Structural monitoring and analyses on the stability and health of a damaged railway tunnel

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Abstract. In this paper, a study of stability and health of a newly-built railway tunnel is presented. The field test was implemented to monitor the secondary lining due to the significant cracking behaviors influenced the stability and health of the tunnel structure. Surface strain gauges were installed for monitoring the status of crack openings, and the monitoring outputs demonstrated that the cracks were still in the developing stage. Additionally, adjacent tunnel and poor condition of surrounding rock were identified as the causes of the lining cracking by systematically characterizing the crack spatial distribution, tunnel site and surrounding rock conditions. Reconstruction of partial lining and reconstruction of the whole secondary lining were designed as the maintenance projects for different cracking regions based on the construction feasibility. For assessing the health conditions of the reinforced lining, embedded strain gauges were set up to continuously measure the strain and the internal force of the reconstructed structures. For the partially reconstructed lining, the outputs show the maximum tensile elongation is 0.018 mm during 227 days, which means the structure has no obvious deformation after maintenance. The one-year monitoring of full-section was implemented in the other two completely reconstructed cross-sections by embedded strain gauge. The outputs show the reconstructed secondary lining has undertaken the pressure of surrounding rock with the time passing. According to the calculated compressive and tensile safety factors, the completely reconstructed lining has been in reliable and safe condition during the past year after reinforcement. It can conclude that the aforementioned maintenance projects can effectively ensure the stability and health of this tunnel.

Keywords: field test; secondary lining; cracks; maintenance; monitoring

1. Introduction

Mountain tunnel has an essential role in the underground structures of highway and railway projects, and assessment and maintenance become an important task in these transportation infrastructures. Once structural defects occur in the tunnel, assessment and maintenance will be a tedious and resource consuming operation. Especially, how to ensure the stability and health of the damaged railway tunnel become a serious challenge with the rapid development of tunnel construction (Sandrone and Labiouse 2011, Zhao et al. 2019a).

Although cracking is the most common outcome of a damaged tunnel lining structure (Chiu et al. 2017, Wang 2010, Zhao et al. 2019b), the damages caused by cracks cannot be ignored. The cracks usually present with different forms caused by various affecting factors (Asakura 2003, FHWA 2015, He et al. 2009, Lai et al. 2017, Yamada et al. 2007). Various studies have assessed the impact of cracks in the tunnel, and this work was mainly performed through tunnel-wide visual observations by inspectors. With the development of visual inspection, a great deal of recent research into crack has focused on automated methods (Doulamis et al. 2018, Protopapadakis et al. 2018). The image processing (Liu et al. 2002a) and machine learning (Loupos et al. 2015, Protopapadakis et al. 2019, Ren et al. 2020) techniques ensure the successful implementation of automated monitoring such as image-based (Yu et al. 2017, Zhang et al. 2014), robot-based (Protopapadakis et al. 2016, Loupos et al. 2018) and UAVs’ (Tan et al. 2018) monitoring. Therefore, the aforementioned techniques can make the construction or selection of crack become a reliable work, which is always influenced by a great variety in concrete surface defect types. For this reason, the application of automated speedy inspection and proactive maintenance procedures is a reliable method, which would help minimize tunnel closures and provide accurate health assessments.

In most cases, lining cracking may cause potential hazards such as tunnel leakage (Yuan et al. 2013, Yuan et al. 2017), concrete spalling (Yu et al. 2013), steel corrosion et al., which not only may reduce the capacity of lining structure but also do harm to the operational safety. As
reported, for the several construction and operation of tunnels, the cracking of the secondary lining represents a great impact on the health of the tunnel (Liu et al. 2020a, Liu et al. 2020b). Consequently, a better understanding of the status and effect of lining cracking is absolute necessity for maintenance. Field test can be considered as an effective method to monitor the structural safety and health. Among them, measuring structural deformation (Qiao et al. 2016, Gao et al. 2018), structural internal force (Milczewski et al. 2012) and changes of surrounding environment (Li et al. 2008, Xing et al. 2017) are the most common projects applied in field test. Monitoring projects not only can give guidance for safe construction and operation but also can avoid risk and hazards. For this reason, considering the hazards caused by cracks, the monitoring of structural health is particularly important. Nevertheless, few studies concentrated on the stability of the strengthened lining for the need of timely tunnel operation.

