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The study of special geological environment conditions in the design of supporting structures for large and unusually shaped foundation pits

Shulan Guo, Changhong Yan and Liangchen Yu

School of Earth Sciences and Engineering
Nanjing University, Nanjing, Jiangsu Province 210023, PR China

Abstract

A large underground transportation hub, which was completed in 2016,is located on the west side of the Nanjing Youth Olympic Center, which is close to the embankment of the Yangtze River. The foundation pit for the hub is of an unusual shape and variable depth, and has required deep excavation. A further complicating factor in construction has been the area's wide distribution of loose sediments of Quaternary age. The near-surface is primarily comprised of newly deposited soft soil of considerable thickness; the lower part is a riverbed-phase sandy soil containing rich groundwater, and most of it is confined. The B2-J1 area is the core area of the project. The bottoms of the foundation pits were located in the layers of B, C_1, and C_2, which exhibit poor stability. The site is also close to the Yangtze River, which is characterized by high-level groundwater. After considering the engineering geological conditions, the potential associated geological problems and the function and shape of the foundation pits, we divided the soil layers of the foundation pits into two areas (the NW area and the SE area).The support structure was designed for the "pit in pit" and the "pit leaning pit" phenomena of the two areas, and the support effect was verified viaFLAC3D numerical simulation software.

1. Introduction

In recent years, there has been an increase in underground engineering construction along the lower reaches of the Yangtze River. The foundation pits are characteristically large-scale, unusually shaped, and require deep excavation. In addition, the complex geological environment of the area places considerable demands upon the design and construction of the supporting structures. Thick, loose sediments of Quaternary age are widely distributed across this area. In particular, the newly deposited soft soil of the Holocene is widely distributed and very thick. Deep foundation pit engineering is mostly conducted in this soft soil layer (Yan et al., 2015; Yuan and Zhao, 2011; Zhang et al., 2013; Zhang et al., 2014). However, the

supporting structures for these pits are temporary, and they have been constructed with only a small design safety factor. The designers have generally focused on the construction costs and time, the overall development process, the progress of construction, and the mutual influence of adjacent foundation pits (Hu et al., 2012; Wang and Wang, 2018), while largely ignoring the rational use of geological conditions at the construction sites; such an approach leads to a high risk of engineering accidents. Blindly adopting standard designs is likely to result in a significant waste of resources, and to lead to a high risk of engineering accidents.

The existence of different conditions within each site (particularly the hydrogeology and engineering geology) means that the design of supporting structures for these types of foundation pits should be flexible; that is, the safety of these structures can only be improved by tailoring their design to the local conditions and accounting for surrounding buildings. Some studies that illustrate this point have been published. Tian and Li (2010) studied the requirements for an unusually shaped foundation pit for a subway station; based on the complex geological conditions and prevailing high groundwater levels, they proposed that bored piles should be adopted for the main retaining structure, and that three-axis mixing piles should be used for water-stop curtains and steel pipes (Tian and Li, 2010). Chen and Wang (2007) examined an example of deep foundation pits constructed within a complex geology. The supporting structure for the foundation pit was composed of large-diameter rings, a lattice supporting framework, and densely-packed bored piles; in addition, a three-axis cement mixing pile on the outside of the pit was used as the water-stop curtain (Chen and Wang, 2007).Huang et al. (2017) studied a deep, unusually shaped foundation pit project in Nanchang to verify that the pile–anchor–concrete supporting structure could effectively control its own deformation during the excavation of the foundation pit, ensuring its overall stability while effectively reducing disturbance near the subway facilities(Huang et al., 2017).

This paper presents a study of a deep foundation pit with complex geological conditions, and conducts related research by analyzing the geological environment conditions of the site and selecting a reasonable design plan for foundation pit support. This paper can provide a theoretical basis and practical guidance for the design and construction of deep foundation pits along the lower reaches of the Yangtze River.

2.   Background

As is illustrated in Figure 1, the project site is located in the Jianye District of Nanjing City in the Jiangsu province of China. The scale of the project is huge; it includes seven districts (B1, B2–J1, B3, J2, J3, J4, and J5). The area we studied, located in district B2–J1, is the core of the project, and is the site of a deep, large, and unusually shaped foundation pit that comprises a three-story interchange underground structure. The lower layer is where the main line tunnel will connect with the proposed cross-river tunnel; the middle floor is a ramp that connects underground passages and nearby roads; finally, the upper level accommodates Yangtze River Avenue and the ramp that connects the main venue of the Nanjing Youth Olympic Games, as well as nearby above-ground roads.

