Study on Supporting Structure Design for Deep Foundation Pit in Water-rich Stratum

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Abstract. The construction and development of underground space are of great strategic significance for optimizing urban spatial layout and comprehensively utilizing land resources. With the rapid development of underground ring roads and public space, the construction of large-scale deep foundation pits in water-rich strata becomes increasingly tricky. How to analyze the stability and optimize the design of foundation pit supporting structures is a technical problem that has been tackled by scholars in recent years.Based on an underground space comprehensive development project, this paper will determine that the enclosure structure composed of 30m ultra-long borehole filling column, concrete support and steel pipe support has good applicability to the project through a comprehensive comparison of the existing foundation pit support technology.Meanwhile, the internal force, deformation, stability, and overturning resistance of the enclosure structure achieved by the supporting scheme under different construction conditions were checked and analyzed in detail. Then, the calculation results were comprehensively compared with the deformation control standards of supporting structures. Taking pile A as an example, the sliding safety factor, anti-overturning and anti-uplift stability coefficients when excavated to 0 .8m are 3.38, 1.87 and 3.33, respectively, which meet the theoretical value requirements.The calculation results show that the supporting structure of the project has good stability, which has a certain reference significance for the optimal design of supporting schemes in similar foundation pit projects.

Keywords: Water-rich strata; deep foundation pit; enclosure structure; force analysis

1 Introduction

The land demand contradiction between urban development and transportation becomes increasingly fierce. To alleviate the contradiction, China is entering a high-speed development period of underground space. The underground road system is playing an increasingly important role in improving urban traffic [1-2]. Foundation pit construction

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is an important task in the construction process of underground spaces and underground loops, and has significant safety risks. Especially for large-scale deep foundation pit construction in water rich strata, it is easy to induce collapse accidents due to the instability of groundwater and other adverse factors. The foundation pit support structure system is an important guarantee for ensuring construction safety, so how to optimize and verify the rationality of the design scheme is a key issue that needs to be paid attention to in the process of foundation pit construction structure design[3,4].

The optimization design method for large-scale deep foundation pit supporting structures has been deeply investigated by many scholars. Under the background of the ultradeep foundation pit in Fuzhou Metro, for instance, Jin et al. [5] simulated and analyzed the displacement, axial force, and ground settlement deformation of supporting structures through Midas software, and verified the safety of the supporting scheme through numerical checking and a comparative analysis with field measured data. Ye et al. [6] used the finite element simulation method to explore the influencing mechanism of supporting parameters on the deformation of a foundation pit, optimized the parameters of the supporting structure through simulation, and then obtained the optimal supporting scheme. Bao [7] also used the numerical simulation method to analyze the stress state of a foundation pit supporting structure, obtained the displacement and deformation of the pile foundation, and determined the effective supporting scheme; Ou et al. [8] established a numerical model of a double-row pile supporting structure in a deep foundation pit by ABAQUS finite element software, and analyzed the influence of supporting structure parameters such as row spacing, pile diameter, and stiffness on the supporting effect. According to the existing studies, it can be known that the numerical simulation method is often used to check the stability and safety of foundation pit supporting structures. the stress and deformation of supporting structures are mainly considered in the analysis, and the optimal design parameter combination is determined by adjusting various parameters.

However, evident individual differences are observed in the foundation pit supporting form and the structure type. In the determination of design parameters, it is necessary to consider the safety level of foundation pits, geological and hydrological conditions [9], groundwater hazards [10], and the influence of surrounding environments [11]. Especially in the construction of deep foundation pits in water-rich strata, the instability of groundwater will easily affect the overall safety and stability of foundation pits, making it necessary to check the design parameters of the foundation pit supporting scheme and structure in detail to ensure a good supporting effect. Taking an underground ring road and public space construction project in Guangdong as an example, the structural characteristics of the foundation pit and different supporting schemes were analyzed in detail in this study, and a supporting structure composed of 30 m super-long bored filling columns, concrete supporting, and steel pipe supporting was put forward. Finally, the supporting scheme was verified to be feasible and safe through the detailed calculation of the structural stress, deformation, overall stability, and overturning resistance achieved by this envelope system under different working conditions.

