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Integrated Detection and Restoration Program of Water Gushing Induced Cracks in Shield Segments for Xi'an Metro in China

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ABSTRACT

Various forms of damage, such as cracks, breakages and dislocations of shield tunnel segments, exert negative effects on the structure stress during the operation of a tunnel. Based on the water gushing accident that occurred in a section of a shield tunnel between North Street Station and Wulukou Station of a Xi'an subway, the segment damage caused by water gushing and the sources of damage were analyzed through field investigation, ground penetrating radar (GPR) detection, ultrasonic crack detection and displacement monitoring. Two treatment schemes are proposed on that basis: the balloon injection for concrete structures (BICS) method was used in the treatment of segment cracks, while reinforcing steel mesh and high-performance polymer mortar were used to treat the dislocation. The evaluation indicates that the treatment plans have met the expectations. Thus, the treatments used for other similar engineering damages can be improved by the results of this study.

KEYWORDS: Xi'an metro, Segment, Monitoring, BICS, Shield tunnel, Crack.

INTRODUCTION

The segment will bear the pressure of a shield tunnelling machine, along with the pressure of the surrounding rock, grouting and ground water during construction and operation. The segment should also ensure the comprehensive performance of a tunnel regarding waterproofing, fire prevention and durability. Influenced by construction technology, operation load and operation environment, segments may suffer various forms of damage, such as cavity formation, cracks, breakage, dislocation and uplift, thus reducing the bearing capacity of the structure, shortening its life span and even reducing the stability or damaging the lining structure (Zhang et al., 2012; Yang, 2009). Thus, scientific analysis of the safety of a shield tunnel and developing means to properly address damage, such as cracks and dislocations, during construction and operation of a shield tunnel, are urgent issues (Yang, 2012).

Zhang and Zhang (2009) summarized the types and characteristics of shield tunnel damage and analyzed the causes of such damage and its influence on tunnel safety. After a theoretical study on the causes of damage, such as dislocation and crack of segments in a Shanghai subway, Ye et al. (2007) performed an engineering project to address the damage. Focusing on the segment crack of a shield tunnel caused by jack propulsion, Zhang et al. (2008), using a loading model of a segment combination, studied the distribution and transmission mode of stress in a segment. They found the main cause of the crack and proposed corresponding treatment measures. Analysis of the segment dislocation during propulsion based on numerical simulation revealed the

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changing law of dislocation, with the effect of jacking force exerted on the size and development law of dislocation was reported (Zhang et al., 2008; Li et al., 2011). Chen and Mo (2008, 2009), using the software packages of ANDINA and ANSYS, respectively, conducted numerical simulations on the segment crack during construction and operation. They discovered the rule of crack development near bolt holes and then proposed a project to increase the anti-cracking ability of concrete near bolt holes. According to the occurrence time of segment dislocation, Zhang (2007) categorized dislocation into three types: before installation, while construction is in progress and after construction. By analyzing the cause and prevention measure of dislocation, he arrived at the conclusion that the solution to underground cracks mainly relies on carbon fiber reinforced polymer (CFRP) and Balloon Injection for Concrete Structures (BICS). Lee and Chang (2013, 2001) developed two plans regarding the breakage and dislocation of subway segment in Taipei: 1) repairing the damaged segment by CFRP reinforcement to change the stress on the tunnel and 2) changing the damaged segment. Lai et al. (2006) performed a case study on the repair of the crack of a double-arch tunnel using CFRP reinforcement. The tunnel structure was safe according to the pressure sensor buried during construction. Buratti et al. (2013) proposed that steel fiber reinforced concrete could be used in reducing the formation of cracks of a tunnel lining.

The above-described research studies have achieved great progress on understanding the mechanism of a segment crack and its treatment method. However, few studies exist on the damage that water gushing causes to a shield tunnel segment or on repairing shield tunnel cracks using BICS. Because subway tunnels require improved performance regarding structure durability and waterproofing compared with mountain tunnels, studies are urgently needed on the state monitoring, analysis of the cause, treatment method and effect of segment cracks. Therefore, taking as an example the construction engineering of the Xi'an metro, this paper analyzes the segment damage caused by water gushing and the source of the damage through comprehensive monitoring and then proposes a proper treatment method. Finally, tests and evaluations are conducted on the effect of measurements used on improving the construction technology of a shield tunnel.

