Analysis of Interaction between Adjacent Buildings and Deformation of Foundation Pit

Jihui-Ding, Taotao-Li, Xiaohui-Wang, Tuo-Zhao, Weiyu-Wang

***Abstract*—When the soil body of deep foundation pit is excavated, the stress state of surrounding soil body is changed, and displacement of the soil bottom and side wall is occured. These deformations may eventually cause passive deformation of adjacent buildings, thereby affect their normal use and even destruction. Taking the deep foundation pit of Shijiazhuang pile-anchor-support structure as an object, the interaction between the supporting system of the foundation pit and the surrounding building is analyzed by the finite difference method. The result shows:(1) When there is no buildings on the outside of foundation pit wall, the spatial effect of the soil body deformation of the wall is obviously restrained by the short side wall, the range is 0.22 times the length of the foundation pit or 2.8 times the depth of the foundation pit. (2) When there is the building outside of the pit wall, the building is located in the middle of the long side of the foundation pit and within 1.5 times the depth of foundation pit, the deformation of the soil in the middle of the wall is enlarged, the range is 1.85 times of the length of the building (or 0.57 times of the length of the foundation). (3) When the building is at the end of the long side of the foundation pit, its range of influence is 1.49 times of the length of the building (or 0.46 times of the length of the foundation pit) away from foundation pit. The increasing quantity of the horizontal displacement and the surface subsidence of the building in the middle are smaller than in the corner.**

***Index Terms*—Pile and anchor cable support; Adjacent building; Finite difference method; Interaction**

I. INTRODUCTION

Deep foundation pit is a space system with plane dimension and depth, and its force and deformation have obvious spatial effect. The soil body excavation of deep foundation pit changes the stress state of surrounding soil, and the displacement of soil bottom and side wall. These deformations may eventually cause passive deformation of adjacent buildings, thereby affect their normal use and even destruction. Jihui Ding, Man Yuan, Qin Zhang etc.[1,2] put forward the concept of efficiency factor of earth pressure. It is considered that the horizontal deformation of the cantilever form on the top of the retaining structure was similar to that of the simply supported beam under uniformly distributed load, the efficiency factor of earth pressure acting on the cantilever retaining structure of deep foundation pit was calculated, and the spatial distribution of deformation and internal force of retaining structure were analyzed. Man Yuan, Jihui Ding and Qin Zhang [3] discussed the spatial effects of the two-row-pile retaining and protecting structure of deep foundation by the utilization factor of earth pressure. Jihui Ding, Fei Fan etc.[4] introduced the fiber grating sensor in the monitoring of the lateral pressure of foundation pit slope, which could realize the on-line, dynamic and real-time monitoring, and the field test results showed that spatial effect was significantly reflected in the deformation, earth pressure and other aspects. Weiyu Wang and Tuo Zhao [5] analyzed the spatial effects of horizontal and vertical displacements of foundation pit and wall soil. With the increase of the excavation depth, the deformation of the negative angle is obviously smaller than the middle position of the slope. By analyzing the observation data of the settlement of the outer soil of the retaining structure of deep foundation pit Clough and O'Rourke[6] found that the surface settlement of hard clay and sand decreases with the distance from the retaining structure and the deformation areas were 2 times to 3 times deeper than the pit， where the deformation areas were 2 times the depth of the pit in soft clay and a cohesive soil of medium hardness. Hsieh and Ou[7] were divided the influence area of the surface settlement of the retaining structure outside the foundation pit into the major influence area and the minor settlement area. The surface settlement outside wall of the foundation pit was affected by 4 times the pit depth. The vertical displacement of the ground surface was the biggest at the edge of the retaining structure， and its maximum value is 0.5 times of the depth of the pit depth. Yang Bo and Xiaobo Feng [8] analyzed the influence of foundation pit excavation on the deformation of the corner buildings By numerical simulation. The buildings in the corner of the foundation pit had uneven vertical deformation in the direction of the slope wall and the normal direction, and shown the spatial distribution of the settlement. Youming Lu [9] analyzed the influence of foundation pit excavation on the settlement difference of building through numerical simulation of a deep foundation pit. Shu Liu [10] analyzed the action law of foundation pit excavation on the displacement of nearby buildings. When the spacing between the inside edge of the building and the slope wall of the foundation pit is relatively large, the excavation of the building is very small. Songhui Chu, Tuo Zhao and Fei Fan [11] analyzed the diffusion region of soil stress near the bottom of a building by the principle of stress diffusion.

According to the deep foundation pit of a space dimension in Shijiazhuang, the pile-anchor-support structure is selected, the interaction between the bracing system and the surrounding buildings is analyzed by the finite difference method, the basis is provided for optimization design and subarea design of deep foundation pit.