The foundation pit (depth 27m, area *c*. 1.0km^2) is adjacent to the Youth Olympic Center, International Style Street, and the Yangtze River Dike. The foundation pit of the main road (i.e., the lower layer) is 80m away from International Style Street, and 120m away from the Youth Olympic Center. The engineering geology and the hydrogeological conditions are complex. The lithology of the site is as follows: the upper part is the soft and silty soils of the river floodplain; the lower part is riverbed-phase coarse granular soil and medium-coarse sand; the bottom part is mudstone. The strata within foundations sit that hold many layers of mineral-rich, pressurized groundwater. Faced with such foundation pits with complex engineering geological conditions and irregular shapes, it is necessary to ensure the

effectiveness, economic efficiency, and timely completion of the supporting structures of the foundation pit by carefully considering the geology (Wang et al., 2006). In view of the technical problems of complex foundation pits and the difficult design in district B2–J1, here we comprehensively consider the characteristics of this whole project, its development schedule, and its costs, and explore potential engineering geological problems based on the differences between the engineering geological conditions of the site and the underground structures. Additionally, we have divided the pit into two horizontal areas (plane sections), and propose an optimum design that considers the shape and the function of the foundation pit and involves layers and partitions for the supporting structure, which effectively solves the design and construction technical problems of the deep and large supports in district B2-J1.
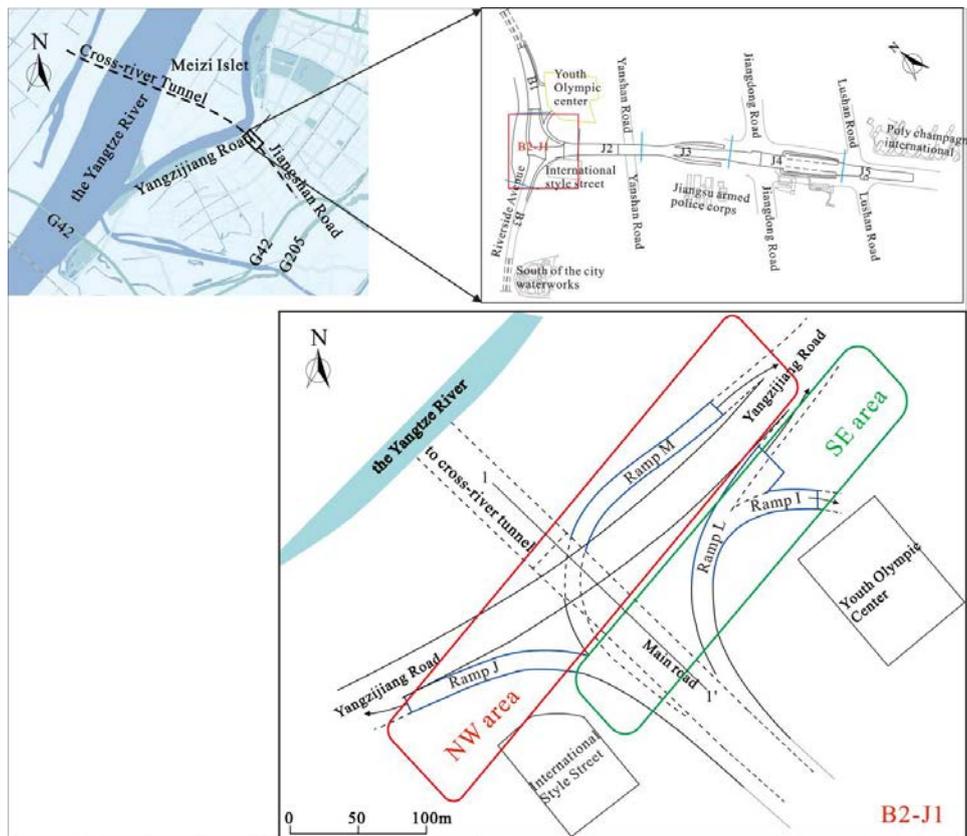
Fig. 1. Location and plane layout of the foundation pit of B2-J1.

2.1   Geological conditions

The study site is located within the floodplain of the lower reaches of the Yangtze River. The ground elevation is 6.0–1.0m, and the terrain is flat. The strata throughout the excavated depth can be divided into six layers. The layers are illustrated in Figure 2 and their lithology in provided in Table 1.

