Design and Numerical Simulation of Deep Foundation Pit Near Subway Lines

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Abstract

In view of the unfavorable influence of the deep foundation pit excavation on the subway line, such as the uneven settlement, collapse and cracking of the lines and the surrounding buildings, combined with the practice of the deep foundation pit near the Xing he international subway tunnel, the theoretical calculation, Foundation Pit Support Structure Formed by Cast - in - Place Pile Combined with Internal. The results show that the retaining structure can effectively ensure the stability of deep foundation pit itself. The results of numerical analysis show that the horizontal displacement and vertical displacement of the cast - in - situ pile and surrounding soil meet the design requirements, which can ensure the deep foundation pit and the surrounding buildings to avoid the adverse impact of excavation. This paper provides a useful reference for the design and construction of deep foundation pit under the complicated environment of urban subway lines.

Keywords

Subway lines, Deep foundation pit support, numerical simulation.

1. Introduction

With the continuous extension of China's subway lines and the acceleration of urbanization, the development of underground transportation has become an important mean how to solve urban traffic congestion and protect farmland. The golden zone for real estate development is needed a metro line where are a large number of deep pit projects near it. However, excavation unloading of deep foundation will inevitably affect the adjacent subway lines, causing disturbance of the surrounding strata which may cause settlement deformation of the soil around the subway line tunnel, and even deformation is too large to destroy the tunnel, seriously threatening the safety of subway tunnel structure and trains normal operation.

The deep foundation pit problem has become one of the hot spot and the difficulty in the engineering community at present. The design and construction of deep foundation pits are mostly semi-theory and semi-empirical, so it is necessary to study how to ensure the economic and safety of urban subway lines near deep foundation pits. Therefore, the foundation pit supporting parameters and support scheme should be carefully designed for its special geological conditions and construction conditions to ensure the construction safety and stability of the subway line near the deep foundation pit in the process of construction design for the deep foundation pit adjacent to the subway line.

2. The Design of Deep Foundation Pit

2.1 Project Overview

Xinghe International Deep Foundation Pit is located at southwest of the intersection of Jintian Road and Fuhua Road, between Fu hua Third Road and Fu hua Road,Shen zhen city, the north of the Exhibition Center of Futian Central District, and the land line is 176.9m long in the north-south direction, 55.75m in the east-west direction, perimeter 450.4m, red line area 9814㎡and excavation depth 17.4m.

The west side of the foundation pit is adjacent to the Subway Exhibition Center and underground shopping mall under construction -the lower part of the mall is the main tunnel of the Metro Line 4-in which the entrance and exit of No. 4 of the exhibition center and the partial support pile have entered the red line of the construction site. The excavation depth of the subway on the west side of the foundation pit is about 23m. The upper part is made of soil nailing wall support about 8m and the lower part is made of digging holes and bite piles with internal support. The upper soil nailing and anchor rods have entered the area of the foundation pit.

The subway line 1 is about 18m on the north side of the pit. The excavation depth of Metro Line 1 is about 15.8m. The piles are supported by the piles, where the upper soil nailing and anchor rods (cables) do not enter the scope of the foundation pit. There is a 9m depth cable-drilling shaft on the north side of the pit, which is only 1.9m away from the underground exterior wall line. When passing through the subway line 4, a digging pile is used as a supporting method. Some digging piles have entered the construction site within the red line, as shown in Figure 1.

2.2 The Determination of Supporting Scheme

Combined these characteristics, not only the stability of the pit should be considered, but also should be controlled the deformation and reduced the adverse effects of long-term precipitation on the subway and nearby buildings. Considering the rationality of the foundation pit, feasible construction, surrounding environment and maintenance cost, the program adopts cast-in-place pile + three-way support. The specific arrangement is as follows:

(1) Fender piles

In the west side of the foundation pit, the B-zone of the Xinghe International adopts clutching borehole grouting pile. The design pile diameter is 1.2m and pile spacing is 1.0m. Plain concrete piles and reinforced concrete piles are intertwined. The east side of the foundation pit is the Jinzhonghuan foundation pit. If the bored pile is used for supporting, the disturbance of the walking of the construction machinery to the soil may affect the adjacent foundation pit supporting structure. To avoid the damage of the construction for Jinzhonghuan foundation pit supporting structure caused by the pit , manual digging and grouting pils with a pile diameter of 1.2m and a pile spacing of 1.15m are used to support and overlap 5cm.

(2) Internal supports

The horizontal internal support adopts reinforced concrete components. The excavation depth of the foundation pit is 17.4m. Three concrete supports are designed and the elevations are 3.0m, -1.35m, and -5.75m, respectively. The main support section is designed to be 0.8m x 0.9m and is cast using concrete C30.