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II. General Situation of Engineering

A. *Foundation pit and surrounding environment*

As shown in Figure 2.1, there is a five-story building in the form of brick-concrete structure around the east side of the foundation pit. The load on each floor is considered as 15kPa, and the total load is 75kPa. The buried depth of the residential building is 1.5m, the length A is 40m, and the width B is 20m. The excavation depth of deep foundation pit H is 10.0m, the distance between the building and the foundation wall is C, and the distance from the south wall is D.

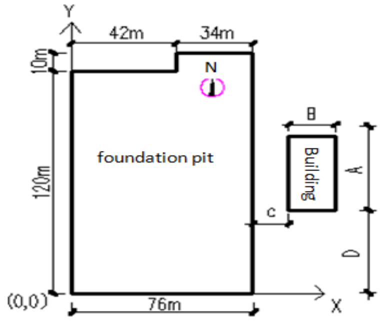

Fig. 2.1 plane plan of foundation pit

Table 2.1 Distribution and main parameters of a section soil layer

No.	Class	Thick-ness (m)	Unit Weight (kN/m^3)	Cohesion (kPa)	internal friction angle (°)	Soil nailing resistance (kPa)	Anchor frictional resistance (kPa)	Soil resistance coefficient (MN/m^4)
1	Miscellaneous fill	0.70	19.00	10.00	12.00	20.0	28.0	2.68
2	Loess silty clay	1.90	19.50	31.30	14.40	63.0	66.0	5.84
3	Loess silty clay	4.60	19.10	23.30	17.90	59.0	65.0	6.95
4	Silt	2.70	19.30	8.10	24.70	59.0	64.0	10.54
41	Fine sand	1.10	18.50	0.00	33.50	70.0	40.0	19.09
4	Silt	1.30	19.30	8.10	24.70	60.0	64.0	10.54
5	Medium sand	2.60	18.50	0.00	34.50	67.0	80.0	20.35
6	Silty clay	0.70	19.60	13.50	30.20	43.0	60.0	16.57
62	Silt	4.20	19.50	8.70	29.00	60.0	66.0	14.79
6	Silty clay	1.10	19.60	0.00	30.20	43.0	60.0	15.22
7	Silt	3.20	19.60	8.70	19.60	60.0	65.0	6.59
8	Coarse gravel	5.00	19.00	0.00	34.60	85.0	220.0	20.48
9	Pebble	0.90	19.00	0.00	34.60	85.0	200.0	20.48

B. *Design parameters of support system*

According to the geological conditions in Shijiazhuang area (see Table 2.1), the safety grade of foundation pit is considered at the first level and the coefficient of importance is 1.0. Deep foundation pit is supported by single row piles with multi-layer prestressed anchor cables(as shown in Figure 2.2).The main parameters of design are shown in table 2.2 and table 2.3.The length of the support pile is 14.0m, the diameter is 1.0m, and the spacing distance is 2.0m, and the length beneath the pit bottom is 4.0m. The width of the crown beam is 1.0m, and the height is 0.8m. The grade of concrete protection in pile and crown beam is C30, the thickness of concrete protective layer is 35mm. The reinforcement adopted on the outer surface of the slope wall is HRB400 steel networks, the spacing is 150mm, the diameter is 8mm, the strength grade of the sprayed concrete is C20, and the total thickness of the surface layer is 80mm. The waist beam is the 2 ϕ 18a U-steel. Three layers of prestressed anchor cables are installed (as shown in Figure 2.2).The geometric and material parameters of the prestressed anchor cable are shown in Table 2.2 and Table 2.3 respectively.

In the outer 2.0m of the top line of the foundation pit, the pedestrian load of 5kPa is considered, and then the vehicle load of 20kPa is considered 3.0m in width outside 2.0m of the slope wall, the building load is 75kPa. The overall stability safety factor is 1.76 by the Swedish strip method. When excavating to the bottom of the foundation pit, the minimum anti-overturning safety factor is 1.78, and the heave stability safety factor is greater than 1.80.

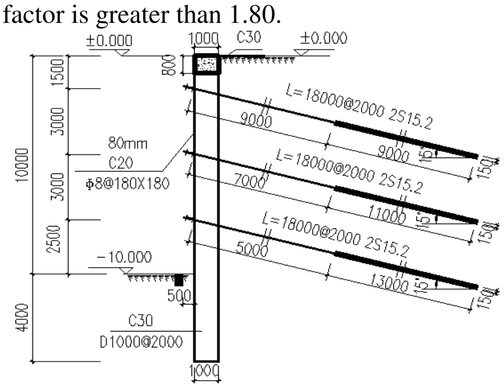

Fig. 2.2 Sectional diagram of pile anchor support system

III. Establishment of Model of Pile Anchor Support Structure System

A. *Assumed conditions*

(1) The soil layers within the influence area of excavation are assumed to be homogeneous and isotropic elastic-plastic bodies.