The strata in the site are sedimentary, and primarily belong to the floodplain and riverbed facies of the Yangtze River; in particular, there are thick strata of Quaternary (Holocene) age. As shown in Table 1, the lithology of the strata in the site can be divided into four parts: the upper part (which is widely distributed across the site and is up 10 m thick near the Yangtze River) is filling (stratum A); the central part is dominated by alluvial gray silty clay, silt, and silty soil (strata B and C_1); the lower part is fine sand, medium-coarse sand, gravel sand, and mixed gravel and gravel (strata C_2, D, and E); finally, the bottom is strong–medium weathered mudstone (stratum F).
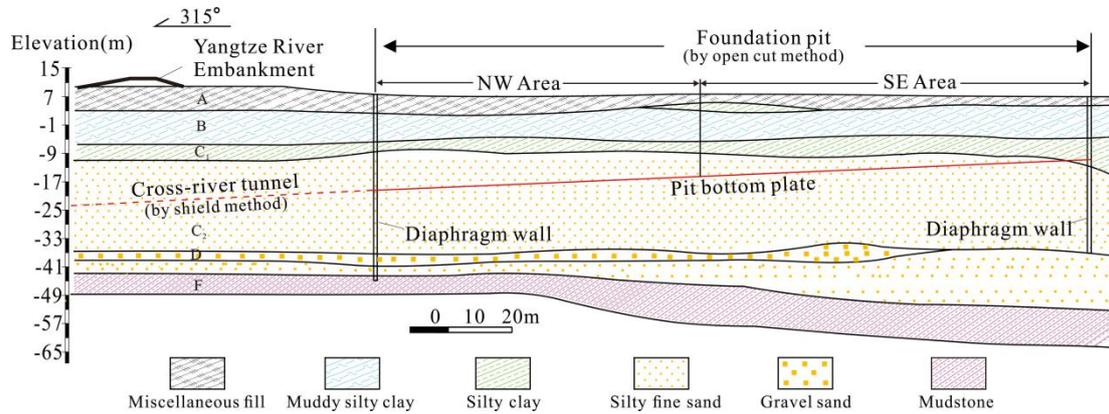
Fig. 2. Profile of the strata and foundation pit in section 1-1' shown in Figure 1.

Table 1
Engineering geological layers in area B2–J1

Numbering	Stratum	Geochronology	Description	Thickness (m)
A	Miscellaneous fill	Q_4^{ml}	Mottled, loose, mixed soil of construction waste	0.70~10.6
B	Muddy silty clay	Q_4^{al+l}	Gray, flow-soft plastic, with humus, shell fragments, and silt	3.10~10.0
C_1	Silty clay	Q_4^{al}	Blue-gray, saturated, poor grade, partially with silty clay	5.20~23.0
C_2	Silty fine sand	Q_4^{al}	Blue-gray, medium dense ~ dense, poor grade, with a small layer of silty clay	4.50~20.0
D	Gravel sand	Q_4^{al+pl}	Blue-gray, dense, general grade, with coarse sand, gravel	0.55~16.0
E	Silty fine sand	Q_4^{al+pl}	Gray, saturated, dense, general grade; diameter of gravel is2–15mm	0.50~12.5
F	Mud stone	K_2p	Brownish red, undeveloped joints; cracks are filled by gypsum, which is easily softened by water	0.48~16.1

2.2   Evaluation of engineering geological conditions

According to the geotechnical investigation report, the soils in the site are Quaternary sediments. A thick fluvial sedimentary formation overlies mudstone, and a miscellaneous fill layer lies on the top. Due to long-term sorting and deposition by the Yangtze River, the upper strata are primarily composed of clay and muddy silty clay, while the lower strata are mainly composed of silty fine sand and gravel sand, which form the typical dual-structure strata and create many aquifers, and contains multiple layers of confined aquifers with high groundwater levels. As shown in Figure 2, the geotechnical layers are of different thicknesses, and, as illustrated in Table 1, their lithology is complex and varied. Several laboratory and in situ tests were performed to obtain the soil properties.

The average values of these soil properties are listed in Table 2.We can see from Table 2 that the upper part is a medium compressive soil of poor permeability that is relatively dense and of high strength (layers A, B); the middle part is soft, loose soil of poor permeability with poor engineering properties (layers C_1, C_2); the lower part is a compact, coarse-grained soil of good permeability with good engineering geological properties, and contains mineral-rich groundwater within a confined aquifer (layers D, E); finally, the bottom part is a strongly-weathered mudstone, which acts as an impermeable layer within a buried depth of 41~56 m (layer F). The complex geological conditions caused by the aquifers, and the associated high

risk of precipitation during construction, can lead to geotechnical problems and even geological disasters, which can result in catastrophic engineering accidents(Ghasemi et al., 2016; Liu and Jiang, 2006; Ma et al., 2007).

Table 2
Geotechnical properties of the soil.