The vertical support members of the support use Φ800mm bored piles and welded steel structures to form support columns.

(3) Seepage isolated curtain

In order to reduce the impact of project precipitation on the surrounding environment, the borehole of the foundation pit on the west side of Zone B adopts a bored secant pile with a lap length of 20cm as a seepage screen, no longer setting up a separate waterproof curtain. On the east side of the foundation pit, manual digging bored piles and double-row jet grouting piles are used as water-stop curtains.

(4) Foundation pit drainage

When the earth is excavated, it is advisable to construct a sump in an appropriate position in the pit, and at the same time it should be pumped into a pump. As the depth of excavation increases, the depth of the sump is gradually deepened.

When the pit is being excavated, a drainage ditch is set at the top of the pit. On the one hand, water accumulates in the drainage pit, and on the other hand, it blocks the flow of outside water into the pit. Before the collection water is discharged into the municipal pipe network, a tertiary sedimentation tank is required for sedimentation.

When the pit is excavated in the end, a drainage ditch is set up in the bottom of the pit, in the corner of the pit and other appropriate places to set water collection pits in order to facilitate drainage of water in the pit.

3. The Calculation of the Supporting Structure

The safety level of the foundation pit is based on the design of the "first-class". The importance coefficient of the side wall of the pit is taken as $\gamma 0 = 1.1$, and the ground loading q = 20.0 kPa. The "Rankine" earth pressure formula is used for stratified calculations, in which strata 1, 2, and 5 to 8 are "estimating water and earth pressures together",and strata 3 and 4 are"soil and water separated". The active earth pressure above the pit bottom is a "triangle" distribution pattern. The "rectangular mode" is used below the pit, in which the active earth pressure coefficient and the passive earth pressure coefficient are calculated as follows:

$$Kai=tan2(45^\circ \varphi i/2) \quad (1)$$

$$Kpi=tan2(45^\circ \varphi i/2) \quad (2)$$

Where: Kai- coefficient of active earth pressure; Kpi- coefficient of passive earth pressure; i-internal frictional angle, °.

The calculation parameters are shown in Table 1 below.

Table 1. Calculation Parameter Table

Tier Number	Name	Tier Thickness	γ (kN/m^3)	C (kPa)	φ(°)	K_{ai}	$\sqrt{K_{ai}}$	K_{pi}	$\sqrt{K_{pi}}$
①	Plain Fill	4.06	18.5	5	8	0.756	0.869	1.323	1.150
②	Silt	0.60	19.3	12	10	0.704	0.839	1.420	1.192
③	Silty Soil of Silty-fine Sand	2.40	19.3	12	10	0.704	0.839	1.420	1.192
④	Clay Containing Coarse Sand	3.00	20.2	10	25	0.406	0.637	2.464	1.570
⑤	Pebbly silty clay	1.50	17.9	26	22	0.455	0.675	2.198	1.483
⑥	Gravel Silty Clay	7.70	17.9	26	22	0.455	0.675	2.198	1.483
⑦	Fully Weathered Mid-level Granite	5.60	22	5	40	0.217	0.466	4.599	2.145
⑧	Strongly Weathered Mid-level Granite	4.20	22.1	45	35.0	0.271	0.521	3.690	1.921

3.1 Lateral Earth Pressure Calculation

(1) Rankine calculation of active earth pressure.

When the calculation point is above the water table:

$$ea=\sigma zKa-2\sqrt{K_a} \quad (3)$$

When the calculation point is below the water table:

$$ea=\sigma zKa-2C\sqrt{K_a}+(zi-hwa)(1-Ka)\gamma w \quad (4)$$

(2) Rankine calculation of passive earth pressure.

When the calculation point is above the water table:

$$ep=\sigma zKp+2\sqrt{K_p} \quad (5)$$

When the calculation point is below the water table:

$$ep=\sigma zKp+2\sqrt{K_p}+(zi\text{-}hwp)(1\text{-}Kp)\gamma w \quad (6)$$

From the above calculation results, the net soil pressure below the base can be obtained. Among them, the net soil active earth pressure is positive and the net passive soil pressure is negative. The net soil pressure distribution is shown in Figure 2 below.

