Effects of Large-Scale Unloading on Existing Shield Tunnels in Sandy Gravel Strata

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Abstract The influence of large-scale unloading of soil on existing metro tunnels is a difficult problem in the operation of Metro in sandy gravel strata. In order to predict and control the tunnel deformation and ensure the safety and normal operation of the metro, three-dimensional numerical models are proposed in this study. These models based on the line 5 of Chengdu subway engineering and the adjacent unloading projects analyze the deformation of existing metro tunnels under large-scale unloading of soil. The results show that the maximum bulge after unloading excavation of foundation pit is 11.1 mm, which is lower than the limit value of foundation pit uplift proved by relevant studies; the maximum deformation value of left tunnel is 9.56 mm, and that of right tunnel is 8.33 mm, which is less than the proposed 10 mm deformation control standard. In addition, the paper analyses the restraining effect of different reinforcement measures on soil deformation, such as advanced tubal curtains and horizontal beams, anti-floating anchor cables. The results show that the deformation of soil under different reinforcement measures is greater than the specified limits, while the comprehensive reinforcement measures can restrain the deformation of soil well. The numerical simulation results in this paper verify the effective reinforcement of comprehensive reinforcement measures for large-scale unloading in sandy gravel strata, which can provide reference experience for large-scale unloading excavation construction in similar sandy gravel strata.

Keywords Shield tunnel · Pit excavation · Sandy gravel strata · Anti-floating stability measures · Numerical modelling

1 Introduction

Foundation pit projects in the dense urban areas frequently are constructed on existing subway tunnels. These large-scale unloading will break the original mechanical balanced state, cause rebound deformation
and settlement of the surrounding soil, which will lead to additional stress and deformation of adjacent existing metro (Finno and Bryson 2002; Hsieh and Ou 1998; Liu et al. 2005; Li et al. 2017; Lo and Ramsay 1991; Duan et al. 2019a; Wang et al. 2019a). Increasing concerns have been raised about the effects of large-scale unloading on the existing subway tunnels in urban underground projects. A large number of scholars have used a variety of methods to study the effects of foundation pit excavation on adjacent subway structures, including centrifuge tests (Ng et al. 2013, 2015a; Xu et al. 2014; Fang et al. 2019; Zhou et al. 2019a; Wang et al. 2019b), field tests (Yan et al. 2018; Lai et al. 2016a; Tan et al. 2014; Xiao et al. 2018a; Liu et al. 2011; Cheng et al. 2018; Yu et al. 2013) and numerical simulations (Wang et al. 2019c; Duan et al. 2019b; Zhang et al. 2019a, 2018a; Doležalová 2001; Ng et al. 2015b; Zheng and Wei 2008; Yin et al. 2018; Lai et al. 2016b).

Through physical model tests, the effects of unloading conditions on stress-strain of existing tunnels are studied. Kusakabe et al. (1985), Kojima and Yashiro (2005) based on model tests, the influence of excavation unloading of soil in sandy soil on existing tunnels is studied. Byun et al. (2006) studied the influence of foundation pit excavation above existing tunnel on stress and strain of tunnel structure by establishing 1:12 test model. Field measurement is the most direct method to study the proximity between unloading project and existing metro tunnel. Burford et al. (1988) monitored the structural uplift deformation of the existing metro tunnel near the Shell Center foundation pit project in London for a long time from 1959 to 1986. Sharma et al. (2001), Kivi et al. (2012) installed a precise monitoring system in a tunnel in Singapore to monitor the effect of large excavation on the deformation of adjacent tunnels. With the growing number of such cases, predicting the tunnels displacements has been increasingly important to reduce the risk of excavations. Most researchers simulated the interaction behavior between tunnels and excavation by using numerical methods. Chakeri et al. (Kivi et al. 2011; Xiao et al. 2018b; Zhang et al. 2015) took foundation pits crossing subjacent tunnels as an engineering background, and established three-dimensional numerical models for analysis by using the finite difference software FLAC3D. Some semi-analytical methods to evaluate the heave of underlying tunnel induced by adjacent excavation are presented and verified by field measurement results (Liang et al. 2016; Zhang et al. 2013; Zheng et al. 2018).

