in Fig.1. Monitoring points are evenly arranged, and spacing of adjacent point is about 15m.

Deformation of Supporting Structure

Figure 5 shows the displacement curve of SMW . Figure 6 shows the displacement curve of double row piles wall.

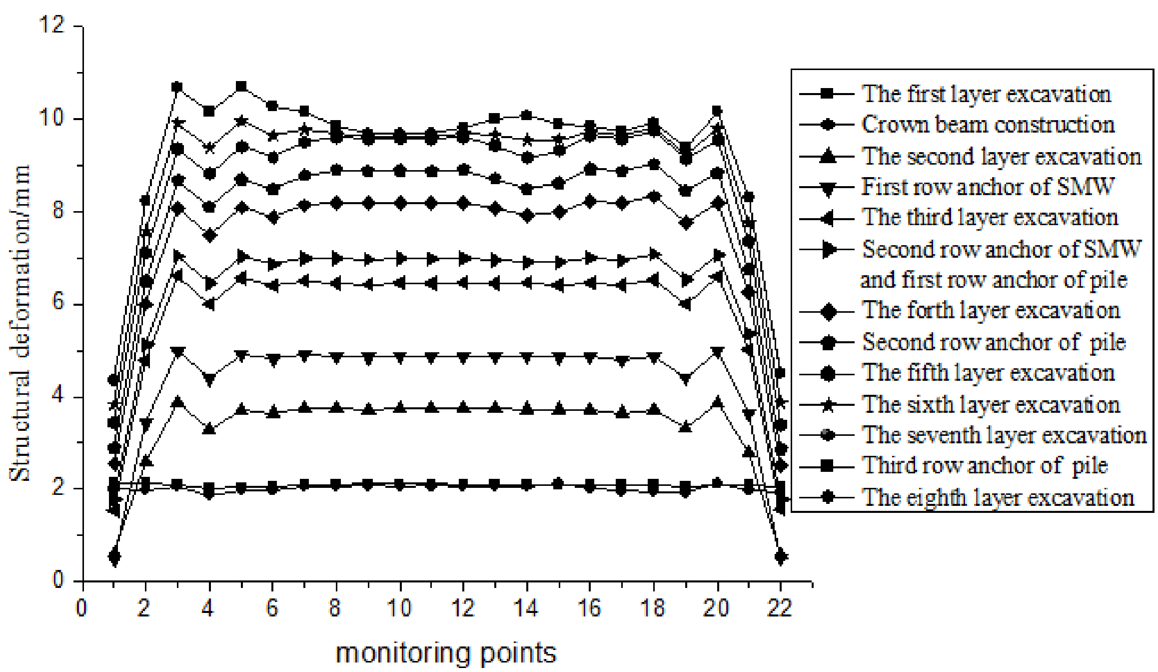

Figure 5: Supporting structure of SMW retaining wall deformation

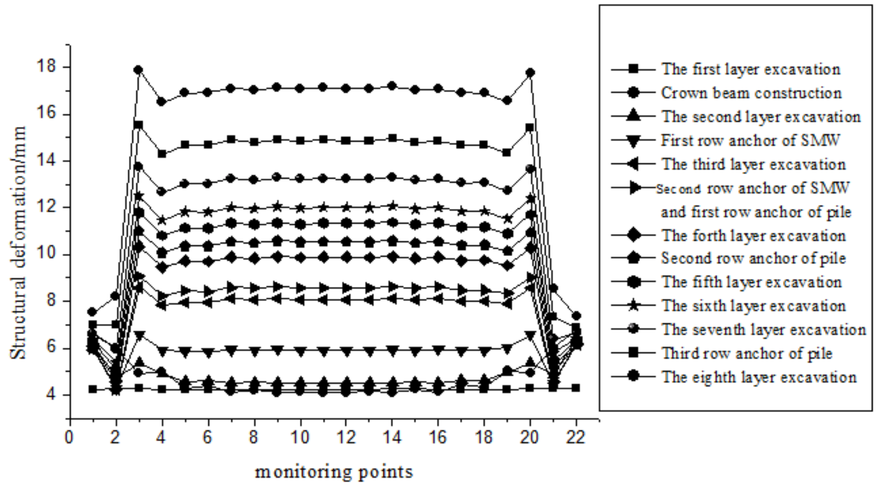

Figure 6: Deformation of double row piles supporting structure

Figure 5 and 6 show the following conclusions.