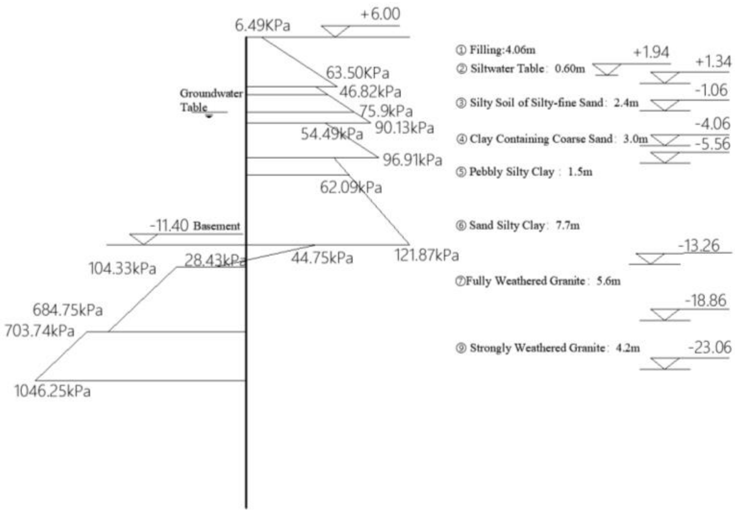


Figure 1. Foundation Pit Pressure Distribution

3.2 Support Structure Design

The main support cross-section of the foundation pit is 0.8´0.9m. The cross-section of the connecting beam between the supports is 0.7´0.8m. The cross-section of the crown beam is 1.2´0.8m, and the cross-section of the support waist beam is 0.7´0.9m. Steel protective layer takes 25mm. Four pairs of supports are set in this section, and the spacing is taken as 7.5m; the two diagonal supports have a spacing of 5.8m and the maximum column spacing is 10.7m.

3.2.1 Design Numeric of Support Axial Force

(1) The first floor support reaction force calculation

The first layer must be set to ensure the stability of the foundation pit before the second layer is supported. First, calculate the distance y1 from the first excavation surface where the earth pressure is zero, as shown in Figure 3. It is assumed that the point where the earth pressure is zero is in the clay-containing coarse sand in the soil layer4.

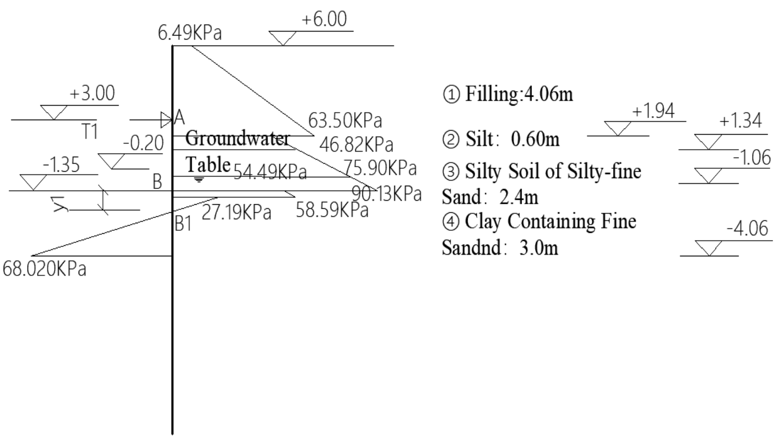


Figure 2. The First Floor Support Counter-force Calculation Chart

According to the principle of equal active earth pressure and passive earth pressure:

$$(e_{a4}^{1'} - e_{p4}^{1})/(e_{p4}^{2} - e_{p4}^{1}) = y1/(2.71-y1) \tag{7}$$

Find: y1 = 0.77m, exists in the fourth soil layer, so the assumption is correct.Then, using AB1 as a simple beam, take a moment on point B1, and let ΣM_{B1}=0, then the first fulcrum reaction force is T1=251.75 kN.

(2) The second floor support reaction force calculation

Calculate the distance y2 from the second excavation surface when the earth pressure is zero, as shown in Fig. 4. The point where the earth pressure is zero is assumed to be in the soil6 gravel silty clay.