However, the previous practice and theoretical research are lacking in the analysis of the deformation and loading condition of existed metro tunnels under large-scale unloading in the sandy gravel strata (Qiu et al. 2019; Wang et al. 2018a; Zhou et al. 2019b; Chang et al. 2011; Hu et al. 2003). Sandy pebbles are the products of long-term transport of rocks interacting with flowing water and riverbed. Sandy gravel strata are generally composed of cohesive soil or sand-pebble, coarse sand and pebble, which are characterized by loose structure, uneven distribution, low cohesion, low plasticity, great compressive stress but little tensile stress and strong discreteness (Zheng et al. 2019; Zhang et al. 2018b; Zhao et al. 2018; Tan et al. 2018). At present, in the sandy gravel strata (Li et al. 2018; Liu et al. 2018) represented by Chengdu, Lanzhou, etc. in China, the subway construction has just begun, and more and more approaching construction problems of new foundation pit unloading projects and existed subway tunnels will appear. Therefore, it is necessary to further study this type of problem.

The line 5 of Chengdu subway engineering located in the sandy gravel strata of Chengdu Plain, China, which will be put into use in the end of 2019. When the metro is completed, the municipal tunnel above the metro will be constructed, and this adjacent unloading project will have an impact on the existing metro tunnel. Taking an adjacent unloading project of line 5 in Chengdu subway as background, numerical simulation on the deformation and loading condition of existed metro tunnels under large-scale unloading and effect of anti-floating self-stabilization measures of tunnel were studied in this paper. The results show that the elastic modulus of strata is improved to a certain extent, and the rebound of pit bottom soil is effectively reduced. This research not only guides the construction of follow-up projects, but also enriches the construction experience of adjacent projects in sandy gravel strata, providing relevant reference to the similar engineering in the future.
2 Engineering Overview

2.1 Engineering Geology

The planned construction between Saiyuntai Station and Dafeng Station of line 5 of Chengdu Metro is located at the main trunk of the traffic, which has dense surface buildings and complex underground stilts. According to geological survey, the top-down distribution of strata in the study area is shown in Fig. 1.

2.2 Introduction of Engineering

The total length of line 5 of Chengdu Metro is about 49 km. The section works between Saiyuntai Station and Dafeng Station whose stake is from K0 + 760 to K0 + 800 underneath pass throat area of Baoji-Chengdu railway, and the building map diagram is shown in Fig. 2. According to the engineering plan, line 5 of Chengdu Metro will be operated by the end of 2019. After the subway starts operation, the railway throat area will be reconstructed, and the municipal tunnel will be implemented simultaneously. The relative spatial position of the municipal tunnel and line 5 of Chengdu Metro is shown in Fig. 3. The municipal tunnel will be constructed by cut-and-cover method and divided into two parts: the south side foundation pit and the north side foundation pit. The foundation pit on the south side has been excavated before the excavation on Line 5 of Metro, so the unloading of the foundation pit on the north side will affect the structure of the lower subway.

The relative horizontal position and vertical position of the municipal tunnel and line 5 of Chengdu Metro are shown in Fig. 4. The plane dimension of the north side foundation pit is 35 m × 59 m, including the west side relief road, the main foundation pit I, the main foundation pit II and the east side relief road. The foundation pit excavation unloading depth is about 12 m, and the minimum distance from the bottom of the foundation pit to the vault of the shield tunnel below is only 2 m. The burial depth of shield tunnels is
10.8 to 17.8 m, in which inside diameter is 6 m and outside diameter of 6.4 m.

In this project, the minimum clearance between the bottom of the foundation pit of the municipal tunnel and the tunnel vault of the subway line 5 is only about 2 m, and the unloading of a large range of soil will affect the tunnel below (Zhang et al. 2019b; Huang et al. 2011; Wang et al. 2013). In order to ensure the structural safety and normal operation of the subway line 5 tunnel, it is necessary to combine with relevant norms and similar successful projects (Liu 2019; Hu et al. 2018). Considering that the soil unloading in the Chengdu sandy gravel strata is relatively lacking in the construction experience of the nearby subway, the safety control standard for the Metro Line 5 is formulated in conjunction with the Urban rail transit engineering monitoring technical specification and Chengdu has operated subway safety control standards. As shown in Table 1.

