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Research Article

Design of the Supporting Structures for Large and Unusually Shaped Foundation Pit near the Yangtze River

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A large underground transportation hub is located on the west side of the Nanjing Youth Olympic Center, which is close to the embankment of the Yangtze River. The near-surface primarily comprises newly deposited soft soil of considerable thickness; the lower part is a riverbed-phase sandy soil containing two confined aquifers. The foundation pit requires deep excavation and has unusual shapes of "pit in pit" and "pit leaning pit." For the convenience and safety of excavation, the piezometric head of the upper confined aquifer, where the pit bottom is located, reached 1 m below the bottom plane through precipitation, while that of the lower confined aquifer also dewatered down to a safe water level to avoid an uplift problem. After considering the engineering geological conditions, 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) and proposed the support scheme correspondingly. The numerical simulation results and completed construction safely verified the feasibility of the support scheme.

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. Thick, loose sediments of Quaternary age are widely distributed across this area. Deep foundation pit engineering is mostly conducted in the soft soil of the Holocene [1–4]. 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 [5–7], while largely ignoring the rational use of geological conditions at the construction sites. 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 [8–11].

A deep foundation pit with complex geological conditions is located on the west side of the Nanjing Youth Olympic Center along the lower reaches of the Yangtze River. First, the engineering background, such as the geological conditions and evaluation of it, was described. Then, the foundation pit was partitioned to two areas. Furthermore, the layout of dewatering wells and supporting design were discussed. Finally, the effect of supporting structures was analyzed. The work presented in this paper provides 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 foundation pit we studied, located in district B2–J1, is the core of the project, which consisted four ramps (I, J, L, and M) and a main road connecting the cross-river tunnel. Ramp J, L, and