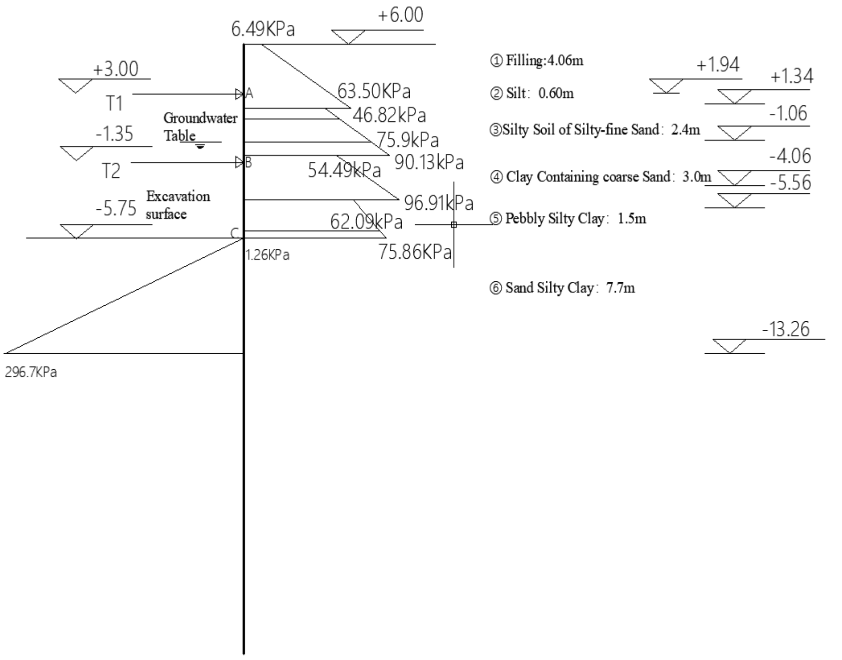


Figure 3. The Second Floor Support Counter-force Calculation

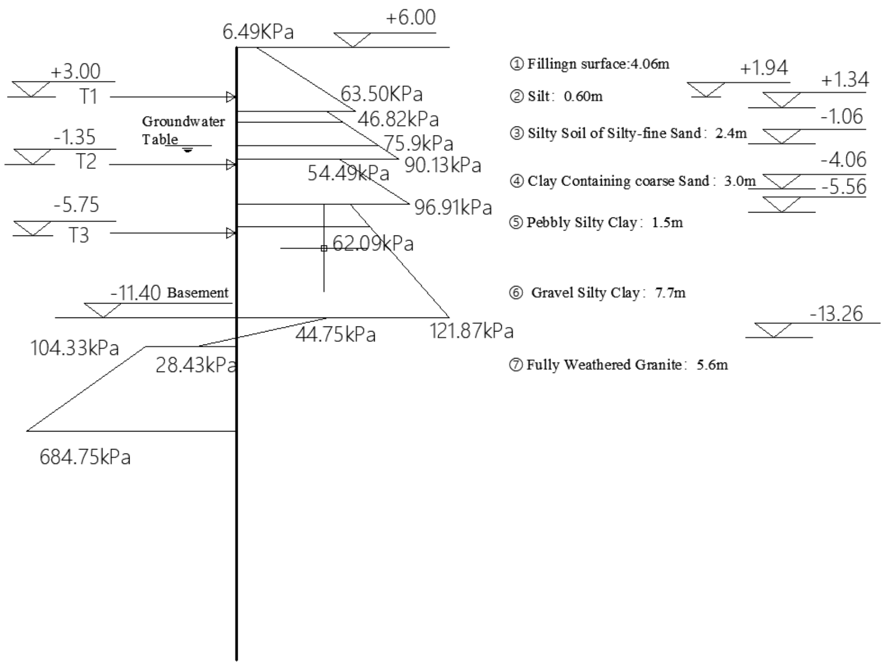


Figure 4. The Third Floor Support Counter-force Calculation Chart

The calculation shows that there is no point where the earth pressure is zero below the excavation surface of the foundation pit. Therefore, the excavation surface is used as the zero point of soil pressure, ie, y2=0.

Take AC as simply supported beam, take moment to point C, and let ΣM_{B3}=0. At this moment, T1 is involved in the calculation with known fulcrum force, then T2=252.41kN.

(3) The third floor support reaction force calculation

Calculate the distance y3from the second excavation surface when the earth pressure is zero, as shown in Fig. 5. The point where the earth pressure is zero is assumed to be in the soil6 gravel silty clay.

According to the geometrical relationship, it can be obtained: y3 = 1.14m.

Using AB3 as a simple beam, take a moment on point B3 and set it to ΣM_{B3}=0. At this time, T1 and T2 are calculated with known fulcrum forces. Then T3 = 495.29 kN.