### 3 Comprehensive Reinforcement Measures

#### 3.1 Advanced Tubal Curtains and Horizontal Beams

In order to reduce the influence of municipal tunnel construction unloading on the additional deformation and internal force of the existing shield tunnel structure (Wei et al. 2019; Luo et al. 2019; Wang et al. 2019d; Lai et al. 2018), the soil above the arch of line 5 of Chengdu Metro shield tunnel is strengthened by using the joint support of advanced tubal curtains and horizontal beams. There are two layers of advanced tubal curtains, the lower side advanced tubal curtains whose longitudinal length is 51.5 m, diameter is 800 mm and circumferential distance is

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**Fig. 3** Diagram of relative position between municipal tunnel and line 5

**Fig. 4** Plane position diagram
850 mm are semicircular along the tunnel vault, and the upper side advanced tubal curtains are horizontally placed under the bottom of the municipal tunnel, which layout diagram is shown in Fig. 5. The advanced tubal curtains that use locks to ensure the stability of the interface are 67. After the construction of the advanced tubal curtains are completed, the micro-expansion concrete is filled to enhance the longitudinal bending stiffness of the advanced tubal curtains.

### 3.2 Anti-Floating Anchor Cables

In order to further strengthen the safety of the subway operation (Qiu et al. 2018, 2019; Wei et al. 2018; Wang et al. 2018b), the prestressed anchor cables and the tunnel segments are connected to control the floating of the shield tunnel. The affected area under the foundation pit of the municipal tunnel and within 100 m of the longitudinal tunnel segment, the prestressed anchor cables are arranged at the bottom and side of the tunnel segments, and the layout of anchor cables of each ring tunnel segment is shown in Fig. 6. Seven tension points are set for each segment, a total of 933 tension points are set in the range of 100 m. Each prestressed anchor cable is about 10 m, the anchor end is about 8 m, and the free end is 2 m. Through mechanical analysis, the prestressed anchor cable that is flexible structure is composed of 3 steel strands whose diameter is 15.2 mm and pre-stress force is 200 kN.

### 4 Numerical Modelling

#### 4.1 Finite Element Model and Selected Parameters

The excavation foundation pit of the municipal tunnel, which is 12 m high, 59 m long and 35 m wide, is built above line 5 of Chengdu Metro. The numerical calculation model was established by using Midas NX finite element software. In order to ensure that the three-dimensional model has enough calculation accuracy and reduce the convergence calculation time, the calculation model is divided into 35,261

### Table 1 Safety control standards of Chengdu Metro line 5

| Monitoring items and scope                      | Shield tunnel in operation |
|------------------------------------------------|----------------------------|
| Horizontal and vertical displacement of tunnel | ≤ 10 mm                   |
| Radial convergence of tunnel                   | ≤ 10 mm                   |
| Deformation curvature radius of tunnel         | R ≥ 10 mm                 |
| Deformation relative curvature of tunnel       | ≤ 1/2500                  |
| Opening of segment joints                      | ≤ 2 mm                    |
| Lateral height difference of track             | ≤ 4 mm                    |
| Void content of track bed                      | ≤ 5 mm                    |
| Crack width of structure                       | ≤ 0.2 mm                  |

Fig. 5 Strengthened sketch of advance tubal curtains and horizontal beams

Fig. 6 Seven tension points are set for each segment, a total of 933 tension points are set in the range of 100 m. Each prestressed anchor cable is about 10 m, the anchor end is about 8 m, and the free end is 2 m. Through mechanical analysis, the prestressed anchor cable that is flexible structure is composed of 3 steel strands whose diameter is 15.2 mm and pre-stress force is 200 kN.
units, including 43,921 nodes, according to the impact range of the project construction on the surrounding environment, the length was 180 m (X direction), the width was 130 m (Y direction), and the calculated depth was 50 m (Z direction), which can eliminate the influence of boundary conditions. In order to reduce the redundant calculation, the mesh generation around the foundation pit is more compact, and the grid division in the distance of the foundation pit is sparse. The overall model is shown in Fig. 7a. The modified

Fig. 6  Layout of anti-floating anchor cables

Fig. 7  Computational model and strengthened structural diagram. a Integral mesh. b Strengthened. c Advanced tubal curtains and horizontal beams. d Anti-floating anchor cables
Mohr–Coulomb constitutive relation is adopted in the model. The soil is simulated by C3D8R three-dimensional eight node solid element, the tunnel segments adopt the shell elements, the foundation pit retaining structures are simplified to be equivalent to the 2D plate elements, the advanced tubal curtains and internal supporting structure of steel pipe are made of B31 three dimensional first order beam element, and the anti-floating anchor cables are simulated by 1D dembedded truss. The reinforcement structures are shown in Fig. 7b–d. The boundary conditions restrict the normal displacement, the bottom boundary restricts the vertical displacement, and the upper boundary is the free surface. At the same time, because the advanced tubal curtains are embedded beam element, the rotation constraint is applied in Z direction.

