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Research Article

Causal Analysis on the Lining Exfoliation and Treatment Design of an Operational Tunnel

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Abstract: According to the actual situation of the secondary lining of a expressway tunnel in Chongqing, this paper analyzed the specific reasons for lining exfoliation with corresponding test reports. According to this, a quick treatment scheme for lining exfoliation is proposed, which can make the treatment timely and effective, and suggestions for treating similar diseases in tunnels are put forward, which can provide reference for similar projects.

Key words: Operational tunnel; Lining exfoliation; Causal analysis; Treatment design

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1 Project overview

A certain tunnel is an extra-long tunnel on the Yuhe (Chongqing-Hechuan) Expressway of China National Highway 212, and is one of the all-round control projects. The tunnel is a single tunnel with two lanes, where the left and right tubes are placed separately. The right tube is 4,011 meters long, and it was bored through in December 2001.

The tunnel is located in the Zhongliangshan anticline of the Huaying Mountain broom-shaped fold bundle in the arc structure belt in the southeast of Sichuan. The secondary structure is the Datianwan reverse fault and some secondary small faults.

① Zhongliangshan anticline

It is the main structure of this tunnel, which traverses north and south, and is the southern extension of the Huaying Mountain broom-shaped fold bundle. It is characterized by tight anticline folds, asymmetric flanks, gentle in the east and steep in the west, and the axis of the anticline is twisted and crooked in reversed S-shape, with varying axial tilt, many structural branches, many independent high points, and many fractures.

② Datianwan reverse fsult

Located in the Jialingjiang Formation and Leikoupo Formation in the west flank of the anticline, the ground surface is manifested as follows : deep gullies are formed in the fault zone, and the lithology and occurrence of the rocks on both sides of the gullies are obviously different. The fault is roughly parallel, extending 2km along the axis, and the fracture width is 8-10m. The fault occurrence is as follows: inclination E57°S, dip angle 71°, crossing the left tube at ZK21+674, and crossing the right tube at YK21+677.

③ Joint

There are three sets of tensile joints of 91° ∠ 58°, 210° ∠ 50°, and 324° ∠ 63° in the sandstone developing at the entrance of the tunnel. The cracks are 1~3mm wide, and are rust-colored, brown-black, with clay fillings; a group of 300°∠69° tensile fractures developed in the axis of the anticline, the fractures developed and extended much longer, and cutting and dissolution occurred.

The main lithology of the tunnel: From the two flanks of the anticline towards the axis, the tunnel crosses the Middle-Jurassic Shaximiao Formation (J_{2S}), the Middle-Jurassic Xintiangou Formation (J_{2X}), and the Middle- and Lower-Jurassic Ziliujing Formation ($J_{1\text{-}2z}$), Lower-Jurassic Zhenzhuchong Formation (J_{1z}), Upper-Triassic Xujiahe Formation (T_{3xj}), Middle-Triassic Leikoupo Formation (T_{2l}), Lower-Triassic Jialingjiang Formation (T_{1j}), Lower-Triassic Feixianguan Formation (T_{1f}), The Middle-Permian Changxing Formation (P_2^C) and Longtan Formation (P_2^L) strata successively. The strata above the second segment of the Triassic Feixianguan Formation (T_{1f}^2) are completely exposed on the ground surface, and the Quaternary strata only appear on the gentle slopes of karst depressions and cave openings.

The surrounding rocks of the tunnel belong to type II, III, IV, and V.

Among them, the part of the tunnel where the secondary lining partially exfoliated is the type III surrounding rock, which is interbedded with gray-dark gray medium-thick shell limestone and asphaltene mudstone, with joint fractures developing.

2 On-site investigation and detection of the exfoliation of secondary lining of the tunnel

In February 2017, the secondary lining of the K22+356 ~ K22+368 segments of the right tube of the tunnel partially exfoliated. In addition to the partial exfoliation of secondary lining, there were 13 obvious longitudinal faulting of slab ends on the secondary lining of the segments, and the segments with faulting of slab ends were through cracks, extending along the secondary lining of the mold (Figure 1-3).