Layer	Soil Type	Unit Weight (kN/m³)	Specific Gravity, Gs	Water Content (%)	Void Ratio	Coefficient of Lateral Pressure, K_0	Standard Penetration Test, N	Compression Modulus, E_s (MPa)	Shear Strength Parameters	
									c (kPa)	φ(°)
A	Miscellaneous fill	19.3	2.72	32.6	0.87	0.42	8	4.16	26	25.3
B	Muddy silty clay	17.0	2.68	41.9	1.17	0.50	3	3.15	27	15.2
C_1	Silty clay	19.4	2.68	26.5	0.75	0.37	12	12.49	17	32.2
C_2	Silty fine sand	19.4	2.72	25.3	0.74	0.35	28	13.35	15	32.7
D	Gravel sand	20.0	2.73	25.8	>0.57	0.25	96	18.07	0	45
E	Silty fine sand	19.3	2.72	24.7	0.74	0.35	42	15.10	6	33
F	Mudstone	21.4	2.77	15.7	--	0.53	--	--	100	44.9

The pits were constructed by the open-excavation method. The center of the pits is excavated to a maximum depth of 27 m, which gradually decreases outwards. The soil layers involved in the excavation depth include A, B, C_1, and C_2. Layer A is prone to collapse during excavation. The muddy soil of layer B is soft and of uneven thickness; it, and the fine sands of layers C_1 and C_2 in the middle of the excavated depth, exhibits large variations in lithology and compressibility. The bottom of the foundation pit is located in layer B, which must be reinforced with a mixing pile because of its poor stability. Furthermore, several laboratory and in situ test results indicate that layer B exhibits significant rheological properties and is thixotropic. Under the action of various loads during construction, it is prone to slow flow deformation. In the case of dynamic loads in particular, liquefaction, suspension flow, and subsidence are highly probable. However, most of the foundation pits in the project area are located in layers C_1 and C_2 (slightly dense and fine sand), which belong to the liquefied soil layer below groundwater level. When the above layers are selected as the foundation, the layer can be reinforced with anti-floating measurements. Beneath the foundation pit, layers D(coarse sand)and E(gravel) have abundant groundwater and a confined aquifer, which ensure a close hydraulic relationship between the C_1 and C_2 aquifers. The project area is close to the Yangtze River, and is located in an area with high-level groundwater that contains a diving aquifer and a multi-layered confined aquifer. Precipitation must be carried out for the mineral-rich groundwater. However, a large reduction in groundwater level can lead to seepage and stress changes within the soil, which in turn can lead to differences between the groundwater levels inside and outside the foundation pit. In addition, considerable water pressure is generated, and the water is prone to inrush, piping, and flowing soil, which can lead to the deformation and collapse of the side walls.

Another factor to consider is that the excavation of a foundation pit can destroy the natural stress state of soil. The soil that comprises the sides and bottom of the pit is unloading during the excavation of the pit. The soil layers comprise a binary structure: the upper part of soft soil, which is characterized by poor permeability, is regarded as a water-repellent layer; the lower part of fine sand is a confined aquifer. As the foundation pit is excavated within the soft soil and the top of the confined aquifer, a sudden collapse of the pit bottom can likely be triggered due to the low shear strength of the excavated sediments (soft soil and fine loose sand) (Meng et al., 2010; Wang et al., 2012; Wu et al., 2010). High water pressure within the

excavated sediments can also cause deformation of the supporting structure, leakage of any water-blocking curtain, and potential unpredictable damage to the surrounding environment.

2.3   Plane partition of foundation pit

The foundation pit of area B2–J1 has a maximum excavation depth of 27 m; the excavation width in the east–west direction is about 258 m, while its length in the north–south direction is 320m.Its deepest part is its junction with the cross-river tunnel. The foundation pit is also served by ramps (J, M, L, and I) that are connected to above-ground roads and adjacent buildings. Table 3 shows the strata that were excavated for the foundation pit, and the variation in the shape and depth of the associated tunnel and ramps.

Table 3
The characteristics of the foundation pit in area B2–J1.

Foundation pit	Depth (m)	Strata within excavation depth	Plane shape of the foundation pit
The main road	27	A, B, C_1, C_2	Straight line
Ramp M	17	A, B, C_1, C_2	Parabolic shape with large bending rate
Ramp J	16.3	A, B, C_1, C_2	Curve with small bending rate
Ramp L	13.5	A, B, C_1	Curve with small bending rate
Ramp I	12	A, B, C_1	Curve with small bending rate

District B2–J1 is divided into two areas (a NW area and a SE area) based on the excavation depth, the engineering geological conditions, and the surrounding environment of the different sections (Figure 1).The foundation pit of the NW area is close to the embankment of the Yangtze River, and it has a more complex shape and a greater excavation depth. As shown in Figure 2, the soil within the excavation depth is dominated by soft soil and fine sand, and the plastic zone and plastic flow deformation of the soil around the foundation pit are large, resulting in a high probability that the outer sides of the supporting structure will collapse into the pit and collect at its base, which in turn could lead to land subsidence on the outer sides of the supporting structure. The foundation pit of the SE area is further from the embankment; it has a curved shape, and its shallow depth means that soft soil dominates the excavation depth. Due to the thixotropic nature and flow deformation of soft soil, the stability of the supporting structure and the surrounding buildings must be ensured during excavation, and deformation must be controlled within a reasonable range.