The specific soil and structure parameters were determined by the “Special Exploration Report of sandy gravel strata of Shield Tunnel of Line 5 of Chengdu Metro” and the empirical values of mechanical calculation parameters of each rock layer in Chengdu area. Detailed formation mechanics calculation parameters and structural parameters are shown in Tables 2 and 3.

4.2 Simulation of Construction Conditions

Because the major study is the influence of the large unloading of the soil above the line 5 of metro on the subway structure, the excavation of the subway shield tunnel is not simulated in detail, and the influence of the shield tunnel construction on the strata is not considered. The displacement clearing operation is performed after the initial stress field is activated and the tunnel construction is completed.

When the foundation pits are excavated, the foundation pit supporting structures are first applied, and then the soils are excavated. The excavation sequence is from the west side relief road of foundation pit to the east. The foundation pit is divided vertically into multi-layers. The depth of each excavation is 2 m. When the main foundation pit II and the east side relief road are excavated, the method of vertical stratification and horizontal segmentation is adopted to excavating the soil within 6 m above the bottom of the pit. The test section of 6 m long foundation pit excavation above the tunnel is set up, as shown in Fig. 8.

In order to further compare and analyze the treatment effect of reinforcement measures under different working conditions, at the same time, the unreinforced conditions, the reinforced conditions of advanced tubal curtains and horizontal beams and the reinforced conditions of anti-floating anchor cables were studied. It should be noted that the unreinforced excavation conditions are that the combined anti-floating measures are not used, and the conventional reinforcement measures for foundation pit excavation are adopted, which includes retaining piles, temporary support and layered and block excavation. The reinforced conditions of advanced tubal curtains and horizontal beams are the conventional unloading control measures of foundation pit and the reinforced measures of advanced pipe curtain and horizontal beam. The reinforced conditions of anti-floating anchor cables are the conventional unloading control measures and anti-floating anchor cables reinforcement measures.

| Types            | $\gamma$(kN·m$^{-3}$) | $\nu$ | $c$(kPa) | $\phi$(°) | $E_{od}^s$(MPa) | $E_{oed}^s$(MPa) | $E_{er}^s$(MPa) | $K_0$ | $H$(m) |
|------------------|------------------------|-------|----------|----------|----------------|-----------------|----------------|-------|-------|
| Miscellaneous fill | 18                     | 0.27  | 8        | 10       | 8              | 8               | 24             | –     | 3     |
| Silty clay       | 19.5                   | 0.32  | 37.1     | 17.1     | 6              | 6               | 18             | 0.40  | 0.6   |
| Loose pebbles    | 18.5                   | 0.33  | 0        | 30       | 5.5            | 5.5             | 16.5           | 0.33  | 3.2   |
| Lower dense pebbles | 21                    | 0.32  | 0        | 35       | 23             | 23              | 69             | 0.30  | 4.2   |
| Medium dense pebbles | 22                   | 0.28  | 0        | 40       | 29             | 29              | 87             | 0.25  | 12    |
| Dense pebbles    | 23                     | 0.30  | 0        | 45       | 33             | 33              | 99             | 0.20  | >20   |
5 Result Analysis

5.1 Deformation

5.1.1 Springback Deformation at the Bottom of Foundation Pit

Figure 9 shows the changing rule of the deformation of the bottom of foundation pit under different excavation stages. After the excavation of the west side relief road is completed, the maximum uplift deformation at the bottom of the pit is 4.75 mm, while the soil above the left side tunnel of the west side relief road has a certain degree of sinking, with a maximum of about 3.9 mm (Fig. 9a). After the excavation of the main foundation pit I, the maximum bulge at the bottom of the pit is 7.95 mm, and the maximum uplift at the bottom of the main foundation pit I is 5.17 mm. Currently, the settlement of the soil above and around the left-line tunnel gradually becomes smaller. (Fig. 9b). After the excavation of the main foundation pit II, the maximum bulge at the bottom of the pit is mainly located at the bottom of the main pit I, which is about 9.69 mm (Fig. 9c). The range of the uplift of the three foundation pits continued to increase, and the settlement range of the soil on the east side gradually decreased. After the excavation of the municipal foundation pit is completed, the whole bottom of the pit is bulged, and the maximum bulge is 11.1 mm (Fig. 9d).