2 Project Profile

2.1 Basic information about the project and main foundation pit

The underground ring road of this project is about 1.43 km long, and the second phase of public underground space covers an area of about 49000 m2. The plan sketch of the project is shown in Figure 1(a), and the plan of the foundation pit range in Area 2 is shown in Figure 1(b). For the 2-1 section, the general excavation depth of the foundation pit is 9.691–12.928 m, and the local deep pit is 4.20 m in drawdown. The length of the foundation pit in this section is about 207.5 m, the width is 17.8–41 m, and the area is about 5870 m2. In the 2-2 section, the depth of the foundation pit is about 6.6–18 m, which can reach 24.6 m in some areas, and the length, width, and area of this section are about 355 m, 36.4–127.5 m, and 23813 m2. The safety level is II at the foundation pit part less than 15 m in depth and I at the foundation pit ≥ 15 m in depth.

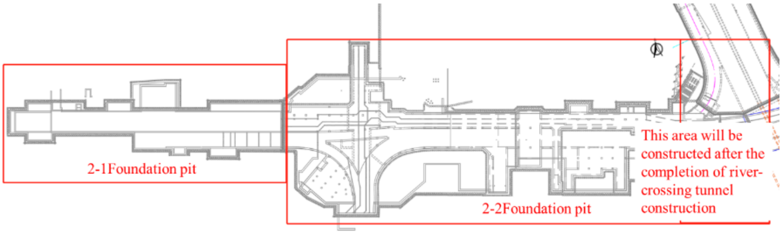


Fig. 1. Plan of Foundation Pit Range in This Project

2.2 Engineering geological conditions

This project is located in the plain area of the Pearl River Delta. The terrain of the site to be built is relatively flat as a whole, and the Quaternary overburden is relatively thick. The stratum structure of the project site is mainly composed of plain fill, mucky silty clay, mucky silty clay mixed with mealy sand, mucky sand, mucky silty clay, sandy clayey soil, completely weathered granite, and strongly weathered granite. The buried depth of the stable groundwater level at this site is 0.10–5.10 m, with an average buried depth of 2.58 m, and the corresponding elevation is 1.42–4.86 m, with an average elevation of 3.31 m. According to the collected hydrogeological data of adjacent projects and the drilling data at this stage, the groundwater distributed at the proposed site is mainly phreatic water in pores, confined water, and fissure water in rock strata.

2.3 Supporting structure design for the foundation pit

The supporting of large-scale deep foundation pits can be divided into two types—supporting type and reinforcement type—according to their action principle. The common supporting methods include sloping, retaining type, reverse building method, steel sheet pile, row pile, underground continuous wall, soil nail wall, and bolt supporting combined retaining wall [12]. Among them, the retaining structure is a common foundation pit supporting method [13], which can realize the free combination and collocation of supporting materials and give full play to the performance of materials, e.g., steel support is light, reusable, simple in construction, and can play a supporting role immediately after installation, while the layout and mode of concrete supporting are basically not limited by the plane shape of the foundation pit, accompanied by high rigidity and good integrity. Based on the structural characteristics of the foundation pit of this project, the applicable scenarios of various supporting schemes were comprehensively compared, and an envelope structure composed of 30 m super-long bored filling columns and combining concrete supporting with steel pipe supporting was preliminarily selected.

2.3.1 Main foundation pit supporting structure.

The main foundation pit supporting structure was composed of drilled grouting piles, with four kinds of pile diameters, i.e., 0.8, 1, 1.2, and 1.6 m, and the pile length ranged from 15 m to 37 m. The water-stopping curtain consisted of 850@600 triaxial mixing piles, which were sleeved into a ring, and the pile length varied from 22.7 m to 31 m. The supporting structure at the northeast corner of the foundation pit in Area 2 was the supporting structure during river-crossing tunnel construction, which was composed of φ1200 mm@1400 mm drilled grouting piles with a length of 30 m. The supporting structure of the partition wall between the foundation pit in Area 2 and Area 6 on the east side was a water-stopping curtain made of drilled grouting and triaxial mixing piles. The layout of foundation pit enclosure is shown in Figure 2.

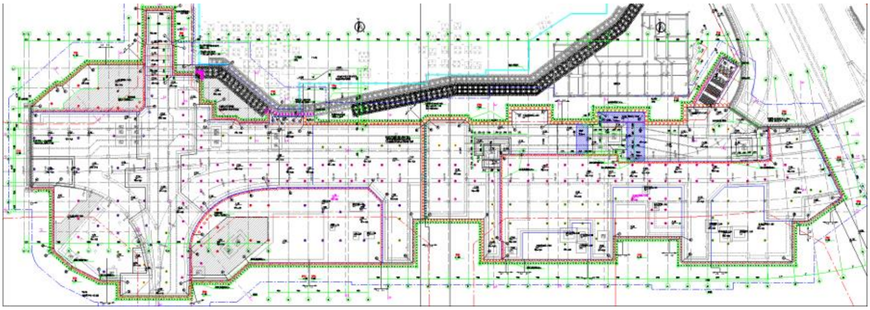


Fig. 2. Planar Graph of Foundation Pit Enclosure

2.3.2 2-1 and 2-2 foundation pit supporting structures.

