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Fracture behaviors of tunnel lining caused by multi-factors: A case study

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Abstract. The cracking and spalling caused by fracture of concrete lining have adverse impacts on serviceability and durability of the tunnel, and the subsequent maintenance work for damaged structure needs to be specific to the damaging causes. In this paper, a particular case study of an operational tunnel structure is presented for the serious cracking and spalling behaviours of concrete lining, focusing on the multi-factors inducing lining failure. An integrated field investigation is implemented to characterize the spatial distribution of damages and detailed site situations. According to results of nondestructive inspection, insufficient lining thickness and cavity behind lining are the coupled-inducement of lining failure bahaviors. To further understanding of the lining structure performance influenced by these multiple construction deficiencies, a reliable numerical simulation based on extended finite element method (XFEM) is performed by using the finite element software. The numerical model with 112 m longitudinal calculation, 100 m vertical calculation and 43 m vertical depth, and the concrete lining with 1450 solid elements are set enrichment shape function for the aim of simulating cracking behavior. The numerical simulation responses are essentially in accordance with the actual lining damaging forms, especially including a complete evolutionary process of lining spalling. This work demonstrates that the serious lining damaging behaviors are directly caused by a combination of insufficient thickness lining and cavity around the surrounding rocks. Ultimately, specific maintenance work is design based on the construction deficiencies, and that is confirmed as an efficient, time-saving and safe maintenance method in the operational railway tunnel.

Keywords: fracture; field investigation; numerical simulation; maintenance; XFEM

1. Introduction

The fracture of a concrete structure is a non-negligible deterioration to the structural safety and durability, considering the stress concentration at the crack tip (Khan 2012, Real *et al*. 2012) and further fracture development in the cracking regions. With the great increase in construction of mountain tunnels, the maintenance of the secondary lining has become a vital issue for existing tunnels. The fracture of the tunnel lining cannot be avoided from the construction period to the operation stage, and cracking and spalling are the common forms of concrete fracture (FHWA 2005, Asakura and Kojima 2003). Lining failures present distinct characteristics and locations (Arnau *et al*. 2017) resulting from the particularity of underground engineering. However, a considerable amount of published literature has demonstrated that the fracture of concrete is caused by various inducements (MLIT 2014, Yamada *et al*. 2007). For tunnel structures, geological conditions (Wang 2010, Zhang *et al*. 2017, Lai *et al*. 2017) or other factors (Bian *et al*. 2016, Tan el at. 2018) are typically considered as the causes of concrete fracture.

Considering the fracture of concrete, field test (Zhang *et al*. 2018, Kumar *et al*. 2017), theoretical analysis (Wang *et al*. 2015), and numerical simulation are the most common method to study the damaging behaviors of concrete structure. Among them, numerical simulation is used as an effective way to verify the crack's initiation (Brnic *et al*. 2012, Jiang and Du 2017, Yan *et al*. 2018), propagation (Barros *et al*. 2013, Choubey *et al*. 2014), and influences (Yuksel and Kalkan 2007, Zhou *et al*. 2018) on the damaged concrete structure. Fracture mechanics is a new branch of mechanics aimed at dealing with defects or cracks in materials. Linear elastic fracture mechanics (LEFM) is based on the concepts of Griffith's energy balance and the stress intensity factor. Kaplan (1961) first introduced the concept of fracture mechanics for concrete and carried out an experiment on fracture toughness. To consider a relatively large nonlinear fracture process zone of a quasi-brittle material,

Barenblatt (1959, 1962) presented the concept of the cohesive zone model (CZM). Dugdale also introduced a similar cohesive zone model to discuss the yielding behaviour at the crack tip and in the plastic zone. Hillerborg (1976) introduced a linear-softening model based on CZM defined by the fracture energy and proposed a set number of traction displacement relationships for concrete. Moreover, bilinear-softening models were used to present the size effect in conjunction with the initial and total fracture

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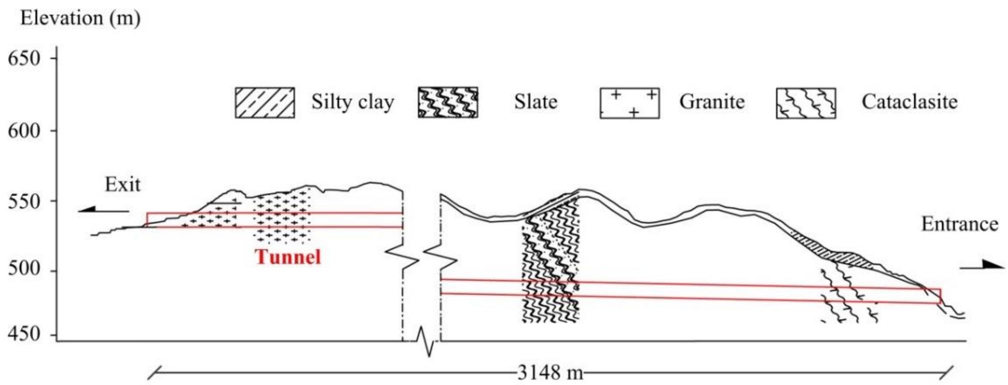