(2) The Mohr-Coulomb model is used as constitutive relation of soil, and the supporting structures are all ideal linear elastic materials.

(3) In the process of foundation pit excavation and support, it is assumed that the soil parameters and the parameters of the support structure are not changed.

Table 2.2 Geometrical parameters of anchor cable

Soil layer number	Depth (m)	Horizontal spacing (m)	Dip angle (°)	Total length (m)	Length of anchorage section (m)
1	1.50	1.50	15.0	18.0	9.0
2	4.50	1.50	15.0	18.0	11.0
3	7.50	1.50	15.0	18.0	13.0

Table 2.3 Material parameters of anchor cable

Soil layer number	Drilling diameter (mm)	Reinforcement grade	Types of strand	Specifications	Lock value (kN)
1	150	HRB400	1×7	2S12.5	130
2	150	HRB400	1×7	2S12.5	130
3	150	HRB400	1×7	2S12.5	130

B. Calculation model and calculation parameters

Considering the influence of buildings around the foundation pit, the molded dimension is taken 2H in vertical direction and 8H in the horizontal direction. The coordinate origin is shown in Figure 2.1. The soil parameters are shown in Table 3.1. Displacement boundary condition of foundation pit is set as follows: the normal displacement of the boundary interface of the four vertical faces is required to constraint; the horizontal boundary of the top surface of the model surface is the free surface; the horizontal boundary of the bottom surface of the model is a fixed constraint surface.

Table 3.1 Main parameters of each layer of soil

No.	Thickness (m)	Unit Weight (kN/m^3)	Cohesion (kPa)	Internal friction angle (°)	Poisson ratio	Bulk modulus (MPa)	Shear modulus (MPa)
1	1.00	19.00	10.00	12.00	0.33	34.07	13.07
2	1.90	19.50	31.30	14.40	0.35	54.03	18.01
3	4.60	19.10	23.30	17.90	0.32	54.20	22.17
4	5.10	19.00	10.98	25.41	0.31	85.87	36.15
5	2.60	18.50	0.00	32.00	0.30	114.75	52.96
6	6.00	19.50	24.64	18.75	0.32	164.02	63.20
7	3.20	19.60	8.70	19.60	0.32	176.62	72.25
8	5.60	19.00	0.00	33.11	0.28	164.55	84.85

Because there is reinforcement in the coagulation component (revetment pile, crown beam) that have the concrete of grade C30, the elasticity modulus is 33.6GPa. Taking into account the micro cracks and other defects of the actual reinforced concrete members, the elasticity modulus of retaining pile and crown beam is reduced by 0.8, and the elasticity modulus is 26.8GPa, density is 2.50×103kg/m3, Poisson's ratio is 0.20. Density of waist beam is 7.850×103kg/m3，the elasticity modulus is 20.50GPa， Poisson's ratio is 0.25.The friction and cohesion between the pile and the surrounding soil can be simulated by setting up the parameters in Table 3.2.

The anchor section needs to be considered the function of the grout, the density of the prestressed anchor rope is 7.8×103kg/m3, the elastic modulus is 195.0GPa, the tensile strength is 1.54×105MPa, and the prestressed force is 90kN. Bond strength of cement paste with unit length of prestressed anchor cable is 1.50×104N/m, Stiffness of cement mortar of unit length is 5.6×108N/m2, friction angle of cement slurry is 20°, outer perimeter is 0.472m.The density of the surface layer is 2.4×103kg/m3, the elastic modulus is 10.5GPa, the Poisson's ratio is 0.25, and the thickness is 0.08m.

Table 3.2 Characteristic parameters of shear and normal coupling spring of slope protection pile

Class	Cohesive force per unit length（N/m）	Internal friction angle (°)	Stiffness per unit length（N/m^2）
Shear coupling spring	1.5×10^4	17.0	1.0×10^8
Normal coupling spring	2.0×10^4	22.0	1.9×10^8

IV. THE INFLUENCE OF BUILDING LOCATION ON DEFORMATION

A. Horizontal displacement analysis of slope wall

The horizontal displacement of the slope top is obtained through the simulation of the pile-anchor supporting foundation pit. The horizontal displacement with the changes of the building position is as shown in Figure 4.1. Y is the distance from foundation pit corner, and L is the length of the foundation pit，and H is the depth of the foundation pit.

