Study on Construction and Disturbance Control Techniques for the Reconstruction and Expansion of Long-Term Operating Metro Stations

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Abstract. To ensure the safety of the long-operating metro stations during the reconstruction and expansion process, the control technique of station deformation was investigated by numerical simulation using the principle of displacement allocation. The percentage of stepwise settlement is 25.7%, 56.4% and 65.7%, 22.5% respectively, which is the main stage of construction deformation control; through the study of the impact of reinforcement measures on the station reconstruction and expansion process, expanding the scope of grouting and improving the parameters of the slurry have a poorer effect on the deformation control of the station, and the settlements of Line 3 and Line 2 are controlled within the safety threshold when using the bar reinforcement measures; the on-site monitoring results show that the displacement distribution principle better controls the structural settlement and deformation, and the monitoring indicators are all within the safety threshold. The results of the study can provide experience and reference for the construction process of similar long-term operation station reconstruction and expansion.

Keywords: Tunneling; Principles of displacement allocation; Construction impact control; Site monitoring.

1 Introduction

With the rapid development of urbanization in China, the construction of the metro in some cities has entered the stage of line extension and encryption, and in recent years the metro reconstruction and expansion projects in Xi'an, Guangzhou, Shanghai, Beijing, and other cities have been emerging [1-3]. However, due to the design and construction limitations of the metro lines or stations constructed in advance, the lack of reserved interchange space in existing stations, and the harsh conditions of the reconstruction and expansion construction have led to an increase in the construction difficulty of the new metro lines, which has brought higher challenges to the development and construction of urban metro [4, 5].

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At present, scholars and experts have conducted a large number of studies on the reconstruction and expansion of existing metro lines or stations, including: Qingfeng Liu et al used numerical simulation and on-site monitoring to explore the impact of new construction on existing lines and strata based on the project of Kunming Metro Line 4 Parallel Underpassing Line 2 [5]; Shutong Gao used numerical simulation to investigate the impact of late construction of a four-lane parallel tunnel on the pipe joints of the existing tunnel below, and proposed grouting reinforcement measures [6]; Qingguo Zhou proposed grouting reinforcement measures for the construction of shield tunnel in pebble layer for Line 5 of Chengdu Metro and studied the impact of grouting scope and grouting process on the construction [7]; Qingbao Zhang et al. proposed the principle of "Shield when you can" for the project of late line under the first operating station, and put forward the principle of "shield when you can" for the project of late line under the first operating station [8]. Wang Jun based on the Qing Hua Yuan Tunnel of the Beijing-Zhangjiakou high-speed rail analyzed the impact of shield tunnel construction on the construction disturbance of the near-connected bridges, and gave the construction disturbance control technology of "stratum reinforcement, barrier protection, and dynamic monitoring" [9]; Guangyao Cui et al based on a new interval tunnel group construction project of Beijing Metro Line 19, used FLAC3D to analyze the effect of pipe shed curtain pre-reinforcement measures, and optimized its construction method [10]; Lixin Wang et al [11] based on local on-site monitoring data, used BP neural network inversion and MIDAS GTS NX calculations to accurately predict the final settlement value of the roofing project across the underground tunnel construction. construction. In summary, the existing research mainly focuses on the construction disturbance law, structural deformation and impact, and construction impact control of the later reconstruction and expansion construction on the prior existing station or line, while there are fewer researches on the construction control technology for the construction control of the long-term service station's reserved engineering renovation and so on [12~14].

Relying on the reconstruction and expansion project of Dongsi Shitiao Station of Beijing Metro, based on the principle of dislocation distribution of the deformation of reconstruction and expansion of the existing station, numerical simulation was used to compare the construction control effect of expanding the grouting scope, improving the grouting slurry, and applying screw support, etc., to give the step-by-step settlement control standard of the construction stage of the PBA method, and combined with the on-site monitoring values for verification. The research results can provide a reference for the construction control of urban underground reconstruction and expansion projects.

2 Deformation Prediction of Existing Metro Station Renovation and Expansion

2.1 Principle of Shift Distribution

The principle of dislocation allocation believes that the surface settlement or structural deformation caused by underground engineering construction can be allocated to each control stage in construction, and through the settlement or deformation control in each construction stage, the deformation of surface or structure can be avoided from exceeding the limit, and the construction perturbation can be controlled in the safe range [15, 16]. The principle of displacement allocation principle is shown in Fig. 1.