Fig. 1 Geological conditions of the tunnel (units: m)

energy (Mier 1996). The CZM has also been used to account for the macroscopic response of concrete by considering its microstructure. Borges and Pituba (2017) utilized a representative volume element consisting of three-phase materials to capture the mechanical behaviour of concrete, which considered the matrix, inclusions, and interface zone. Belytschko and Black (1999) utilized extended finite element methods (XFEM), a crack geometry can be represented by discontinuous shape functions instead of surface elements.

Moreover, maintenance work needs to be designed based on the different inducements of cracking, which must be proved in a reasonable manner (Abderahmane *et al*. 2017, Ganesan *et al*. 2017). A single inducement of lining-damaging behaviours was easily determined in the previous studies, but some complex engineering failure cases were inappropriately defined as being caused by a single factor. Therefore, an in-depth study of secondary lining damaging behaviours based on a combination of various inducements is meaningful and should include an integrated and credible verification process.

This paper presents a case study of lining damaging behaviours, utilizing field investigations and numerical analysis, intended to determine the accurate causes for the lining failure. Realistic concrete failure in field, coupled-inducement and application of XFEM in this study are considered different from previous works. Furthermore, the mechanical response of the tunnel structure with multiple construction deficiencies needs to be analyzed to interpret lining failure behaviours appropriately.

2. Profile of the operational railway tunnel

The railway tunnel studied passes through complex mountain-valley terrain, and several serious lining-failure phenomena have been observed during the tunnel's operation period. The geological conditions and a typical transverse section of the railway tunnel are shown in Fig. 1, in which the tunnel's longitudinal length is 3,148 m, and maximum burial depth is 270 m. The principal strata in the area are comprised of strong, weathered silty slate and have developed joint fissures. Flaggy and fragmentized structures are the major characteristics of the rock mass, and the rock stratum is mostly horizontally distributed with little bedrock fissure water. Small amounts of granite and cataclasite are found near the tunnel's entrance and exit. Fractures are the main geologic feature of the region, where several fracture zones have developed. Additionally, there are no other special adverse geological conditions or obvious seismicity around the tunnel site.

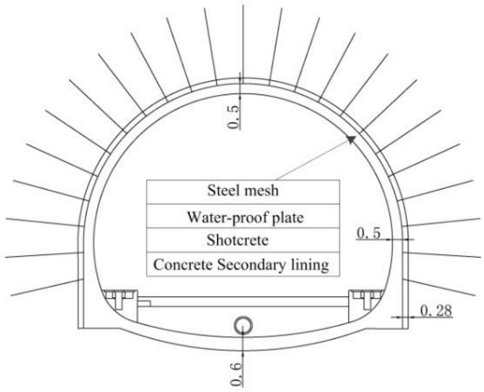
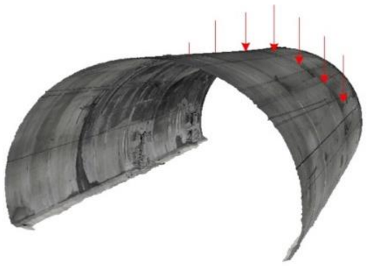


Fig. 2 Typical cross-section of the tunnel (units: m)

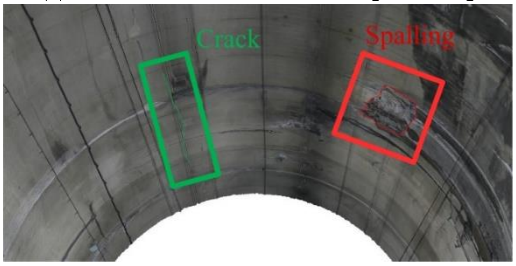
The typical structure of lining in this tunnel is shown in Fig. 2 (MOT 2001), which is designed following the composite lining standard of 10.5 m height and 8.9 m width. The primary lining is constructed of 0.28 m shotcrete, steel mesh with 0.25 m×0.25 m spacing, and an anchor rod system. In the steel mesh, round bars, 8 mm in diameter, were used in both the longitudinal and circumferential directions. In the anchor system, a 25 mm-diameter hollow grouting anchor rod and a 22 mm-diameter mortar anchor rod, 1 m length and 1.2 m circumferential spacing, were respectively attached to the arch and the sidewall of the surrounding rocks. Before the tunnel face was excavated, 42 mm steel pipes were fixed in the longitudinal direction of the surrounding rocks. The secondary lining was constructed of reinforced concrete, in which the thicknesses of arch and sidewall are 0.5 m, and the lining of the inverted arch is 0.6 m.

