WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2023.145271

ARCHIVES OF CIVIL ENGINEERING

Vol. LXIX ISSUE 2 2023

pp. 339 –352

Research paper

Behavior of damaged TBM tunnel under MJS and Micro-disturbance grouting treatment: a case study

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Abstract: The operating subway tunnel is often damaged due to excessive deformation in China. In order to ensure the safe for operation, remediation and protection measures must be taken, especially in soft soil areas. This paper presents a case study on remedial scheme of damaged TBM (Tunnel Boring Machine) tunnel adjacent to excavation combining with MJS (Metro Jet System) and micro-disturbance grouting technology in Hangzhou, China. The track bed settlement, horizontal displacement and convergence of the TBM tunnel caused by MJS and micro-disturbance grouting construction were analyzed and discussed. The results showed the characteristics of soil layer under the tunnel have significant influence on the treatment effect. Even if multiple grouting was adopted, the treatment failure may occur under the combination action of external loads such as traffic load or surcharge load, which should be considered when civil engineers design remediation scheme. The results can provide practical experience and guidance for similar treatment scheme of damaged TBM tunnel.

Keywords: MJS, damaged TBM tunnel, micro-disturbance grouting technology, treatment

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1. Introduction

With the large-scale construction of urban metro networks in China, more and more attention has been paid to the remediation of operating subway tunnels, especially in soft clay. TBM tunnel in soft clay is prone to damage due to the particularity of tunnel structure [1–4]. According to Zhu et al. [5], damages of the TBM tunnel are primarily caused by adjacent engineering activities or inadequate protection, like deep foundation excavations [6–8], tunnel excavations [9, 10] and extreme surcharges [11]. The grouting technology is widely adopted to renovate the operating subway tunnel considering its easy operation and little impact on subway operation. A reasonable grouting scheme can not only control the long-term settlement, but also the differential settlement of over-deformed operating TBM tunnel [10, 12, 13]. From the above studies, the grouting is an effective treatment method to remediate and control over-deformed running TBM tunnel. However, a comprehensive treatment scheme combining MJS (Metro Jet System) and grouting technology are rarely reported.

This paper presents a case study on the treatment scheme of an over-deformed operational TBM tunnel of Hangzhou Metro Line 2 near a deep foundation pit construction. The site conditions of the over-deformed operating TBM tunnel are described at first. Then, the monitoring data of the over-deformed operating tunnel are also analyzed. Due to adjacent foundation pit excavation, a remediation scheme combining MJS and micro-disturbance grouting technology is introduced in detail. Finally, the remediation effect is investigated and discussed by analyzing the measures, like track bed settlement, horizontal displacement, and horizontal convergence of the TBM tunnel.

2. Site conditions

The over-deformed TBM tunnel is a section of the up-track of Hangzhou Metro Line 2 between Dufu Village Station and Liangzhu Station, which is operated in the year 2017. The studied section is from SDK41+468.55 to SDK41+535.75 along Gudun road, totaling 67.2 m. The foundation pit excavation is located on the north side of the TBM tunnel, which consists of two phases. The excavation depths of the two phases are 5.85÷7.5 m and 10 m, respectively. The nearest distance between the foundation pit and the TBM tunnel is about 17.8 m. The plan layout of the site is shown in Fig. 1. The depth below the ground surface at the top and bottom of the tunnel is about 11.12÷15.72 m and 17.32÷21.92 m. The TBM tunnel is mainly located in the muddy silty clay layer and partially in the clay layer. The underlying soil of the tunnel in the studied section is muddy clay layer ④$_3$ with a thickness of about 0.3÷3.6 m. And the clay layers ⑦$_1$ and ⑥$_{31}$ are the underlying soil of ④$_3$. The longitudinal geological profile of the studied TBM tunnel is plotted in Fig. 2. The soil physical and mechanical properties from the site, which includes cohesion (c), friction angle (φ), void ratio (e), foundation bearing capacity is shown in Table 1.