Figure 1. Partial exfoliation of the tunnel secondary lining

Figure 2. Faulting of slab ends on the secondary lining on the right side of vault of the k21+241 segments

Figure 3. Faulting of slab ends on the secondary lining on the right side of vault of the k21+275 segments

2.2 Tunnel inspection results

2.2.1 Lining thickness inspection results

The lining thickness inspection lines were laid on the tunnel vault, left and right arch waist, and left and right side walls respectively.

The inspection results show that the thickness of the secondary lining on the K22+345~K22+380 segments of the right tube of the tunnel is 40cm~64cm.

2.2.2 Lining cavity inspection results

The inspection lines for lining cavities were respectively laid on the vault of the tunnel and the left and right arch waists.

The inspection results show that there are 9 defects behind the lining of the K22+345~K22+380 segments of the right tube of the tunnel, and the defect volume is about 8.1m3. Among them, the vault is void in 4 places, and the arch is void in 4 places.

2.2.3 Lining strength test results

The positions of concrete strength coring testing were respectively set at the side wall and the arching position of the lining;

A total of 5 molds of secondary lining concrete were coring tested. Among them, there were 3 molds in the adjacent chunking positions, where 2 sets of core samples were taken for each mold from the side wall and the arching line. For the 2 molds in the K21+259-K21+271 and K21+452-K21 +464 (designated pile serial number) segments, one set of core samples was taken for each mold.

The measured concrete strength of the coring segment is 30.6~37.0MPa.

2.2.4 Lining clearance inspection results

There are a total of 35 lining segments in the key disease segment inspection. The driving boundary of the inspected segments was not invaded, but the distance from the contour line to the local (near the arch line) measurement point is small.

The typical inner contour cross-section is shown in the figure below(Figure 4 and 5).

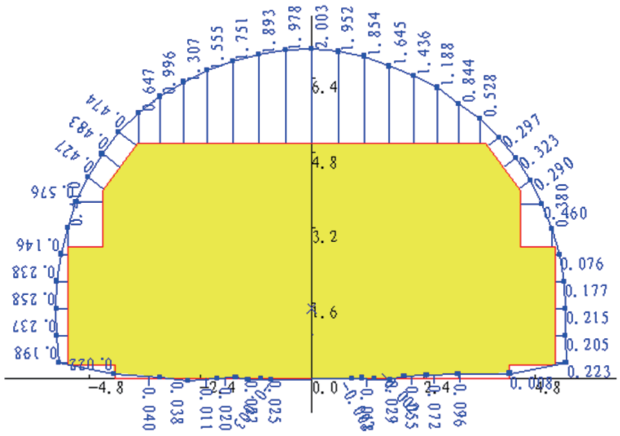

Figure 4. Measured lining boundary contour map of cross-segment k2+485

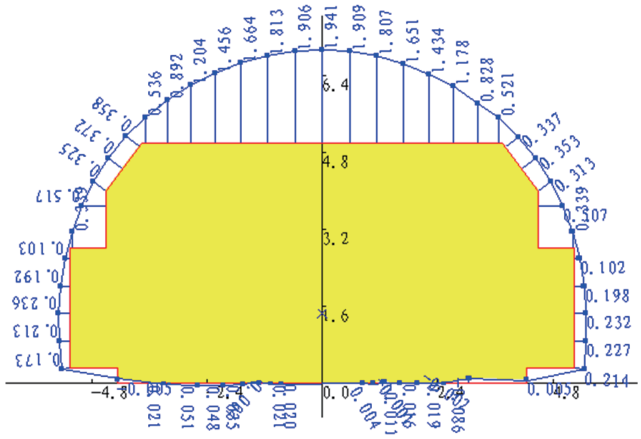

Figure 5. Measured lining boundary contour map of cross-segment k2+526

2.2.5 Inspection results of cold joints in lining construction

There are 12 cold joints in the construction (the lining is more severely deformed), most of which are distributed on the right side of the vault, about 2m from the vault. The typical lining faulting diseases are described as follows:

(1) The K21+259 ~ K21+271 (designated pile serial number) segments are fault by 6cm, the crack width is 4cm, and the depth is about 60cm. It is a through crack and extends along the entire secondary lining.

(2) The secondary lining on the right side of the K21+446 ~ K21+470 (designated pile serial number) segments is faulted by 5.5cm, the crack width is 4cm, and the depth is about 60cm. It is a through crack and extends along the entire secondary lining.