A supporting system combining concrete supporting with steel pipe supporting was applied to a 2-1 foundation pit. The size of the first concrete crown beam was 1.2×0.8 m, the size of the concrete support was 0.8×0.8 m, and the spacing was 6–10.5 m; the 2nd to 4th concrete purlins were 1.3×0.9 m in size, 1×0.9 m in concrete support size, 7.5 m in spacing, and C30 in concrete strength. The model of steel purlins was duplex H700×300×13×24; the supporting steel pipes were φ800×16 in size, with a spacing of 3.04–4.37 m. 2-2 foundation pit was supported by concrete, with concrete crown beam sizes of 1.2×0.8, 1.4×0.8, 1.6×0.8, and 1.3×0.9 m, support sizes of 0.8×0.8 and 1×0.9

m, and a standard section spacing of 8 m; the concrete purlins were 1.3×0.9 m in size, the size of concrete support was 1×0.9 m, and the standard section spacing was 8 m; the concrete strength was C30. The supporting structure for the foundation pit was a water-stopping curtain composed of φ1200 mm@1400 mm drilled grouting piles + triaxial mixing piles. The schematic diagram of the elevation layout for the foundation pits is shown in Figure 3.

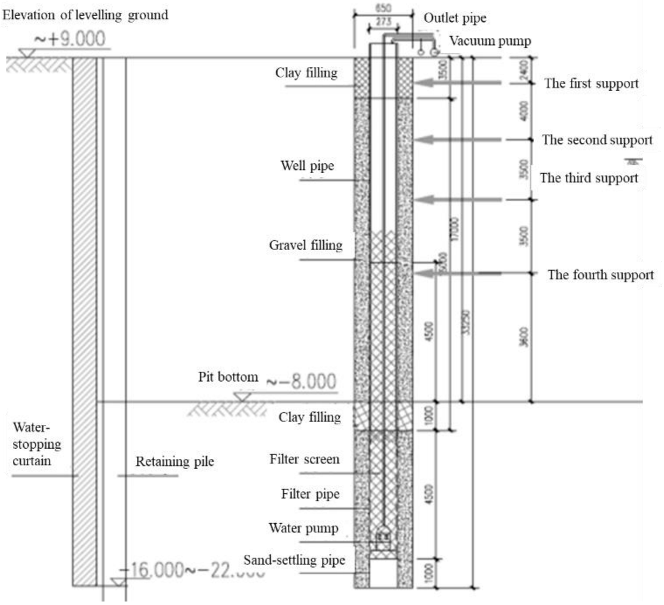


Fig. 3. Schematic Diagram of Elevation Layout for Foundation Pits

2.4 Supporting system construction process

For the 2-1 foundation pit, concrete support was combined with steel pipe support. Steel support played a dominant role except the concrete support as the first support. The construction process of the crown beam, waist beam, and concrete support is shown in Figure 4. Firstly, the preparation work before construction was carried out, and the crown beam and the supporting position were subjected to setting out. Secondly, the trench was excavated according to the setting-out position, and the pile head was broken. After cleaning up the operation site, the soil at the bottom of the support was compacted, and a cushion layer was laid at the supporting position. Then, reinforcing steel bars were tied, and the supporting-side die blocks were installed for the sake of reinforcement. The purlins and supports should be cast as a whole, and the super-long bracing bars (exceeding 100 m) should be cast in sections. After the concrete strength reached 2.5 MPa, the side formwork should be removed for curing, and the excavation should be continued to the top surface of the support after the design strength was reached.

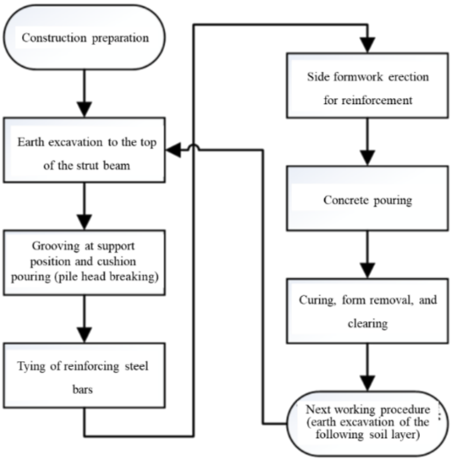


Fig. 4. Process Flowchart of Crown Beam, Wasit Beam, and Concrete Support Construction

The construction process of the steel support is displayed in Figure 5. Firstly, the base surface was treated, and the protrusions on the surface were cleared to ensure its flatness. Secondly, the purlin range and the axis position for support installation were marked, based on which the brackets and purlins were installed. Subsequently, the triangle brackets and steel purlins were installed and hoisted. Prestress was applied to the brackets and purlins by jacking with a jack, putting the iron wedge in the clearance, artificially hammering the triangular steel wedge, and loosening the jack. The corresponding steel support was removed for the following working procedure after the strength of the baseplate and middle plate reached the design strength.