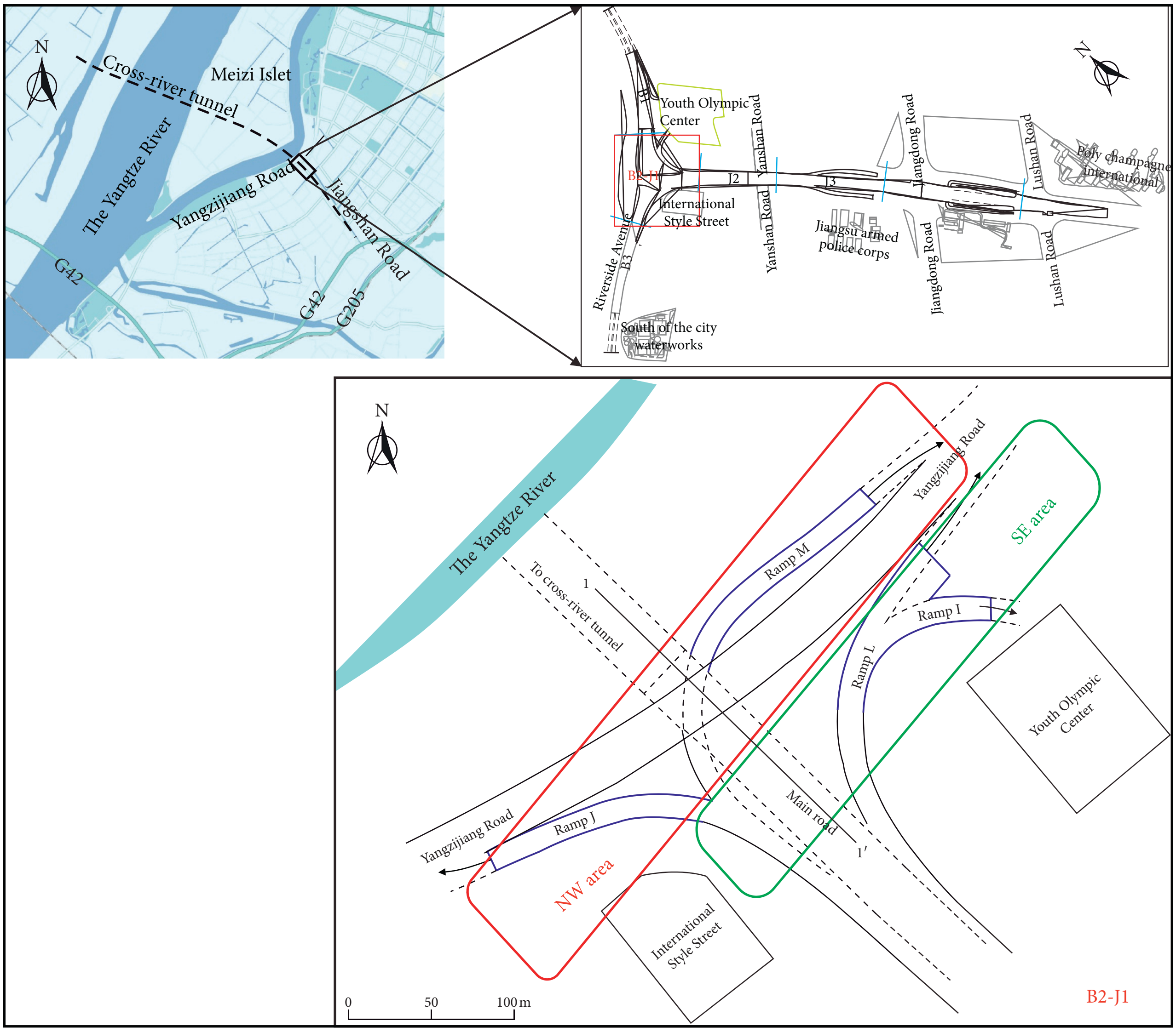


Figure 1: Location and plane layout of the foundation pit of B2-J1.

M connect Yangzijiang Road on the ground and ramp I connects the Youth Olympic Center, which will be constructed in the future. The foundation pit (depth 27 m, area *c.* 1.0 km^2) is adjacent to the Youth Olympic Center, International Style Street, and the Yangtze River dike. The shape of this foundation pit is irregular and the depth is not uniform. The bottom elevation of the main road foundation pit reduces gradually from the southeast to the northwest, ranging from −11.88 m to −19.45 m, downward toward the tunnel, while that of the four ramp pits increases from the main road to the ground, ranging from −11.46 m to −2.82 m, respectively.

2.1. Geological Conditions. The study site is located within the floodplain of the lower reaches of the Yangtze River. The ground elevation is 6.0–1.0 m, and the terrain is flat. The strata throughout the excavated depth can be divided into six layers. 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 to 10 m thick near the Yangtze River) is filling (layer A); the central part is dominated by alluvial gray silty clay, silt, and silty soil (layers B and C_1); the lower part is fine sand, medium-coarse sand, gravel sand, and mixed gravel and gravel (layers C_2, D, and E); finally, the bottom is strong-medium weathered mudstone (layer F). Among them, layer A is the unconfined aquifer with the water table of 6.5 m, overlying an aquiclude composed of layers B and C_1. Layers C_2, D, and E are the confined aquifer with a piezometric head of 5.5 m. Layer F contains mudstone, which can be regarded as an aquiclude.

2.2. Features of the Foundation Pit. The foundation pits were constructed by using the open-excavation method. The soil layers involved in the excavation depth include A, B, C_1, and C_2 (Figure 2). The main features of the foundation pit are as follows:

(1) The shape of the foundation pit is abnormal. Because the underground interchange project foundation pit

Table 1: Geotechnical properties of the soil.

Layer soil type		Geochronology	Unit weight (kN/m^3)	Specific gravity (Gs)	Water content (%)	Void ratio	Coefficient of lateral pressure (K_0)	Standard penetration Test (N)	Compression modulus, E_s (MPa)	Shear parameters, c (kPa)	Strength, φ (°)
A	Miscellaneous fill	Q_4^{ml}	19.3	2.72	32.6	0.87	0.42	8	4.16	26	25.3
B	Muddy silty clay	Q_4^{al+1}	17.0	2.68	41.9	1.17	0.50	3	3.15	27	15.2
C1	Silty clay	Q_4^{al}	19.4	2.68	26.5	0.75	0.37	12	12.49	17	32.2
C2	Silty fine sand	Q_4^{al}	19.4	2.72	25.3	0.74	0.35	28	13.35	15	32.7
D	Gravel sand	Q_4^{al+pl}	20.0	2.73	25.8	>0.57	0.25	96	18.07	0	45
E	Silty fine sand	Q_4^{al+pl}	19.3	2.72	24.7	0.74	0.35	42	15.10	6	33
F	Mudstone	K_2p	21.4	2.77	15.7		0.53			100	44.9