（1）Deformation of monitoring points 1, 2 and 21, 22 are far less than the deformation of other points. This shows that the deformation of double pile and SMW is affected by spatial effect. After the excavation, deformation of retaining wall at the endpoint is much smaller than deformation of the intermediate position of retaining wall.

（2）In Figure 5 shows the displacement curve corresponding to the front two conditions. In Figure 6 shows the displacement curve corresponding to the front three conditions. The above two kinds of curves show that the deformation of all the positions of retaining wall are substantially equal When the excavation depth is relatively shallow. This shows that the displacement of the supporting structure with a spatial effect is subject to conditions. Its conditions are affected by excavation depth and supporting structural rigidity.

（3）As shown in figure 5, the ratio of the maximum deformation and minimum deformation is about 2.75. As shown in figure 6, the ratio of the maximum deformation and minimum deformation is about 2.5. This shows that under the influence of spatial effects, the deformation in the middle of the supporting structure is 2 ~ 3 times than the deformation in the location of endpoint . With the increase of the ratio of the bending stiffness of Supporting Structure and the excavation depth , the effect of spatial effect will be reduced .

Surrounding surface subsidence

Figure 7 shows the surface settlement curve after the SMW 15.0m. Figure 6 shows the surface settlement curve after the double row pile retaining wall 15.0m.

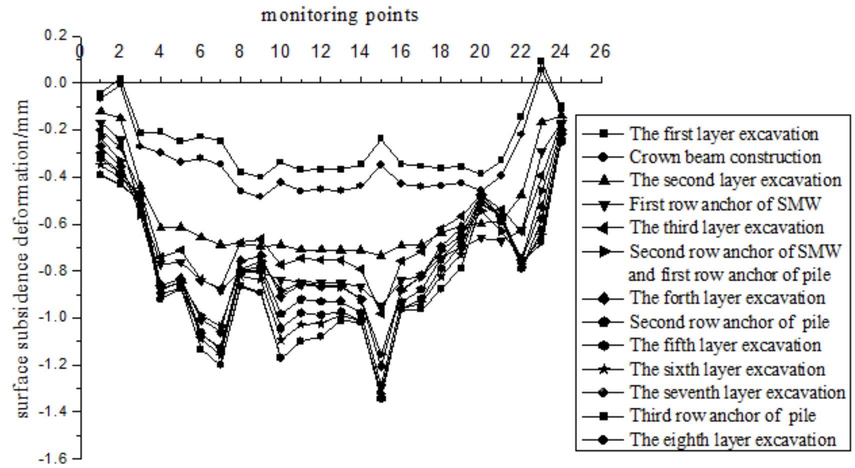

Figure 7: Surface settlement deformation near SMW

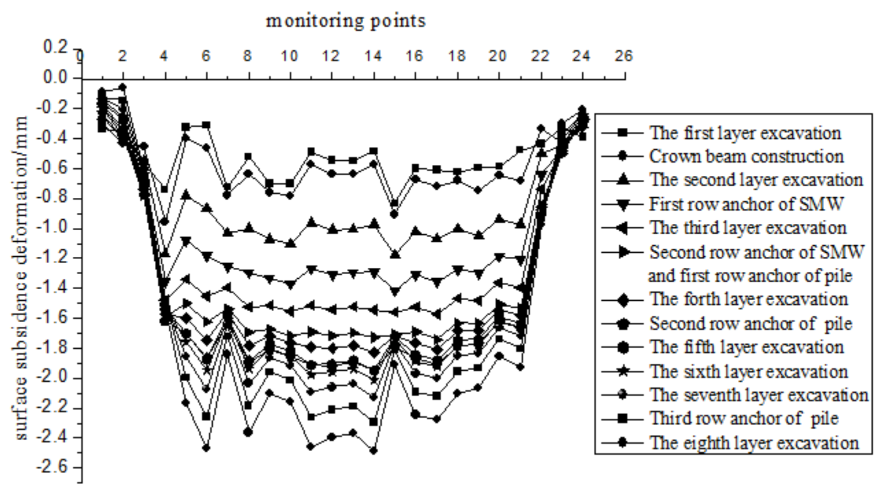

Figure 8: Surface settlement deformation near double row pile

Figure 7 and 8 shows the following conclusions.