The T1, T2, and T3 calculated from the foregoing are: T1=251.75 kN/m, T2=252.41 kN/m and T3=495.29 kN/m. The maximum axial force calculated value is: T = 495.29kN/m, then the design value of the support axial force is: N =1.25 γ_0 T*8.5=5788.7kN

3.2.2 Support moment calculation

(1) Bending moment produced by the self-weight of the support beam

$$q=1.25\gamma_0 qo=1.25*1.1*0.8*0.9*25=24.8kN/m \quad (8)$$

$$M1=1/824.8*10.72=354.92kN.m \quad (9)$$

(2) Bending moment produced by construction load

If the construction load is q=10kN/m, then:

$$M2=1/*10*10.72=143.11kN.m \quad (10)$$

(3) Bending moment produced by the initial eccentricity of the supporting section

The initial eccentricity of the section takes 3/1000 of the calculated length of the support,

Then,

$$M3=5788.7*10.7*3/1000=185.82 kN.m \quad (11)$$

In summary, the supporting bending moment is:

$$M=354.92+143.11+185.82=683.85kN.m \quad (12)$$

3.3 Pile's Maximum Bending Moment Design Value

(1) Pile depth and pile length calculation

Based on the above analysis, using AB3 as simply support beam, the fulcrum reaction force at point B3 is Pb3, which can be obtained from the force balance conditions:

$$Pb3=Eak-(T1-T2-T3) \quad (13)$$

Solution: Pb3=273.07kN.

$$\text{Let } x=\sqrt{\frac{6p_{b3}}{\gamma(K_p-K_a)}} \quad (14)$$

Assume that the position of fixity of the pile is located in the completely weathered medium-grain granite in the soil layer 7, and is located at a distance of 7 layers x and the lower pile B3D is a isolator. Take ΣM_D=0 and obtain x = 5.35 m.

Hence, the embedded depth: hd = 5.35 + 1.14 = 6.49 m, and the actual embedded depth is 7 m. The length of the pile can be further obtained: L = 7 + 17.4 = 24.4m.

(2)The maximum bending moment calculation value of pile

Assumed that the point where the shear force is zero is located in the silt fine sand of soil layer 3 and the distance is h1 from the ground. Obtained: h1 = 5.93m. If the hypothesis is reasonable, the zero point of shear force is located in the soil 3 silty fine sand. At this time, MC=165.16 kN·m.

Similarly, assumed that the point where the shear force is located in soil layer 4 with clay-containing coarse sand and soil layer 6 with gravelly silty clay, the respective distances from the ground are h2=9.53m and h3=15.20m, which is reasonable assumption. At this time, the MCs are 268.02 kN·m and 565.79 kN·m, respectively.

Therefore, the calculated maximum bending moment is: MC=565.79 kN·m.

（3）The maximum bending moment design value of pile

The design value Mmax of the maximum bending moment of the pile is:

$$Mmax = 1.2\gamma_0 MC = 1.25\times1.1\times565.79 = 777.96 \text{ kN·m} \quad (15)$$

In the formula: γ_0 - The importance coefficient of the side wall of the foundation pit, the value of the foundation pit is 1.1.

Adopted clutching borehole grouting pile, pile diameter 1.2m, pile spacing 1.0m, lapping 5cm, this section is made of two types of piles: A type of pile is a plain concrete pile and B type pile reinforcement adopts 22 28 length uniform configuration. Protective layer thickness takes 50mm, stirrups φ8 @ 200 and reinforcing ribs take φ14 @ 2000. Concrete strength C30, f_c =14.3N/mm2 , main ribs using HPB335; f_y =300N/mm2. The experience is calculated to meet the requirement of reinforcement.

3.4 Overall Stability Check of Foundation Pit

The determination of the position of the most dangerous sliding arc circle center is generally used as an algorithm, and the foundation pit is calculated by the Tongji Twilight slope stability analysis software. A total of six slip surfaces are selected for this trial. The results of the trial are shown in Figure 6 and Table 2 below.

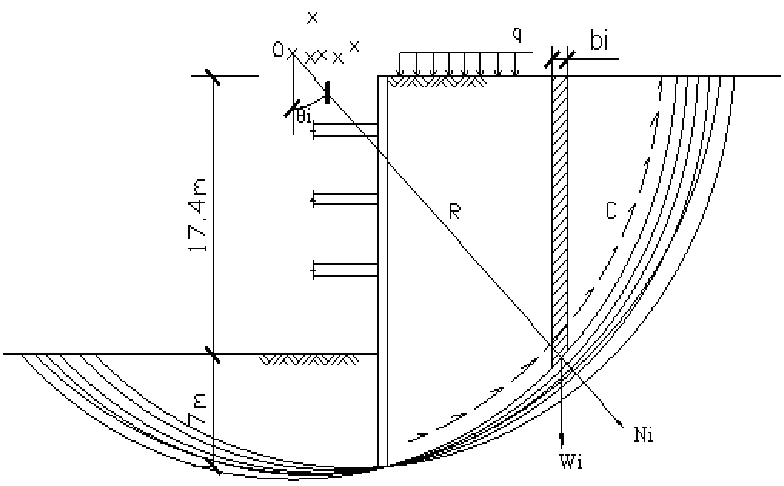


Figure 5. The Overall Foundation Pit Stability Calculation

Table 2. The Overall Foundation Pit Stability Result

Circular Sliding Surface No	Security Coefficient Fs	Coordinate Of Circle Center (m)	Radius(m)	Calculation Method
1	2.0552	(33.61,31.18)	25.80	Swedish Circle Method
2	2.0368	(32.49,31.34)	26.13	
3	2.0487	(31.74,31.22)	26.15	
4	2.0700	(31.83,33.70)	28.57	
5	2.1102	(34.76,31.92)	26.41	
6	2.0656	(30.47,31.46)	26.67	