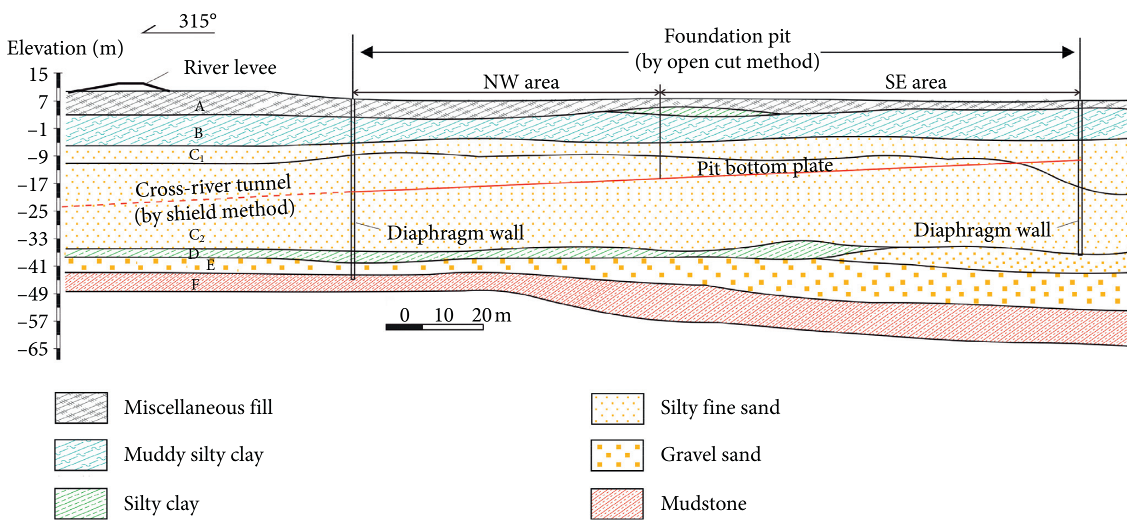


Figure 2: Profile of the strata and foundation pit in section 1-1′ shown in Figure 1.

needs to connect aboveground 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 "pit leaning against pit" will therefore exist in the foundation pit (Figure 3). Additionally, the surrounding environment is complex and deformation control requirements are high, which makes the supporting structure design very demanding.

(2) Poor engineering geological conditions prevail. Most of the foundation pit is located in the soft soil layer. The foundation pit is primarily composed of soft plastic-flow and plastic silty clay with very thick layers of mud. 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.

(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 pressurized water; the top surface of the confined aquifer varies greatly to the extent that the confined aquifer can be exposed.

2.3. Layout of the Drainage Wells. 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) [12–15]. 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 [16–18]. Therefore, we proposed the drainage wells as shown in Figure 4.

3. Design of the Supporting Structure of the Foundation Pit

3.1. Plane Partition of Foundation Pit. The foundation was 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 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. The foundation pit of the SE area is further from the

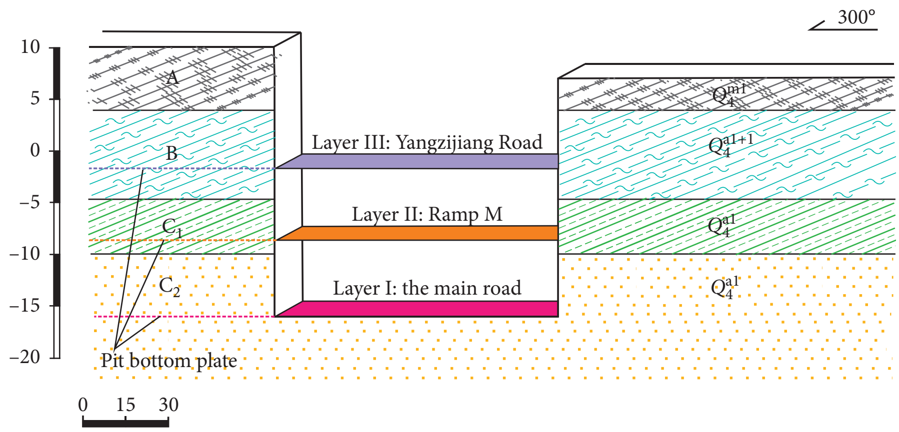


Figure 3: Excavation cross section of the "pit in pit" in the underground interchange area.