In this paper, the detailed research work presents a comprehensive scientific engineering method of monitoring, investigation, design, maintenance and evaluation for a damaged tunnel. Based on the results of the field before and after maintenance, the stability and health of the secondary lining are analyzed and discussed.

2. Engineering background

2.1 Profile of the newly built railway tunnel

The newly-built tunnel is a single line railway tunnel in Guizhou Province, China (Fig. 1). The longitudinal length is 1627 m and the maximum burial depth is 107 m. The complex topographical conditions cause asymmetrical loading on the tunnel trunk in several places. The principal strata, where the newly-built railway tunnel situated, is comprised of monoclinic limestone and mudstone intercalated with limestone. Small amounts of shale intercalated with limestone and coal seam from the late Permian period are found nearby the tunnel and the adit. It can be obtained that the surrounding rock is developed with joint fissures and that the major classification of underground water is bedrock fissure water.

The lining cracking was observed in several regions in the tunnel, and the damaged lining types include IIIb, IVb and Vc as shown in Fig. 2. Among them, the most seriously damaged lining is IVb-type lining, which has a height of 8 m and a width of 5.5 m. In the primary lining, a grid steel frame is arranged with 1.3 m spacing; a round bar with a 6 mm diameter is adopted as the steel mesh with a spacing of 0.25 m×0.25 m in the longitudinal and circumferential directions. The shotcrete used in the primary lining is 0.15 m thickness with a 25 MPa (MOHUC 2015) compressive strength. The grouted anchor rods are fixed in the surrounding rocks of the main tunnels after excavating with
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2.2 Profile of the lining cracking

Fig. 3 demonstrates the distribution of cracks. Longitudinal cracks and reticular cracks were observed as the typical cracking patterns. The cracks were found around side-wall regions from 1 m to 3.5 m above the train track and the crack openings were from 0.5 mm to 4 mm. The longitudinal crack initiated at right side-wall regions and it could be seen that this crack linearly and continuously spread along the longitudinal direction of the secondary linings; the maximum crack opening was approximately 4 mm, and the crack depth was greater than 0.2 m, as measured by the drilled samplings (Fig. 4(a)). Moreover, the maximum height of the reticular cracks was 6 m (Fig. 4(b)), and all of the reticular cracks were treated by injecting epoxy resin or cement slurry. There were no cracks found at the ballastless track.

3. Crack measurement of the damaged lining

3.1 Experimental scheme for crack measurement

In order to identify the development status of the cracks (most of the crack openings exceed the limited value recommended by MOHUC 2015), the monitoring project of crack opening was implemented in field. The surface strain gauges were selected as the sensor element to measure the crack opening, which can effectively avoid the disturbances caused by construction, lighting and other factors. In the field test, 6 monitoring points on the longitudinal crack were monitored and surveyed every 20 m. In addition, other 9 monitoring points on the reticular crack were monitored and surveyed on both right and left side-walls. 15 surface strain gauges installed at both side-walls from mileage DK267+430 to DK268+069, which are considered of crack positions, initial opening values, crack types and supporting parameters of lining. The arrangement of the monitoring points is placed as the red legends in Fig. 3. Moreover, due to operation of this tunnel was scheduled for three months later, the crack monitoring project must be finished within 40 days before maintenance.

All of the sensor elements were provided by Changsha Kingmach Hightechnics Co., LTD. The surface strain gauge with temperature compensation function (JMZX-212HAT) used in monitoring cracks is shown in Fig. 5(a), which has 2 με precision and 1 με resolution. The surface strain gauge has a±1500 με measurement ranges with 0.5% precision and 129 mm gauge length, and the installation instruction is illustrated in Fig. 5(b).

The initial value of the strain needs to be recorded when the sensor is stable, and then the value of the strain changes once the structure is affected by the force or other conditions. The variable quantity of the true strain can be calculated as following equation

$$\varepsilon = (\varepsilon_i - \varepsilon_0) + (T_1 - T_0)(F_m - F_e)$$

where $\varepsilon_i$ is the current measured value, in $\mu \varepsilon$; $\varepsilon_0$ is the initial value; $T_1$ and $T_0$ are current measured temperature and initial temperature respectively; $F_m$ is linear expansion coefficient of steel string, in $\mu \varepsilon/\degree \mathrm{C}$; $F_e$ is linear expansion coefficient of epoxy resin, in $\mu \varepsilon/\degree \mathrm{C}$.
3.2 Results and analysis of crack openings