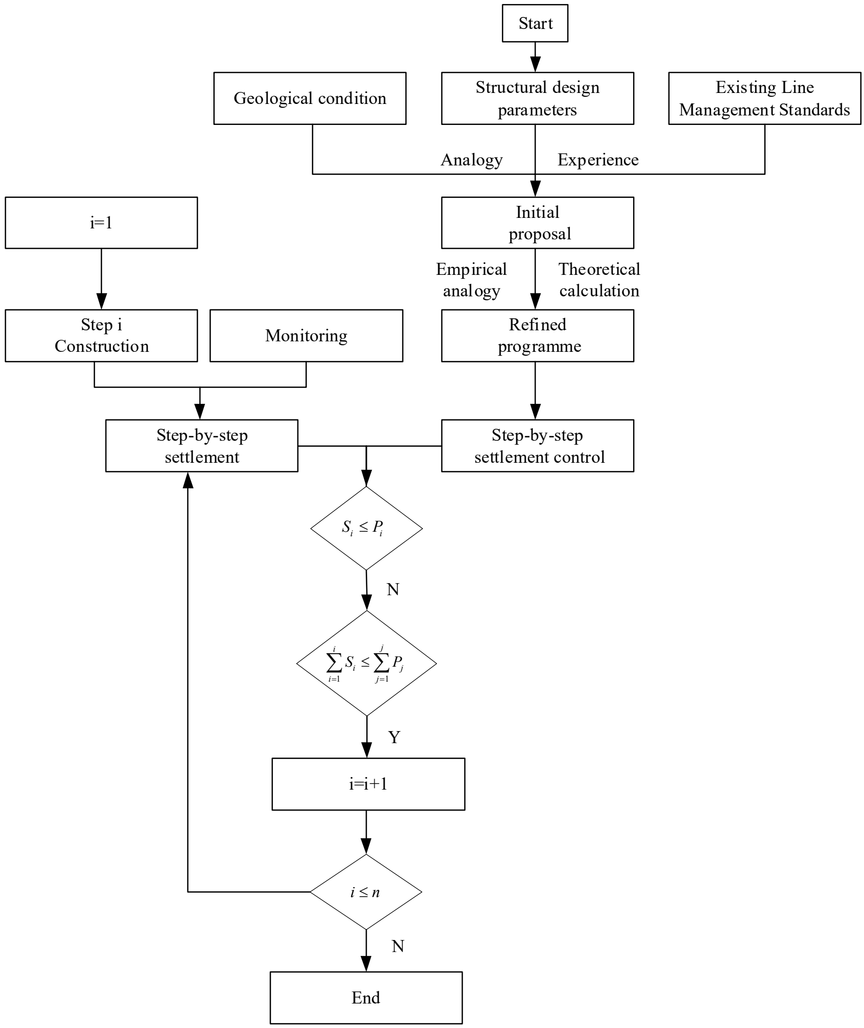
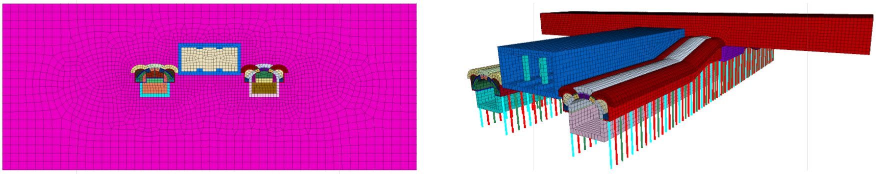


Fig. 1. Deformation distribution principle of the framework.

2.2 Numerical Model.

FLAC3D is used to establish a complete model of the existing metro station reconstruction and expansion, as shown in Figure 2. The size of the model is 150m×150m×60m (length × width × height). Normal constraints are applied around the model, fixed constraints are applied at the bottom, and the top is set as a free surface. The soil, primary support, secondary liner, existing station, and supporting piles are all simulated with solid units in the calculation model, the soil follows the Mohr-Coulomb yield criterion, and the supporting structure adopts the linear elasticity principal relationship. Soils in the deep hole grouting and over-grouting zones are simulated by increasing the modulus of elasticity of the soil, and the grouted piles are simulated by using pile units (PILE). The model has a total of 555,405 units and 358,561 nodes. The parameter values of the modeled soil body, grouting reinforcement zone, and supporting structure are shown in Table 1.