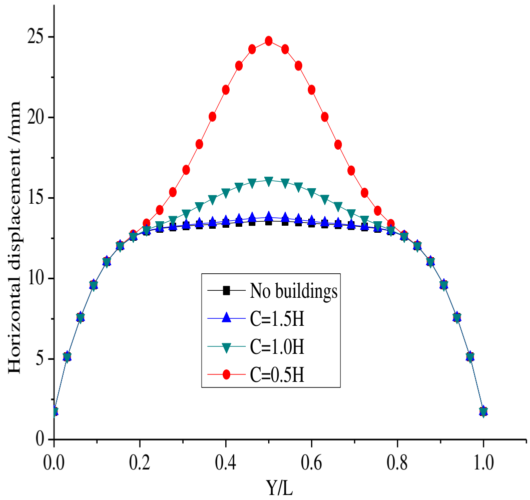

Figure 4.1 Horizontal displacement of slope top of the foundation pit

As shown from Figure 4.1, when there is no buildings on the outside of foundation pit wall, the horizontal displacement of slope top at the both ends of the long side of the foundation pit has obvious spatial effect. The influence range is (0.0~0.22)L or (0.0~2.8)H from the corner of the foundation pit, and the spatial effect of the foundation pit should be taken into account in the range where is obviously affected by the short side. In the other range that is (0.22~0.78)L is almost not affected by the short side of the foundation pit, and slope can be designed in accordance with the inner plane strain problem in this range.

When there is building on the outside of foundation pit wall and the building is located the middle side of the slope wall, the horizontal displacement of the slope top is shown in Figure 4.1. The effect of building on slope horizontal displacement of foundation pit is mainly happened in the middle of the slope wall, which range is (0.22~0.78）L or 1.85A (A is the length of the building). The maximum horizontal displacement of the slope wall at middle of the foundation pit is 24.744mm, and increased by 0.825 times than no buildings. The horizontal displacement of the slope top is almost not affected in the other range.

Figure 4.2 is the horizontal displacement of slope at the top of the foundation pit when the building position is changed. As the corner effect of the foundation, when the building in the end of foundation pit, the maximum horizontal displacement of the slope top is 21.686mm, and is reduced 12.3% compared to the buildings in the middle of the foundation pit.

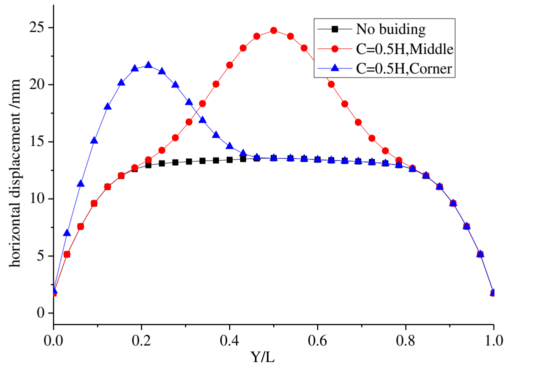

Figure 4.2 The horizontal displacement of the slope wall of the foundation pit

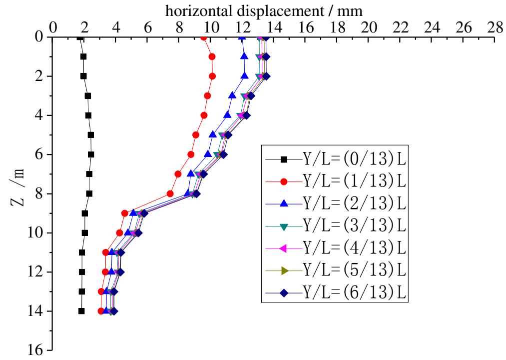

Figure 4.3 Horizontal displacement diagram of slope wall without build

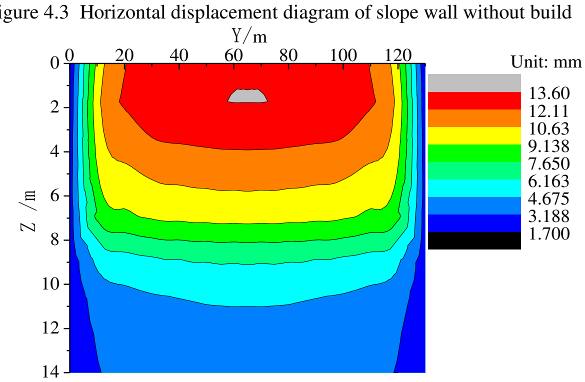

Figure 4.4 Nephogram of horizontal displacement without building

Figure 4.3~4.12 shows the change of horizontal displacement of pile wall with depth. As shown in Figure 4.3 and Figure 4.4, when there is no building outside the foundation pit, the horizontal displacement of the deep wall increases gradually with the increase of the distance from the corner. When the distance from foundation pit corner is greater than (1/13) L, the horizontal displacement of the deep layer changes very little, and the maximum of horizontal displacement is 13.553mm.