Fig. 1. Plan layout of the site

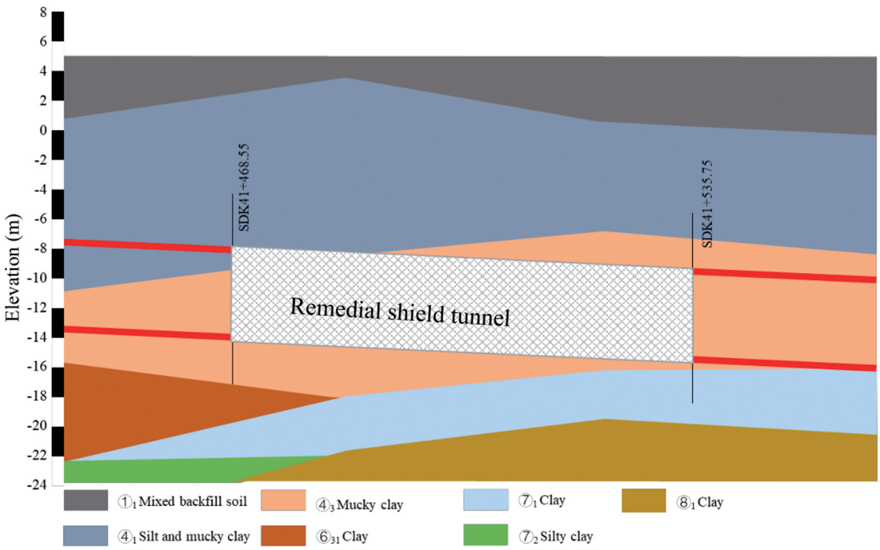


Fig. 2. (Color) Partial longitudinal geological profile of the up-track tunnel

Based on the geological exploration result, the groundwater in the site consists of pore phreatic water of loose rock and pore confined water loose rock. The depth below the ground surface of phreatic stable water level is 1.3÷4.1 m below the ground, which is mainly recharged by atmospheric precipitation and lateral runoff, and changed with seasons. The confined pore confined water is distributed in ⑦1, and the depth below the ground surface of water head is 4.58÷5.79 m.

Table 1. The soil physical and mechanical properties

Stratum	Symbol	Elevation of layer top (m)	Cohesion c (kPa)	Angle of internal friction φ (°)	Void ratio e	Foundation bearing capacity (kPa)
Mixed backfill soil	①$_1$	2.57÷5.39	15	8	–	80
Silt and mucky clay	④$_1$	−3.05÷1.64	9	12	1.372	60
Mucky clay	④$_3$	−10.65÷ − 5.87	10	13	1.346	75
Clay	⑥$_{31}$	−16.64÷ − 12.64	18	16	1.149	90
Clay	⑦$_1$	−17.75÷ − 11.25	35	14.5	0.911	220
Silty clay	⑦$_2$	−22.14÷ − 15.48	25	18	0.730	200

3. Site tunnel characteristics and deformation

The affected TBM tunnel has an outer diameter of 6.2 m and an inner diameter of 5.5 m. The tunnel lining is assembled by staggered joints of six segments, which are connected by high-strength bolts in the longitudinal and circumferential directions. The segment is prefabricated reinforced concrete segment with strength grade of C50.

According to the settlement monitoring results, the cumulative track bed settlement of up-track tunnel is presented in Fig. 3. From Fig. 3, the local settlement of the up-track TBM tunnel was obvious, and the settlement area is mainly between ring SCJ105~SCJ155. The maximum settlement was –14.4 mm at ring SCJ130 during excavation construction on September 27, 2019, which was about three times the control value. Based on the variation of track bed settlement at ring SCJ130, the track bed settlement did not tend to be stable,