(a) (b)

Fig. 2. Station calculation model.

Table 1. Model parameters.

Material	Density (kg/m^3)	Cohesive force(kN)	Angle of internal friction (°)	Poisson's ratio	Modulus of elasticity (GPa)
Tunnel primary support	2300	/	/	0.25	30
Tunnel second lining	2500	/	/	0.24	32.5
Pile	2500	/	/	0.2	30
Grouting reinforcement zone	2200	35	25	0.28	1.03

2.3 Deformation Prediction Results and Step-By-Step Prediction Values.

After the completion of the construction of the existing station reconstruction and expansion, the settlement of the structure of Metro Line 3 and the track of Metro Line 2 at various stages and their percentages are shown in 2 and Table 3.

Table 2. Step-by-step settlement value and proportion of existing line 3.

Phase	Cumulative settlement (mm)	Stepwise settlement (mm)	Percentage of settlement (%)
1	-0.946	-0.946	25.7
2	-1.183	-0.237	6.5
3	-3.258	-2.075	56.4
4	-3.620	-0.362	9.8
5	-3.677	-0.057	1.6

Table 3. Track settlement value and proportion of existing line 2.

Phase	Cumulative settlement(mm)	Stepwise settlement(mm)	Percentage of settlement(%)
1	-2.106	-2.106	65.7
2	-2.113	-0.007	0.2
3	-2.831	-0.718	22.5
4	-2.920	-0.089	2.7
5	-3.204	-0.284	8.9

It can be seen from Table 2~3:

1) The cumulative settlement of the existing Line 3 and Line 2 in the process of station reconstruction and expansion is -3.677mm and -3.204mm respectively, and the structural deformation of Line 2 far exceeds the safety control threshold (3.0mm), and corresponding reinforcement measures must be taken.

2) In the process of station reconstruction and expansion, the step-by-step settlement of the existing Line 3 Stage 1 and Stage 3 are -0.946mm and -2.075mm respectively, corresponding to the settlement ratio of 25.7% and 56.4%; the step-by-step settlement of the existing Line 2 Stage 1 and Stage 3 are -2.106mm and -0.718mm respectively, corresponding to the settlement ratio of 65.7% and 22.5%.

3) Stage 1 and Stage 3 in the process of station reconstruction and expansion are the step-by-step settlements of the existing Line 3 and the existing Line 2, which account for a larger proportion and are the main stages of construction deformation control.

2.4 Construction Control Measures for Renovation and Expansion of Existing Stations.

Construction control measures. To control the construction deformation of the existing station reconstruction and expansion within the safety threshold, the proposed construction control measures are shown in Table 4, and numerical simulation is used to verify the control effect of the three measures.

Table 4. Construction control measures

Control measures	Remarks
Expanded grouting	Expanded from 0.95m outside the initial support to 1.5m outside the initial support.
Strengthening slurry parameters	Adjustment of slurry parameters and grouting pressure
applying screws	The modulus of elasticity of the screw is taken as 200 GPa.

Extended slurry range control effect. The structural deformation and its rate of change after the use of extended grouting scope during the reconstruction and expansion of the existing station are shown in Table 5.

Table 5. Structural deformation and rate of change after expansion of the grouting range

Phase	Line 3			Line 2		
	Pre-improvement	Improved	Difference	Pre-improvement	Improved	Difference
1	-0.946	-0.287	69.7%	-2.106	-1.996	5.2%
2	-0.237	-0.054	77.2%	-0.007	-0.016	-2.4%
3	-2.075	-1.795	13.4%	-0.718	-0.757	-0.1%
4	-0.362	-1.484	/	-0.089	-0.151	69.7%
5	-0.057	-0.057	0%	-0.284	-0.284	0%
Total	-3.677	-3.677	0%	-3.204	-3.204	0%

Table 5 shows that:

1) After increasing the grouting range, the cumulative settlement of the existing Line 3 is still -3.677mm, and this measure has no effect on the cumulative settlement; increasing the grouting range has the best effect on the control of Stage 4 of Line 3, with 309.9%, and it has almost no effect on Stage 5.

2) After the increase of grouting scope, the cumulative settlement value of the existing metro line 2 has no change, and it is still -3.204mm; the increase of grouting scope has the most obvious effect on the settlement control of stage 4, with 69.7%, and the effect on the rest of the stages is small.