(3) The secondary lining on the right side of the K21+294 ~ K21+306 (designated pile serial number)

segments is faulted by 2cm, the crack width is 1cm, and the depth is about 50cm. It is a through crack and extends along the entire secondary lining.

2.2.6 Inspection results of defects behind the lining

There are 39 voids in the right tube of the tunnel behind the lining within the survey line, of which 29 voids were found in the vault survey line; 9 voids were found in the arch waist survey line; and 1 void was found in the side wall survey line.

2.2.7 Inspection results of secondary lining steel bars

Within the range of the survey line, the right tube of the tunnel has 24 segments with secondary lining containing steel bars, and the cumulative length is 289m.

2.2.8 Initial steel support inspection results

9 segments adopted steel support (steel arch frame or grille arch frame) for the initial support in the right tube of the tunnel within the range of the survey line, and the cumulative length is 439m.

3 Causal analysis of tunnel diseases

Combining the comprehensive analysis of the site topography and geology with the inspection reports, the main reasons for the secondary lining exfoliation of the tunnel are as follows:

(1) According to the inspection report, in addition to the partially exfoliated secondary lining in the segments, there are 13 obvious longitudinal faulting at slab ends in the secondary lining. The faulted segments are through crack, which spans the secondary lining of the entire mold, and there is also risk of secondary linings falling off. Therefore, due to construction technology and other reasons, there are suspected concrete construction cold joints on the secondary linings of the side wall and arch waist (the construction cold joint runs through the single-mold concrete longitudinally), which destroys the overall stressed structural system of the secondary lining and is an important reason of secondary linings falling off.

(2) Due to the simultaneous occurrence of two parallel longitudinal cracks or construction cold joints on the side wall and the arch waist, the secondary lining structure from the vault to the arch waist may topple and fall off after the following actions:

1) The weight of the secondary lining structure of this part;

2) The weight of the secondary lining of the vault acts on this part;

3) External forces such as surrounding rock pressure and groundwater.

(3) According to the inspection report, there are 39 voids behind the secondary linings within the survey line in the right tube, among which 29 voids were found in the vault survey line; 9 voids were found in the arch waist survey line; and 1 void was found in the side wall survey line. There is a cavity between the partial secondary lining and the initial support, which makes the secondary linings bear uneven forces.

4 Tunnel treatment design

4.1 Overall design concept

As the tunnel is an important passage from Chongqing to Beibei, it is under heavy traffic pressure and needs to be opened to traffic as soon as possible. This treatment is defined as an emergency rescue project. Therefore, the general concepts of treatment design are as follows:

(1) For segments that have been given emergency reinforcement, adopt temporary reinforcement measures as far as possible, and the treatment measures of H-beam + shotcrete shall be adopted.

(2) For the remaining segments with serious diseases and has not yet been given emergency reinforcement, the treatment measures of grille arch frame + shotcrete are adopted this time to improve the construction efficiency.

(3) Strengthen observation and monitoring on diseases that do not affect structural safety.

4.2 Treatment design of temporarily reinforced segments

For the segments that have been temporarily reinforced, the following scheme is adopted:

(1) Review the treatment segments, and construct temporary protective frames in the segments to temporarily protect or relocate roads, pipe trenches, and electrical and mechanical facilities.

(2) Apply foot-locking anchors to the I18 I-beam that has been constructed.

(3) Chisel off the inner surface of the secondary lining concrete, clean the surface, chisel off hair,

apply interface glue, and plant shear pins.

(4) Mechanically groove the side wall to ensure that the H-beams are supported on a stable foundation.

(5) Replace the 18 H-beam at the side wall; a layer of steel mesh is placed outside the H-beams, and the H-beams are connected by connecting steel bars in the longitudinal direction.

(6) Repair the local area where the secondary lining has fallen off:

1) Cleaning, chiseling hairs off, and planting reinforcement on the interfaces of existing linings (three sides);

2) Spray CF35 accelerated steel fiber concrete, reserve the connecting bars for the later shotcrete, and proceed to the next step after it reaches the design strength.

(7) Spray 24cm-thick CF35 accelerated steel fiber shotcrete, and cure it to the design strength.

(8) The surface of the shotcrete should be polished, and reflective film should be applied to the ends.