From the bottom bulge value of the foundation pit shown in Fig. 10, it can be seen that the maximum bulge of the foundation pit occurs at the center of the main foundation pit I, about 11.1 mm, and the ridge change of the main foundation pit II is 8–10 mm. The main foundation pits have a relatively large degree of uplift, while the foundation pits of east and west side relief road are relatively small. This is mainly because the main foundation pit has a larger excavation size.

### Table 3 Structural parameters

| Types                          | γ (kN m⁻³) | E (kPa)  | ν      | Sectional parameters |
|-------------------------------|------------|---------|--------|----------------------|
| Segment                       | 24         | 3.8 × 10⁷ | 0.2    | D = 6.4 m, d = 6.0 m |
| Advanced tubal curtain        | 25         | 3.15 × 10⁷| 0.3    | Φ800 mm              |
| Horizontal bean               | 25         | 3.15 × 10⁷| 0.3    | Φ800 mm              |
| Anti-floating anchor cables    | 78         | 1.95 × 10⁸| 0.3    | Φ150 mm              |
| Retaining pile                | 25         | 3.0 × 10⁷ | 0.2    | Φ1200 mm             |
| Temporary support             | 78         | 2.1 × 10⁸ | 0.3    | Φ169 mm              |

Annotation: γ is volume weight, ν is poisson’s ration, c is cohesion, φ is friction angle, E is elasticity modulus, $E_{50}^{sec}$ is secant stiffness of triaxial test, $E_{ref}^{sec}$ is tangent stiffness of primary consolidation load experiments, $E_{ref}^{er}$ is unloading elasticity modulus.

Fig. 8 Sketch of excavation test of foundation pit
The subsequent construction of the municipal tunnel should focus on strengthening the real-time monitoring of the main foundation pit I and the main foundation pit II. It is necessary to strengthen the rigidity of the retaining structure and add some temporary support to ensure that the rebound of the bottom of the pit is controllable. In addition, due to the unloading effect of the soil, the soil in the passive region rebounds and the retaining structure moves into the pit, and the wall at the bottom of the pit undergoes lateral deformation to squeeze the soil in the passive zone, which result in a large uplift of the soil within the central extent, due to the restraining effect of the retaining structure, the soil bulge in a certain area of the foundation pit wall is small. The existing research shows that the excavation of foundation pit will lead to the unloading of the soil at the bottom of the pit. Under the condition of soft plastic clay layer, the rebound amount of the soil at the bottom of the pit can reach 0.5% \( H \) ~ 1.0% \( h \) of the excavation depth of the foundation pit. Due to the small difference between the compression modulus and the unloading modulus, and the larger unloading modulus, the uplift deformation of the soil at the bottom of the pit is relatively small. The field test

**Fig. 9** Deformation of foundation pit bottom at different excavation stages. a After the excavation of west side relief. b After the excavation of main foundation pit I. c After the excavation of main foundation pit II. d After the excavation of east side relief road.

**Fig. 10** Distribution of pit bottom upheaval after excavation of foundation pit.
results of related research show that the deformation of the bottom of the pit generally does not exceed 2.0% of the excavation depth. The excavation depth of the foundation pit is 12 m, so the maximum deformation of the bottom of the pit is generally 24 mm, which is larger than the predicted value of the uplift of the municipal foundation pit (Liu 2019). It shows that the unloading process control measures and strata reinforcement measures taken during the excavation of the municipal tunnel foundation pits to some extent inhibit the rebound deformation of the bottom of the pit and meet the engineering requirements.