3) During the reconstruction and expansion of the existing stations, the deformation control of the existing Line 2 and Line 3 using the measure of expanding the grouting scope is less effective; the structural settlement still exceeds the safety threshold.

Changing slurry parameters to control the effect. The structural deformation and rate of change of the existing Line 3 and Line 2 after changing the slurry parameters in the existing stations are shown in Table 6.

Table 6. Structural deformation and rate of change after changing grouting parameters

Phase	Line 3			Line 2		
	Pre-improvement	Improved	Difference	Pre-improvement	Improved	Difference
1	-0.946	-0.313	-66.9%	-2.106	-1.988	-5.6%
2	-0.237	-0.050	-78.9%	-0.007	-0.025	257.1%
3	-2.075	-1.814	-12.6%	-0.718	-0.743	3.5%
4	-0.362	-1.433	/	-0.089	-0.151	69.7%
5	-0.057	-0.008	86.0%	-0.284	-0.273	-3.9%
Total	-3.677	-3.618	-1.6%	-3.204	-3.180	-0.7%

It can be seen from Table 6:

(1) After increasing the elastic modulus of the grouting zone, the cumulative settlement of the existing Line 3 was reduced from -3.677 mm to -3.618 mm; the stepwise deformations of the existing Line 3 in Stages 1, 2, and 5 all showed significant changes, with the change rates of 66.9%, 78.9%, and 86.0%, respectively;

(2) After changing the parameters of the grouting slurry, the cumulative settlement

of the existing Line 2 was reduced from -3.204 mm to -3.180 mm, which still exceeded the safe construction threshold of the structure; the step-by-step deformation of the existing Line 2 in Stage 4 had significant changes, with a change rate of 69.7%;

(3) During the reconstruction and expansion of the existing station, the improvement of the grouting slurry parameters had little effect on the deformation control of the station, and the deformation of the structure was still greater than the safety control threshold, requiring further reinforcement measures.

Apply screw control effect. The settlements of the existing lines 3 and 2 and their rates of change after the use of the fillet reinforcement scheme for the existing station reconstruction and expansion works are shown in Table 7.

Table 7. Deformation and rate of change of existing structure after applying the lead-screw

Phase	Line 3			Line 2		
	Pre-improvement	Improved	Difference	Pre-improvement	Improved	Difference
1	-0.946	-0.347	63.32%	-2.106	-2.14	/
2	-0.237	-0.036	84.81%	-0.007	-0.01	/
3	-2.075	-0.737	64.48%	-0.718	-0.22	69.36%
4	-0.362	-1.33	/	-0.089	-0.25	/
5	-0.057	-0.41	/	-0.284	-0.26	8.45%
Total	-3.677	-2.860	22.22%	-3.204	-2.880	10.11%

As can be seen from Table 7:

(1) After the existing station reconstruction and expansion using screw reinforcement measures, the step-by-step settlement of Line 3 in Stages 1, 2, and 3 are significantly reduced, with a change rate of 63.32%, 84.81%, and 64.48%, respectively; the cumulative settlement of Line 3 is reduced from 3.677mm to 2.860mm, with a change rate of 22.22%.

(2) After adopting the screw reinforcement measures, the stepwise settlement of the existing Line 2 is significantly reduced only in Stage 3, with a change rate of 69.36%; the cumulative settlement of Line 2 is reduced from 3.204mm to 2.880mm, with a change rate of 10.11%.

(3) The settlement of the existing Line 3 and Line 2 can be controlled within the safety threshold by using the fillet reinforcement measure, and it is recommended that the fillet reinforcement program be adopted in the reconstruction and expansion construction of this existing station.

2.5 Determination of Stepwise.

From the results of the analyses in Sections 2.3 and 2.4, and in conjunction with the engineering safety control criteria, step-by-step settlement control values were determined for each construction phase of the existing Lines 3 and 2, as shown in Tables 8 and 9.