From the above assumed slip surfaces, it can be considered that the slip surface 2 is the most dangerous, R=26.13m, and the safety factor Fs=2.0368>1.3~2.0, which satisfies the requirements.

4. Numerical Simulation Study

4.1 Simulation Establishment

The excavation process of the foundation pit is simulated by PLAXIS 8.0 finite element analysis software step by step . The horizontal and vertical dimensions of the numerical model are240m and the vertical direction is 90m. The meshing is as shown in Figure 7. Set the geometric model boundary conditions to apply a completely fixed constraint to the bottom and apply a sliding constraint to the vertical boundaries on both sides.

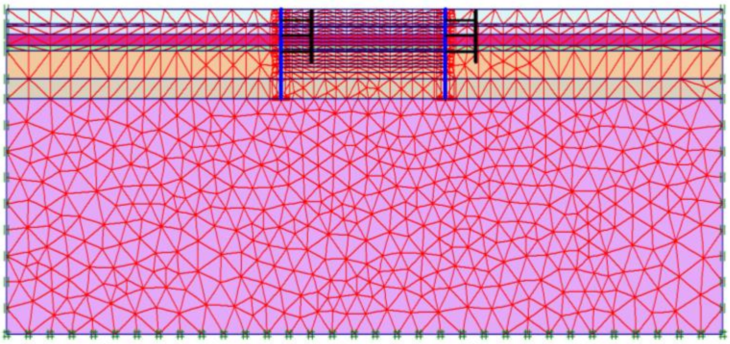
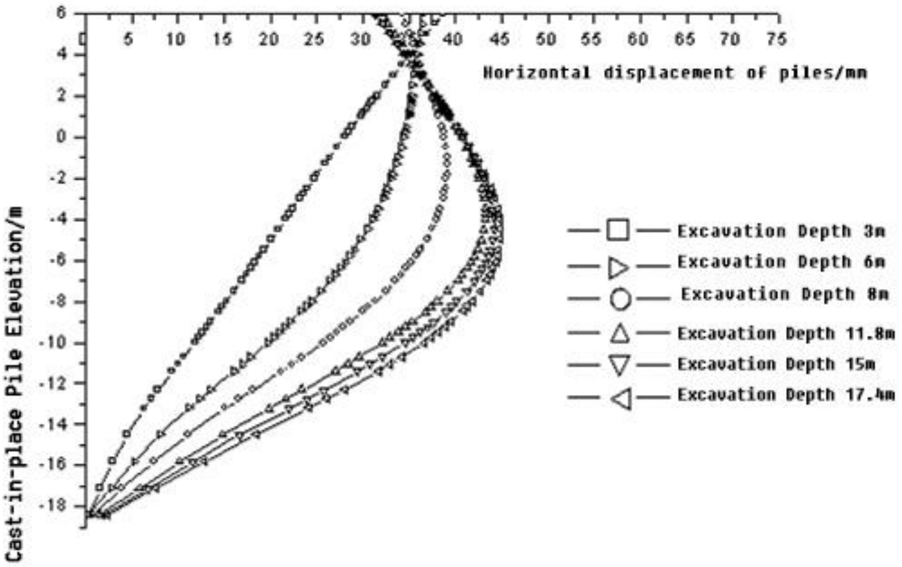