Monitoring of crack opening lasted 37 days and discontinued due to the following maintenance work. Fig. 7 demonstrates the monitoring results, from which the variation values and change rates of crack opening can be calculated by comparison of the specified two monitoring periods. It can be obtained from the diagrams that the maximum variation value of crack opening is 0.247 mm. Moreover, all the variation value of crack opening at the measuring points (No. 2-No. 5) around the right side-wall are above 0.16 mm. The change rates of opening of these 4 measurement points are greater than 0.06 mm/d. In addition, variation values of crack opening in No. 11 and No. 12 are above 0.17 mm, and the change rate of opening was greater than the 0.06 mm/d. The monitoring outputs show that the crack openings still increase (except No. 9, No. 10 and No. 14, which were destroyed by workers), so there was a tendency for further damages of the tunnel lining. Consequently, the tunnel structure was under risk and appropriate maintenance should be implemented.

4. Maintenance works

4.1 Causes of lining cracking

A specific investigation was conducted to search for cracking inducements in this tunnel. For the purpose of checking the quality of concrete, two drilled samples of the lining concrete with a 93 mm diameter and 103 mm height were collected. Tested compressive strengths of these drilled cores are 32.4 MPa and 30.8 MPa, which meets the design requirements. In addition, another drilling test was applied to the inverted arch regions of the tunnel; the design depth from the bottom of the cable trough to the bottom of the inverted arch is 1.1 m, and the drilling depth is 1.9 m. The result of the drilling test shows that there was no weak intercalation around the inverted arch regions. Ground penetrating radar was used in non-destructive testing, and there was no cavity behind the lining. According to the aforementioned investigation, the most obvious finding is that the construction factors are not the causes of lining cracking. Further investigation shows that concrete collapsing, cracking and large deformations, etc., were not observed during the construction period.

After excluding the aforementioned factors, two causes are considered as the major inducements of lining crack as follows.

(1) Adjacent high speed rail tunnel

An adjacent high speed rail tunnel is located west of this newly built railway tunnel (Fig. 8(a) and Fig. 8(b)). Importantly, the minimum altitude difference of the railway tracks is 2.7 m and the minimum spacing between tunnel central lines is 14.8 m. It is widely accepted that the small clear-distance between two parallel tunnels plays a significant role in the stability of lining structure.
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(2) Poor condition of middle rock pillar

Fig. 9 demonstrates the condition of the middle rock pillar between the aforementioned two tunnels, which contains the exposed surrounding rocks behind the shotcrete and the drilled cores. It can be observed that the surrounding rock developed with joint fissures (Fig. 9(a)), and the drilled cores of the surrounding rock are broken as shown in Fig. 9(b). The surrounding rocks near the tunnelling faces were oblique with 45° angle, which led to a geological asymmetrical load on the tunnel.

4.2 Practical maintenance works

Because most of the crack openings still increase, maintenance works must be applied as soon as possible. Injecting epoxy resin or cement slurry was implemented for treating tiny reticular, surface longitudinal crack or circumferential crack.

According to investigated inducements of lining cracking, the influence of adjacent tunnel cannot be solved, so strengthening the rock mass condition is the only way. Besides, most of the cracks almost reached half of the lining thickness, the bearing capacity of the secondary lining cannot be ensured. Thus, there are two other maintenance methods implemented in the lining structure where crack openings still increase.

(1) Demolition and reconstruction of partial lining

Demolition and reconstruction of partial lining was implemented under the condition of only one side-wall appeared cracks (DK267+430 to DK267+569) or no dense
cracks (DK267+836 to DK268+018 and DK268+058 to DK268+074). The cracked lining structure could not bear loadings, but the other uncracked parts of the lining did not lose the bearing capacity. For this reason, partial lining structures need to be demolished and reconstructed. The detailed maintenance scheme can be summarized as, (1) demolishing 15 cm thickness cracked lining; (2) reconstructing the secondary lining by reinforced concrete with single-layer reinforcing mesh (Fig. 10(a)) and backfilling to the original designed surface; (3) using embedded steel bars to keep a connection between new and old concrete; (4) setting 25 mm×4 m mortar bolt (Fig. 10(b)) in arch foot with 1 m spacing in axial direction; grouting cement slurry to improve rock mass condition.

Demolition and reconstruction of the whole secondary lining were applied in the damaged regions with mileage from DK267+705 to DK267+741 and DK268+015 to DK268+051. Many irregular network cracks appeared in these regions and the crack openings still increase. The cracked area is larger than the uncracked area region, and the bearing capacity of the lining structure could not be guaranteed. Due to the damaging behaviors caused treacherous hazard to the rail line, whole lining structures need to be demolished and reconstructed.