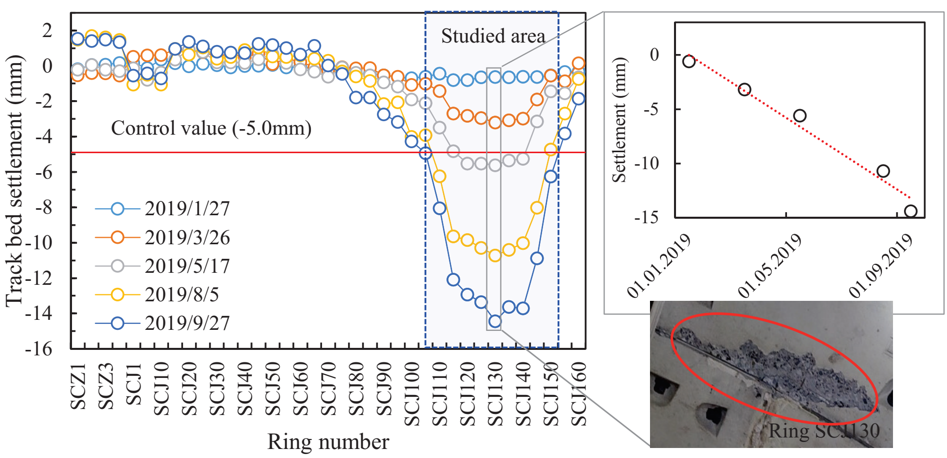


Fig. 3. Track bed settlement of the affected up-track TBM tunnel

but still increased gradually. After the basement structure completion on August 5, 2019, the settlement continued to develop.

Fig. 4 plots the horizontal displacement of the affected up-track TBM tunnel, from which there was an obvious horizontal movement towards the foundation pit from ring 105 to 150. The maximum horizontal displacement was 3.5 mm. After the basement structure was completed, the horizontal displacement tended to be stable gradually.

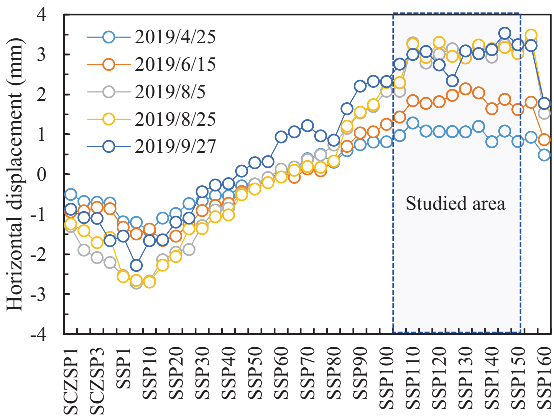


Fig. 4. Horizontal displacement of the affected up-track TBM tunnel

The horizontal convergence (ΔD) of the affected up-track TBM tunnel is presented in Fig. 5. From Fig. 5, the up-track TBM tunnel had evident compression deformation between ring 80 and ring 150 during excavation. The maximum horizontal convergence of the affected up-track TBM tunnel was 5.3 mm at ring 90. The horizontal convergence continued to increase after the basement structure was completed.

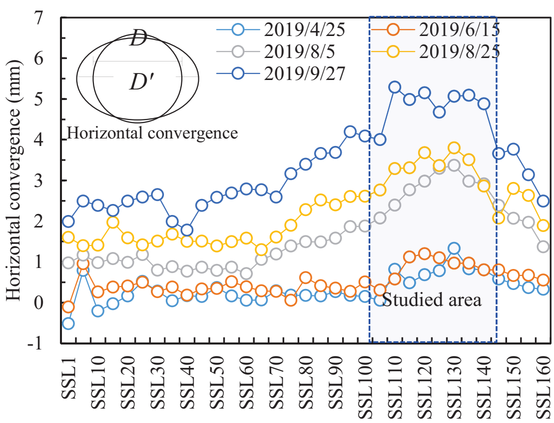


Fig. 5. Horizontal convergence (ΔD) of the affected up-track TBM tunnels

4. Distress remedial scheme

According to construction experience, MJS project is mainly used to limit TBM tunnel displacement. In order to ensure the remediation effect, a row of micro-disturbance grouting holes is added between MJS piles and tunnel sideline to test the effect of settlement treatment of damaged TBM tunnel, so as to provide guidance for subsequent MJS construction. Therefore, MJS combined micro-disturbance grouting scheme was adopted. The construction sequence is shown in Fig. 6. The MJS jet grouting pile at the test position is constructed at first. After the test pile is completed, the construction of the remaining jet grouting piles in the MJS test section are carried out if the strength of piles and the influence on the tunnel meet the requirements of the design. Then the micro-disturbance grouting is constructed.