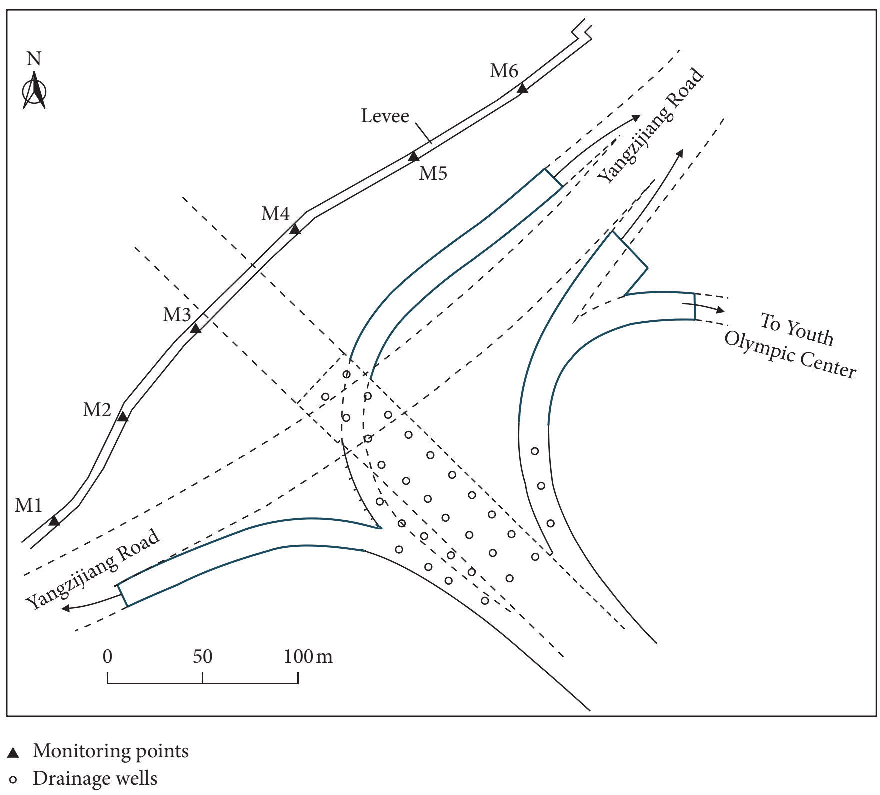


Figure 4: Layout of the drainage wells.

embankment; it has a curved shape, and its shallow depth means that soft soil dominates the excavation depth.

3.2. Design of the Supporting Structure. Because of 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 [19, 20]. The construction of the supporting structure is layered, and the structure 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. Before the foundation pit is excavated, the water level of the foundation pit is reduced to 1 m below the excavation surface.

3.2.1. 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 4–5 m. The affected soil layer is primarily filled with muddy silty soil. 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 11–12 m, and the elevation of its foot is 8–9 m). The embankment top is a cement road (width