5.1.2 Vertical displacement existing subway tunnels

Figure 11 shows the vertical displacement of the left and right line tunnels under different working conditions. Since the west side relief road and the main foundation pit I are relatively far from the line 5 of subway, the vertical displacement of the tunnel is mainly settlement, and the maximum settlement is 3.8 mm. After the excavation of the foundation pit II above the right-hand subway tunnel is completed, the maximum uplift of the right-line tunnel is 6.37 mm, while the deformation of the left-line tunnel is basically zero, and the tunnel undergoes upward uplift deformation after settlement. After the excavation of the foundation pits is completed, the maximum ridge of the right-line tunnel is 9.56 mm, and the maximum ridge of the left line is 8.33 mm, which occurs below the center of the pit bottom and above the tunnel axis.

It can be seen from the above analysis that the maximum settlement and uplift deformation of the tunnel in each working condition occur above the tunnel vault. In order to visually study the effect of soil unloading on the vertical deformation of the subway tunnel along the axis, a research point is selected every 2 m along the longitudinal direction of the tunnel to extract the vertical deformation at the position of the tunnel vault, as shown in Fig. 12. The positive displacement number in the figure indicates that the tunnel has a bulging deformation, and the negative number is the settlement deformation. After the excavation of the west side relief road is completed, the left and right tunnels will undergo settlement deformation in the area below the foundation pit, and

![Fig. 11 Vertical displacement change of tunnels under different excavation conditions. a After the excavation of west side relief road. b After the excavation of main foundation pit I. c After the excavation of main foundation pit II. d After the excavation of east side relief road](image)
the main settlement is about 3–3.8 mm. As the foundation pit gradually excavated in the direction of the tunnel, the left and right tunnels began to bulge upward. When the excavation of the main foundation pit II is completed, the right-line tunnel in the area below the foundation pit exhibits a bulging deformation, and the maximum bulge amount is about 6 mm. However, the left-line tunnel deformation is almost zero, which means that the settlement and bulging of the tunnel cancel each other out. After the excavation of the foundation pit, the maximum ridge deformation of the right tunnel is about 9.56 mm, and the maximum ridge of the left line is about 8.33 mm, which is less than the proposed 10 mm deformation control standard. In summary, the combination of self-stabilization measures such as advanced tubal curtains and horizontal beams, anti-floating anchor cables and segment reinforcement can improve the elastic modulus of strata and the longitudinal stiffness of segments to a certain extent. Thus, the rebound of the soil at the bottom of the pit is reduced, which has a good control effect on restraining the structural uplift of the tunnel and ensuring the normal operation safety of the Metro tunnel.

It can be seen from Fig. 12 that the maximum deformation position of the left and right tunnels occurs at the middle of the tunnel \( Y = 55 \) m, and near the center of the Y-direction of the municipal frame foundation pit. Therefore, the section is the most unfavorable section showing the safety of the tunnel structure when the soil is unloaded. The vertical displacement of the joint at the vault position of the section is extracted with the deformation value of the excavation step of the foundation pit as shown in Fig. 13. It is noteworthy that when the construction of the main foundation pit II begins, the right tunnel begins to rise upward, the curvature of the tunnel uplift curve increases, and the deformation rate accelerates. At the same time, with the increase of the excavation depth of the foundation pit, the right tunnel has a larger increase rate and uplift value than the left tunnel, and the uplift deformation increases nonlinearly. When the east side relief road starts construction, the rate of change of the right-line tunnel uplift is relatively reduced, but the growth rate of the left-line tunnel is
significantly increased. During the construction, the deformation of the subway tunnel should be monitored closely in real time, and effective and reasonable unloading methods should be adopted in time to ensure the safety and controllability of the subway structure.

5.2 Reinforcement Effect

5.2.1 Reinforcement Advanced Tubal Curtains and Horizontal Beams

In order to further analyze the effect and degree of the active reinforcement measures of advanced tubal curtains and horizontal beams, the vertical displacement of left and right tunnel under three conditions is analyzed by comparing the unreinforced conditions and the reinforced conditions of comprehensive measures. Figure 14 shows the variation of vertical displacement of left and right tunnel under different reinforced conditions. The figure shows that the final vertical displacement of the left and right tunnels exceeds the stipulated 10 mm control standard under the unreinforced condition, which shows that the conventional unloading control measures cannot meet the control requirements of Metro deformation. After adopting advanced tubal curtains and horizontal beams reinforcement measures, the vertical uplift displacement of the tunnel decreases significantly, and the left tunnel uplift displacement decreases to about 10 mm, but the right tunnel uplift displacement still exceeds the limit, so the deformation of Metro Line 5 still does not meet the requirements.