OVERVIEW OF WATER GUSHING ACCIDENT

A subway in Xi'an was constructed using the shield tunnelling method. The depth of the tunnel is 14 m. The distance between the bottom of the tunnel and the earth surface is 20.0 m. The distance between the centres of the tracks is 12.0 m. The tunnel is located in old loess and silty clay layers. The formation distribution from top to bottom is as follows: 3.45 m of plain fill, 1 m of new collapsible loess, 0.6 m of soft saturated loess, 2.2 m of new collapsible loess, 4.4 m of paleosol, 3.3 m of old loess and 3.5 m of silty clay (Figure 1).

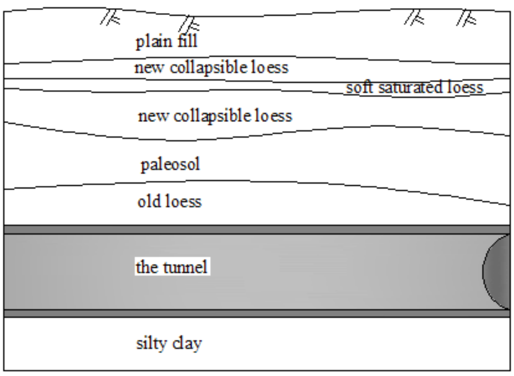


Figure (1): Typical cross-section of the shield tunnel

The segment at the east of Connecting Passage #1 suffers from sand gushing and water gushing. During the initial period of water gushing, the segment suffers from cavity formation and bears an uneven distribution of pressure, directly leading to damage, such as crack and dislocation on segments 481-511.

The Course of Water Gushing

Connecting Passage #1 was excavated from the left line of the tunnel to the right one. The excavation and primary lining used the top and bottom pilot tunnelling method. After the top pilot tunnel broke through on Dec. 9, 2011, the bottom pilot tunnel started to excavate at 3 a.m. the next day. While installing the first steel grating, the underground pipeline was damaged. As a result, the back of segment near the tunnel bottom, 10 m east of the connecting passage, began to gush water and sand. The location of water gushing is shown in Figure 2 and the corresponding stake number is ZDK20+616. However, plugging the hole with sand bags was not effective. The water level at the connecting passage of the left tunnel reached 2.5 m at 10 a.m. that day. The water inflow was approximately 350 m^3 every hour. Until Dec. 24, 2011, the total amount of water inflow was approximately 120,000 m^3. The sand carried out by the water was approximately 300 m^3. The scene of the accident is shown in Figure 3.

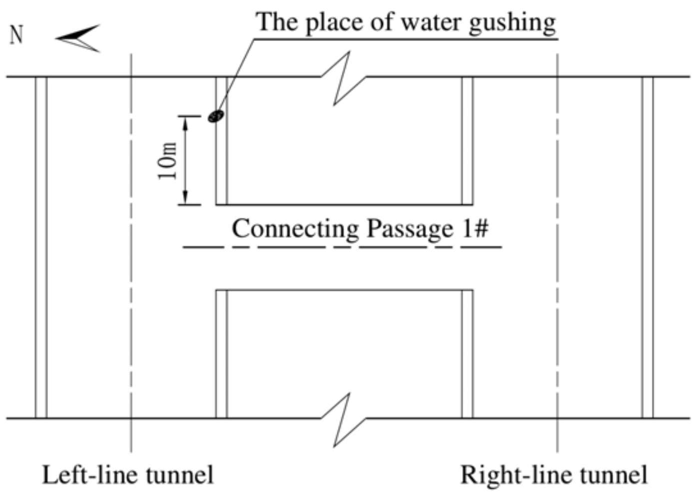


Figure (2): Location of water gushing

Measures Taken for Water Plugging

First, the sand bags were piled up at the location where the water started to gush to reduce the head pressure. This pressure reduction could protect the sand from washing away and prevent cavities from forming in the connecting passage. The second step was supporting the top pilot tunnel. Next, two 4-m anchor pipes were buried at the water gushing hole and the hole was simultaneously sealed using without-shrink two-shot grouting (WSS). However, the amount of water inflow did not decrease after a long time of grouting. Thereafter, an anti-grouting wall was built at the tunnel portal to drain away the water gradually. Next, grouting wells were drilled at Point Location 5 of Circle 493 of the right tunnel and Point Location 7 of Circles 484, 486 and 488 of the left tunnel to block off the upstream water. As the segments near the grouting well changed abruptly, some of the segments suffered from cracks, dislocation and breakage. The point and depth of each grouting well were adjusted timely according to the monitoring results. Each grouting well was drilled to the silty clay layer under the left tunnel, so that it could be lifted by the grout. Hence, the water was stopped by squeezing the gap between sand layers. The pressure was kept at approximately 1.0 MPa while grouting. Monitoring results indicated that the segment significantly rose, so the grouting was immediately stopped.

