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Finite Element Analysis of Ultra-deep Foundation Pit Covered Top-Down Excavation Based on PLAXIS

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Finite Element Analysis of Ultra-deep Foundation Pit Covered Top-Down Excavation Based on PLAXIS

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Abstract. The construction process of Xujiapeng ultra-large and ultra-deep foundation pit was simulated by finite element software Plaxis with the use of HSS soil constitutive model. The surface settlement around the foundation pit was "concave" shape and the settlement value was about 30mm. The diaphragm wall had a maximum deformation of 32.29mm to the direction of the internal under the overload, load of building and water and earth pressure. The foundation pit produced a slight distortion under the action of uneven load. A slight distortion occurred under the action of uneven load in the foundation pit.

1. 0 Preface

With the construction of China's subways, a large number of foundation pit projects have emerged, and they are developing in a direction of larger scale, deeper depth and more complicated working conditions. The foundation pit engineering can be influenced by multiple factors. The construction should not only ensures the safety of the foundation pit itself, but also the impact on the surrounding environment, when the foundation pit is being excavated. The engineering accident caused by the excavation of the foundation pit has been common.

It is imperative to conduct an accurate mechanical analysis of the support structure and surrounding environment. However, the traditional limit equilibrium method is only able to calculate the internal force of the support structure, whose deformation cannot be reflected. The elastic resistance method is useful to calculate the deformation of the support structure, but it is hard to reflect the deformation of the surrounding soil. With the development of computational intelligence, it is possible to simulate the foundation pit excavation process with the use of the finite element method and obtain the internal force and deformation of the support structure and surrounding soil.

PLAXIS, a finite element program developed by the Netherlands, is good at solving axisymmetric and plane strain problems. Itis user-friendly, automatically meshes, and contains soil, beam, plate, contact and other elements and various geotechnical constitutive models. It carries out step-by-step calculation and simulation of the project and has strong applicability to the foundation pit excavation project. So in this paper, the PLAXIS finite element program is used to simulate the foundationpitexcavation process.

## 2. Project overview and geological conditions

2.1. Project Overview

After the Wuhan Metro Line 7 and the Sanyang Road Highway Tunnel are built across the Yangtze River, the Xujiapeng Station is built south of the river. Xujiapeng Station becomes the first "Underground engineering Co-built by Cross-river Highway Tunnel and Large-scale Interchange Subway Station" station of China. The station integrates the subway interchange hub, road tunnel and property development. The foundation pit is large in scale, deep in depth and complex in structure. Xujiapeng Station is located at the intersection of Heping Avenue and Qinyuan Road. It is the interchange hub of No.5, No.7 and No.8 subways. The total length is 264m, the width is from25m to 78m, and the depth of foundation pit is 38.36m. The excavation area reached 15,000 m^2.
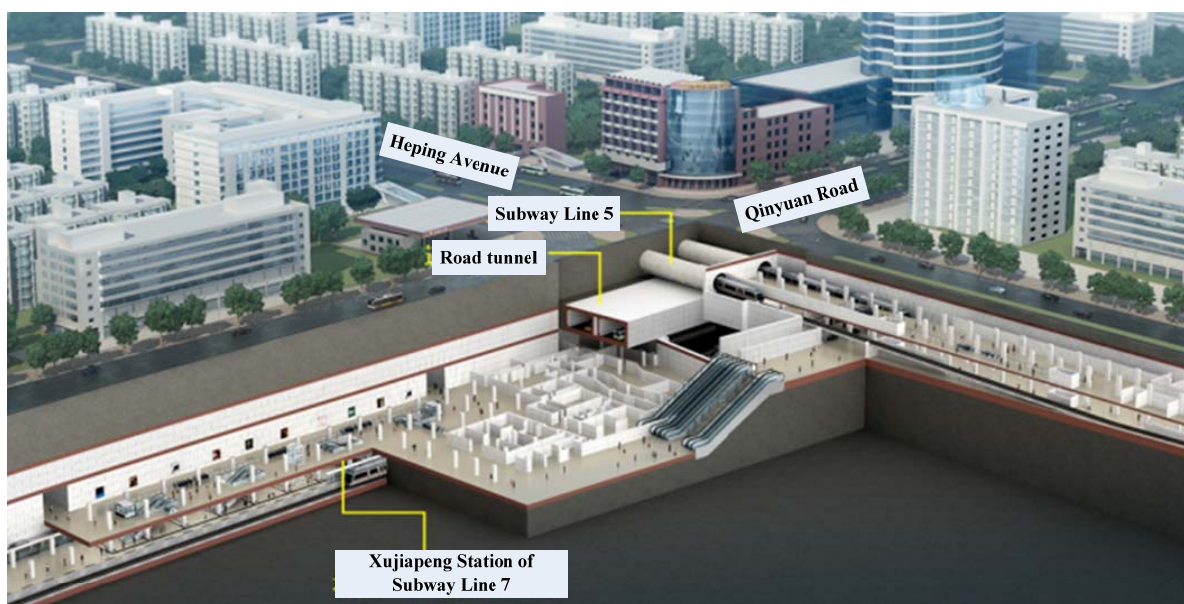
Figure 1. Station renderings of Xujiapeng