The main features of the foundation pit are set out below.

(1) The shape of the foundation pit is abnormal. Because the underground interchange project is a large passage that connects above-ground and underground roads, the excavation area of the foundation pit must be large, the excavation depth must be different, and its shape is extremely irregular out of necessity. The phenomena of the "pit in pit" and the "pit leaning against pit" will therefore exist in the foundation pit (Figure 3). Furthermore, because the excavation of the foundation pit is undertaken in sections, progress within each section will differ. Additionally, the surrounding environment is complex, deformation control requirements are high, and the supporting structure design is demanding.

(2) Poor engineering geological conditions prevail. Most of the foundation pit is located in the soft soil layer. The foundation pit wall and the bottom of the pit are primarily composed of soft plastic-flow and plastic silty clay with very thick layers of mud, and fine sand. Consolidation settlement and creep are prone to occur during construction, and the bottom of the pit is prone to bulging deformation, which is extremely unfavorable to the stability of the supporting structure.
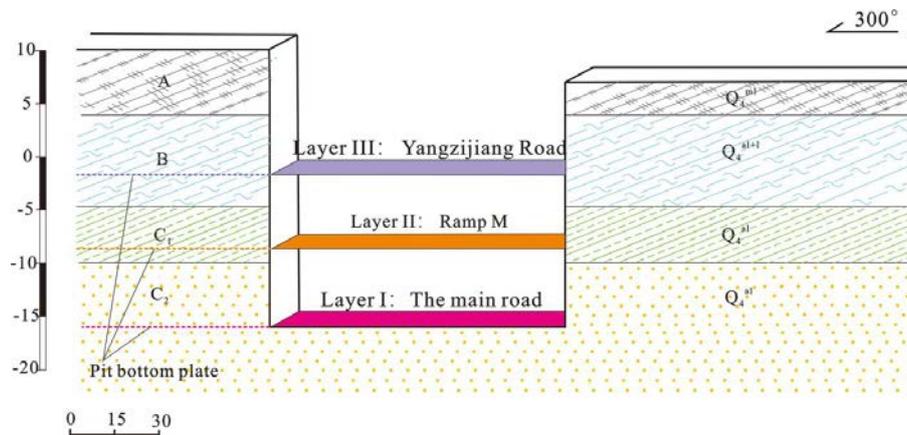
Fig. 3. Excavation cross-section of the "pit in the pit" of the underground interchange area.

(3) The hydrogeology is complex. The upper part of the pit exhibits pore diving, the water level is buried shallow, and the lower part has two layers of confined water; the top surface of the confined aquifer varies greatly to the extent that the confined aquifer can be exposed. Precipitation and depressurization measures must therefore be put in place to prevent a surge of water in the bottom of the pit.

2.4   Design of the supporting structure of the foundation pit

According to the situation of the foundation pit that has been previously introduced, the design of the supporting structure for the pit is similarly considered within the two areas: the NW area and the SE area. The pits were constructed by the open-excavation method. The construction of the supporting structure is layered, and was constructed during the excavation of the foundation pit. Excluding the underground continuous wall, the remaining structure is the retaining structure when the foundation pit is excavated, and does not participate in the main structure stress during the use phase. The control requirements of foundation pit deformation are as follows: the maximum horizontal displacement of the retaining wall is ≤3 ‰H (H is the depth of the pits), and the maximum settlement outside of the pit is 2.5‰H. Before the foundation pit is excavated, the water level of the foundation pit is reduced to 1 m below the excavation surface.

2.5   Design of the supporting structure in the NW area

The engineering geological conditions of the NW area are more complex than those of the SE area, and its underground structure is unusual. The site terrain is undulating, and the height difference is about 4–5m. The affected soil layer is primarily filled with muddy silty soil. Additionally, the groundwater is unconfined groundwater, and its level varies considerably. During the dry season (which was when the actual transportation hub was constructed), the groundwater is deeply buried. The north side of the foundation pit is adjacent to the Yangtze River embankment, which is a soil embankment (the elevation of its top is 11–12m, and the elevation of its foot is 8–9m). The embankment top is a cement road (width6m). The embankment contains a large amount of construction waste and soil filling that has built up over many years. After years of compaction, the strength of the soil layer is high. There is a retaining wall near the river that is clad in stone to protect the shore. The deepest part of the foundation pit in the NW area is 27m, and the "pit in pit" is the focus and the reason why the support design is difficult (Figure 3). Considering the engineering geological and surrounding conditions of the foundation pit, we divided the supporting excavation of the foundation pit in the NW area into two phases. In the first phase, the uppermost layer III of the foundation pit is excavated in stages, and the basin is excavated to a design elevation of -0.4 m. To ensure