Table 8. Settlement control value of existing line 3

Phase	Cumulative settlement control value	Stepwise settlement control values	Cumulative percentage	Percentage distribution
1	0.5	0.5	12.5%	12.5%
2	0	0	12.5%	0.0%
3	1.5	1.0	50.0%	37.5%
4	3.4	1.9	85.0%	35.0%
5	4.0	0.6	100.0%	15.0%

Table 9. Track settlement control value of existing line 2

Phase	Cumulative settlement control value	Stepwise settlement control values	Cumulative percentage	Percentage distribution
1	2.2	2.2	73.3%	73.3%
2	2.2	0	73.3%	0.0%
3	2.4	0.2	80.0%	6.7%
4	2.7	0.3	90.0%	10.0%
5	3.0	0.3	100.0%	10.0%

3 Field Application Effect Analysis.

3.1 Monitoring Program.

To verify the effectiveness of the deformation control measures proposed in this paper, and to study the effectiveness of the principle of displacement allocation in this project, the deformation of the existing Line 3 and Line 2 structures in each construction stage was monitored using on-site monitoring methods, and the arrangement of the measurement points is shown in Fig.3, and the monitoring instruments and accuracy are shown in Table 10, and the on-site monitoring diagram is shown in Fig. 4.

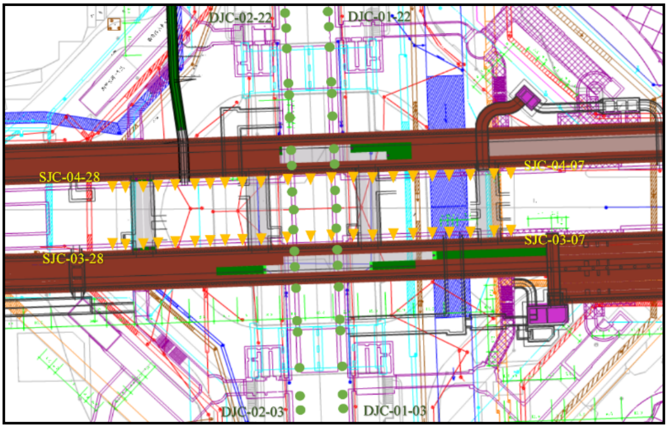


Fig. 3. Structure and track monitoring layout diagram

Table 10. Monitoring instruments

Monitoring Projects	Monitoring Instruments	Monitoring accuracy /mm
Existing structure monitoring	Static Level	0.1
Roadbed, station subsidiary structure, tunnel structure settlement monitoring	Levelling instrument	±0.3
Levelling instrument	Track Ruler	0.1
Seamless line rail displacement, structure lateral displacement	Total station	0.5″/0.6mm+1ppm×D

(a) (b)

Fig. 4. Field monitoring diagram

3.2 Analysis of Site Monitoring Results.

The deformation of the existing Line 3 and Line 2 in the construction of the existing station reconstruction and expansion in each construction stage is shown in Table 11.

Table 11. Field monitoring of structural deformation

Phase	Line 3		Line 2	
	Subside	Percentage	Subside	Percentage
1	0.4	13.79%	2.0	76.92%
2	0	/	0	-
3	0.5	17.24%	0	-
4	1.5	51.72%	0.2	7.69%
5	0.5	17.24%	0.4	15.38%
Total	2.9	100%	2.6	100%

As can be seen from Table 11:

(1) After adopting the screw reinforcement scheme, the cumulative settlement of the existing Line 3 during the construction of the metro station reconstruction and expansion is 2.9 mm, and the cumulative settlement of the existing Line 2 is 2.6 mm, which is both smaller than the safety control threshold.

(2) The settlements of Stages 3 and 4 of the existing Line 3 are 0.5 mm and 1.5 mm, corresponding to 17.24% and 51.72% of the settlement ratio, and the settlement of Stage 1 of the existing Line 2 is 2.0 mm, corresponding to 76.92% of the settlement ratio, and the settlement ratio of the on-site monitoring results is similar to that of numerical simulation.

(3) Existing Line 3 and Existing Line 2 settlements in all stages did not exceed the control threshold, the construction of the existing station main body reconstruction and expansion was completed, and the principle of displacement allocation has a good effect on the deformation control of the station.

4 Conclusion.

Based on the results and discussions presented above, the conclusions are obtained as below:

(1) Without reinforcement measures, the cumulative settlement of the existing Line 3 and Line 2 in the process of station reconstruction and expansion is -3.677 mm and -3.204 mm, respectively, and the structural deformation of Line 2 far exceeds the safety control threshold (3.0 mm), so reinforcement measures must be taken.