(9) Restore the tunnel's mechanical and electrical facilities.

(10) Demolition of temporary protective frames, temporary supports, etc. (there will be entry and withdrawal every day during the construction period).

(11) Long-term monitoring of the entire tunnel (Figure 6 and 7).

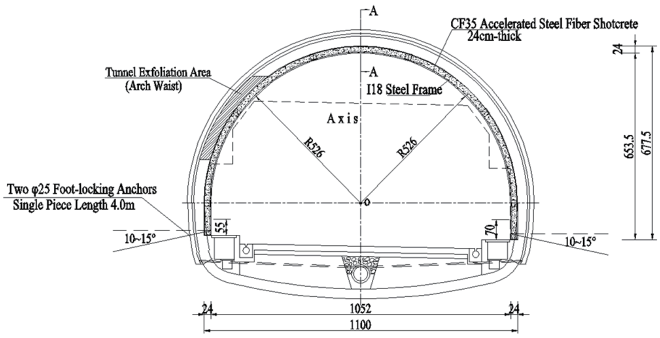

Figure 6. Treatment design for reinforced segments

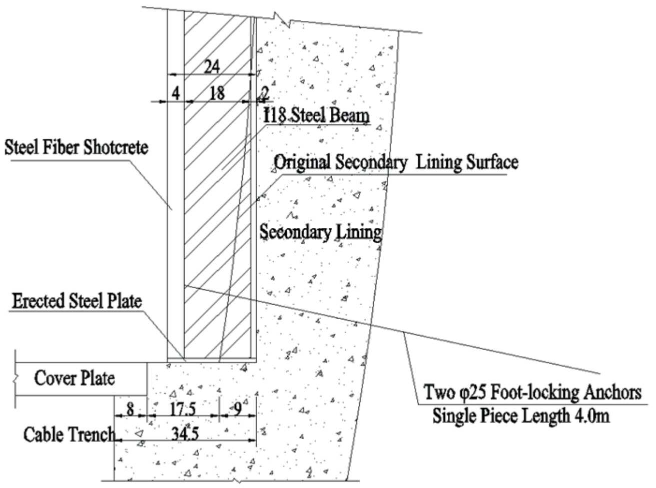

Figure 7. Design of h-beam bottom

4.3 Treatment design for segments not yet temporarily reinforced

For the remaining segments with serious diseases and the segments that have not yet been reinforced, the grille arch frame + shotcrete treatment measures were adopted this time:

(1) Review the segments to be treated, and construct temporary protective frames in the segments to temporarily protect or relocate roads, pipe trenches, and electrical and mechanical facilities.

(2) Chisel off the interior of the secondary lining concrete surface, clean the surface, chisel off hairs, apply interface glue, and plant shear pins.

(3) Mechanically groove the side wall to ensure that the grille steel frame is supported on a stable foundation.

(4) Construct H14 grille steel frames (grille arch frames should be prefabricated in advance), with a spacing of 0.3m; a layer of steel mesh is placed on the inside and outside of the steel frame each, and the steel frame is connected by steel bars longitudinally, and lock foot-locking anchor rods are used at the same time.

(5) Spray 24cm-thick CF35 accelerated steel fiber shotcrete, and cure to the design strength.

(6) The surface of the shotcrete should be polished, and reflective film should be applied at the ends.

(7) The electrical and mechanical facilities of the tunnel were restored.

(8) Demolition of temporary protective frames, temporary supports, etc. (During the construction period, there will be entry and withdrawal every day).

(9) Long-term monitoring of the whole tunnel (Figure 8 and 9).