Figure (3): Scene photos of tunnel water gushing

DETECTION OF GPR

The earth's surface within ZDK20+530 ~ ZDK20+620 subsided after the accident. The subsidence mainly occurred at the left tunnel. GPR detection was used on the earth's surface at an antenna frequency of 100 MHz; the line layout is shown in Figure 4 and the waveform of Line 3 is shown in Figure 5. The following conclusion can be reached through the analysis of Line 3: because strong reflections are detected at 2-4 m and 13-23 m within ZDK20+590～ZDK20+620, the stratum is incompact or saturated. There must be a differential settlement in the stratum because of the line-up fracture in the above-mentioned stratum. Since there are no strong reflections detected or fractures exhibited in the line-up, the stratum within ZDK20+530~ZDK20+590 is normal. The survey lines indicate that the stratum within ZDK20+590~ZDK20+620 suffers from differential settlement and is partly incompact or saturated. The strata in Line 5, Line 6, Line 7 and Line 8 suffer from differential settlement and are partly incompact or saturated; the strata in Line 4 and Line 9 are equally distributed and show no obvious abnormity. The stratum influenced by water gushing ranges from 13 m to 23 m in depth and the surface area of the stratum is shown in Figure 4.

MONITORING OF SEGMENT CRACK AND DISLOCATION

Crack Detection

The depth of the crack can be determined by measuring the crack width using a calibrated magnifying glass, positioned with handheld reinforced concrete detection radar and measurements using ultrasonic waves. The principle of ultrasonic detection is shown in Figure 6. As shown in Figure 7, cracks mainly range from 20 mm to 60 mm in depth; among those, 45 range from 20 mm to 40 mm and 32 range from 40 mm to 60 mm. The cracks primarily range from 0.05 mm to 0.3 mm in width; among those, 93 are between 0.05 mm and 0.2 mm, 14 are between 0.2 mm and 0.3 mm, 10 are between 0.3 mm and 0.5 mm and 4 are over 0.5 mm. The largest crack appears at the adjacent plate of L2B5 on Circle 495, with a maximum width of 1.0 mm and a maximum depth of 134.9 mm (Pan, 2012).

Investigation on Dislocation

Circular dislocations among different plates in one circle decrease the contact area between the plates. Among the 11 circular dislocations, the largest one is 2 cm. Water gushing and sand gushing lead to different longitudinal dislocations of the segment. The largest dislocation, which is located in Circles 492 and 493 of the tunnel, is approximately 8 cm and the effective height of the section is 14 cm.