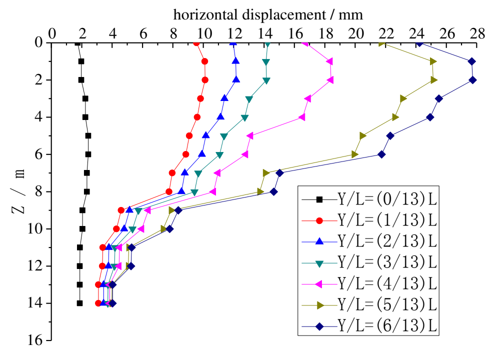

Figure 4.5 Horizontal displacement diagram of slope wall when C=0.5H

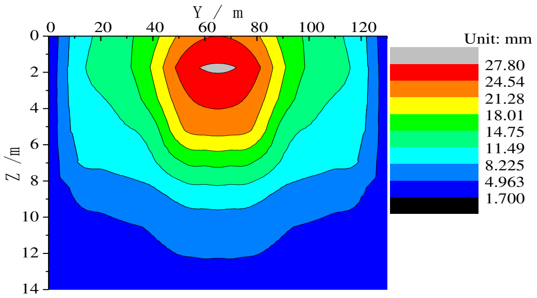

Figure 4.6 Nephogram of horizontal displacement when C=0.5H

From Figure 4.5 and Figure 4.6, when the building is in the position that C=0.5H, and Y is greater than (1/13) L, the deep horizontal displacement increases gradually ; while Y=(6/13) L , the horizontal displacement of the deep wall reaches 27.742mm.

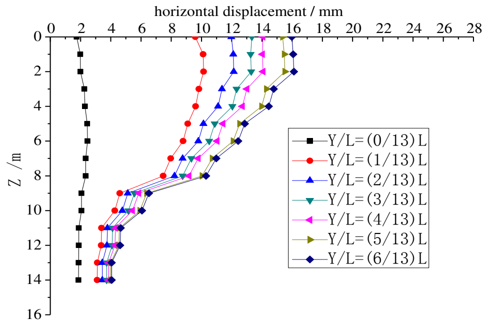

Figure 4.7 Horizontal displacement diagram of slope wall when C=1.0H

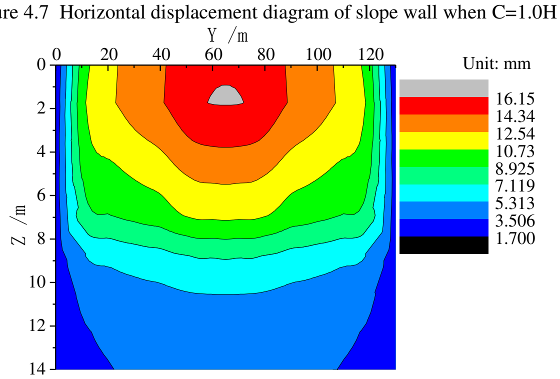

Figure 4.8 Nephogram of horizontal displacement when C=1.0H

From Figure 4.7 and Figure 4.8, when C=1.0H and within 1.85A (A is the length of the building) range in the middle of the foundation pit, the maximum of horizontal displacement reaches 27.742mm, and increased by 0.187 times than without buildings. The deep horizontal displacement of the wall at the foundation pit is increased obviously in the range of 1.85A in the middle of the slope of the foundation pit compared to the condition of no building. When the Y is greater than (6/13) L , the horizontal displacement of the deep wall is increased by 16.12mm compared to no buildings.