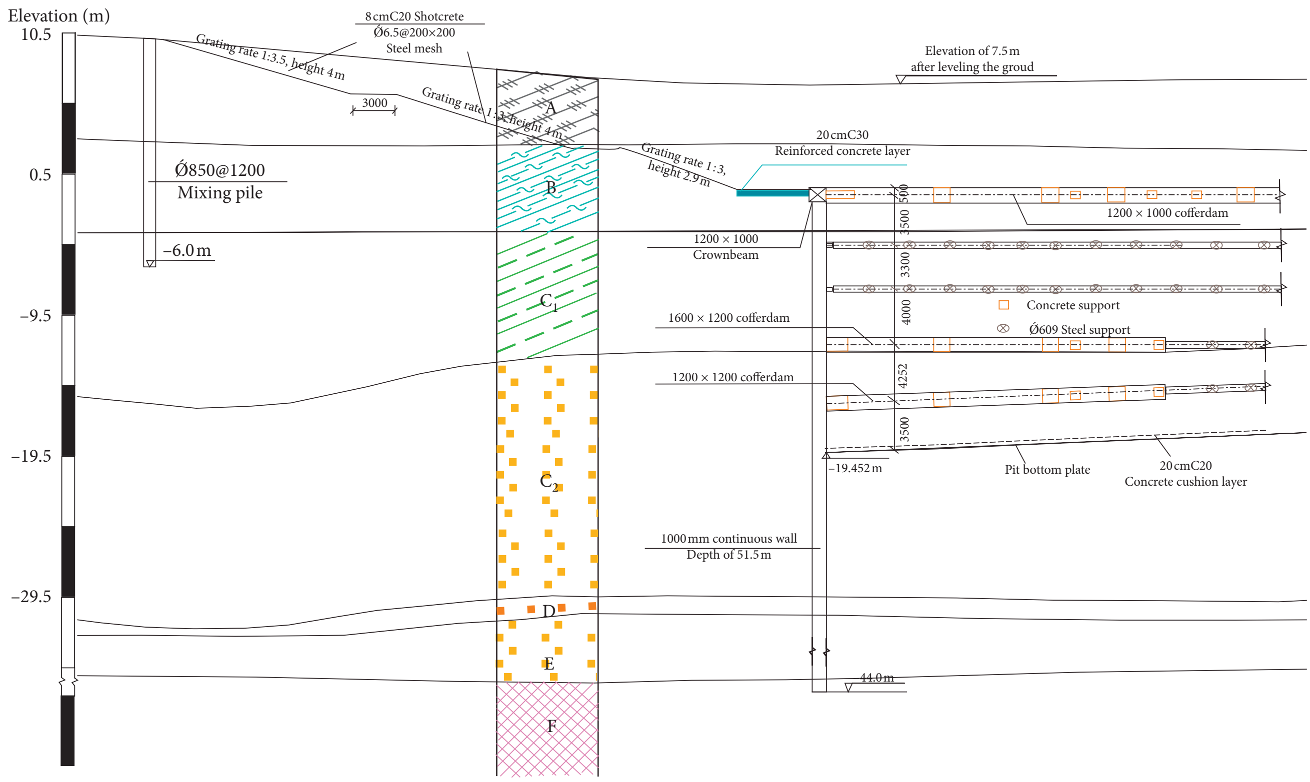


Figure 5: Schematic diagram of the supporting structure in the NW area.

6 m). 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 27 m, and the "pit in pit" is presented which leads to the difficulty of the support (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 5). In addition, soil layer B is soft soil, the thickness of which varies considerably; 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 (20 cm thickness) is set at the bottom of the foundation pit (Figure 4). The pit is surrounded by an underground continuous wall (thickness 1 m; embedded depth 51.5 m) that enters the bedrock.

3.2.2. The SE Area. The foundation pit of the SE area is further away from the Yangtze River embankment . As is illustrated in Figure 1, foundation pit in this area presents an 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. The soil layer in the excavation depth is primarily layer B silt soil and layer C_1 silt. The west side of the foundation pit is adjacent to International Style Street.

The surrounding environment places high requirements on the engineering to prevent deformation. 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 6). The length of the three-axis mixing pile is 22.9 m, and the length of the bored pile is 23.9 m. 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 2 m below layer C_1 and provide support for the grid-shaped underground continuous wall at the junction with the main road.

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 situation is further complicated because the foundation pits for the Youth

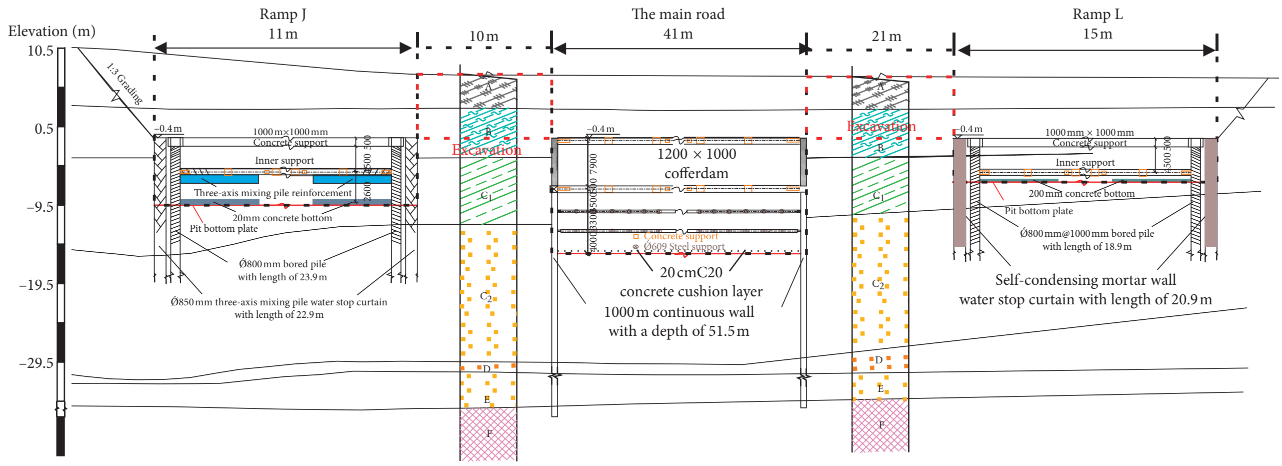


Figure 6: Schematic diagram of the supporting structure in the SE area.