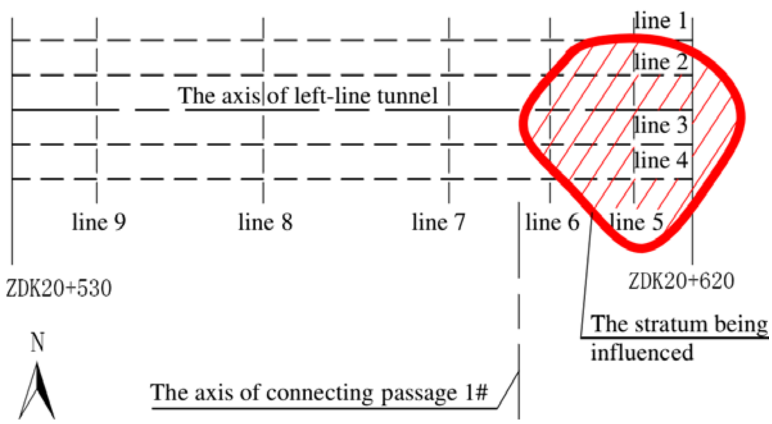


Figure (4): Layout of GPR measuring line

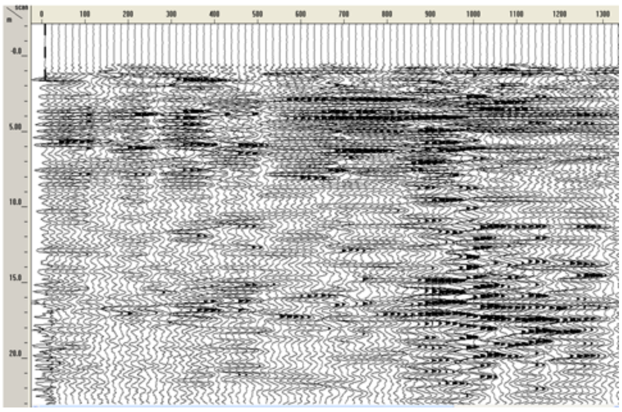


Figure (5): Wiggle waveform of GPR

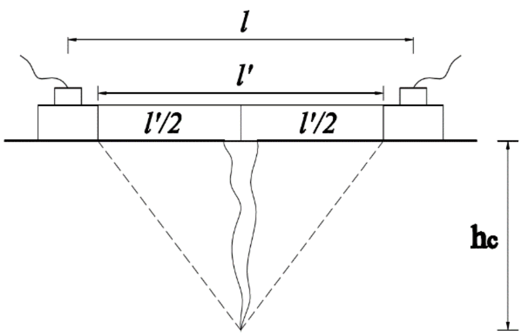


Figure (6): The principle of ultrasonic detection

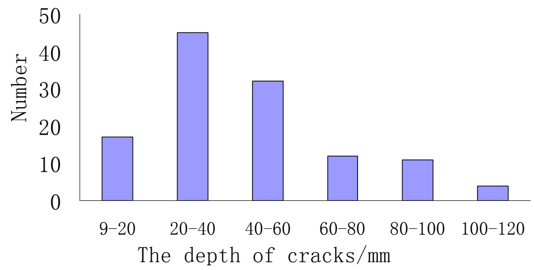


Figure (7): Statistical results of the cracks

ANALYSIS AND MONITORING ON DISPLACEMENT

After the water gushing accident, the frequency of monitoring the tunnel was increased to two-hour intervals by monitoring the convergence and deformation, the displacement of the vault and the land subsidence. Timely analysis was conducted on the monitoring results to set 7 sections at the settlement point of vault, 14 sections at the convergence and deformation of the segment and 8 rows at the subsidence of the land (Pan, 2012; Xue et al., 2014).

Due to environmental limitations, some of the sections could not be monitored. According to the monitoring results (Figure 8), at the beginning of water gushing, Section C of the tunnel, affected by the hogging moment, was pulled from the outside and pushed from the inside. The soil around the segment fell apart, failing in a manner that offered sufficient subgrade reaction for the segments. As a consequence, the convergence value continued to increase as the segment moved towards the outside. As grouting continued, the convergence value decreased, because the subgrade reaction was replaced by the grouting pressure. As grouting continued, the grouting pressure on the segment surpassed the subgrade reaction, leading to additional stress on the structure. Pushed from the outside and pulled from the inside, the segment moved toward the inner side of the tunnel. The lateral displacement of the segment totalled 4.5 cm when grouting was complete. The segment subsided after water gushing. Because the subsidence did not last long and the volume of subsidence was small, the segment started to rise two days after grouting. The segment rose rapidly from Dec. 16 to Dec. 24. The maximum of longitudinal displacement was 5.5 cm.