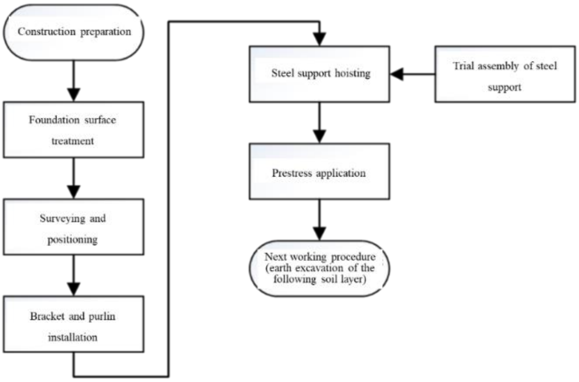


Fig. 5. Process Flowchart of Steel Support Construction

3 Checking Calculation of Support Design

3.1 Checking the calculation of internal force and deformation

The m-method based on the elastic foundation beam method can be used for the checking calculation of the internal force and deformation analysis of the supporting structure in the process of vertical excavation. The principle of this method is described as follows: The foundation soil is considered as the soil spring in the pit and the water and soil pressure outside the pit, and a finite element model of the soil spring and supporting structure is established [14]. The set elastic piles will be affected by the horizontal force H_0 and bending moment M_0 on the ground, and the pile body will flex and deform under the horizontal load $q(z)$. By decomposing the excavation and supporting the process of the foundation pit, the internal force and deformation under each working procedure can be calculated, and finally, the results of each working procedure can be enveloped to determine the overall internal force and deformation. According to the relevant technical regulations on foundation pit support, the deformation control of the foundation pit in this project was considered Grade II, and the corresponding importance coefficient γ_0 of the foundation pit's sidewall structure was set to 1.0. The shear index parameters of soil layers are listed in Table 1.

Table 1. Shear Index Parameters of Soil Layers

Soil layer No.	Namer of soil layer	Shear index			
		Direct quick shear		Consolidated quick shear	
		Internal friction angle φ (kPa)	Cohesion c (°)	Internal friction angle φ (kPa)	Cohesion c (°)
②$_{1-2}$	Mucky silty clay	5.5(4.5)	9.0(8.2)	9.8(8.4)	17.1(14.4)
②$_{1-2a}$	Mucky silty clay mixed with silt	6.0(5.5)	8.0(7.3)	10.7(9.5)	17.2(15.5)
②$_{1-22}$	Mucky sand	20	3	25	3
③$_3$	Mucky silty clay	4.7	8.6	11.0	19.5
⑤$_2$	Sandy clayey soil	18	22	20	28
⑦$_1$	Completely weathered granite	20	25	22	30
⑦$_2$	Strongly weathered granite			25	32

During the calculation through the m-method, the lateral displacement, turning angle, bending moment, and shear force at a depth of y can be respectively solved, in which the lateral displacement at a depth of y is solved as follows:

$$y = y_0 A_1 + \frac{\varphi_0}{\alpha} B_1 + \frac{M_0}{\alpha^2 EI} \cdot C_1 + \frac{H_0}{\alpha^3 EI} \cdot D_1 \tag{1}$$

The turning angle at the depth of y is:

$$\varphi = \alpha y_0 A_2 + \varphi_0 B_2 + \frac{M_0}{\alpha EI} \cdot C_2 + \frac{H_0}{\alpha^2 EI} \cdot D_2 \tag{2}$$

The bending moment at the depth of y is:

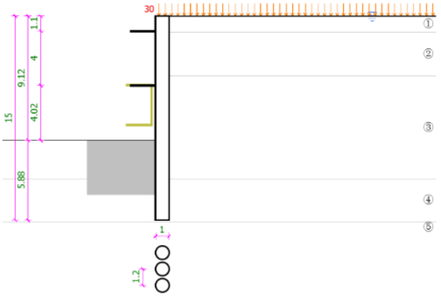
$$M = \alpha EI(\alpha y_0 A_3 + \varphi_0 B_3) + M_0 C_3 + \frac{H_0}{\alpha} D_3 \tag{3}$$

