World Journal of Engineering Research
ISSN: 2959-9873
DOI: https://doi.org/10.61784/wjer3004

RESEARCH ON MICRO-DISTURBANCE PRE-CONTROL TECHNOLOGY FOR SUBWAY SIDE FOUNDATION PIT

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Abstract: With the continuous deepening of the development and utilization of urban underground space, how to carry out deep foundation pit construction next to the subway while ensuring the safety of subway operation has become a major challenge in the engineering field. Taking the Hangzhou Convention and Exhibition Center project as an example, this study explores the safety control of long and deep foundation pit construction next to the subway through micro-disturbance pre-control technology under high-density rail transit environment. This paper first analyzes the geological conditions and construction environment of the project, then constructs an empirical prediction function that affects tunnel deformation, and proposes the foundation pit support control concept of "early isolation, strong block division, soft pit division". Based on three-dimensional finite element analysis, the effectiveness of the proposed technology is verified, providing a theoretical basis and practical guidance for similar projects.
Keywords: Subway side foundation pit; Micro-disturbance pre-control technology; Deformation control; Finite element analysis; Hangzhou convention and exhibition center

INTRODUCTION

The "14th Five-Year Plan" released by the state in 2021 proposes to build a "resilient city" and improve the city's ability to cope with risks. The efficient and reasonable development and utilization of underground space is an important part of the construction of a "resilient city". Therefore, in the next few years, the scale of underground space development and utilization will be further expanded, and it will show a larger, deeper and more three-dimensional development trend. In the process of underground space development and utilization, the high-density distribution of urban rail transit has led to the emergence of a large number of deep foundation pit projects close to the subway. The subway shield tunnel is extremely sensitive to changes in the surrounding environment. Improper construction may affect the structural safety and normal operation of subway facilities.

1 PROJECT OVERVIEW

The Hangzhou Convention and Exhibition Center project is located in Nanyang Street, Xiaoshan. There are scattered residential houses and industrial plants on the northwest side of the site, and the operating Metro Line 1 is under the middle of the site. The roads around the project include the Meishi Line, Nanfeng Line, Yannan Line, Gangcheng Avenue (main road) and the planned Zhemei Road Tunnel, with convenient transportation. The underground building area is 220,000 square meters. The project is divided into foundation pits on both sides of the north and south areas, with the shield tunnel of Metro Line 1 in operation (crossing from east to west). The minimum distance between the two foundation pits is 40.8 meters, and there is a connecting passage above the tunnel.

2 RESEARCH ON PRE-CONTROL INDICATORS OF LONG AND DEEP FOUNDATION PITS BESIDE OPERATING SUBWAYS

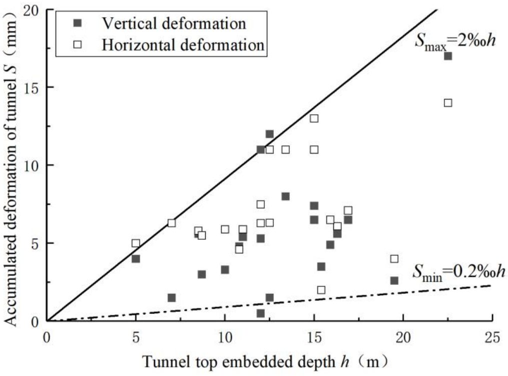
In terms of deformation control of existing tunnels, relevant specifications have been proposed one after another, such as: "Technical Specifications for Safety Protection of Urban Rail Transit Structures" (GJJ/T202-2013) proposed a warning value of 10mm and a control value of 20mm for horizontal and vertical displacements of tunnels; on the basis of national standards, Zhejiang Province's "Technical Regulations for Safety Protection of Urban Rail Transit Structures" (DB33/T1139-2017) divides the control indicators of horizontal and vertical displacements of shield tunnels into four levels, namely horizontal displacement: 5mm, 8mm, 14mm, 20mm; vertical displacement: 5mm, 10mm, 15mm, 20mm. Strict deformation control standards put forward higher technical requirements for the prediction of tunnel deformation before construction and the setting of corresponding protection measures. Cases of Excavation Projects beside Existing Tunnels can be seen in Table 1.