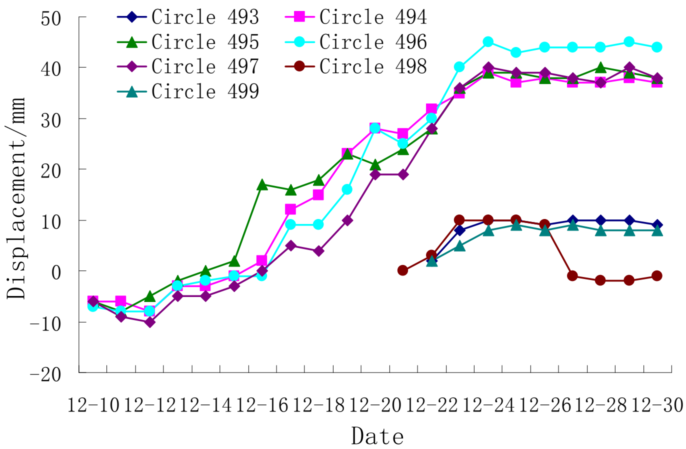


Figure (8): Vault settlements *vs.* time

TREATMENT OF SEGMENT DAMAGE

Treatment Scheme

As 77% of the segment cracks range from 20 mm to 60 mm in depth and from 0.05 mm to 0.2 mm in width, repair instead of reinforcement is required to ensure the structural durability and water proofness of the tunnel. For that reason, the BICS method was used in repairing the segment cracks of this tunnel. BICS is a construction method patented by a Japanese company named SHO-BOND. Adding intumescent resin into a synthetic rubber injector generates a constant pressure of approximately 300 kPa that continuously presses the polymer resin into the crack gradually so it can reach the depth of the crack. The advantage of using the resin is to press the air in the gap into the capillary tube of the concrete. Because the air is exhausted naturally through the concrete, air-lock is effectively avoided. Therefore, the grouting material can be effectively injected into the tiniest end of the capillary tube. As a result, the structure is perfectly restored. More specifically, the advantages of BICS method compared with other methods in crack treatment are as follows:

(1) Grooves and corners in cracks can be completely injected with the grouting material and the grouting material can penetrate into the crack tip with the width of 0.02 mm. The strength of post-curing liquid cement is larger than that of concrete parent material.

(2) Simple and reliable pressure control process can be achieved. Particular rubber materials and rigorous technology design can ensure the constant pressure of the injector. Moreover, the waste is avoided effectively because of the inner core design.

(3) The working time of treatment process can be largely shortened and there are no technical requirements for workers.

(4) Cracks in different structures including permeable cracks and dynamic cracks can be almost repaired thoroughly by the fast sealing material and curing grouting material without shrink.

Additionally, the construction process of BICS method is divided into 7 steps, which are:

(1) Surface Treatment

The dirt and dust within the scope of 5 cm around the crack on the concrete surface should be removed using grinding wheel and wire brush.

(2) Bonding Injection Pedestal

Injection pedestal is bonded in the center of the crack using the sealant BK-SEAL.

(3) Sealing up Cracks and Curing

The sealant BK-SEAL is injected around the injection pedestal along the trend of crack. After that, the BK-SEAL curing will be conducted until setting and hardening.

(4) Installation of the Injector

The injector junction should be tightly installed on the injection pedestal.

(5) Injecting Operation

The main agent and sclerosing agent of BL-GROUT are mixed. The feed tube joint is connected to injector junction and then the injecting operation can be performed. The injecting operation should be stopped when the outer diameter of injector has increased to an acceptable value.

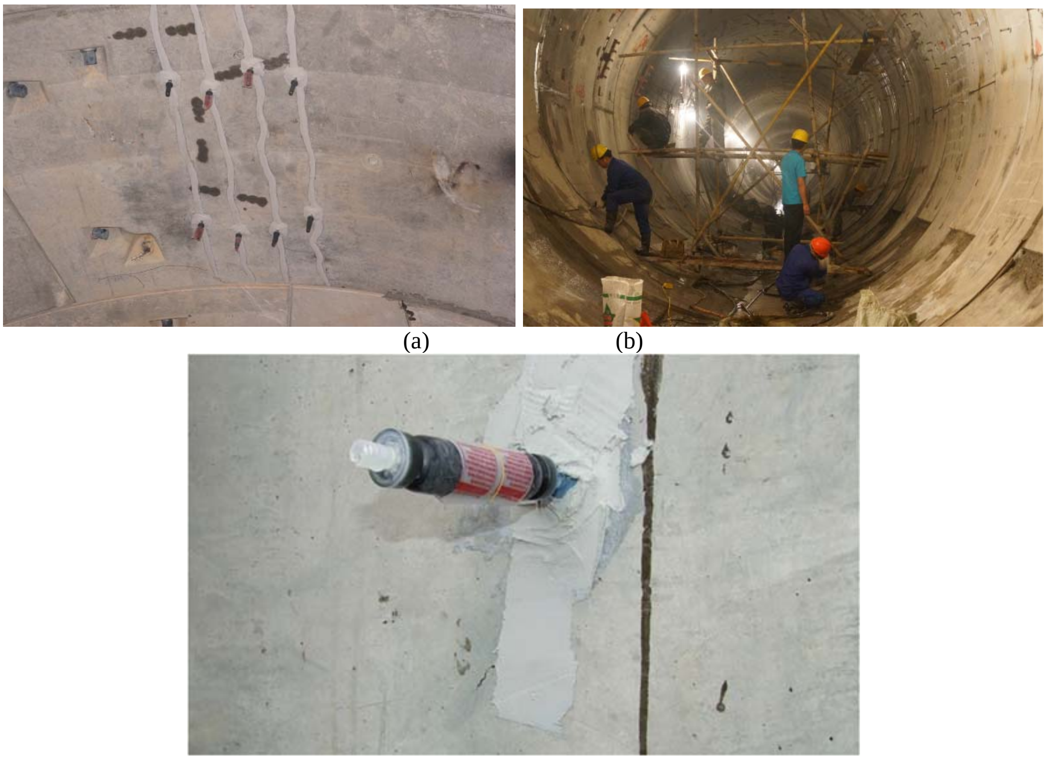
(6) Solidification and Curing of Grouting Material