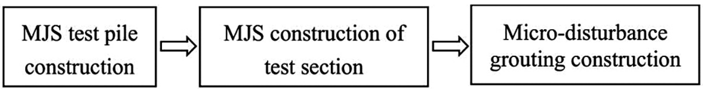


Fig. 6. Construction sequence of remedial scheme

4.1. MJS construction

A total of 78 piles are evenly arranged on both sides of the tunnel from SDK41+468.55 to SDK41+535.75 (matched ring number 155 to 100). The length of MJS pile is 8.6÷10.4 m. A semicircle section is constructed from 2.4 m below the bottom of the tunnel to the top of the tunnel. The jet direction is away from the damaged TBM tunnel. The reinforcement of MJS adopts ordinary Portland cement (with compressive strength of 42.5 MPa) with water-to-cement ratio of 1.0. The staggered piling method was employed during the construction process. And the construction interval of adjacent piles was not less than 24 hours. During the construction process, the deformation of the damaged TBM tunnel is monitored at all times. Finally, the parameters of MJS construction, MJS pile quality, response of damaged TBM tunnel (settlement, horizontal displacement, horizontal convergence, and leakage) are summarized and analyzed, which can guide the next construction. The main parameters of MJS technology are shown in Table 2.

Table 2. The main parameters of MJS technology

Parameters	Values
Cement content	50÷55%
Water-to-cement ratio	1:1
Pile diameter (mm)	2400
Grout pressure (MPa)	40 (±2)
Air pressure (MPa)	0.5÷1.0

Continued on next page

Table 2 – *Continued from previous page*

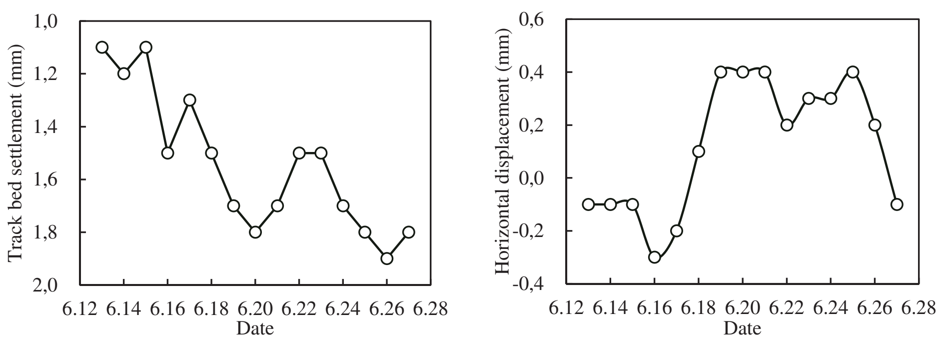
Parameters	Values
Air flow (N·m^3/min)	1.0÷1.6
Formation pressure coefficient	1.3÷1.6 (Adjustable)
Pile perpendicularity error	≤ 1/200 (G.E.-P.B.E.)
Lifting speed (cm/min)	2.5 (full circle), 5 (semicircle)
Slurry flow (L/min)	80÷100

Note:
1. Both lifting speed and slurry flow are specific parameter when the pile diameter is 2400 mm and the shotcrete pressure is 40 MPa.
2. G.E. represents ground elevation and P.B.E. is pile bottom elevation.
3. Formation pressure means the external formation pressure at the depth of grout pipe. The formation pressure coefficient is used to ensure a reasonabe grout pressure for formation stabilization.

4.1.1. Test pile construction

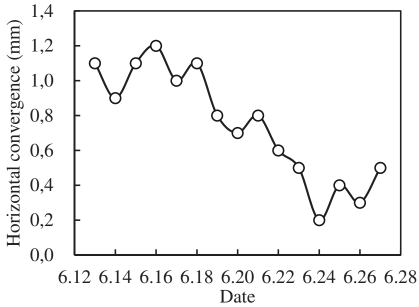
The positions with small deformation (ring number 153 to 155) are selected as the test section for pile test. Both diameters of the four test piles are 2400 mm, with a length of 8.6 m. The pile centers on both sides are 4.6 m from the center line of the damaged TBM tunnel. In order to ensure the safety of the tunnel, test piles on the south side are carried out first. The construction is planned in the sequence of North M39, South M38, North M38, South M39. The interval time of jet grouting with adjacent pile positions in a row shall not be less than 24 hours. The test pile construction starts from June 13, 2020 to June 27, 2020. During MJS test pile construction, the variation of behavior of damaged tunnel adjacent to test piles (ring number 153 to 155) is shown in Fig. 7.