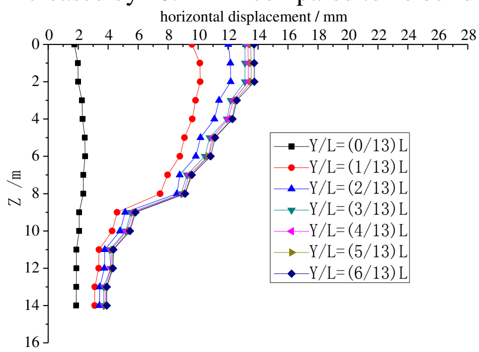

Figure 4.9 Horizontal displacement diagram of slope wall when C=1.5H

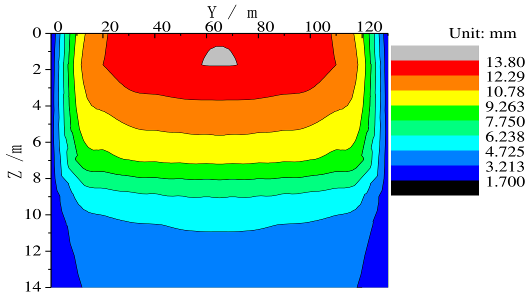

Figure 4.10 Nephogram of horizontal displacement when C=1.5H

From Figure 4.9 and Figure 4.10, when C=1.5H, within 1.85A range in the middle of the foundation pit, the horizontal displacement has little effect on buildings, the horizontal displacement maximum is 13.743mm and is close to the value of no building. When C is greater than 1.5H, the influence of the building on the horizontal displacement of the slope wall at the foundation pit can't be considered.

From Figure 4.11 and Figure 4.12, when the building is located the corner of the foundation pit and C=0.5H, the changed region of the top horizontal displacement is mainly occurred within 0.46L or 1.49A from the corner of the foundation pit. The existence of buildings in the corner of the foundation pit increases the deep horizontal displacement of the slope wall near the corner. When the building is in the corner, the maximal deep horizontal displacement of the slope wall is 22.468mm and is decreased by 9.2% compared to the building in the middle of the long side of the foundation pit.

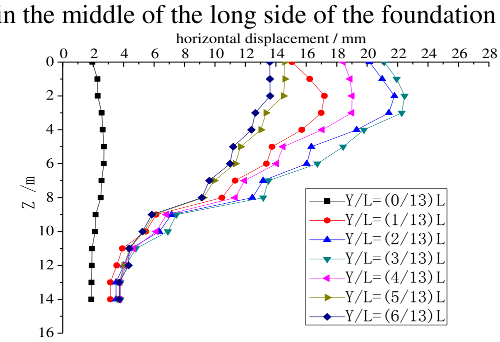

Figure 4.11 Horizontal displacement diagram of slope wall when C=0.5H and with building in the corner

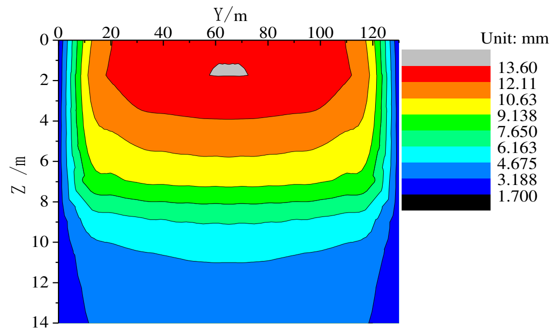

Figure 4.12 Nephogram of horizontal displacement when C=0.5H and with building in the corner

B. Ground Settlement Analysis

Figure 4.13 and 4.14 is the vertical displacement curve and nephogram of the earth's surface. As shown in Figure 4.13 and Figure 4.14, from the slope wall to the far from the slope wall, the surface settlement is in a "trough" form. The surface settlement increases first and then decreases with the distance from the slope wall of the foundation pit. The surface settlement increases gradually from the corner of the slope wall to the middle part of the slope wall.

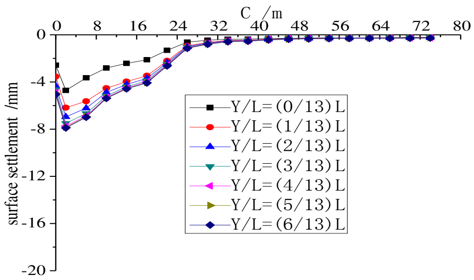

Figure 4.13 Surface settlement diagram without building

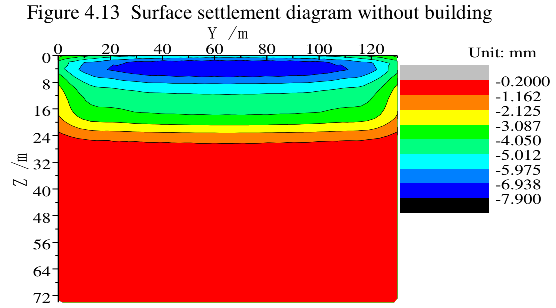

Figure 4.14 Nephogram of surface settlement diagram without building

Figure 4.15 and Figure 4.16 is the vertical displacement curve and nephogram of the earth's surface settlement when C is 0.5H. From Figure 4.15 and Figure 4.16, the groove range of surface settlement compared to the condition of no building increases and is close to the width of the building(i.e. 20m). As a result of the existence of the building, the maximal settlement of the stratum around the slope wall is increased from 7.889mm to 18.411mm.