(7) Surface Cleaning

After solidifying and curing, the injector can be removed using hammers and chisels. And the concrete surface should be burnished using grinding wheel.

The progress of field construction is shown in Figure 9.

The longitudinal dislocation of the segment affects the safety of the structure. The effective height of the section of the largest dislocation is 14 cm. Hence, the dislocation should be reinforced in its bearing capacity of stress through high-performance polymer mortar CARBO100-II and reinforcing steel mesh. The structure is shown in Figure 10.



(a) (b)

(c)

Figure (9): Scene photos of BICS construction

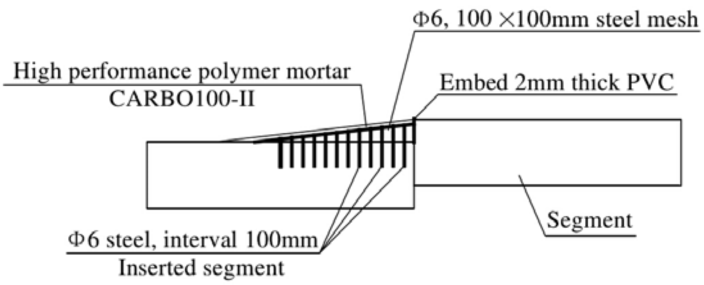


Figure (10): Strengthening scheme of segment dislocation

Evaluation of the Treatment Effect

The contrast of the appearance before and after treatment is shown in Figure 11. The surface of the segment is relatively smooth after the treatment and the filling is dense in the cracks. To study the treatment effect of segments, the ultrasonic crack detector was used to detect the segment after treatment. The finite element method was used to analyze the stress of the segment.

(1) Segment Ultrasonic Detection after Treatment

Using the ultrasonic method, a comprehensive analysis is conducted on the contrast between parameters (such as transit time, sonic velocity, amplitude, wave width,… and so on) and their standard reference value. The wave velocity at the repaired crack is consistent with the average one at the standard reference point. This result indicates that both the surface and the inside of the segment are densely filled.

Therefore, the treatment works well (Lai, 2012).

(2) Finite Element Simulation

To study the security of the tunnel, the segment of Circle 495 was analyzed by performing a simulation using ANSYS. The segment thickness at the crack location is consistent with the design thickness after repair. The thickness of the segment is reduced by 0.9 times (27 cm) based on the simulation to ensure the safety of the tunnel. The simulation results are shown in Figures 12 and 13.