(2) The step-by-step settlement of the existing Line 3 station and the existing Line 2 station in the excavation stage of the guide hole and the initial support arch stage of the station reconstruction and expansion process accounted for a larger proportion, corresponding to the settlement of 25.7%, 56.4% and 65.7%, 22.5%, and these two stages are the main stages of the deformation control of the construction.

(3) In the process of station reconstruction and expansion, the deformation control effect of stations with expanded grouting scope and improved grouting slurry parameters is poor, and the structural deformation is still greater than the safety control threshold; when using screw reinforcement measures, the settlement of the existing Line 3 stations and Line 2 stations are controlled within the safety threshold.

(4) The on-site monitoring results show that the structural settlement and deformation are better controlled by using the principle of distributive displacement and the screw reinforcement scheme, and the cumulative settlements of the existing Line 3 and Line 2 are 2.9 mm and 2.6 mm, respectively, which are within the safety threshold.

References

1. Hu Guide, Meng Xiangfei, Liu Zhichun, Lin Panwang and Xulin. (2021) Study on the freezing method and construction mechanical properties of the double-line shield expansion subway station. Tunnel Construction (English & Chinese) (04), 579-587.
2. An Donghui and Shao Wen. (2020) Analysis of the influence of subway station expansion and reconstruction project on the original structure. Railway Standard Design (11), 129-135.
3. Chen Hui. (2020) Research on the reconstruction and expansion of the vehicle base of Xi'an Metro Line 2. Research on Urban Rail Transit (07), 209-213.
4. " Journal of China Highway " Editorial Department. Summary of academic research on traffic tunnel engineering in China. 2022. Journal of China Highway (04), 1-40.

5. Liu Qingfeng, Wu Jian and Liu Kai. (2020) Impact analysis and key technology of shield parallel crossing construction on existing tunnels. Science, Technology and Engineering (12), 4939-4947.
6. Gao Shutong. (2020) Numerical analysis of adjacent construction of subway overlapping parallel shield tunnels. Modern Tunnel Technology (S1), 480-484.
7. Zhou Qingguo. (2021) The construction control technology of the subway in sandy pebble stratum near the existing shield interval. Science, Technology and Engineering (06), 2459-2470.
8. Zhang Qingchuan, Dai Zhiren, Shi Yaxin, Li Tan, Wang Jun and Wang Tianming. (2020) The new tunnel is close to the key technology of the existing subway tunnel. Journal of Railway Engineering (06), 58-63 + 91.
9. Wang Jun. (2022) Analysis of the influence of large-diameter slurry shield tunneling on the adjacent existing subway bridges. China Safety Production Science and Technology (04), 176-184.
10. Cui Guangyao, Tian Yuhang, Xiao Yi, He Jihua Meng and Linghan. (2022) Construction scheme optimization of adjacent tunnel group of subway small spacing tunnel in a high-risk urban environment. China Safety Production Science and Technology (03), 156-161.
11. Wang Lixin, Wang Qiang, Zhong Yujian, Xu Shuo, Qiu Junling, Lai Jinxing and Wang Ke. (2022) Inverse analysis of the influence of adjacent construction on subway structure based on BP neural network. Tunnel construction (S2), 102-113.
12. Liu Bingke, He Shaohui, He Jiaxin and Zheng Jinlei. (2021) construction technology of ultra-deep shaft and ultra-small curvature radius tunnel of a subway. Science, Technology and Engineering (04), 1601-1607.
13. W. Guttmann, (2023) 'Dependences Between Domain Constructions in Heterogeneous Relation Algebras', Relational and Algebraic Methods in Computer Science, pp. 105–121.
14. H.-L. Dang and V.-Q. Nguyen, (2020) 'Closed-form formulation of construction-induced vibrations on existing building at the Metro Line 3 project in Hanoi: Application to control the construction procedures', Geotechnics for Sustainable Infrastructure Development, vol. 62, pp. 345–350.
15. Li Jidong, Tao Lianjin, Wang Guofeng and Hao Zhihong. (2013) The application of displacement distribution principle in metro close crossing project. Journal of Railway Science and Engineering (04), 68-75.
16. Zhang Sherong, Du Xiaoyu, Chen Yuan, Chen Keqiang, and Peng Zhenhui. (2017) Application of ground displacement distribution control principle in large section tunnel with small spacing bias mutation. Railway Standard Design (06), 105-110.