Table 1 Cases of Excavation Projects beside Existing Tunnels

No.	Project name	Adjacent to subway	Tunnel top burial depth h（m）	Pit depth H（m）	Pit length L（m）	Horizontal spacing l（m）	Tunnel maximum deformation S		Soil reinforcement measures in passive zone	Pit support
							Vertical deformation S_v（mm）	Horizontal deformation S_h（mm）		
1	A foundation pit in Shanghai[1]	Line 4	15	13	75	5.5	6.5	11	Three-axis cement mixing pile	Ground-anchored wall; row of piles
2	A deep foundation pit in Yangpu District, Shanghai[2]	Line 2	15.4	7.5	49	17	3.5	2	Three-axis cement mixing pile	-
3	A foundation pit in Shanghai[3]	A station	8.5	5.3	100	5.2	5.6	5.8	Jet grouting reinforcement	Ground-anchored wall; bored piles; SMW pile isolation piles
4	A deep foundation pit in Shanghai World Expo Green Valley[4]	Cross-river tunnel	16.3	9.6	200	6.7	5.6	6.1	-	Ground-anchored wall
5	New Jiahe Wanggang Station[5]	Existing Jiahe Wanggang Station	12	8.2	15	3.9	11	6.3	-	Ground-anchored wall
6	Shanghai Daning Commercial Center[6]	Line 1	15.9	8	30	7.9	4.9	6.5	Cement mixing pile	Gravity wall + row of piles
7	A foundation pit[7]	Line 1	13.4	6.4	100	3	8	11	Three-axis cement mixing pile	Ground-anchored wall; bored piles
8	A foundation pit in Nanjing Road, Shanghai[8]	Line 2	11	10	100	3.2	5.4	5.9	Jet grouting pile reinforcement	Ground-anchored wall
9	A foundation pit in Shanghai[9]	Line 1	19.5	13	50	6.5	2.6	4	Mixed pile skirt reinforcement	Ground-anchored wall
10	Jing'an Temple Station on Line 7[10]	Line 2	12	15.5	107	10	0.5	-	Jet grouting pile reinforcement	SMW piles; jet grouting piles
11	Plot 1788, Nanjing West Road[11]	Line 2	16.9	11.4	114	9.5	6.5	7.1	Three-axis cement mixing pile	Ground-anchored wall
12	Shanghai Huidefeng foundation pit[12]	Line 2	12.5	12.5	80	9	12	11	Cement mixing pile skirt full-height reinforcement	Ground-anchored wall; SMW piles
13	A foundation pit in Shanghai[13]	Line 1	7	10	42	15	1.5	6.3	Cement mixing pile full-height reinforcement	Ground-anchored wall
14	A	Line 2	10	16	130	17	3.3	5.9	-	Ground-anchor

	foundation pit in Hongqiao District, Shanghai[14]									ed wall
15	A foundation pit in Shanghai Plaza[15]	-	10.8	6	100	4.8	4.8	4.6	High-pressure jet grouting pile	Ground-anchored wall; bored piles
16	A foundation pit in Pudong District, Shanghai[16]	Line 4	8.7	19.5	87	3	3	5.5	-	Ground-anchored wall
17	A foundation pit in Huaihai Middle Road, Shanghai[17]	Line 1	29.1	24.3	211	5	12	9.5	SMW method pile full-height, strip drawing	Ground-anchored wall
18	A foundation pit in Suzhou[18]	Line 3	22.5	14	100	8.5	17	14	-	Ground-anchored wall; bored piles
19	A foundation pit in Suzhou[19]	Line 4	12.5	12.5	80	9	1.51	6.32	-	Ground-anchored wall
20	A foundation pit in Hangzhou[20]	-	15.4	7.5	49	17	-	2	Skirt strip drawing reinforcement; Mixed pile	Ground-anchored wall; bored piles
21	A foundation pit in Tianjin[21]	-	15	15	75	16.5	7.4	13	-	Ground-anchored wall; isolation piles; bored piles
22	A complex building in Guangzhou[22]	-	5	18	92	15	4	5	-	Ground-anchored wall
23	A foundation pit in Ningbo[23]	Line 1	12	11.4	120	16.4	5.3	7.5	Cement mixing pile	Drilled piles; retaining piles

Just as Figure 1-4 and Table 2, for the side foundation pit, the main factors affecting the cumulative deformation S of the tunnel include: tunnel top burial depth h, foundation pit depth H, foundation pit length L, and horizontal distance l between the foundation pit and the tunnel.