The station is a four-story cast-in-place reinforced concrete structure. From top to bottom, there are the property development layer, the highway tunnel layer, the station hall layer (equipment interlayer), and the subway station platform. The vertical section of the station is as follows.
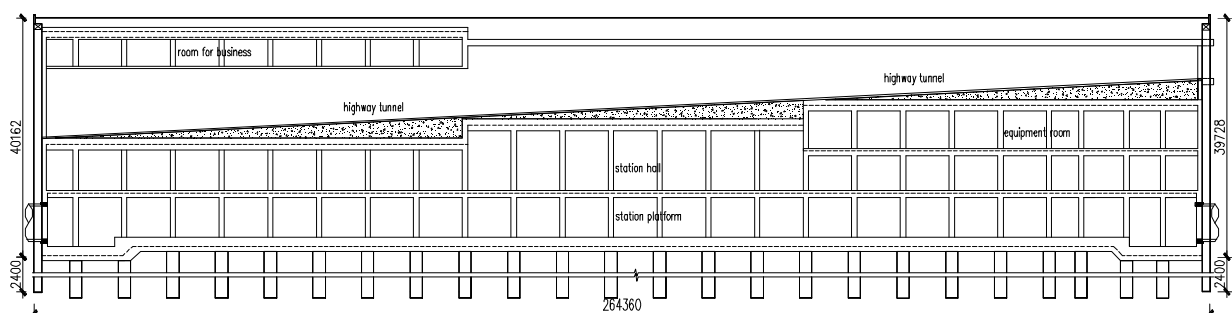
Figure 2. Vertical section of the station (unit: mm)

Within the influenced scope of the station excavation, there are Huiyu Garden, Binjiang City Garden, Wuchang District Environmental Sanitation Bureau dormitory and other buildings. The Huiyu Garden is an 8-story frame house with shallow foundation, which is only 17.65m away from the edge of the

foundation pit. Considering the safety of the buildings around the station and reducing the impact of foundation pit excavation on the surrounding environment, this station intends to use the covered top-down excavation method.

2.2. Geological conditions
Xujiapeng subway station is only 800m away from the Yangtze River. The site geomorphology unit is a river accumulation plain and belongs to the Class I terrace of the Yangtze River. The terrain is flat and surface elevation is generally about 22.37m to 23.97m. The surface layer is loose artificial fill layer (Q^{ml}), the engineering performance is poor, and with silt soil distributed locally (the depth is 2m to 4m). The upper part is mainly the Quaternary Holocene alluvial phase (Q_4^{al}) soft-plastic state cohesive soil, silt, silty clay interbed, the engineering performance is poor, too. The middle layer is slightly dense and medium dense fine sand. The fine sand has a slightly higher strength and general engineering performance. The underlying bedrock is the shale siltstone and glutenite of the Baiji-Lower Tertiary Donghu Group (KE), and tit is relatively complete.

   The groundwater of the station is divided into pore-bearing water, upper layer stagnant water and bedrock fissure water. The thickness of the pore-bearing water aquifer is about 40m. The upper clay layer and the lower bedrock are relatively water-repellent layers. The station is close to the Yangtze River and has a complementary relationship with the Yangtze River.

3. Numerical modelling

3.1. Soil constitutive model and parameters
Small strain hardening model (HSS) is used in the simulation. The HSS model increases the shear strain level $\gamma_{0.7}$ and the initial small strain modulus G_0 on the basis of the HS model, taking the small strain stiffness of the soil into account. The model can reflect the hardening characteristics of the soil and its stiffness depends on the stress history and path, so it is easy to distinguish the difference between loading and unloading soil, and has strong applicability to the soil affected by the volume. In view of the fact that the HSS model has a better reflection of the interaction between structure and soil under working load conditions. The model has obvious advantages at describing the compression hardening, shear hardening, addition-unloading and small strain of soil compared with Mohr-Coulomb, Druker Prager, etc and is more suitable for simulating the foundation pit excavation process. The elastic continuous plate model is used for simulating the diaphragm wall, the middle floor and the top floor. The column and the pile foundation are equivalent to the plate of the corresponding thickness according to the modulus value. The steel support adopts a sturdy model, and the Poisson's ratio is 0.2. The parameters of the soil and the support components are selected as follows.