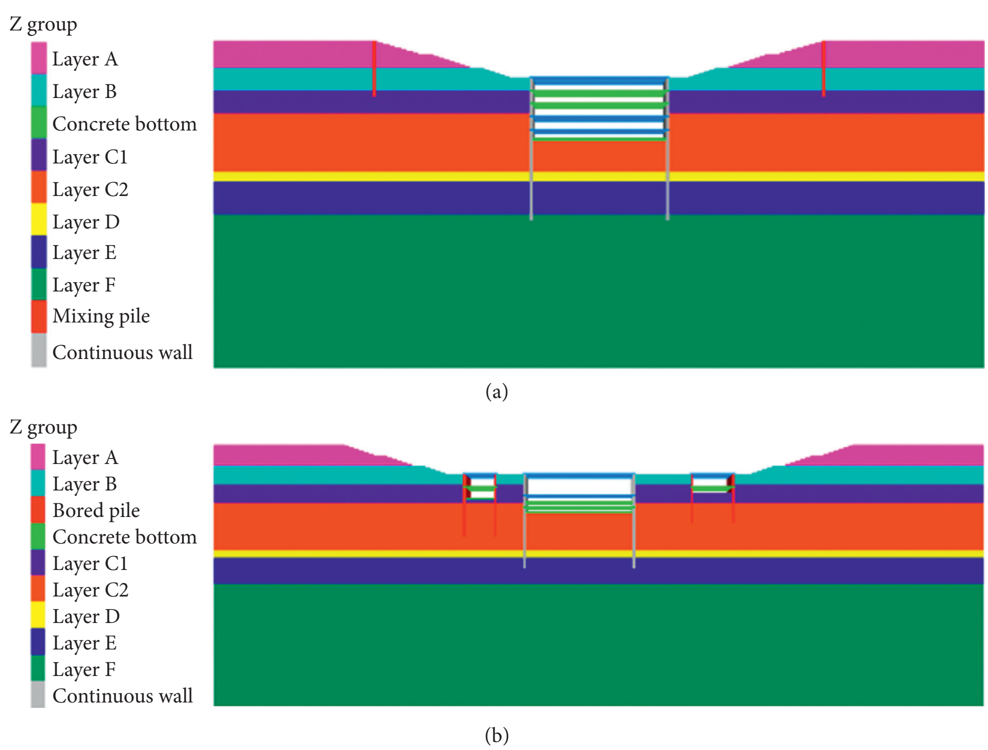


Figure 7: Simplified model of the pits in district B2-J1. (a) Model of the NW area. (b) Model of the SE area.

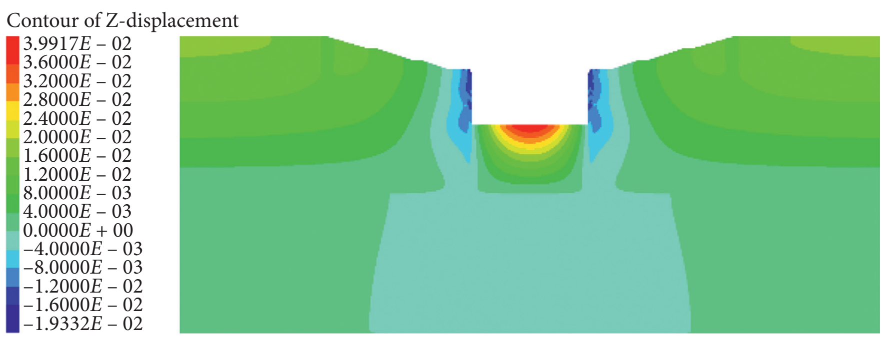
Olympics Center are still under construction, and to ensure their stability, a self-condensing mortar wall (depth of 20.9 m) is used to reinforce the side near the Youth Olympic Center.