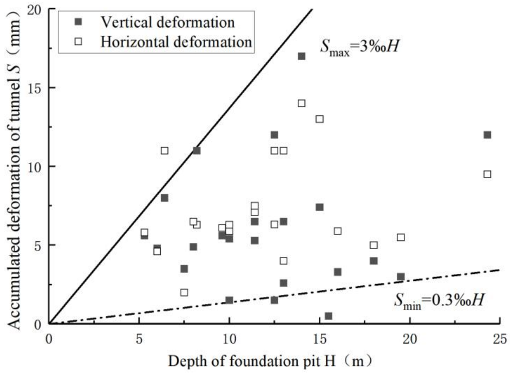
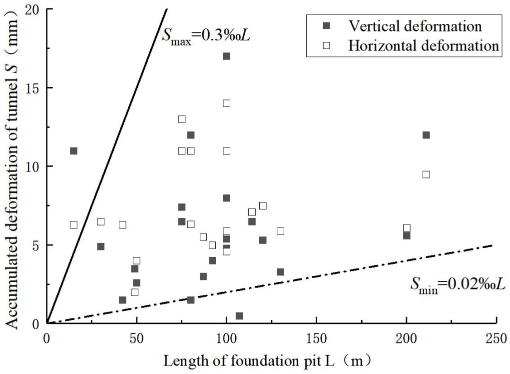


Figure 1 Relationship between Tunnel Cumulative Deformation and Tunnel Top Burial Depth *h*

Figure 2 Relationship between Tunnel Cumulative Deformation and Foundation Pit Excavation Depth *H*



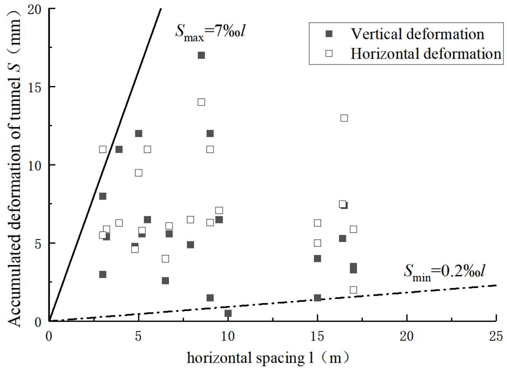


Figure 3 Relationship between Tunnel Cumulative Deformation and Foundation Pit Length *L*

Figure 4 Relationship between Tunnel Cumulative Deformation and Horizontal Spacing *l*

Table 2 Statistics of the Impact of Side Foundation Pits on Tunnel Structure

Proportional coefficient	Range of variation	Mean
(*S*/*h*)	0.2‰-2‰	1.1‰
(*S*/*H*)	0.3‰-3‰	1.65‰
(*S*/*L*)	0.02‰-0.3‰	0.16‰
(*S*/*l*)	0.2‰-7‰	3.6‰

Note: The order of magnitude of the foundation pit length *L* is 10 times that of the tunnel top burial depth *h*, foundation pit depth *H*, and horizontal spacing *l*. The order of magnitude of the four variables needs to be unified when comparing, that is, the average influence of the foundation pit length *L* is 1.6‰.

For the side foundation pit, the main factors affecting the cumulative deformation S of the tunnel structure are: tunnel top burial depth h, foundation pit depth H, foundation pit length L, and horizontal spacing l. The influence on the deformation of existing tunnels is from large to small in the order of horizontal spacing l> foundation pit depth H> foundation pit length L> tunnel top burial depth h.

Combining the above four influencing factors and a large number of existing tunnel side foundation pit engineering cases under sandy soil conditions, an empirical prediction function between the tunnel cumulative deformation Smax and the factor variables is established on this basis, assuming that g1 is a variable related to the foundation pit excavation form, and g2 is a variable related to the foundation pit construction protection measures.