3. Investigation of lining failure and construction deficiency

3.1 The lining failures caused by the fracture of concrete



(a) The 3-D model of the damaged lining



(b) Crack and Spalling around the vault region

Fig. 3 Observation of the damaged region

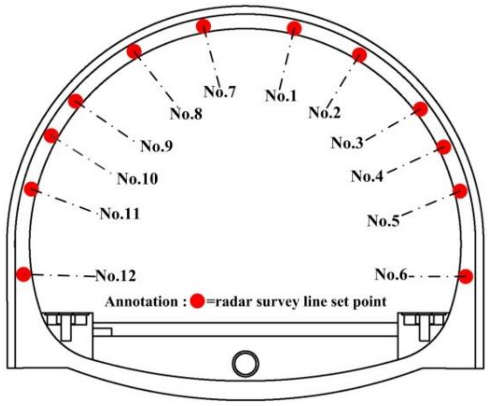
The damaged region ranges from location DK226+995 to DK227+015, which is 20 m along the axis direction. Because the lining failures are mostly around the vaults, and the tunnel is still in operation stage, a three-dimensional visual model of the tunnel was established by taking photos. A high-quality, photo-realistic model was used to investigate the condition of the failure conditions without any limits.

The most seriously damaged region was around the location DK227+006.6, the cross-section indicated by red arrows in Fig. 3(a). A close-up view of the seriously damaged region from the 3-D graphical model is shown in Fig. 3(b), and from that, a longitudinal crack and lining spalling can be observed. The field investigation found that the arch lining had the most damage and could severely impact the railway operation's safety. Concrete fracturing has also led to cracking and spalling in the same cross-section.

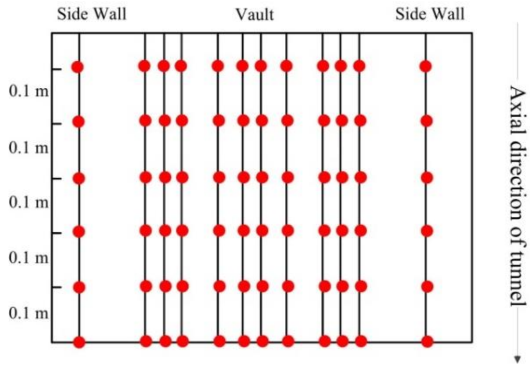
Collapses, cracking of the primary lining, or large deformations around this area had not been encountered during the construction period. Therefore, considering the serious degree of damage, a further investigation into other site conditions is necessary to determine the causes of the damage, and subsequent maintenance will need to be customize according to the specific inducements.

3.2 Investigation of construction deficiencies by geological radar

An emergency inspection was implemented after the cracking and spalling of lining were observed in the field. The steel reinforcement frameworks were easily observed. Thus, the insufficient thickness of the lining could be considered as the fracture's inducement. For further understanding of the lining thickness, geological radar was used to detect the construction deficiencies. As indicated by the red legends in Fig. 4(a), there were 12 geological radar survey-line set points in each cross-section, set every 0.1 m



(a) Survey point layout in circumference



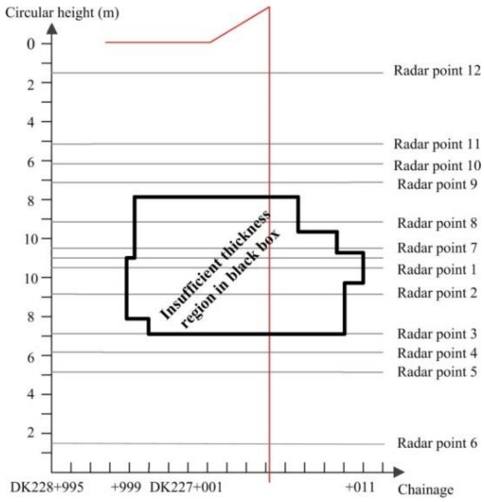
(b) Survey point layout in axial

Fig. 4 Non-destructive inspection in field

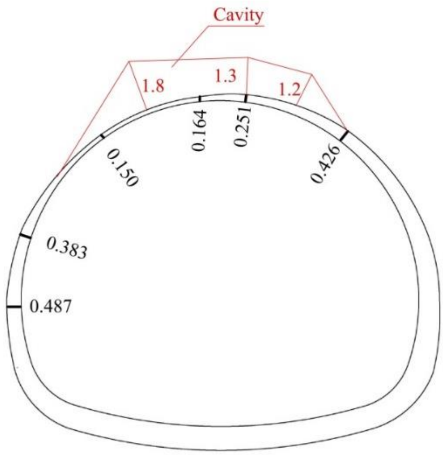
along the direction of the tunnel axis, as shown in Fig. 4(b). According to design specification requirements, the lining thickness was less than 90% of the design thickness of 0.45 m for this tunnel structure. The detection results of the insufficient and sufficient lining thickness regions are shown in Fig. 5(a), and the lining thickness is qualified in other unspecified detection points. According to the detection results, an insufficient lining thickness is a common construction deficiency within the tunnel's highly damaged region.