Figure 6. Foundation Pit Calculation Model

4.2 Simulation Results Analysis

(1) The computed result bored pile displacement

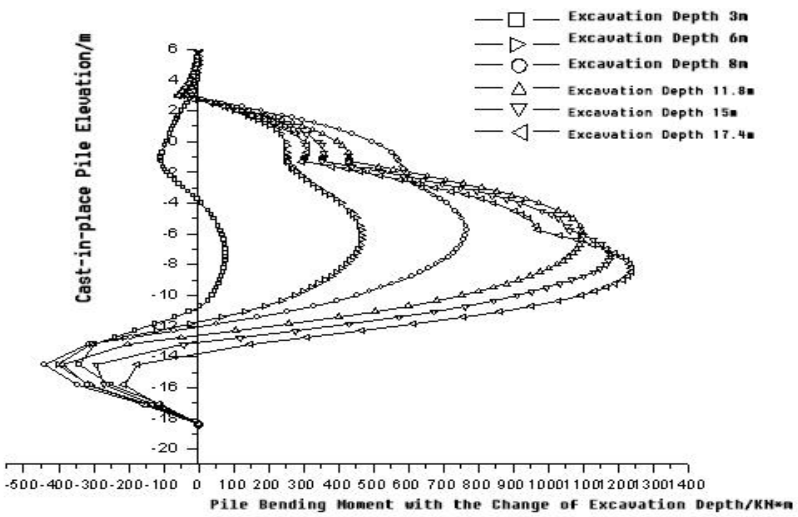


Pile' s Horizontal Displacement Excavation Depth

Figure 7. Pile's Horizontal Displacement Excavation Depth

Table 3. Displacement and Maximum Displacement of Bored Piles

Excavation Depth(m) / Project		3	6	8	11.8	15	17.4
Pile Displacement(mm)		38	36	34	32	31	31
Maximum Displacement	Displacement Size(m)	38	36	39	43	44	45
	Location Elevation(m)	0	0	-1.475	-3.75	-4.25	-4.75



Pile Bending Moment with the Change of Excavation Depth

Figure 8. Pile Bending Moment with the Change of Excavation Depth

From Fig. 8 and Table 3, the horizontal displacement of the pile shows a parabolic shape with the excavation depth and the maximum displacement of the pile top occurs at 3m when excavating. The maximum displacement of the bored pile reaches a maximum of 45mm after excavation 17.4m.

(2) Bending moment analysis of bored pile

Figure 9 shows the bending moment diagram of the bored pile with the excavation depth of excavation. The maximum bending moment is located at a distance of 14.25m from the top of the pile, and the theoretically calculated maximum bending moment is 15.20m from the top of the pile, which shows the result is close.

(3) Surface subsidence deformation

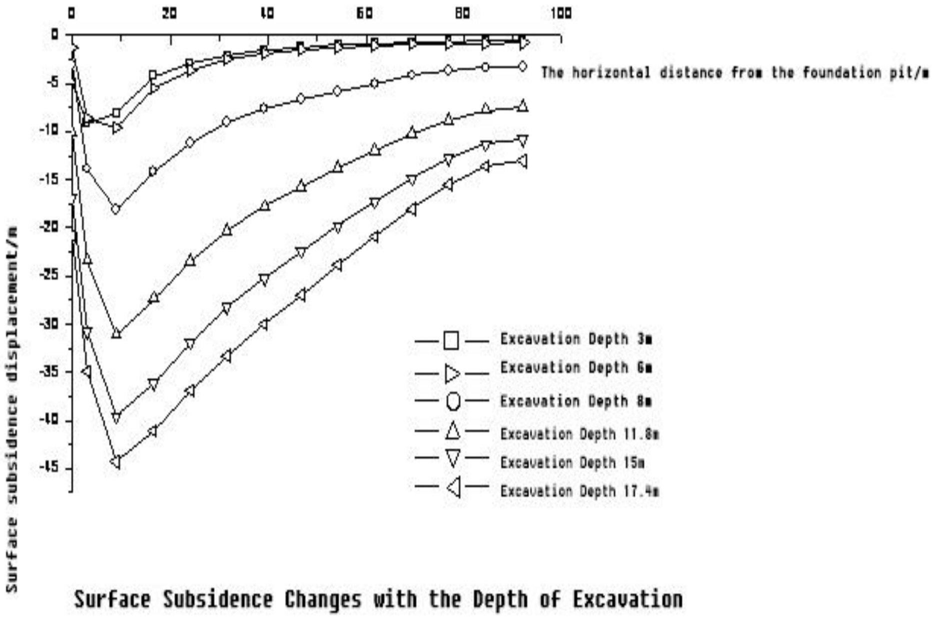


Figure 9. Surface Subsidence Changes with the Depth of Excavation

As can be seen from Figure 10, the maximum settlement at the top of the pile is 20mm, then the maximum settlement displacement at the surface is 44mm and its position is 9m away from the foundation pit.

(4) Effective Stress Distribution

The distribution of effective stress in the foundation pit is shown in the following figure after excavation.