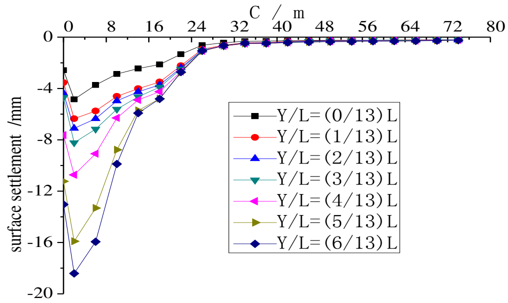

Figure 4.15 Surface settlement diagram when C=0.5H

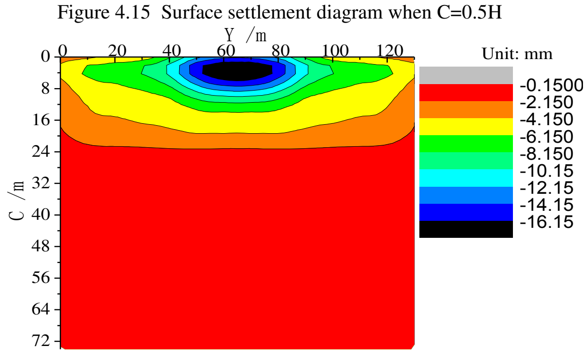

Figure 4.16 Nephogram of surface settlement diagram When C=0.5H

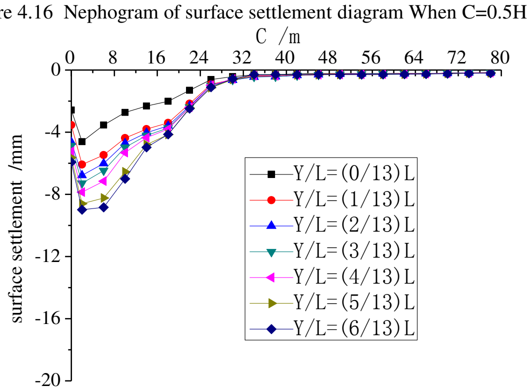

Figure 4.17 Surface settlement diagram when C=1.0H

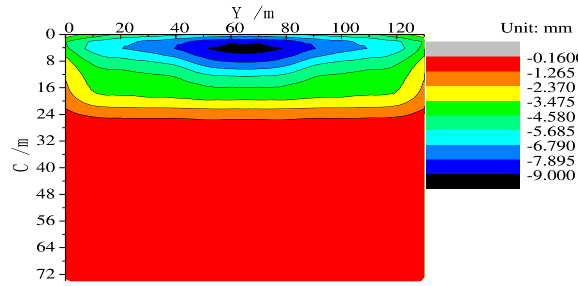

Figure 4.18 Nephogram of surface settlement diagram When C=1.0H

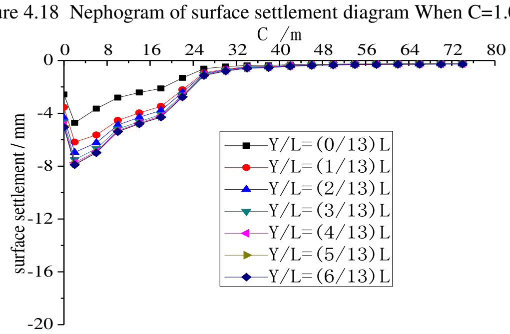

Figure 4.19 Surface settlement diagram when C=1.5 H

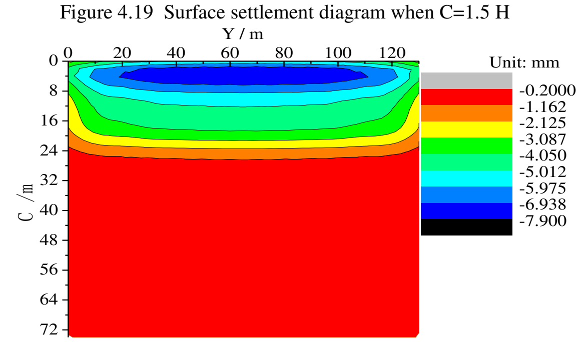

Figure 4.20 Nephogram of surface settlement diagram When C=1.5H

Figure 4.17 and Figure 4.18 are the vertical displacement curve and nephogram of the earth's surface when C is 1.0H, and Figure 4.19 and Figure 4.20 is the vertical displacement curve and nephogram of the earth's surface when C is 1.5H. From Figure 4.17 to Figure 4.20, as the distance of the building from the foundation pit increases, surface settlement near the slope wall of the foundation pit gradually returns to form of settling groove without building.