The shear force at the depth of y is:

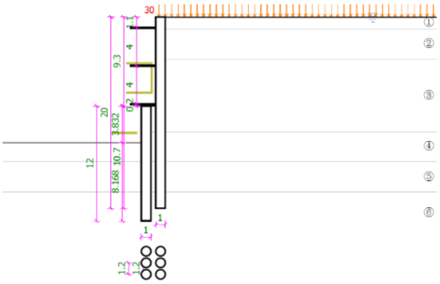
$$H = \alpha^2 EI(\alpha y_0 A_4 + \varphi_0 B_4) + \alpha M_0 C_4 + H_0 D_4 \tag{4}$$

where y_0 is the horizontal displacement on the group; H_0 and M_0 are the loads applied to the group; φ_0 represents the turning angle on the ground; A_1, A_2...; D_4 are a group of dimensionless constants, which can be acquired through table look-up.

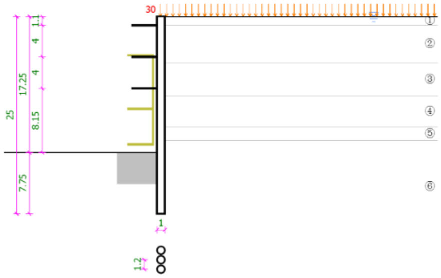
In this project, the foundation pit's drilled grouting piles were divided into nine types, and the construction conditions for each type are displayed in Figure 6.



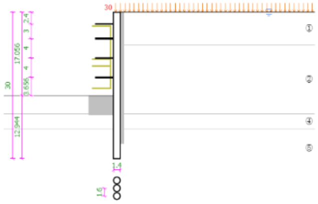
（a）Grouting pile +2 concrete supports (pile A)



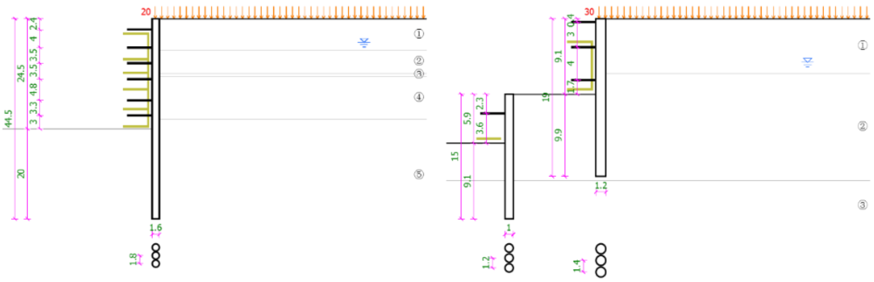
（b）Grouting pile +3 concrete supports (pile C/K)



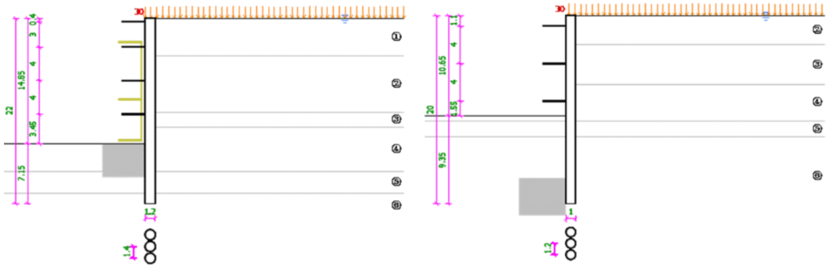
（c）Grouting pile +3 supports (pile D)



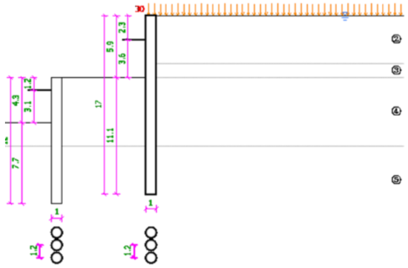
（d）Grouting pile +4 supports (pile E)



（e） Grouting pile +5 supports (pile F) （f） Grouting pile +3 supports (pile G)



（g） Grouting pile +3 supports (pile H) （h） Grouting pile +3 supports (pile J)



（i） Grouting pile +2 supports (pile M)

Fig. 6. Working Conditions of Drilled Grouting Piles

The excavation pressure distribution, pile displacement, bending moment, and shear force can be calculated by the m-method. With pile A as an example, the whole calculation process was introduced in detail. It was known that the design depth of the foundation pit where pile A was located was 9.12 m, the safety level was II, the structural importance coefficient γ_0 of the foundation pit side wall was 1.0, the ground elevation was 4.7 m, the working load at the ground was set to 30 kPa, the top elevation of cast-in-place piles was 4.7 m, the pile length was 15 m, and C30 concrete was adopted. The supporting structure of pile A was provided with two concrete supports, the supporting positions were 1.1 and 5.1 m, respectively, and the support stiffness was 100 MN/m2. The soil parameters at the location of pile A are shown in Table 2.