safety and to control the deformation of the embankment, slope protection is carried out by using a supporting structure of lattice beam (beam) and a spray anchor within the embankment. In the second phase, the supporting structures of layers I and II are carried out. To ensure the stability of the embankment and other foundation pits, the foundation pit is supported by an underground continuous wall and internal supports (Figure 4). In addition, soil layer B is soft soil, the thickness of which varies considerably, but it remains relatively thick despite some excavation within the layer; in other words, although part of it is excavated, it is still very thick. Additionally, in order to ensure the stability of the slope after grading, it is necessary to use a three-axis cement mixing pile for reinforcement. Moreover, concrete C_{20}cushion (thickness 20cm) is set at the bottom of foundation pit (Figure 4). The pit is surrounded by an underground continuous wall (thickness1m; embedded depth 51.5m) that enters the bedrock.
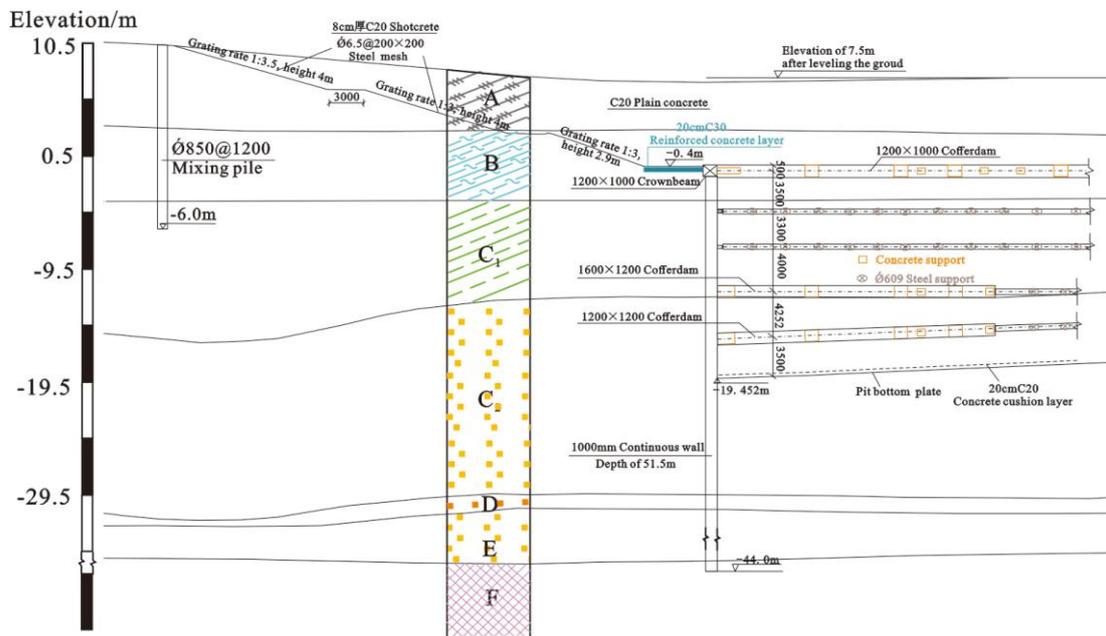
Fig. 4. Schematic diagram of the supporting structure in NW area.
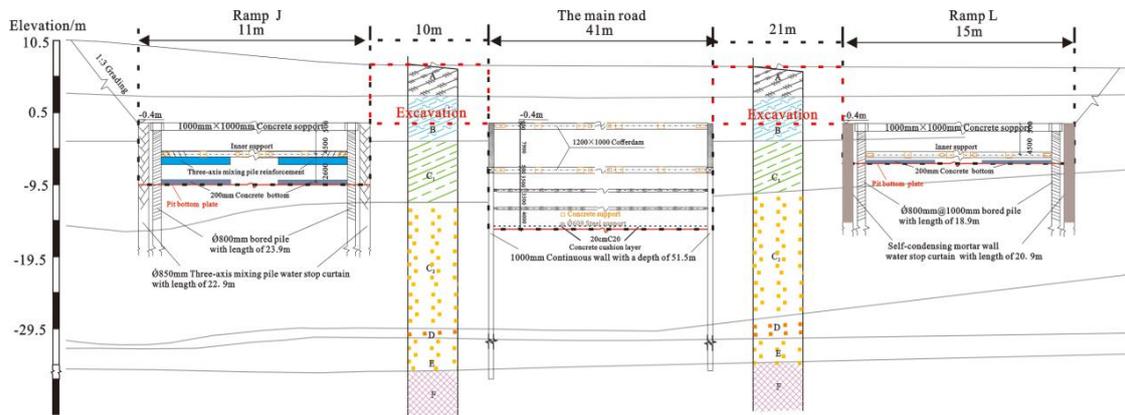
Fig. 5. Schematic diagram of the supporting structure in the SE area.