4. Discussion

We used the FLAC3D simulation software which considers the stratification of the soil layer, the block excavation, and the interaction between the soil and structure to verify the effect of the support scheme. The model is provided in Figure 7 (NW area: 237 m × 10 m × 100 m; SE area: 294 m × 10 m × 100 m). 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 1, and the simulation results are provided in Figures 8 and 9.

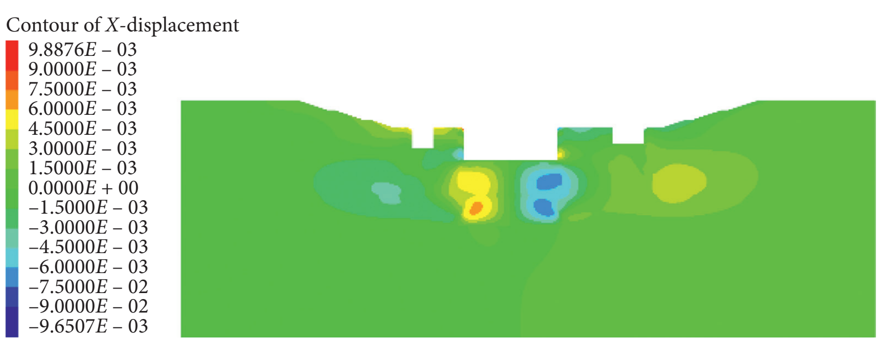
According to the design, the control requirements of foundation pit deformation are as follows: the maximum horizontal displacement is ≤3‰ H (H is the depth of the

(a)

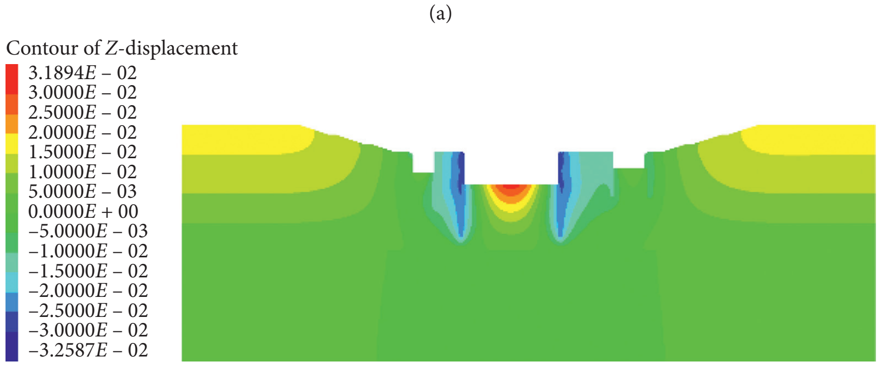


(b)

Figure 8: Contour of displacement in the NW area. (a) Contour of X-displacement. (b) Contour of Z-displacement.



(a)



(b)

Figure 9: Contour of displacement in the SE area. (a) Contour of X-displacement. (b) Contour of Z-displacement.

Table 2: The control requirements of foundation pit deformation.

Foundation pit	Depth (m)	Maximum horizontal displacement (m)	Maximum settlement (m)
The main road	27	0.081	0.0675
The ramps	15	0.045	0.0375

pits) and the maximum settlement outside of the pit is 2.5‰ H, as illustrated in Table 2.

In the NW area, the simulation result showed that the maximum horizontal displacement is 0.013 m and the maximum Z-displacement is 0.04 m. While in the SE area, the maximum horizontal displacement is 0.0099 m and the maximum Z-displacement is 0.032 m. It can be seen that the support structure design of the foundation pit meets the requirements. In addition, according to such support scheme, the foundation pit has been successfully excavated and the underground transportation hub has been successfully put into use, which also verified the feasibility of the support scheme.

5. Conclusion

In this paper, we have studied the supporting structure of a deep, large-scale, and unusually shaped foundation pit in Nanjing City near the Yangtze River, and drawn some conclusions as follows:

(1) An analysis of the geological conditions and features of deep, large-scale, and unusually shaped foundation pit is crucial, as it can reduce engineering construction costs and shorten the construction period while effectively ensuring construction safety.

(2) In the NW area, considering its surrounding conditions, we proposed a support scheme of combined excavation and underground continuous wall and internal supports and the three-axis mixing pile bottom plate reinforcement.

(3) 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 its necessary to deepen the water-stop curtain.

Data Availability

The data used to support the findings of this study are included within the article, which are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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