From Fig. 7, the MJS test pile construction has little impact on the damaged tunnel. The track bed settlement gradually increases during the whole test pile construction, and the maximum value is 1.9 mm on June 26. The horizontal displacement and convergence are very small and have almost no effect on damaged TBM tunnel.



(a) Track bed settlement (b) Horizontal displacement

Fig. 7 (a), (b)

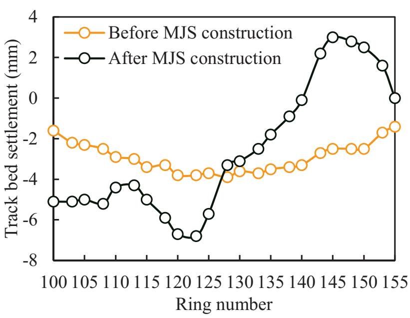


(c) Horizontal convergence

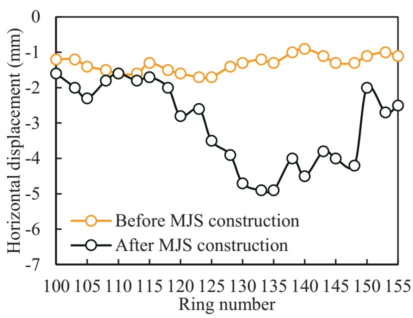
Fig. 7. Variation of behavior of damaged tunnel adjacent to test piles (ring number 153 to 155)

4.1.2. Construction of test section

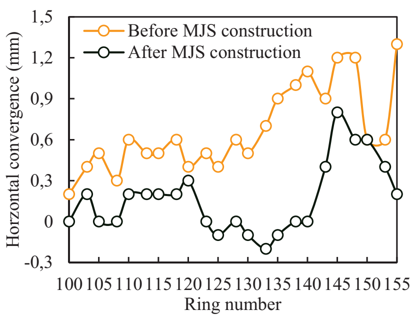
According to the experiences and parameters obtained from test pile construction, the remaining 74 MJS piles are constructed in the test section. The construction method is the same as the test pile construction. During MJS construction of test section, the grouting volume and grouting pressure did not exceed the design value. In addition, the monitoring data of the damaged TBM tunnel were stable and within the control value. Comparison results of damaged TBM tunnel deformation (ring number 100 to 155) are shown in Fig. 8,



(a) Track bed settlement



(b) Horizontal displacement



(c) Horizontal convergence

Fig. 8. Comparison results of damaged TBM tunnel deformation

from which MJS construction has the greatest influence on horizontal displacement of the damaged TBM tunnel. The maximum horizontal displacement is –4.9 mm at ring 133 and 135. From Fig. 8a, the track bed uplift was caused by MJS construction between ring 128 and 155, and the maximum uplift was 3 mm at ring 145. The horizontal convergence of all rings was small. To summarize, the effect of MJS construction on damaged TBM tunnel is not significant.

4.2. Micro-disturbance grouting construction

After the strength of MJS pile meets the design requirements (Unconfined compressive strength, UCS ≥ 1 MPa), a row of micro-disturbance grouting were carried out between MJS pile and tunnel segment to remediate the damaged TBM tunnel. The spacing between grouting holes is 1.2 m. The hole center is 1.2 m from the tunnel sideline, and the grouting depth is 4.6 m below the tunnel centerline. According to the design scheme and treatment effect, the micro-disturbance grouting construction includes three stages: the first, the second and the third stage. The cement-sodium silicate binary slurry was adopted as grouting materials. The main parameters of micro-disturbance grouting construction are shown in Table 3.