2.6   Design of the supporting structure in the SE area

The foundation pit of the SE area is further away from Yangtze River embankment than is the foundation pit of the NW area. As is illustrated in Figure 1, the foundation pit in this area presents a very obvious "pit leaning against pit" state (Ramp J–the main road–Ramp L). The

foundation pit shape of Ramp J in the NW area is unusual in that it resembles a parabola, and it is difficult for the underground continuous wall to meet the requirements of its shape. After grading, the depth of the foundation pit is about 9–11m, and the soil layer in the excavation depth is primarily layer B silt soil and layer C_1 silt. The thickness of the layer B silt soil is 4m, and its engineering properties are poor, while layer C is a confined aquifer. The west side of the foundation pit is adjacent to International Style Street.

(a) Model of the NW area.　　　　　(b) Model of the E area.
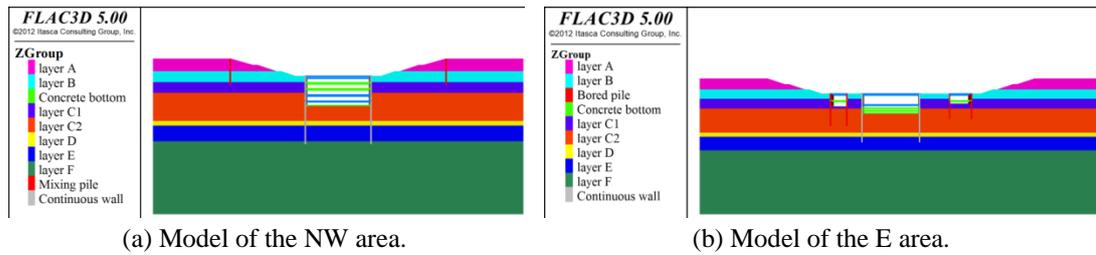
Fig. 6. Simplified model of the pits in district B2-J1.

(a) Contour of X-displacement.　　　　　(b) Contour of Z-displacement.
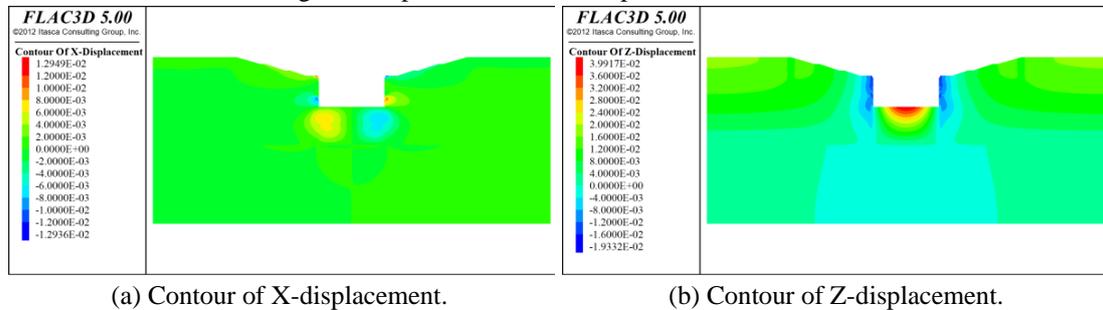
Fig. 7. Contour of displacement in the NW area.

(a) Contour of X-displacement.　　　　　(b) Contour of Z-displacement.
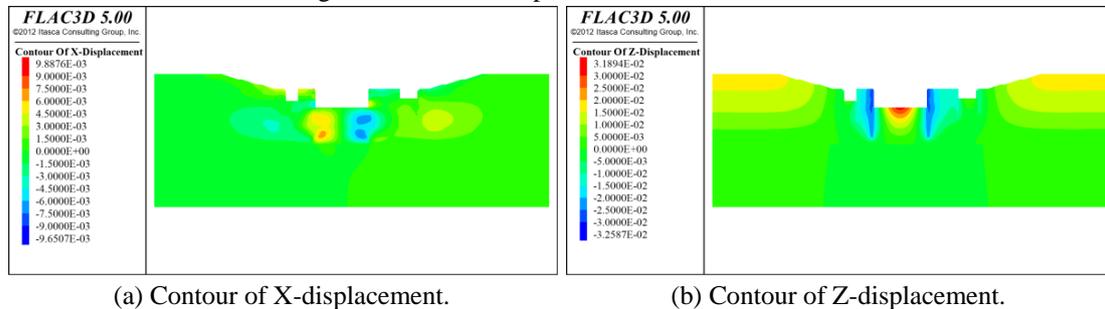
Fig. 8. Contour of displacement in the SE area.