Table 2. Parameter Table of Soil Layers

No.	Rock and soil classification	Thickness (m)	Unit weight (kN/m^3)	c(kPa)	Φ (°)	Separate calculation Joint calculation	c' (kPa)	φ' (°)	M (MPa/m^2)
①	Fill	1.2	19	12	10	Joint calculation	12	10	2.2
②	Mucky silty clay	3.2	17.7	8	6	Joint calculation	8	6	0.92
③	Fine sand	7.6	17.5	3	20	Separate calculation	3	20	6.3
④	Mucky silty clay	3.1	17	9	5.5	Joint calculation	9	5.5	0.95
⑤	Rock (completely weathered)	3.2	19.6	30	22	Joint calculation	30	22	10.48
⑥	Rock (strongly weathered)	20	20	32	25	Joint calculation	32	25	13.2

During the checking calculation of the safety and stability of pile A, the simulation could be implemented under nine different working conditions, i.e., excavation to 0.8 m, support addition at 1.1 m, excavation to 5.2 m, support addition at 5.1 m, excavation to 9.12 m, support replacement at 8 m, support removal at 5.1 m, support replacement at 5.06 m, and support removal at 1.1 m. Through the above calculation model, the bearing reaction of soil layers, the pile displacement, the bending moment, and the shear force under different working conditions could be acquired. The counterforce of the two supports was 1350.1 and 1112.5 kN/m, respectively. The calculation results under the 9th working condition are displayed in Figure 7.

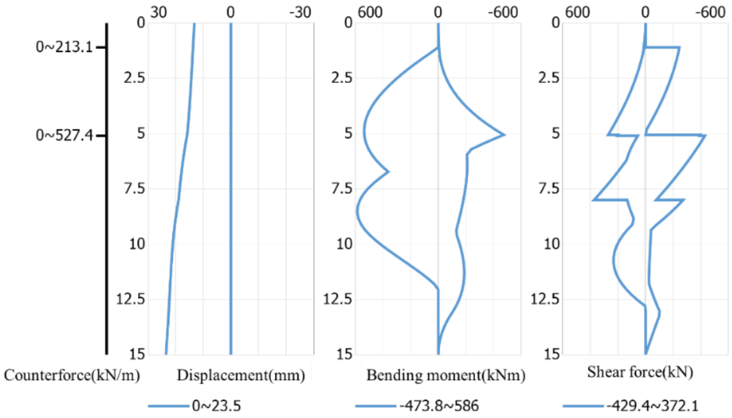


Fig. 7. Internal Force and Displacement under the 9th Working Condition

It could be known from the calculation results that after the support at 1.1 m was removed, the maximum displacement of the pile was 23.5 mm, the bending moment ranged from -473.8 kN/m to 586 kN/m, and the shear force ranged from -429.4 kN to 372.1 kN, thus meeting the design requirements.

3.2 Checking the calculation of foundation pit stability

The checking calculation of the stability of the foundation pit supporting structure is an essential content in the design process, mainly including overall stability, anti-overturning stability, and anti-upheaval stability. In this way, whether the structural design is reasonable and reliable can be judged, ensuring safety during foundation pit construction and its supporting process.

3.2.1 Overall stability

The overall stability of the foundation pit can be generally analyzed using the simple slice method of circular sliding, in which the simple Swedish slice method can be adopted. This method assumes that the sliding surface is an arc surface and ignores the force between slices. When calculating, the sliding moment generated by the shear force of soil slices to the center of the circle should be determined firstly:

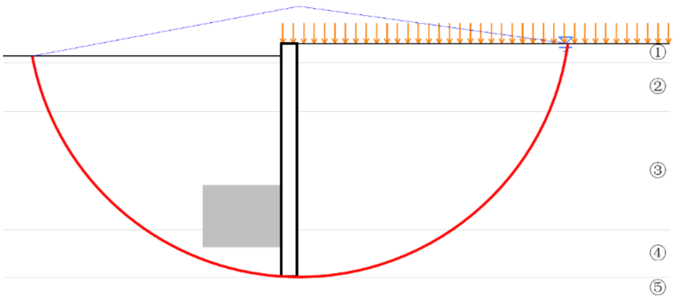
$$M_s = \sum_{i=1}^{n} T_i r = r \sum_{i=1}^{n} G_i \cdot sin\beta_i \tag{5}$$