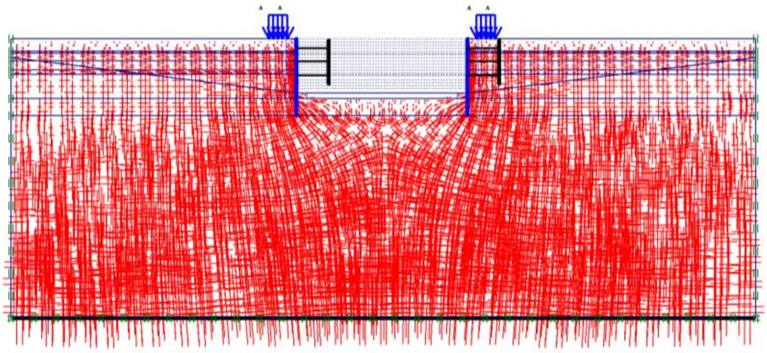


Figure 10. Effective Force Distribution in Excavation of Foundation Pit(5)Horizontal displacement and vertical displacement distribution of each point in the soil

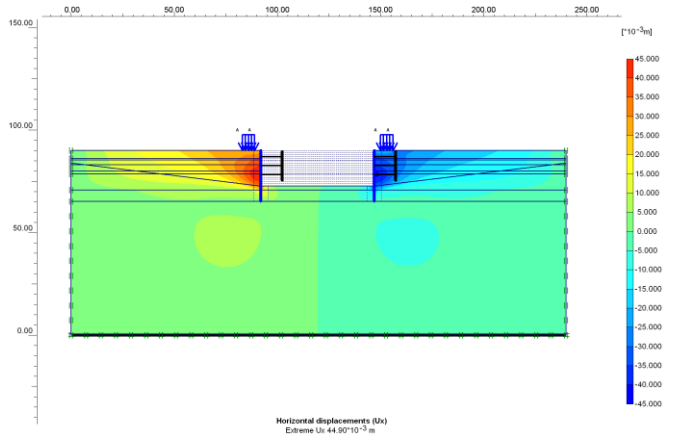


Figure 11. Horizontal Displacement Distribution cloud

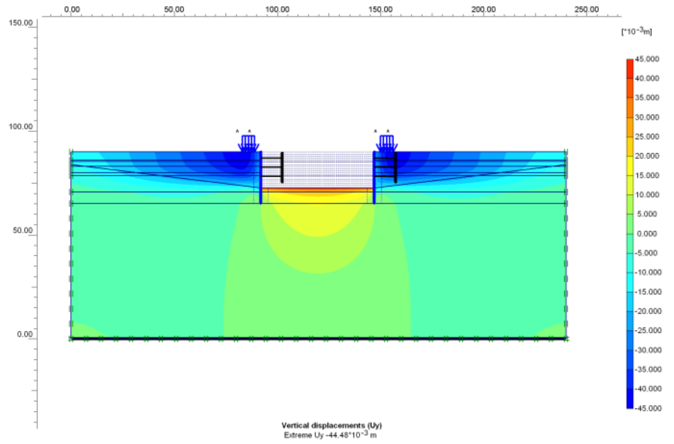


Figure 12. Vertical Displacement Distribution cloud

It can be seen from Figure 12 that the maximum horizontal displacement in the soil will appear in the soil behind the supporting piles with a maximum displacement of 45 mm. It can be seen from Fig. 13 that the maximum vertical displacement in the soil is about 9m away from the foundation pit supporting piles with a size of 45mm. The maximum displacement of the foundation pit is in the middle of the bottom of the foundation pit, and the maximum displacement is 44mm.

5. Conclusion

Through the design and numerical simulation of the deep foundation pit near the subway line, the following conclusions can be drawn:

(1) Considering the unfavorable influence of the deformation of the foundation pit on the subway and adjacent buildings, the form of bored pile + internal support is used. Theoretical calculations show that this type of support can effectively ensure the safety and stability of the subway line near the deep foundation pit.

(2) Numerical simulation shows that the horizontal displacement of the pile exhibits a parabolic shape with the excavation depth. The maximum displacement of the bored pile is 38mm, and the maximum displacement reaches a maximum of 45mm after the excavation of the foundation pit 17.4m; the maximum settlement of the pile is 20mm. The horizontal displacement and vertical settlement displacement of the pile are both small, and the force and deformation of the pile meet the design requirements and can ensure the stability of the foundation pit.

(3) The maximum horizontal displacement in the soil will appear in the soil behind the supporting piles. The maximum displacement is 45mm; the largest downward vertical displacement in the soil occurs near the ground surface and is about 9m away from the foundation pit supporting piles. The size is

45mm, but the surface settlement after 30m is very small; the maximum displacement of the foundation pit is in the middle of the bottom of the foundation pit, the maximum displacement is 44mm, the surface settlement can be effectively controlled after the deep foundation pit of the excavation and support which make the settlement influence range greatly reduce.

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