Table 3. The main parameters of micro-disturbance grouting construction

Parameters	Values
Water-to-cement ratio	0.7÷1.0
Pipe diameter (mm)	32
Grouting hole spacing (mm)	1200
Grouting pressure (MPa)	0.3÷0.5
Cement flow (A) (L/min)	14÷16
Sodium silicate flow (B) (L/min)	5÷10
Cement-Sodium silicate volume ratio	(2÷3) :1

4.2.1. The first stage

The first stage starts from September 6, 2020 to October 31, 2020, and a total of 110 grouting holes in 55 rings have been completed. The construction parameters were adopted based on the design scheme, and each grouting lift is close to the control value of 2 mm. Comparison results of damaged TBM tunnel deformation caused by micro-disturbance grouting in the first stage are shown in Fig. 9a–9c, and the tunnel deformation in the first stage (Fig. 9c) are determined by the difference at the beginning and end of the first stage construction. The micro-disturbance grouting construction in the first stage has obvious effect on the damaged TBM tunnel treatment from Fig. 9. The maximum track bed uplift is 13 mm at ring 113 in the first micro-disturbance stage, and the minimum uplift is 1.3 mm at ring 155. The average of the track bed uplift is 7.8 mm. The changes of horizontal displacement and convergence are relatively small, and no more than 4 mm in the first stage.

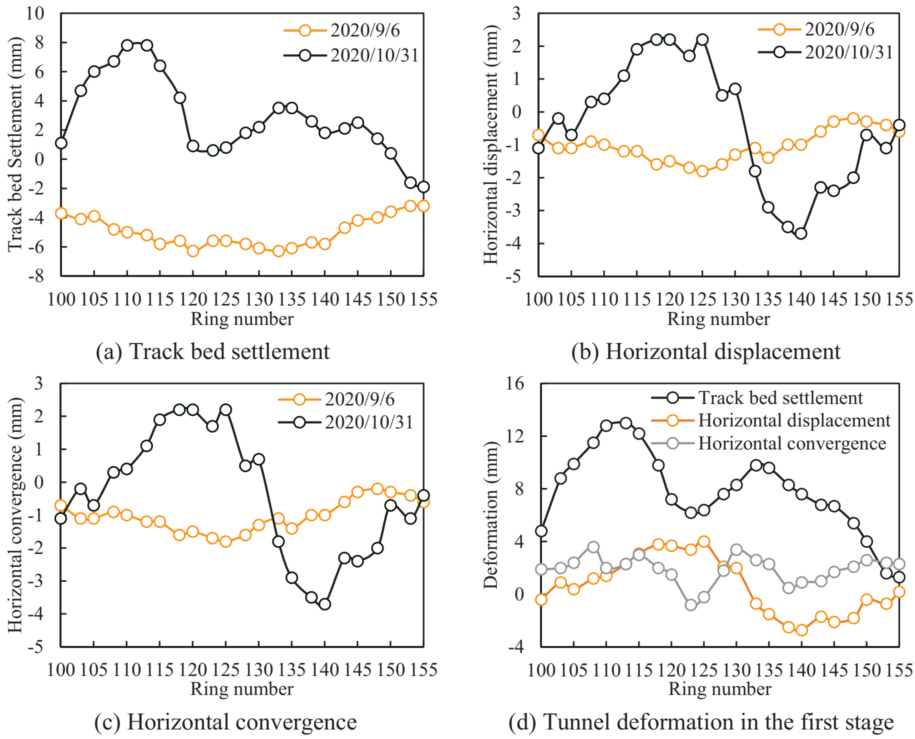


Fig. 9. Comparison results of damaged TBM tunnel deformation

4.2.2. The second stage

Based on long-term monitoring data of Hangzhou metro line 2, the maximum settlement area is located at ring 125 to ring 135. As of September 6, 2020, the maximum settlement of the line 2 is located at ring 130, and the value is –74.7 mm. After the grouting in the first stage, the maximum settlement of the TBM tunnel is –66.1 mm by October 29, 2020. The micro-disturbance grouting scheme of the second stage is the same as the first stage. The grouting construction of the second stage started from November 27, 2020 and ended on January 2, 2021. A total of 44 micro-disturbance grouting was carried out with the same grouting scheme in the first stage. The tunnel deformation at the end of the second stage grouting is shown in Fig. 10a, from which the track bed settlement shows obvious uplift deformation. On January 4, 2021, the maximum uplift is 8.9 mm at ring 130. The changes of horizontal displacement and convergence is small, which is similar to the first stage. Fig. 10b presents the deformation caused by the second stage grouting, which is the difference at the beginning and end of the second stage construction. The average of the track bed uplift caused by the second stage grouting is 5.35 mm, and the maximum uplift is 13.2 mm at ring 130. Both the horizontal displacement and convergence are less than 5 mm, which are relatively small.