Table 1. Soil calculation parameters

Soil layer	Natural severity kN.m^{-3}	Cohesion c/kPa	Internal friction angle $\varphi/°$	Dilatancy angle $\psi/°$	Triaxial consolidation test secant modulus E_{50}^{ref}/kPa	Modulus stress related power index M	Unloading reloading modulus E_{ur}^{ref}/kPa	Initial small strain modulus G_0/kPa	Shear strain level $\gamma_{0.7}$
Artificial	18.3	8	18	0	5000	0.65	25000	110000	0.0001
③-1	18.6	18	9	0	5500	0.8	28000	140000	0.0001
③-3	18.1	12	6	0	3500	0.8	18000	88000	0.0001
③-4	18.6	15	10	0	5000	0.65	25000	125000	0.0001
③-5	18.3	16	14	0	8500	0.5	42000	212500	0.0001
④-1	19.2	0	30	0	17000	0.5	85000	425000	0.0001
④-2	19.3	0	33	3	21000	0.5	110000	525000	0.0001
④-3	19.5	0	35	5	27000	0.5	140000	675000	0.0001
15-2a	24	100	28	0	500000	0.5	2500000	12500000	0.0001

Table 2. Calculation parameters of support structure

Structure parameter	Bottom plate, Diaphragm Wall	roof	Second floor	Third and fourth floor	Column	Squat pile	Steel support
EA(kN/m)	4.73E+07	3.00E+07	3.30E+07	1.50E+07	3.78E+07	8.35E+06	6.26E+06
EI(kN·m)	8.86E+06	2.50E+06	3.33E+06	3.13E+06	4.54E+06	4.89E+04	/

3.2. Model building and meshing

According to the actual engineering environment conditions, the most dangerous calculation section is selected for numerical simulation. The calculated foundation pit depth is 36m and the width is 31m. The model have a range of80m away from both sides of the foundation pit, and 17m away from the bottom of the diaphragm wall to reach the bed rock layer. The Huiyu Garden on the left side of the foundation pit is 17.65m away from the edge of the foundation pit. It is made of rammed pile foundation and has a length of 15m. The Garden is equivalent to a plate unit and applies a load of 15KPa per layer at the top of the group pile. The Binjiang City Garden is 30 layers high on the right side of the foundation pit. It applied pile foundation, and its pile foundation has reached the bedrock, so its effect on the excavation of the foundation pit was ignored. Taking the shield lifting into account, a uniform load of 30 KPa/m is applied at the edge of the foundation pit. A horizontal constraint is applied to both sides of the model and a fixed constraint is applied to the bottom edge. The model soil unit is simulated by a 15-node triangular element. The steel support structure is simulated by the bolt unit, and the rest components are simulated by the plate elements. The contact position between the soil and the support structure is simulated by the contact unit of the refined grid. The diaphragm wall of the project falls into the bottom bedrock, and the joint is blocked by the RJP piles. As a result, the seepage effect of water is not considered in the simulation.
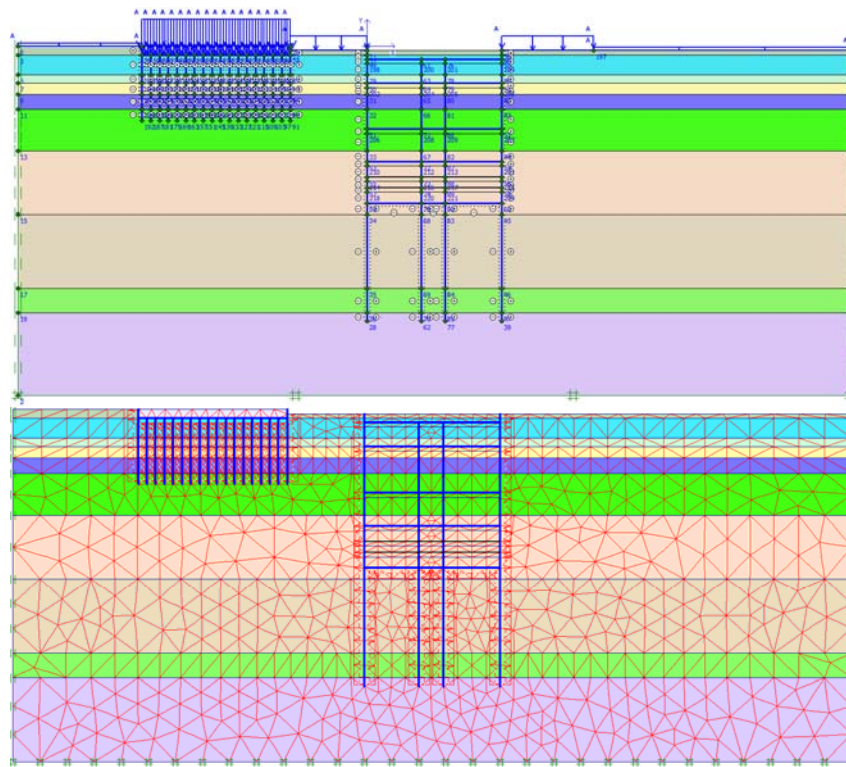
Figure 3. Calculation model and meshing