$$S_{max}=g_1h(l+\lg L)/H+g_2 \quad (1)$$

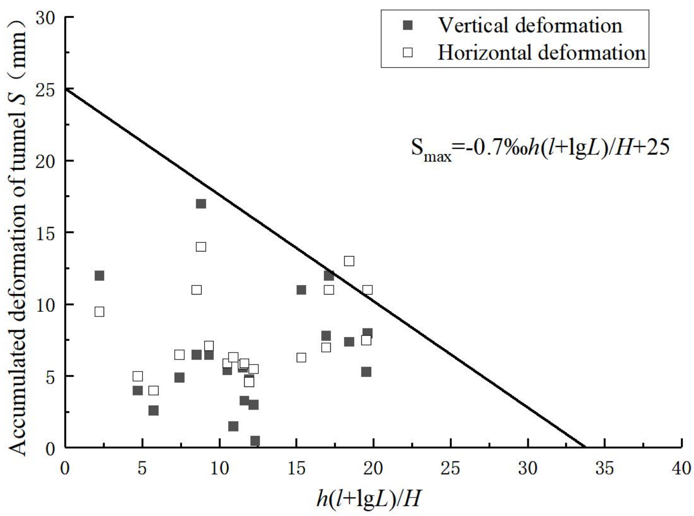


Figure 5 Tunnel Cumulative Deformation Empirical Prediction Function

As shown in Figure 5, the empirical prediction function is obtained: S_{max}=-0.7‰$h(l+\lg L)/H$+25. Among them, g_1 is the function slope, indicating the speed of tunnel cumulative deformation, g_1=-0.7‰; g_2 is the function intercept, indicating the degree of influence, g_2=25mm.

In Table 3, taking the sandy soil area as the background, the tunnel cumulative deformation is uniformly divided into four levels: 5mm, 10mm, 15mm and 20mm, and the corresponding side foundation pit related parameters are predicted respectively, as shown in the Table 3:

Table 3 Reference for Relative Position Indicators of Side Foundation Pit

Tunnel top burial depth *h* (m); foundation pit depth *H* (m); horizontal spacing *l* (m); foundation pit length *L* (m)				
Tunnel-pit vertical relative position *h*/*H*	Tunnel deformation limit 5mm	Tunnel deformation limit 10mm	Tunnel deformation limit 15mm	Tunnel deformation limit 20mm
≤0.5	*l*≥55m *L*≤50m	*l*≥40m *L*≤60m	*l*≥30m *L*≤80m	*l*≥15m *L*≤80m
≤1	*l*≥30m *L*≤40m	*l*≥20m *L*≤60m	*l*≥15m *L*≤60m	*l*≥10m *L*≤60m
≤2	*l*≥15m *L*≤30m	*l*≥10m *L*≤40m	*l*≥5m *L*≤50m	*l*≥3m *L*≤50m
≤3	*l*≥8m *L*≤20m	*l*≥6m *L*≤20m	*l*≥5m *L*≤20m	*l*≥2m *L*≤20m

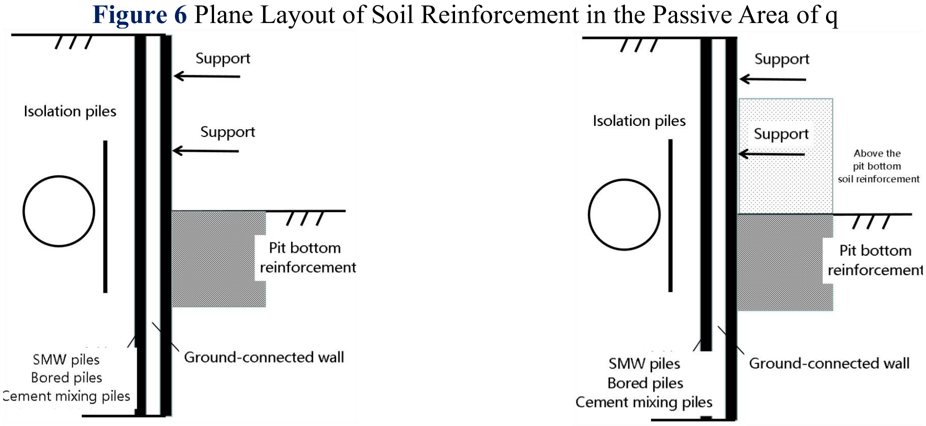
Based on the empirical conclusion of the relative position pre-control index of the side foundation pit, when the tunnel deformation limit is 15mm, the vertical relative position of the tunnel-pit h/H≤2, and the horizontal clear distance l≥5m. Combined with the calculation of the foundation pit working conditions, that is, the tunnel top burial depth h=11m, the foundation pit depth H=5.5m, the horizontal spacing l=6.5m, 11.7m, combined with the deformation experience prediction function (Smax=-0.7‰h(l+lgL)/H+25), it is recommended that the single foundation pit excavation length be controlled within 50m.