5.2.2 Reinforcement Anti-floating anchor cables

In order to obtain the treatment effect of anti-floating anchor cables reinforcement measures, the variation laws of vertical displacement of left and right tunnel under three conditions were compared and analyzed in combining with the unreinforced conditions and the reinforced conditions of comprehensive measures. Figure 15 shows the variation of vertical displacement of left and right tunnel under different reinforced conditions. The figure shows that the uplift displacement of the left tunnel is reduced to about 10.3 mm and that of the right tunnel is reduced to about 11.68 mm after adopting anti-floating anchor cables reinforcement measures, but all of them exceed the deformation limit, which indicates that anti-floating anchor cables reinforcement measures alone cannot meet the control requirements of Metro deformation.

From Table 4, the maximum longitudinal uplift of left and right tunnel is 11.85 mm and 14.32 mm under unreinforced condition after all excavation of foundation pit has been completed. The vertical displacement of the left and right tunnel is reduced to 9.28 mm and 11.27 mm, which reduces respectively by 17.1% and
21.3% after adopting advanced tubal curtains and horizontal beams reinforcement measures. The vertical displacement of the left and right tunnel is reduced to 10.29 mm and 11.68 mm, which reduces respectively by 13.1% and 18.4% after adopting anti-floating anchor cables reinforcement measures. After adopting comprehensive reinforcement measures, the vertical displacement decreases by 29.7% and 33.2% respectively, and the reinforcement effect is more obvious. In conclusion, the anti-floating anchor cables have obvious effect on controlling the longitudinal uplift of tunnel, but the effect is slightly smaller than that of the advanced tubal curtains and horizontal beams reinforcement measures. Comprehensive reinforcement measures can meet the control requirements of Metro deformation, but the two measures cannot meet the control requirements of Metro deformation when used singly.

### 6 Conclusion

1. The comprehensive reinforcement measures such as advanced tubal curtains, horizontal beams, and anti-floating anchor cables have obvious reinforcement effect. To a certain extent, the elastic modulus of the strata is improved. The rebound of the soil at the bottom of the pit is effectively reduced. And the excessive uplift of the tunnel structure is avoided.

2. After the excavation of the foundation pits is completed, the maximum uplifts of the left and right tunnels are 9.56 mm and 8.33 mm respectively, which are less than the control standard requirement of 10 mm and have a certain safety reserve.

3. When the construction of the main foundation pit II begins, the right tunnel begins to uplift
upwards, with the increase of the curvature of the uplift curve and the acceleration of the deformation rate. At the same time, with the increase of excavation depth of foundation pit, the increase rate and uplift value of the right tunnel are larger than that of the left tunnel, and the uplift deformations increase nonlinearly. When the construction of the east side relief road begins, the change rate of the right tunnel uplift decreases relatively, but the growth rate of the left tunnel increases significantly, and the horizontal displacements increase nonlinearly. Therefore, it is necessary to monitor the deformation of metro tunnel in real time and adopt effective and reasonable unloading methods in time, which can ensure the safety of metro structure.

(4) Compared with the unreinforced condition, the vertical displacements of the left and right tunnels are reduced respectively by 13.1% and 18.4% after the anti-floating anchor cables reinforcement measures are adopted; the vertical displacements of the left and right tunnel are reduced respectively by 17.1% and 21.3% by adopting the advanced tubal curtains and horizontal beams reinforcement measures. In conclusion, the anti-floating anchor cables can reduce the vertical uplift deformation of the tunnel to a certain extent, but the effect of controlling the vertical uplift of the tunnel is slightly less than that of the advanced tubal curtains and horizontal beams reinforcement measures. Moreover, the two measures cannot meet the control requirements of metro deformation when used alone.

Acknowledgements The authors gratefully acknowledge the financial support by the National Key R&D problem of China (No.2018YFC0808706), the Project on Social Development of Shaanxi Provincial Science (No.2018SF-378) and the top young talents of “special support program” in Shaanxi Province, Shaanxi Group Tong Zi [2018] No. 33.

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