The detailed maintenance scheme can be summarized as, (1) demolishing the whole secondary lining structure (Fig. 11(a)); (2) reconstructing the secondary lining by reinforced concrete with double-layer reinforcing mesh and backfilling to the original designed surface (Fig. 11(b)); (3) using embedded steel bars (IIIb-type lining structure) or steel bar welding (Vc-type lining structure) to establish connection between new and old lining structure; (4) setting 25 mm×4 m mortar bolt in arch foot location with 1 m spacing in axial direction; grouting cement slurry to improve rock mass condition.

5. Measurement of reconstructed lining

5.1 Embedded strain gauge

An internal force monitoring of the strengthened lining is adopted to evaluate the effectiveness of maintenance works. The benefit of this approach is that the displacement and bearing capacity of the lining structure can be easily obtained, and long-term force state of the structure can be identified and characterized. The strain of the secondary lining is measured via embedded strain gauge (JMZX-215HAT), which has ±1500 µε measurement ranges with 0.5% precision and 146 mm gauge length as shown in Fig.12. The designed theory of the embedded strain gauge is same as the theory of the surface strain gauge.

5.2 Experimental schemes for reconstructed lining

Two different schemes were applied in the reconstructed lining as shown in Fig. 13, which are corresponding to the reconstructed partial lining and whole secondary lining respectively. The first experiment (Fig. 14(a)) is used to measure the internal strain of new concrete, in which the
embedded strain gauge is bonded on annular reinforcement with tie wire. Another experiment (Fig. 14(b)) is used to measure the internal force of concrete, in which a pair of embedded strain gauges are bonded on the lateral and medial annular reinforcements respectively.

### 5.3 Experimental outputs and discussion

#### (1) Reconstruction of partial lining

Strain monitoring lasts 277 days till now, and the time-history diagram of each measuring point (as the blue legends in Fig. 3) is shown in Fig. 15. In Fig. 15 there is a clear trend of stable, the maximum tensile strain $117 \mu$ε in No. 4 and the maximum compressive strain $-98 \mu$ε in No. 2. From this data, it can be obtained that the total deformation of the reconstructed lining is 0.018 mm tensile elongation and 0.016 mm compressed length. The most striking result to emerge from the data is that there is nearly little deformation of the strengthened lining. Taken together, these results suggest that the force state of the reconstructed partial lining is stable, and the factors lead to crack opening increasing have been eliminated by the maintenance work.

#### (2) Reconstruction of whole secondary lining

Strain monitoring project of the reconstructed secondary lining last 328 days and 347 days till now (with mileage DK267+723 and DK268+045 as the yellow legends in Fig. 3). The time-history diagram of each measuring point is shown in Fig. 16. Interestingly, the strain continuously and rapidly changes after the sensors were installed. This phenomenon was caused by the concrete hardening during the casting process, and the shrinkage and solidification of concrete may affect the test data. As Fig. 16(b) shows, there is a significant saltation between 105 days and 121 days in No. 7 measurement point of cross-section DK268+045. This phenomenon should be caused by structural extrusion and adjustment between concrete and bonded strain gauge. Except for the No. 7 and No. 8 measuring points, the remaining measuring points of the secondary lining are
under pressure condition. For this reason, it can be obtained that the secondary lining began to bear loadings from surrounding rock with the extension of time. Taken together, the monitoring data have adjusted to a relatively stable range and the strain value changes slowly.

In order to assess the safety and health of the reconstructed lining, the aforementioned data should be transformed into internal forces. Fig. 17 and Fig. 18 show
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the internal forces of cross-section DK267+723 and DK268+045 in 5 different monitoring time respectively. For the purpose of obtained intuitive engineering data, a reliable evaluation criterion should be used to establish the assessing method.