(1) Deformation of monitoring points 1, 2 and 23,24 are far less than the deformation of other points. This shows that the deformation of surface settlement after the retaining wall will be affected by spatial effect. After the foundation excavation, surface settlement at the endpoint of retaining wall is much smaller than deformation of the intermediate position of retaining wall.

(2) As shown in figure 7 and 8, the surface subsidence mainly produced in the first six conditions in the process of construction .This shows that installation of anchor cable have played an important role in inhibition of surface subsidence near the foundation pit.

Deep horizontal displacement of supporting structure

Figure 10 shows that the deep horizontal displacement curve at different locations of double row pile. Figure 11 shows the deep horizontal displacement curve of different locations of SMW. According to the characteristics of the curve in figure 10 and 11, the area of retaining wall can be divided into 3 groups. As shown in figure 9, the Angle of retaining wall is divided into endpoint location、 near endpoint location and intermediate location of retaining wall.

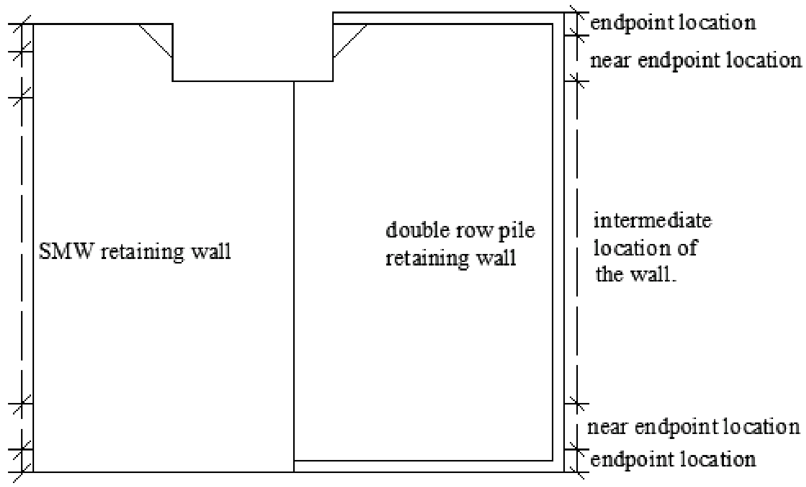

Figure 9: Different zones of a retaining wall

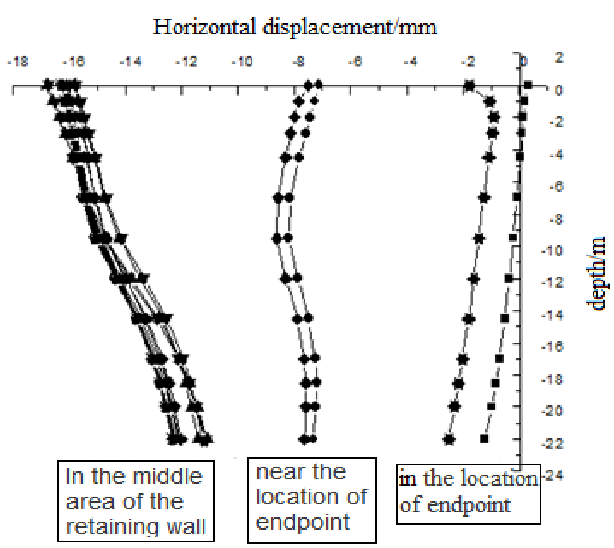

Figure 10: Horizontal displacement of double row pile retaining wall

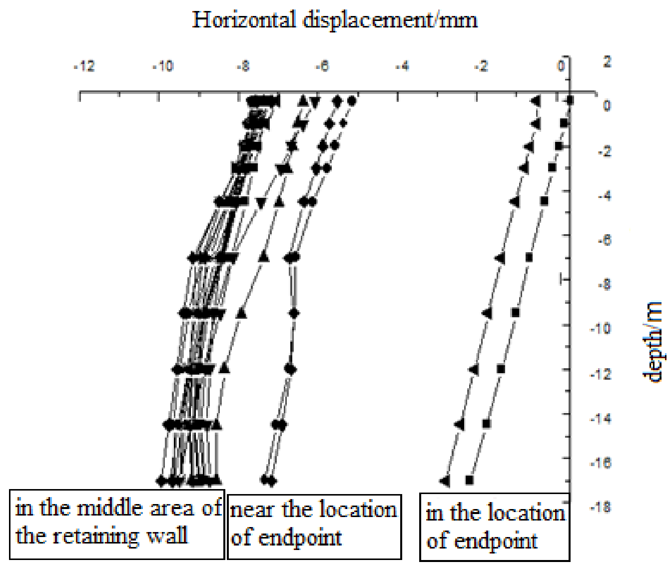

Figure 11: Horizontal displacement of SMW retaining wall

Figure 10 and 11 shows the following conclusions：

(1) In figure 10 and 11,the characteristics of the curve in the location of endpoint are the same. The deep horizontal displacement increase because of the increasing of the depth. In figure 10 and 11, the displacement of the top of supporting structure is almost zero.

(2) Near the location of endpoint, the horizontal displacement curve of supporting structure has a turning point in the Bottom position. The horizontal displacement of supporting structure below the point is reduced under the effect of passive earth pressure.

(3) In the middle area of the retaining wall, the change characteristics of horizontal displacement of supporting structure are as follows: the maximum horizontal displacement of double row piles occurred on the top of the supporting structure. The maximum horizontal displacement of SMW occurred at the bottom of foundation pit.

Deep soil settlement

Figure 12 shows the settlement curve at different depths at the rear side of double row pile retaining wall 15.0m. Figure 13 shows the settlement curve at different depths at the rear side of SMW 15.0m. There're a total of 7 curves in each figure, respectively represent the surface settlement of depth of 0.0m, -3.0m, -5.0m, -12.0m, -14.5m, -17.0m, 18.5 m.