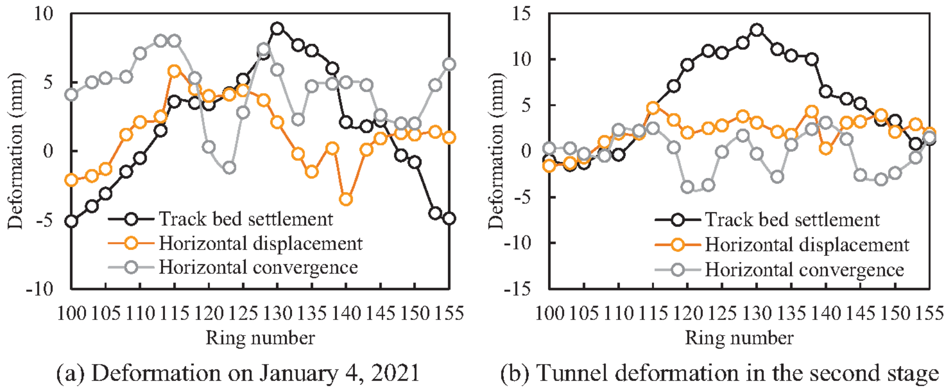


Fig. 10. Variation of the tunnel deformation caused by the second stage grouting

4.2.3. The third stage

Variation of the tunnel deformation after micro-disturbance grouting is presented in Fig. 11, which is the measure difference between January 4, 2021 and March 16, 2021. After the second stage of grouting, the large settlement of the TBM tunnel was still observed based on the monitoring data. Once again, the average of track bed settlement is –8.9 mm from Fig. 11. The maximum track bed settlement is –14.3 mm located at ring 130. The variation of horizontal displacement and convergence is relatively small. Therefore, the third stage grouting was proposed to meet the requirement that the settlement rate is less than ±0.02 mm/d for 3 months.

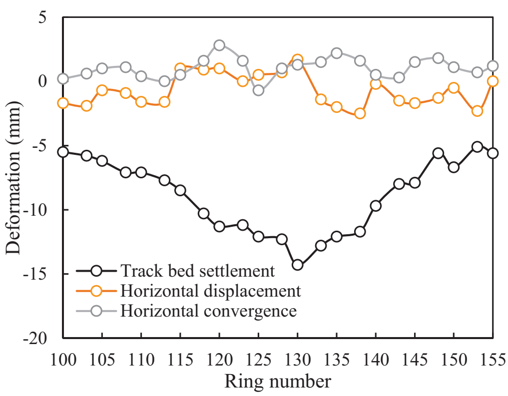
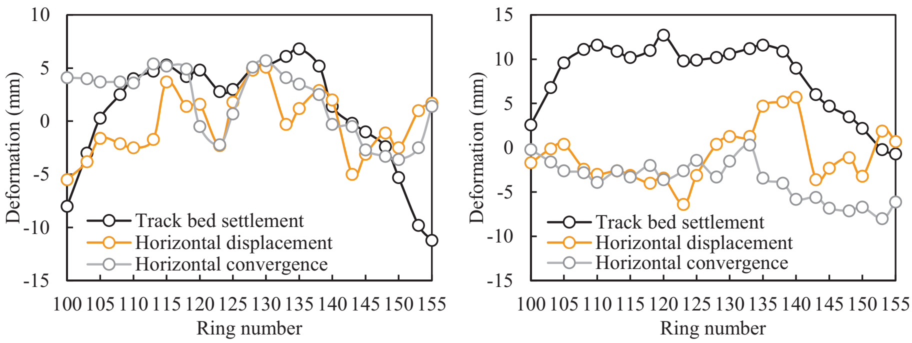


Fig. 11. Variation of the tunnel deformation after the second micro-disturbance grouting

The third stage micro-disturbance grouting starts from March 16, 2021 to July 17, 2021, and the grouting holes and scheme is the same as the first stage. The difference is that grouting depth is 24 m due to the thick muddy soil layer under the tunnel, which is deeper than the first stage. The tunnel deformation at the end of the third stage grouting is shown in Fig. 12a, from which the track bed settlement shows obvious uplift deformation. On July 17, 2021, the maximum uplift is 6.8 mm at ring 135. The deformation caused by the third stage grouting is shown Fig. 12b, which is the difference at the beginning and end of the third stage construction. The average of the track bed uplift caused by the third stage grouting is 8.05 mm, and the maximum uplift is 12.7 mm at ring 120. The maximum horizontal convergence is –6.1 mm at ring 155, and the horizontal displacement is relatively small.