3 CONTROL CONCEPT OF LONG AND DEEP FOUNDATION PIT SUPPORT ON THE SIDE OF THE GROUND PROTECTION AREA

As shown in Figure 6 and 7, the construction control measures of the side foundation pit mainly include soil reinforcement in the passive area of the pit, foundation pit support structure and foundation pit excavation method. In the sandy soil area, the soil reinforcement is mainly cement soil mixing piles, and the plane layout of soil reinforcement includes full-chamber type, skirt type, and strip type. The vertical layout of passive zone soil reinforcement includes reinforcement below the pit bottom, and reinforcement below and above the pit bottom at the same time. Commonly used foundation pit support structures include ground-connected walls, bored piles, SMW piles, cement mixing piles, etc., and the impact of foundation pit construction on the surrounding environment is reduced by appropriately applying isolation piles. In addition, most excavation methods adopt layered and segmented excavation, and support while excavating.

(a) Full-Height Type (b) Skirt Type (c) Strip Type

Figure 6 Plane Layout of Soil Reinforcement in the Passive Area of q



(a) Reinforcement below the Pit Bottom (b) Simultaneous Reinforcement of the Soil at the Pit Bottom and above the Pit Bottom

Figure 7 Side Foundation Pit Support Structure Form

For the side foundation pit project within the protection area of the operating subway (within 50m), especially the sandy soil area where foundation pit precipitation is strictly prohibited, it is proposed to propose the foundation pit support control design concept of "early isolation, strong block, and soft pit". That is:

Early isolation: construct water-stop curtains as soon as possible on both sides of the operating subway, and it is

advisable to use retaining structure systems such as ground-connected walls and cast-in-place piles. The water-stop curtains should be continuously closed and the bottom should enter the weak permeable layer.
Strong block: The foundation pits on both sides of the operating subway should adopt a bored pile + mixing pile structure system with large overall stiffness for primary block division to strictly control the lateral displacement of the tunnel.
Soft pit division: Each block foundation pit should adopt a mixing pile retaining structure system with lower rigidity for secondary pit division, and supplemented by slope reduction, to improve the spatial combination effect of block foundation pit excavation.
Taking the foundation pit engineering of Hangzhou Convention and Exhibition Center project as the background, and based on the research conclusion of the relative position pre-control index of the side foundation pit, when the tunnel deformation limit is 15mm, the length of the small foundation pit is controlled within 50m.
TRD cement soil mixing wall + cast-in-place piles are used as water-stop curtains near the subway on the north side, and TRD plug-in steel cement soil mixing wall is used as water-stop curtains near the subway on the south side; the block foundation pit adopts mixing piles + bored piles double rows of strong enclosure; the single block foundation pit adopts double rows of cement mixing piles for further soft division. Based on the engineering background of the south and north area foundation pits with an east-west length of about 530m, the south side is divided into 8 blocks and 16 small foundation pits, and the north side is divided into 6 blocks and 12 small foundation pits.
Using three-dimensional finite element software, the impact of batch and block jump excavation of the side foundation pit on the adjacent tunnel is analyzed. Construction Conditions can be seen in Table 4 and Three-Dimensional Finite Element Model can be seen in Figure 8.

Table 4 Construction Conditions

Condition 1	earthwork excavation and construction of bottom plate, dismantling of supports (South I-5 area, South I-6 area, South I-7 area, South I-8 area, North I-1 area, North I-2 area, North I-3 area)
Condition 2	earthwork excavation and construction of bottom plate, dismantling of supports (Condition 1 top plate construction completed; South I-1 area, South I-2 area, South I-3 area, South I-4 area, North I-4 area, North I-5 area, North I-6 area and part of the II blocks on the north and south sides)