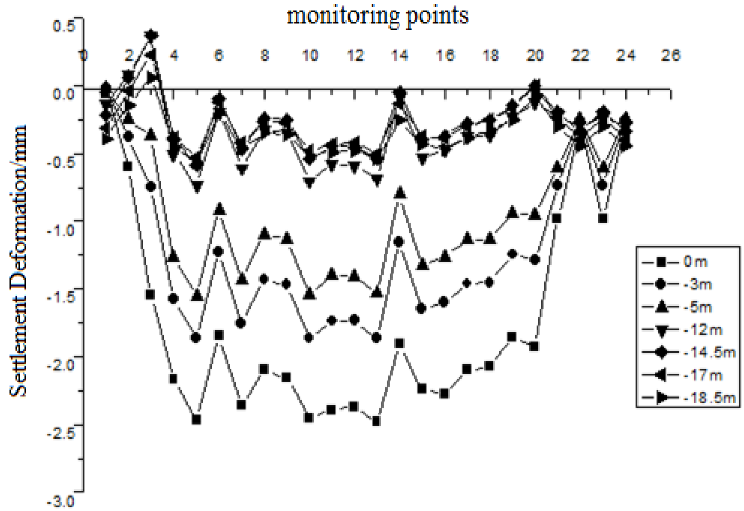

Figure 12: Settlement changes of double row pile surrounding soil

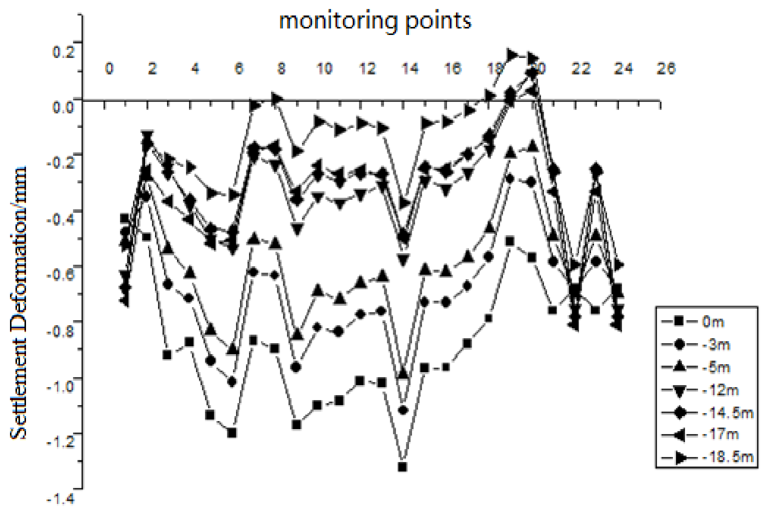

Figure 13: Settlement changes of soil around SMW retaining wall

Figure 12 and 13 show the following conclusions.

（1）Figures 12 and 13 show that the soil settlement below the depth of -12.0m is very small . This shows that when the excavation depth increase, the soil settlement surrounding the retaining wall will decrease gradually, until it disappeared.

（2）The maximum excavation depth of the numerical model is 12.0m. As shown in Figure 12 and 13, according to the difference of two types of supporting structure, the deep soil settlement occurs mainly in the range of 0.0m to -12.0m. This shows that the main areas of soil sedimentation is largest excavation depth of deep excavation.

（3） As shown in Figure 12 and 13,the curves in the range of -14.5 ~ -18m did not show significant spatial effect. This shows that the spatial effect of soil subsidence occurred in the range of the largest excavation pit depth (-12.0m) to the surface (0.0m). This suggests that soil settlement can be affected by the spatial effect within the range of the excavation depth to the surface. Soil subsidence occurs below the maximum excavation depth, as the depth increases, the spatial effects gradually disappear.

CONCLUSION

（1）Deformation of deep excavation is affected by the depth of deep excavation and the flexural rigidity of the supporting structure.

（2）When the excavation reaches a certain depth, the deformation of excavation will be affected by space effect. This leads to the deformation at the endpoint is less than the deformation in the middle position of retaining wall.