Then, the anti-sliding moment of each soil slice induced by the shear strength of the bottom surface is calculated as follows:

$$K = \frac{M_r}{M_s} = \frac{r(tan\varphi \sum_{i=1}^{n} G_i \cdot cos\beta_i + c \sum_{i=1}^{n} \Delta l_i)}{r \sum_{i=1}^{n} G_i \cdot sin\beta_i} = \frac{tan\varphi \sum_{i=1}^{n} G_i \cdot cos\beta_i + c \sum_{i=1}^{n} \Delta l_i}{\sum_{i=1}^{n} G_i \cdot sin\beta_i} \tag{6}$$

where T_i is the tangential component force generated by gravity on the sliding surface; M_r represents the total anti-sliding moment of the circular sliding surface. In engineering, the safety factor is generally required to satisfy $K \geq 1.25 - 1.30$.

With pile A as an example, the sliding force, anti-sliding force, and corresponding sliding safety factor could be respectively calculated through the aforesaid method when the foundation pit was excavated to 0.8, 5.2, and 9.12 m, and the overall stability of the working condition could be judged through comparisons. Taking the working condition when the foundation pit was excavated to 5.2 m as an example, the checking calculation result of the overall stability is exhibited in Figure 8.



Providing that H=0.8 m, K=3.38, the theoretical value should reach 1.3

Fig. 8. Checking Calculation Results of Overall Stability for Pile A upon Foundation Pit Excavation to 0.8 m

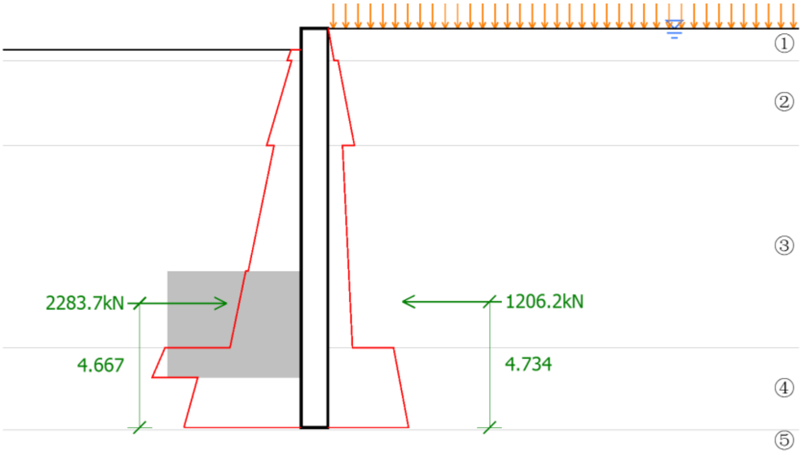
It could be known through the calculation results that during the checking calculation of the overall stability under this working condition, the calculated circular arc radius was 17.44 m, the sliding force generated by the foundation pit was 384.1 kN/m, and the anti-sliding force was 1299 kN/m, the sliding safety factor was 3.38, and the safety factor required by the relevant code was 1.3, that is, the stability of the foundation pit met the code requirements under this working condition.

3.2.2. Anti-overturning stability

During the checking calculation of the foundation pit's anti-overturning stability, it is generally assumed that the supporting structure rotates around the foretoe. The calculated anti-overturning safety factor of the foundation pit is as follows:

$$K_{s2} = M_p / M_a \tag{7}$$

where M_p is the anti-overturning moment of passive earth pressure and fulcrum force on the pile bottom, and M_a is the overturning moment of the main dynamic earth pressure on the pile bottom. Similarly, taking the working condition of pile A upon pit excavation to 0.8 m as an example, the checking calculation results for anti-overturning stability could be acquired. The checking calculation results of anti-overturning stability for Pile A upon foundation pit excavation to 0.8 meters are shown in Figure 9.