(a) Image before treatment (b) Image after treatment

Figure (11): Comparison shots before and after treatment

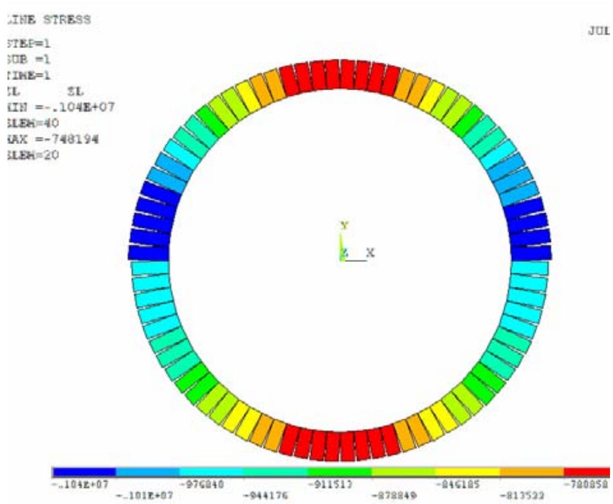


Figure (12): Axial force of the segment after treatment

The segment stress is relatively uniform after treatment and the maximum axial force is 1040 kN. The compressive strength of the segment is only 3.8 MPa. It is far less than the allowable compressive strength (36.5 MPa) of the C50 concrete. The segment complies with the safety requirements. In addition, the safety factor of the reinforced concrete structure under permanent load and variable load should be greater than 2.0. The safety factors of the segment (Figure 13) after treatment are all greater than 2.0. As a result, the segments meet the strength requirements (Ye et al., 2014; Lai, 2012).

(3) Preliminary Cost Evaluation

The segment structure will not be damaged in the restoration process employing the BICS method. There are no technical requirements for operating workers to finish the injecting process, which can largely shorten the working time and the number of workers. Moreover, the waste is effectively avoided because of the inner core design. Generally speaking, the treatment cost of BICS method is only 16-20 dollars per meter, while the treatment cost of chemical grouting method is 80-100 dollars per meter with the fussy procedure. Based on the actual cost of BICS method in this project, it can be seen that the use of BICS method can cut down unnecessary expenses to a a large extent.

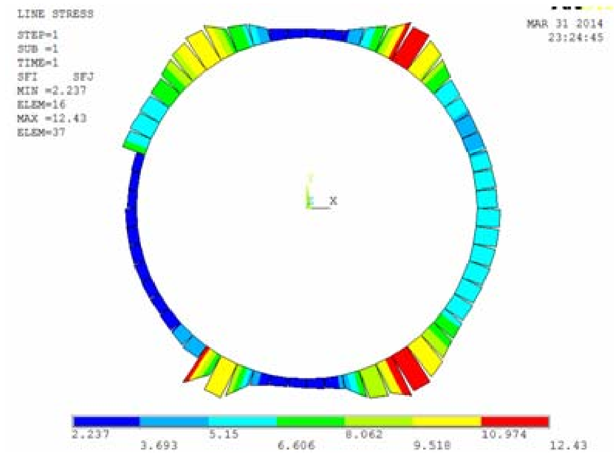


Figure (13): Safety factor of the segment after treatment

CONCLUSIONS

(1) The shield tunnelling method was used for the Xi'an metro construction. The segment at the east of the Connecting Passage #1 in the subway suffers from water gushing and sand gushing. The cavity formation at the beginning of water gushing, together with the additional load caused by the grouting pressure, lead to an uneven distribution of pressure on segments. As a result, segments within a range of 45 m suffer from damage in the form of cracks and dislocations. The largest crack appears at the L2B5 adjacent plate of Circle 495, with a maximum width and depth of 1.0 mm and 134.9 mm, respectively.

(2) Protecting the stratum from water and soil loss by blocking off water and filling the cavity is the main purpose of grouting at the initial stage. The subsidence caused by water gushing can be filled *via* compacting the soil. As the grouting continues, the grouting pressure on the segment will surpass the subgrade reaction and the segment will move towards the inner side of the tunnel. When the grouting is complete, the lateral displacement of segment totals 4.5 cm and the maximum longitudinal displacement is 5.5 cm. The major reason for damage, such as cracks and dislocation, is the cavity caused by water gushing and the additional load caused by grouting pressure.

(3) The breakage of the underground pipeline that leads to water gushing is externally caused. To avoid such damage, one effective measure is to conduct an accurate mapping of the underground pipelines before construction.

(4) Two different solutions were proposed by analyzing the state of damages. The BICS method is proposed for use in the treatment of segment cracks, whereas reinforcing steel mesh and high-performance polymer mortar are proposed for use in the treatment of dislocation. These treatment methods were found to be efficient and reliable. The results obtained

provide a reference for similar engineering damage treatment.

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