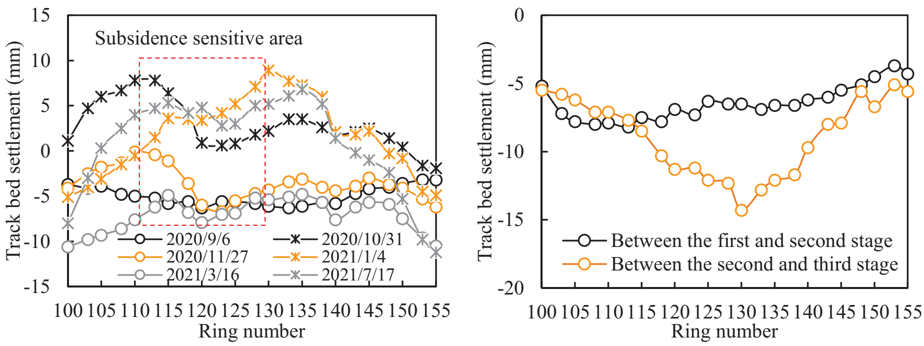


(a) Deformation on July 17, 2021 (b) Tunnel deformation in the third stage

Fig. 12. Variation of the tunnel deformation caused by the third stage grouting

5. Discussion

Figure 13 presents the track bed settlement under different grouting stages. From Fig. 13a, the maximum liftings of three grouting stages were 13 mm (ring 113), 13.2 mm (ring 130) and 12.7 mm (ring 120) respectively, from which the micro-disturbance grouting has significant effect on tunnel uplifting. However, the average track bed settlements at the start of the three stages were –5.0 mm, –3.6 mm and –7.2 mm, respectively. It means that once the grouting was completed, the remedial TBM tunnel quickly sink again. According to the previous monitoring results, the up-track tunnel at ring 115÷130 showed large convergence deformation before tunnel operation, and the mechanical performance of tunnel structure was weakened, which was easy to sink again (subsidence sensitive area). From Fig. 13c, the average of track bed settlement between the first and second stage (26 days) was –6.5 mm, and the maximum settlement was –8.2 mm at ring 113. The average settlement between the second and third stage (71 days) –8.9 mm, and the maximum settlement was up to –14.3 m at ring 130. Therefore, it is difficult to completely stabilize the thick mucky clay under the TBM tunnel by micro-disturbance grouting method. Combining with geological and site conditions, the phenomenon can be speculated for the reasons: (1) thick mucky clay layer under the TBM tunnel; (2) poor mechanical performance of tunnel structure; (3) heavy vehicle loads and surcharge above the tunnel.



(a) During different grouting stages (b) Between two stages

Fig. 13. Track bed settlement under different grouting stages

6. Conclusions

A case study on the remediation of a TBM tunnel adjacent to excavation carried out in the mucky clay layer was studied in this paper. In order to remediate the damaged tunnel and ensure the safe operation of the tunnel, the MJS and micro-disturbance grouting technology were designed carefully. Based on the field monitor results, the tunnel responses induced by remediation were analyzed and discussed, and the conclusions can be summarized as follows.

1. The MJS technology is mainly used to limit the horizontal movement of soil layer around the tunnel, and has little influence on the vertical settlement, horizontal displacement and convergence of TBM tunnel.
2. Combining with MJS and micro-disturbance grouting technology can effectively uplift the tunnel with excessive settlement. However, the characteristics of soil layer under the tunnel have a great impact on the treatment effect. When there is mucky clay under the tunnel, the treatment effect is difficult to maintain, and the repaired tunnel will sink again after grouting.
3. Geological conditions, the mechanical performance of tunnel structure and construction loads have great influence on the treatment effect of damaged TBM tunnel, which should be considered when civil engineers design remediation scheme.

Data availability statement

All data, models, and code generated or used during the study appear in the published article.

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Received: 2022-09-29, Revised: 2022-12-20