Providing that H=0.8 m (overturning), K=1.87, the theoretical value should reach 1.2

Fig. 9. Checking Calculation Results of Anti-overturning Stability for Pile A upon Foundation Pit Excavation to 0.8 m

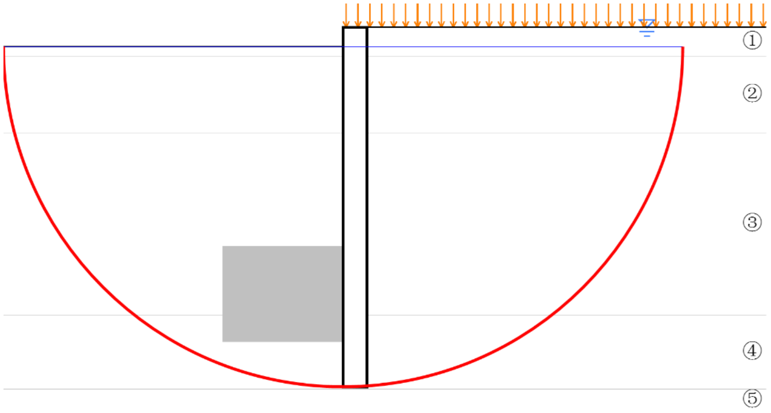
From the calculation results, providing that the foundation pit excavation was 0.8 m, the corresponding anti-overturning safety factor was 1.87, while the theoretical value should reach 1.2. This indicates that the anti-overturning stability of the foundation pit under this condition met the relevant requirements.

3.2.3 Anti-upheaval stability

Foundation pit excavation is the process of unloading the soil at the bottom of the foundation pit, which will cause the soil outside the support to move into the foundation pit due to the disappearance of the stress in the soil inside the support, thus leading to the upheaval of the soil at the bottom of the foundation pit. When the bottom of the foundation pit is soft soil, if the supporting structure is not deeply embedded, the upheaval of the soil at the bottom of the foundation pit will result in the instability of the foundation pit. Therefore, it is necessary to analyze the anti-upheaval stability of the soil at the bottom of the foundation pit with soft soil. The safety factor of the foundation bearing capacity for the supporting structure can be calculated by the following formula.

$$K_{wz} = \frac{\gamma_2 D N_q + c N_c}{\gamma_1 (h_d + h) + q} \tag{8}$$

In the above formula, $N_q = e^{\pi \tan\varphi} \tan^2(45^0 + \varphi/2), N_c = (N_q - 1)/\tan\varphi$, K_{wz} is the safety factor of the foundation bearing capacity for the supporting structure, γ_1 denotes the average unit weight of the soil outside the foundation pit, γ_2 represents the average unit weight of the soil inside the foundation pit, h stands for the buried depth of the supporting structure in the soil, h_d is the foundation pit excavation depth, and q is the ground load. Similarly, with the working condition of pile A upon excavation to 0.8 m as an example. The checking calculation results of anti-upheaval stability for Pile A upon foundation pit excavation to 0.8 meters are shown in Figure 10.



Providing that H=0.8 m, K=3.33, the theoretical value should reach 1.6

Fig. 10. Checking Calculation Results of Anti-upheaval Stability for Pile A upon Foundation Pit Excavation to 0.8 m

It could be known from the calculation results that when the foundation pit was excavated to 0.8 m, and the anti-upheaval safety factor of pile A was 3.33, the theoretical value should have reached 1.6, satisfying the requirement.

Similarly, the overall stability, anti-overturning stability, and anti-upheaval stability of other drilled grouting piles under different working conditions could be checked and analyzed respectively through the above method, so as to judge the safety state of the foundation pit during excavation, supporting, and removal, ensure the safety of the foundation pit by continuously optimizing the parameters, and avoid quality and safety accidents.

4 Conclusion

In this study, taking an actual project of an underground ring road and public space in Guangdong as an example, the existing technical supporting schemes for deep foundation pits were comprehensively compared and analyzed, and the foundation pit supporting form applicable to this project was determined based on the plane layout and structural characteristics of the foundation pit. Moreover, the reasonability of the design scheme was verified through the detailed checking calculation of stress-induced deformation and stability. Finally, the following conclusions were drawn:

- In this project, an envelope structure composed of 30 m super-long drilled grouting piles and combining concrete supporting with steel pipe supporting was adopted. Steel supporting was applicable to the part with an irregular plane shale, while concrete supporting could be used for the irregular part. Meanwhile, steel support, which could achieve a recycling effect, exhibited better applicability and economic efficiency;
- To determine the reasonability of the support design scheme, the stress-induced deformation, overall stability, anti-overturning stability, and anti-upheaval stability of the supporting structure under different construction conditions with different types of piles were subjected to detailed checking calculations and analysis. With pile A as an example, the sliding safety factor, anti-overturning stability, and anti-upheaval stability coefficient upon excavation to 0.8 m were 3.38, 1.87, and 3.33, respectively, which verified the reasonability of the design scheme.

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