Safety evaluating criterion of lining structure is based on railway tunnel design code (MOT 2001). For the reinforced concrete lining structures, when $x \leq 0.55 h_0$, the section strength can be calculated according to the following formula. The schematic diagram for the calculation is shown in Fig. 19.

$$K_1 N \leq R_w b x + R_g (A_e - A_g)$$  (3)

$$K_2 M \leq R_w b x (h_0 - x / 2) + R_g A_e (h_0 - a)$$  (4)

At this point, the position of the neutral axis is determined as follows

$$R_g (A_g e \mp A_e e) = R_w b x (e - h_0 + x / 2)$$  (5)

When the axial force $N$ acts between the center of gravity $A_g$ and $A_g'$, the second term on the left side of the formula takes a positive sign; when $N$ acts outside the center of gravity of $A_g$ and $A_g'$, the negative sign is applied. Where $R_w$ is ultimate bending ultimate strength of concrete, MPa; $R_g$ is the calculated standard value of strength for tensile or compressive strength of reinforcement, MPa; $A_g$ and $A_g'$ are the section area of steel bars in tension and compression zones, m$^2$; $h_0$ is effective height of section, m; $e$ is the distance from the center of gravity of the steel bar to the point of action of the axial force, m; $a$ and $a'$ is distances from the center of gravity of the reinforcing bar $A_g$ and $A_g'$ to the nearest edge of the section, m; $x$ the height of concrete compression zone, m.

When $x > 0.55 h_0$, the section strength can be calculated according to the following formula and the schematic diagram for the calculation is shown as Fig. 20.

$$K_1 N \leq R_w b x + R_g (A_e - A_g)$$  (6)

$$K_2 M \leq 0.5 R_w b h_0^2 + R_g A_g (h_0 - a')$$  (7)

where $R_w$ is the ultimate bending ultimate strength of concrete, MPa; $R_g$ is the calculated standard value of strength for tensile or compressive strength of reinforcement, MPa; $A_g$ and $A_g'$ are the section area of steel bars in tension and compression zones, m$^2$; $h_0$ is effective height of section, m; $e$ is the distance from the center of gravity of the steel bar to the point of action of the axial force, m; $a$ and $a'$ is distances from the center of gravity of the reinforcing bar $A_g$ and $A_g'$ to the nearest edge of the section, m; $x$ the height of concrete compression zone, m.

When the safety factor ($K_s$) of compressive strength is
greater than 2.0 and the safety factor of tensile strength ($K_2$) is greater than 2.4, the tunnel safety can be ensured. In contrast, the lining structure is unsafe once any safety factor cannot meet the limits. Table 1 and Table 2 demonstrate the calculated safety factors of each cross-section. Note that, the calculated internal force and safety factor are based on the sensor locations, and a pair of strain gauges constitute a section in the radial direction of tunnel (like No. 3 and No. 4 constitute a section etc. in Fig. 13(b)).

As Tables show, there is a significant similarity between the two cross-sections (in mileage with DK267+723 and DK268+045, all of the safety factors are greater than the requirements in the tunnel design code. These results provide important insights into the safety of the reconstructed lining structures. These results suggest that all of the monitored cross-sections have enough bearing capacity for keeping stable and safe in the last past year. Minimum safety factors is $K_2=6.57$ in DK268+045 cross-section, which remain has over 2 times safety reservation than the requirement. Taken together, these results suggest that the constructed lining structures are stable nowadays with good mechanical performance and the maintenance work is effective.

### 6. Conclusions

In this study, field tests were conducted in a newly-built tunnel, which was influenced by the lining cracking. The present study is designed to determine the effect of maintenance works in this damaged tunnel. The following points are outlined as outcomes of this study:

- The newly-built tunnel in this study was influenced by seriously damaging behaviors caused by lining cracking. A 37-days monitoring project of crack opening was implemented in field by surface strain gauges, which was aim to find out the status of the lining cracking. Monitoring outputs demonstrate that most of the crack openings still increase, and necessary maintenance work should be implemented for preventing further hazards.
- According to the field investigation, adjacent tunnel and poor condition of surrounding rock were the main inducements of lining cracking. Considering the feasibility of construction, demolition of the damaged lining, reinforcement of surrounding rocks by grouting and reconstruction of lining structure were designed as the maintenance methods.
- Strain monitoring of the new concrete was implemented for the partially reconstructed lining structure. Monitoring outputs show that the total deformation of the reconstructed lining is 0.018 mm tensile elongation and 0.016 mm compressed length. There is nearly little deformation of the strengthened lining during 277 days. The results suggest that the reconstructed partial lining is stable after being strengthened.
- One-year internal force monitoring of the new concrete was implemented for the completely reconstructed secondary lining. The monitoring results show that the second lining has begun to bear loading of surrounding rock with the extension of time. In addition, all of the safety factors of the monitored cross-sections are greater than the code requirements. It can be obtained that the reconstructed lining has enough bearing capacity after being strengthened.

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References