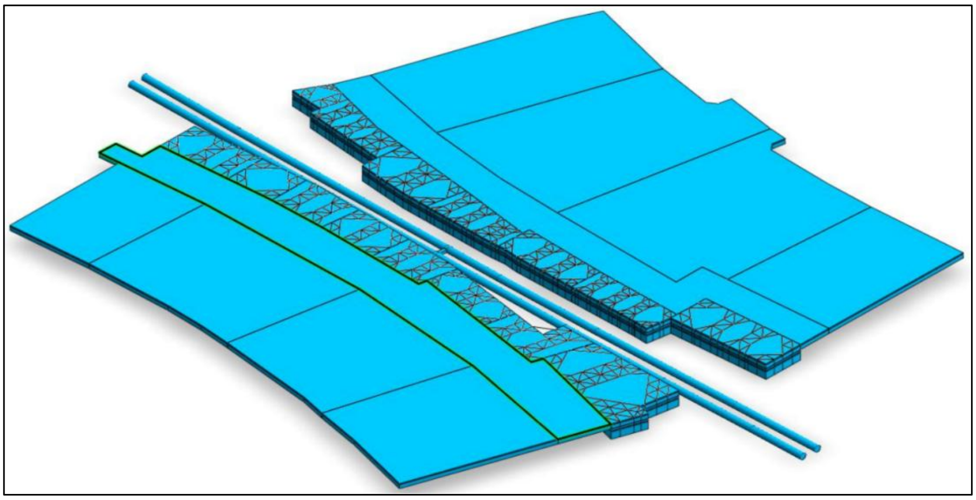
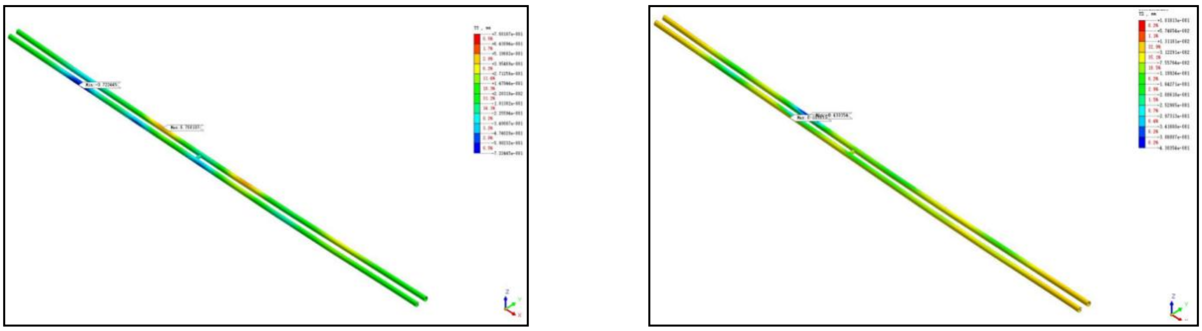


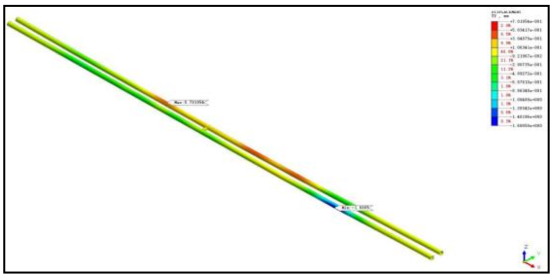
Figure 8 Three-Dimensional Finite Element Model

Just as Figure 9 and 10, comparative analysis of calculation results:

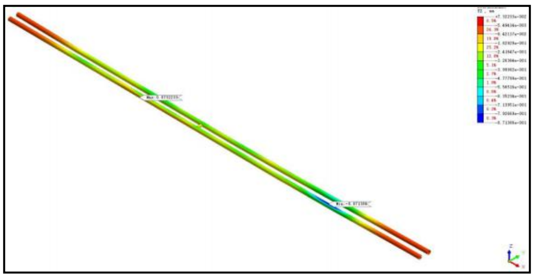


(a) Tunnel Horizontal Displacement (b) Tunnel Vertical Displacement

Figure 9 Condition 1: Earthwork Excavation and Construction of Bottom Plate, Dismantling of Supports



(a) Tunnel Horizontal Displacement



(b) Tunnel Vertical Displacement

Figure 10 Working Condition 2: Earthwork Excavation and Construction of Bottom Plate, Support Removal

The horizontal displacement of the tunnel caused by working condition 1: -0.72mm, and the vertical displacement: 0.43mm;

The horizontal displacement of the tunnel caused by working condition 2: earthwork excavation and construction of bottom plate, support removal: -1.68mm, and the vertical displacement: 0.87mm.

When the tunnel deformation limit is 15mm, the length of the small foundation pit is controlled within 50m, and combined with the foundation pit support control design concept of "early isolation, strong block, soft pit", the calculated horizontal and vertical displacements of the tunnel did not exceed the deformation limit, which further verified the rationality of the concept.

4 CONCLUSION

Taking the Hangzhou Convention and Exhibition Center project as an example, this study proposed a support control method based on micro-disturbance pre-control technology for the difficulties in the construction of long and deep foundation pits next to the operating subway. By constructing a deformation prediction function, a reasonable excavation length control standard is formulated, and the support design concept of "early isolation, strong block, soft pit" is proposed, and its effectiveness is verified by combining three-dimensional finite element analysis. The research results show that the pre-control technology can effectively control the disturbance of foundation pit construction to the subway tunnel and ensure the structural safety of subway operation. Future research can further optimize the pre-control model and apply and promote it in more practical projects.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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