The surrounding environment places high requirements on the engineering to prevent deformation, and the pile foundation-bearing layer is therefore deep. In addition, the joint between Ramp J and the main road must accommodate the unusual shape of the foundation pit while also fulfilling safety and constructional requirements. Therefore, a three-axis mixing pile water-stop curtain is designed outside the foundation pit. Not only does this curtain ensure the safety of the foundation pit and of International Style Street, but it also prevents groundwater leakage. The supporting method adopts both a bored pile and inner supports (Figure 5).The length of the three-axis mixing pile is 22.9m, and the length of the bored pile is 23.9m. To ensure the stability of the foundation pit, a 200 mm plain mat is placed in the base of the excavation. Layer C_1 is slightly dense silt, which belongs to the liquefied soil layer. Therefore, the three-axis mixing pile reinforcement must extend 2m below layer $C_1$and provide support for the grid-shaped underground continuous wall at the junction with the main road. The foundation pit of the main road is similar to that of the NW area in that, because the upper portion is shallow, the design of the pit can take advantage of the supporting structure on both sides. The lower part of the pit adopts the supporting method of

both an underground continuous wall and inner supports. The foundation pit of Ramp L is adjacent to the Youth Olympics Center and numerous other buildings. The depth of the pit is shallow, and it has a curved shape. The stratum within the excavation area is dominated by soil with mud. The situation is further complicated because the foundation pits for the Youth Olympics Center are still under construction, and to ensure their stability, a self-condensing mortar wall (depth of 20.9m) is used to reinforce the side near the Youth Olympic Center. The foundation pit is shallow and can be supported by a bored pile and inner support.

3.   Discussion

FLAC3D software was used to simulate the support effect and verify the effect of the support design, which considers the stratification of the soil layer, the block excavation, and the interaction between the soil and structure. The model is provided in Figure 6 (NW area:237m × 10m × 100m; SE area: 294m × 10m × 100m).The soil and support structure are subdivided into a grid consisting of a finite number of grid points. The steel support and the concrete support are simulated by a space beam element composed of a plurality of two-node beam structural units, using fixed boundary conditions and surrounded by external methods. The bottom is the vertical constraint to the displacement limit, the upper surface is the free surface, and the constitutive model is the Mohr-Coulomb model. The parameters of each soil layer and the supporting material parameters are provided in Table 2, and the simulation results are provided in Figures 7 and 8. It can be seen from the simulation results that the support structure design of the foundation pit meets the requirements. We therefore conclude that this supporting scheme is successful and effective, and that during the excavation of the foundation pit, particular attention should be paid to drainage. The foundation pit is adjacent to the Yangtze River, and is ultra-deep. A combination of a depressurization well and a dewatering well is used for precipitation. Moreover, the drain and the collecting well of the pit should be set before further excavation is conducted. Our case study has illustrated the importance of carrying out a comprehensive analysis of the engineering geological conditions when designing supporting structures for deep foundation pits. Such analyses should take full account, and make use, of the characteristics of the geological body. Furthermore, ensuring that effective supporting methods are adopted will not only ensure the safety of foundation pit construction, but will also result in a significant reduction of engineering construction costs and shorten construction periods.

4.   Conclusion

In this paper, we have used the deep, large-scale, and unusually shaped foundation pit of the underground interchange project in Nanjing City near the Yangtze River as a case study. We have analyzed the engineering geological conditions of area B2–J1 within the city (which is the core of the project), and discussed the associated engineering challenges. The lithology and hydrogeology of the affected strata, and the characteristics of the underground engineering structures, have been used to provide the design of the supporting structures of the foundation pit. Our main points are summarized below.

An analysis of the geological conditions of a supporting structure for a large-scale, unusually shaped foundation pit is crucial, as it can reduce engineering construction costs and shorten the construction period while effectively ensuring construction safety. In the NW area in particular, the combination of deep groundwater, poorly graded soils, and the complexity of the underground structure means that geological disasters, such as from piping and drifting sand, are likely. To minimize this risk, it is proposed that the upper layer be excavated and dug out. This layer contains soil with poor properties, and once the soil load is removed, the active earth pressure of the entire field will be reduced. Furthermore, a supporting structure of lattice beam (beam) and spray anchor should be used to protect the slope. This method will

significantly reduce the overall excavation depth of an underground continuous wall, accelerate the construction period of a foundation pit, and solve the problem caused by an unusually shaped supporting structure. Due to the maximum excavation depth in the NW area, soil layers C_1 and C_2 are involved. The pressure head and the lateral pressure of the soil is considerable. However, lateral deformation and groundwater penetration will be controlled by the proposed supporting structure that combines the underground continuous wall, its inner supports, and the three-axis mixing pile bottom plate reinforcement. In the SE area, the foundation pits with different depths are combined with their different geological conditions, and the suitable supporting scheme for them is provided. Because the area of construction is within thick, soft soil, there exists pressurized water in its lower part that renders it necessary to deepen the water-stop curtain.

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