Fig. 4.21 is the change curve of surface settlement with the location of the building in the middle profile of the foundation pit. When the C is 0.5H, 1.0H and 1.5H respectively, maximal tilt in vertical displacement of building foundation is 0.790‰ , 0.399‰ and 0.21‰ ; maximal vertical displacement of building foundation gradually is changed to 18.414mm, 8.984mm and 4.814mm.

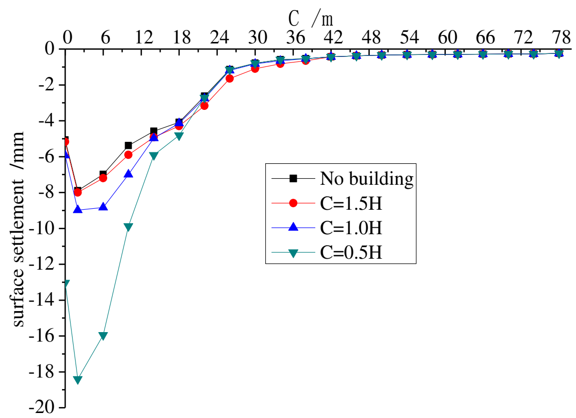

Figure 4.21 Surface settlement diagram With C change

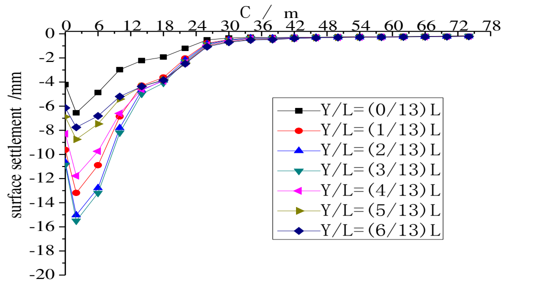

Figure 4.22 Surface settlement diagram With Y/L change and building in the corner

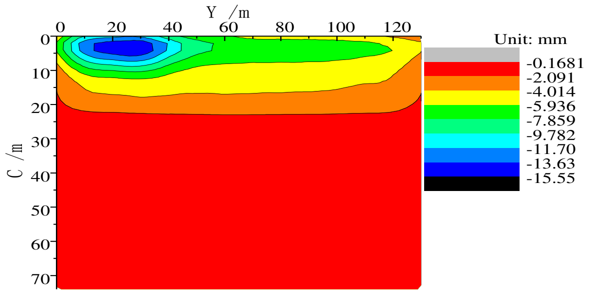

Figure 4.23 Nephogram of surface settlement diagram When C=1.5H and building in the corner

Figures 4.22 and 4.23 are the surface settlement curve and the cloud chart when the building is in the corner of the foundation pit and C is 0.5H. Due to the influence of the building load in the foundation pit corner, the surface settlement is greater than the settlement when the building in the middle. The maximal vertical displacement of the soil outside the slope wall is 15.508mm at (3/13) L from the foundation pit corner, maximal tilt of vertical displacement in building foundation is 0.45‰ .

V. CONCLUSION

(1) When there is no building near the slope wall, the range of main influence from other side is (0.0~0.22)L or (0.0~2.8)H from the corner of the foundation pit, and the spatial effect of the foundation pit is obviously affected; the range that is (0.22~0.78)L from the corner of the foundation pit is almost not affected by the short side of the foundation pit. As the distance between the inside edge of the building and the slope wall increases, the influence on deformation of the adjacent slope wall decreases gradually, and the influence of building on the deformation of foundation pit can't be considered when the distance is 1.5 times the depth of foundation pit. When the building is outside the corner of the foundation pit, the main range of slope soil displacement is 0.46 times the length of the slope or 1.49 times the length of the building.

(2) The settlement at the top of the foundation pit wall with piles and anchor cables support system has a groove form. When the building is in the middle of the slope wall of the foundation pit, the surface settlement and difference of settlement decreased obviously with increase in distance from buildings to slope wall. When the distance from buildings to slope wall is 0.5 times the depth of foundation pit, the width of the groove increases to approximately the width of the building; while the distance is larger than 1.5 times the depth of foundation pit, the groove is gradually regained the settlement form without building conditions, and the influence of foundation pit excavation on the deformation of building foundation is not considered. The maximal settlement and the difference of settlement around the foundation are more unfavorable to the normal use of the building when the building is in the middle of the foundation pit compared to the corner.

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