*3.3. Construction process simulation*
The Xujiapeng station is constructed by the cover top-down excavation method. The simulated excavation and support are divided into the following eight processes:

    (1) Construct the diaphragm wall and lattice column;
    (2) Excavate to -3m, and construct the roof structure at -2m;
    (3) continue to excavate to -9.5m, construct the second floor at -8.5m;
    (4) excavate to -20m, construct the third floor at -19m;
    (5) excavate to -27.5m, and construct the 4th floor at -26.5m;
    (6) excavate to -30.5m, install the first steel support at -30m;
    (7) Excavate to -33m, and install the second steel support at -32.5m;
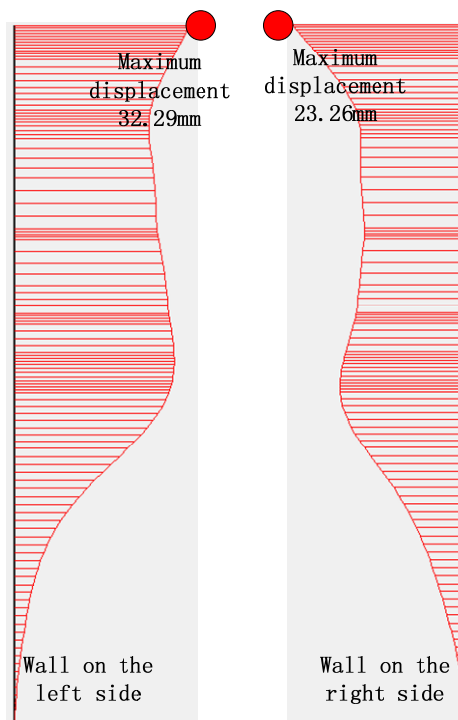   (8) Dig to the bottom and construct the bottom floor.

4. Simulation results analysis
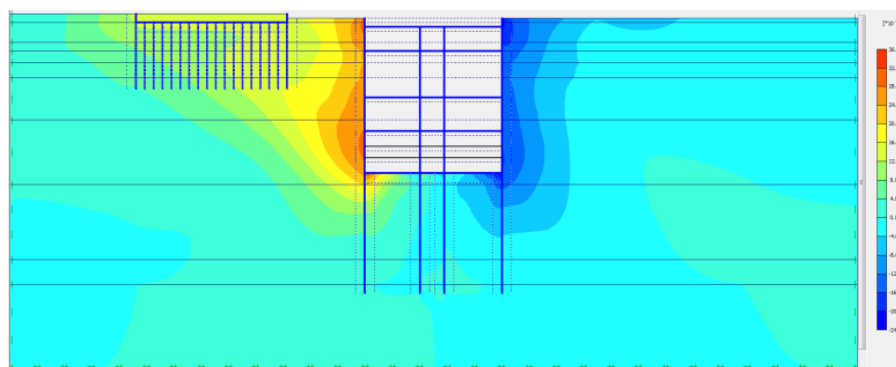
Figure 4. Horizontal displacement cloud image
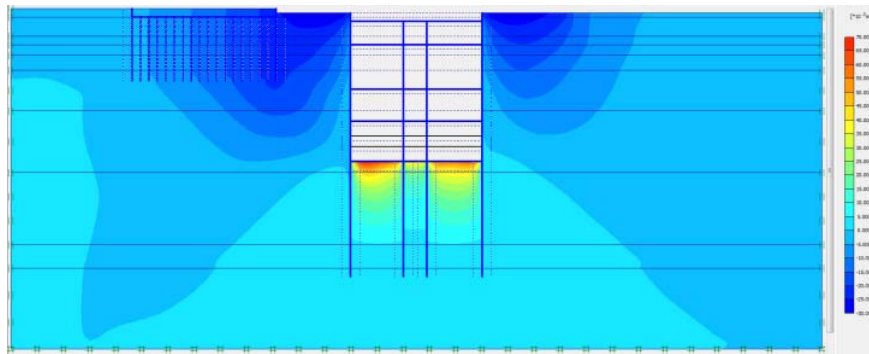
Figure 5. Vertical displacement cloud image