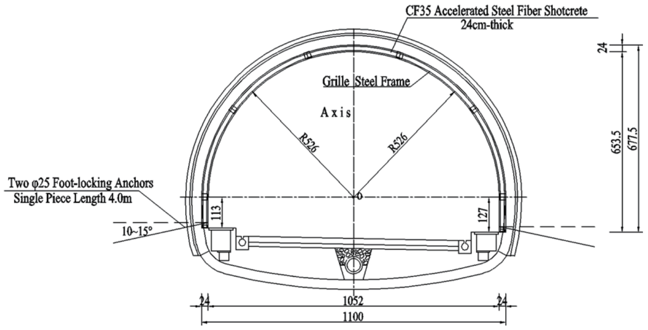

Figure 8. Reinforcement treatment design of grille steel frame

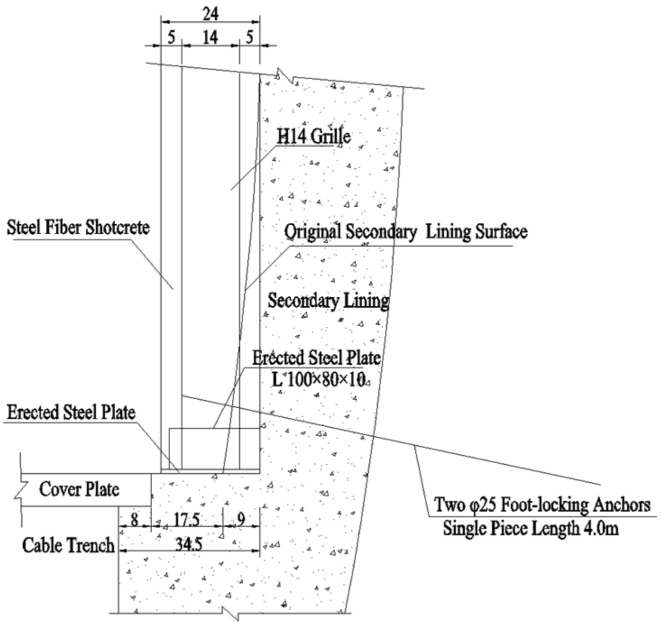

Figure 9. Bottom design of the grille steel frame

4.4 Special treatment of transverse passage intersections and reserved cavity

For the treatment of the transverse passage intersections and reserved cavities in the reinforced segments, H-beam + shotcrete measures were adopted for reinforcement this time. The main construction steps and precautions are the same as the previous segments. At the same time, the intersection position is underpinned, focusing on strengthening the joint structure design. This is mainly manifested in the following parts:

The H-beam connecting steel bars are made of φ22 HRB400 steel bars, in staggered arrangement with circumferential spacing 0.5m; but the joints were densified within the 3m range of the main cavity with respect to the intersection (circumferential spacing 0.3cm); the underpinning structure adopts HM (250mm*175mm) structural steel, the longitudinal length was tentatively set at 5.3m (transverse passage intersection segment) and 4.5m (reserved cavity part), the specific sizes were determined according to the actual size of the cavity on site; strengthened-end structure design (reinforcing ribs were provided on the upper and lower flanges), in which the foot-locking anchor rods were installed at the ends on both sides (Figure 10 and 11).

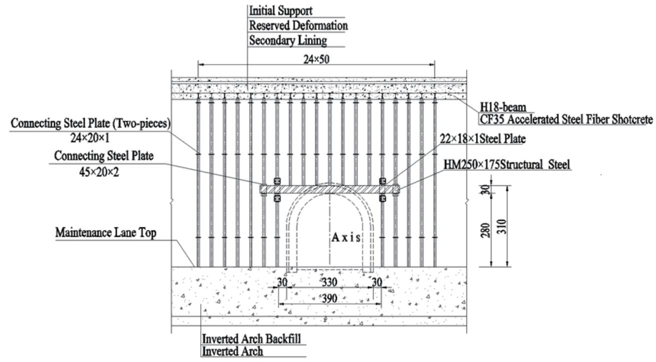

Figure 10. Treatment Design of the Intersection Segment of Transverse Passage

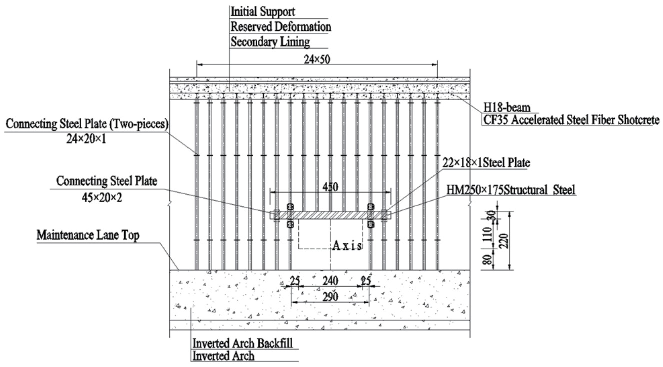

Figure 11. Treatment Design of the Reserved Cavity Segment

4.5 Disease observation and monitoring during construction

Disease observation content during the construction of the right tube of the tunnel: observation of the apparent disease of the tunnel, including network cracks, exfoliation, water leakage, and whether there are new cracks; strengthen the daily observation of the shotcrete segments to prevent the shotcrete from exfoliation. Disease monitoring content during the construction of the right tube of the tunnel:

(1) Monitor the deformation of the lined vault and surrounding displacement of the treatment segment;

(2) Monitor the stress of the existing frames in the treatment segment;

(3) Monitor longitudinal cracks;

(4) During tunnel construction, the frequency of observation and monitoring of related diseases should be strengthened, and any abnormalities should be reported in time to ensure the safety of tunnel

treatment.

4.6 Disease observation and monitoring during operation

Disease observation content during the operation of the right tube of the tunnel: Observation of apparent diseases of the tunnel, including network cracks, exfoliation, water leakage, and whether there are new cracks; strengthen the daily observation of the shotcrete segment to prevent the shotcrete from exfoliation. Disease monitoring content during operation of the right tube of the tunnel:

(1) Monitor 3 types of longitudinal cracks for crack sealing treatment;

(2) Monitor the internal force of the newly added steel support and the internal force of the steel strip and the stripped part;

(3) Monitor the tension of shotcrete;

(4) If possible, it is recommended to carry out long-term real-time monitoring of the tunnel.

4.7 Key points of construction quality control

(1) The position of the constructed joint of the newly-added arch must coincide with the position of the original structure.

(2) The minimum bond strength between the shotcrete and existing lining is 1mpa, and its cement strength grade is no less than 42.5.

(3) Start construction from both ends of a mold of concrete. After chiseled off the interior paint and concrete, steel-frame or grille arch-frame should be installed immediately, and then foot-locking anchors should be installed to ensure safety during construction.

(4) The surface and substrate treatment of the secondary lining in the middle segment must be carried out under the protection of H-beams on both sides to ensure construction safety.

(5) The shotcrete should be sprayed in place, and it is strictly forbidden to be incomplete or void.

(6) The shotcrete spraying operation should be combined with the on-site traffic organization time to arrange the construction time reasonably; longitudinal spraying can be carried out in segments, and layered spraying operations are strictly prohibited.

(7) Before shotcrete is applied, monitoring of crack deformations and strain and stress of H-beams (grille arch frames) should be conducted, and timely measures should be taken if there is any abnormality.

5 Conclusion

(1) In this paper, the cause analysis and emergency treatment design of the exfoliation of secondary lining of the tunnel were carried out with on-site disease detection, original tunnel design data and completion data. The scheme proposed in the paper played a very good role in the rapid repair of the secondary lining of the tunnel, active guarantee for the opening of the tunnel to traffic, and elimination of hidden hazards of traffic safety.

(2) After the tunnel reinforcement is completed, the content mentioned in the paper should still be monitored to ensure the long-term structural safety and operational safety of the tunnel.

References

[1] Merchants Chongqing Communications Research & Design Institute Co.,Ltd. Construction drawing documents of a tunnel emergency treatment project of Chongqing-Hechuan Highway [D]. 2017.

[2] Feng XY. Research on tunnel disease classification and lining crack treatment technology [D]. Beijing: Beijing Jiaotong University, 2002.

[3] Guan BS. Essentials of Tunnel Project Maintenance Management [M]. Beijing: China Communications Press, 2004.

[4] Chongqing Transport Commission. JTC H12-2003 Technical Specification of Maintenance for Highway Tunnel [S]. Beijing: China Communications Press, 2003.

[5] Guan BS. Key Points of Tunnel Engineering Design [M] . Beijing: China Communications Press, 2003.

[6] Wang YC. Tunnel Engineering [M]. Beijing: China Communications Press, 2006.

[7] She J, He C. General treatment methods for secondary lining defect of tunnels [J]. China Railway Science, 2005, 26 (1): 25-30.

[8] Liu HJ, Xia CC, Zhu HH et al. Studies on tunnel damage [J]. Chinese Journal of Underground Space and Engineering, 2007, 3 (5): 947-953.