（3） When the excavation depth is small, the maximum deformation of supporting structure occurs in the top of the support structure. With increasing depth of the excavation, the location of maximum deformation of supporting structure gradually decreased until the pit bottom.

（4） The surface settlement around foundation is formed by accumulation of settlement of each soil layer within the scope of unloading. With the increase of soil depth, the soil settlement deformation decrease gradually.

REFERENCES

[1]. Clough G W O'Rourke T D. Construction induced movements of in situ walls[C]// ASCE Conference on Design and Performance of Earth Retaining Structures, Geotechnical Special . Publication No. 25. New York, 1990, 439–470

[2]. (Xu Zhong-hua. Deformation Behavior of Deep Excavations Supported by Permanent Structure in Shanghai Soft Deposit [D].Shanghai: Shanghai Jiaotong University,2007.)

[3]. (Wang Wei-dong et al. Statistical analysis of characteristics of ground surface settlement caused by deep excavations in Shanghai soft soils [J]. Chinese Journal of Geotechnical Engineering: 2011, （11） : 1659-1666.)

[4]. (Li Lin et al. Analysis of the deformation char acter istics of deep excavations in soft clay [J].China Civil Engineering Journal: 2007, （40） : 66-72.)

[5]. Hsieh P G, Ou C Y. Shape of ground surface settlement profiles caused by excavation[J].Canadian Geotechnical Journal, 1998, 35(6): 1004-1017

[6]. (Xie Bai-jun et al. A Simplified Evaluation Method for Maximum Wall Deflection Induced by Deep Excavation in Clay [J]. Chinese Journal of Rock Mechanics and Engineering: 2012, 31（11）, 2285-2290.)

[7]. (Liu Jian-hang. Prediction and control of ground movement around underground wall of deep foundation-Prediction of ground movement around deep foundation [J]. Underground Engineering and Tunnel, 1993(2):2-15,23.)

[8]. (Shanghai Exploration and Design Trade Association. Shanghai standard code for design of excavation engineering DBJ-61-97[S],1997.)