Figure 6. Deformation curve of continuous wall

The excavation of the foundation pit has an influence on the surrounding surface settlement. As shown in the vertical displacement cloud diagram that the ground subsidence value gradually increases from the edge of the foundation pit to the outside of the foundation pit, and the maximum settlement value appears at 7-9m from the edge of the foundation pit. As the distance from the edge of the foundation pit increases, and the settlement value gradually decreases gradually to zero, which is consistent with engineering experience and theoretical calculation results. From the comparative analysis of the ground settlement on the left and right sides of the foundation pit, the surface subsidence of Huiyu Garden on the left side around the foundation pit has hardly been effected. The settlement curve of both side is similar, but the influence depth is deep with the load of buildings. A settlement of nearly 30mm occursat the building piles. At the same time, the excavation of the foundation pit cause a large unloading of the soil in the foundation pit, and the bottom soil produce a large uplift under the water and earth pressure on both sides. The amount of the left uplift is slightly larger than the right side, and the maximum value exceeds 60 mm.

Table 3. Wall deformation of different excavation process

Construction step	Maximum horizontal displacement (mm)	
	Wall on the left	Wall on the right
Excavate to -3m	28.9	30.25
Excavate to -9.5m	27.21	28.91
Excavate to -20m	27.69	27.98
Excavate to -27.5m	29.57	26.08
Excavate to -30.5m	30.51	25.1
Excavate to -33m	31.4	24.18
Excavate to the bottom	32.29	23.26

From the horizontal displacement map of the foundation pit excavation and the displacement table of the left and right diaphragm walls, the surrounding soil and the supporting structure are displaced to the inner side of the foundation pit due to excavation, and the maximum displacement of the soil is 36mm.A horizontal displacement of about 30 mm occurred at the first excavation step for the reason that there is not concrete for support. After constructing the roof floor, the further deviation of the support structure is restrained because of its large rigidity. The roof floor forms a rigid fulcrum at the diaphragm walls. After the excavation of the lower soil, the wall under the roof is subjected to huge water and earth pressure. The wall bellow roof floor displace to the inner foundation pit, however, the displacement of the diaphragm wall on the roof floor is slightly reduced, and the reduction value is about 1mm to 2 mm. With the further excavation of the foundation pit, the horizontal displacement of the diaphragm wall gradually increases, and the maximum value is 32.29 mm.

Comparing the displacements of the left and right, as shown in the picture that the horizontal displacement of left diaphragm wall is smaller than the wall right side when the depth is less than 20m. Below 20m, the horizontal displacement left side is significantly larger than the right diaphragm wall. The reason is that the Huiyu Garden on the left side of the foundation pit adopts the rammed pile foundation, the load is more than 17 meters away from the edge of the foundation pit, and its load is transmitted deeper along the line of 45. The support structure itself has a large rigidity, and the basement falls into the rock formation. Under the load of 20 meters deep on the side, the support structure has a certain distortion, so the above deformation results appear, which is consistent with the mechanical analysis.

5. Research conclusions

(1) The software of Plaxis can effectively simulate the excavation process of super-large and ultra-deep foundation pits. The HSS model considers the hardening characteristics of soil, and the calculated results are consistent with the theory and practical experience.

(2) The settlement curve of surrounding soil caused by excavation of foundation pit is "concave" shape, and the settlement value of the outer edge of the foundation pitgoes through a process of increasing firstly and then decreasing. . The maximum value appears at the edge of the foundation pit 7-9m, and the settlement amount is about 30mm.

(3) The construction method of covered top-down excavation can make full use of the rigidity of the structural floor, and greatly reduce the horizontal displacement of the surrounding structure. The maximum horizontal displacement of the diaphragm wall is 32.29 mm, which is within the allowable range of the specification.

(4) The load of the building around the foundation pit is transmitted along the 45° oblique line of the foundation. The supporting structure is affected by the load and slight distortion occurs.

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