The geological radar investigation also demonstrated that there was another construction deficiency: a cavity located around the vault region of the cross-section at DK227+006.6. The cavity extended 0.6 m in the longitudinal direction and 1.3 m in the radial direction near the No.1 geological radar measuring point; 6.6 m in the longitudinal direction and 1.8 m in the radial direction around the No.7 geological radar measuring point; and 3 m in the longitudinal direction and 1.2 m in the radial direction around the No.2 geological radar measuring point. Consequently, the detected cavity was another significant construction deficiency considered to be associated with the lining's damage.

Because there are no obvious adverse geological conditions around the tunnel site, the construction deficiencies of the insufficient lining thickness and the cavity are considered as the major inducements of the lining damage. A typical, seriously damaged cross-section with the cavity is shown in Fig. 5(b), considering the investigated realistic thickness.



(a) The region of insufficient thickness



(b) The dimensions of the cavity

Fig. 5 Damaged lining with construction deficiencies (units: m)

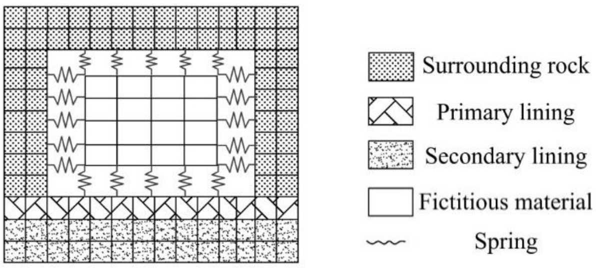


Fig. 6 Model of the cavity around surrounding rocks

4. Numerical simulation of lining fracture

4.1 Numerical model of the cavity

The cavity was modelled by a fictitious material linked with the primary lining and surrounding rocks using elastic springs (Zhang *et al*. 2015), as shown in Fig. 6. The springs were assumed to be elastic without cracking, and the fictitious material was defined as lightweight, assumed to have physical properties 10 times smaller than those of the surrounding rocks. Furthermore, the cavity was simulated as a regular partition for meshing, in which the circumferential range depends on the actual influence range in-site, and the vertical range is in accordance with the average depth.

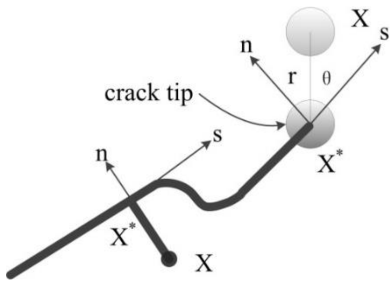


Fig. 7 Normal and tangential coordinates of crack

4.2 Briefly introduction of XFEM

XFEM allows local enrichment functions to be easily incorporated into a finite element approximation. The XFEM does not require the match of geometry discontinuities and mesh. Therefore, the XFEM is an effective method to simulate a discrete crack's initiation and propagation along an arbitrary, solution-dependent path without the need for remeshing. The core of the XFEM is that it improves the traditional finite element shape function based on the partition-of-unity method. The XFEM allows for the existence of discontinuity in the elements, which can be used to enrich the degree of freedom by special displacement functions.

For the purpose of fracture analysis, the enrichment functions typically consist of the near-tip asymptotic functions that capture the singularity around the crack tip and a discontinuous function that represents the jump in displacement across the crack surfaces as shown in Fig. 7 (Dassault Simulia International Inc. 2004). The approximation for a displacement vector function *u* with the partition of unity enrichment is

$$u = \sum_{I}^{N} N_I(X)[N_I + H(x)\alpha_I + \sum_{\alpha=1}^{4} F_\alpha(x) b_I^\alpha] \quad (1)$$

The discontinuous jump function across the crack surfaces, $H(x)$, which is given by

$$H(x) = \begin{cases} 1 & if (x - x^*), n \geq 0, \\ -1 & otherwise \end{cases} \quad (2)$$

where x is a sample (Gauss) point, x^* is the point on the crack closest to x, and n is the unit outward normal to the crack at x^*.

$F\alpha(x)$, which are given by

$$F_\alpha(x) = [\sqrt{r}sin\frac{\theta}{2}, \sqrt{r}cos\frac{\theta}{2}, \sqrt{r}sin\theta sin\frac{\theta}{2}, \sqrt{r}sin\theta cos\frac{\theta}{2}] \quad (3)$$

where (r,θ) is a polar coordinate system with its origin at the crack tip and θ=0 is tangent to the crack at the tip.

4.3 Simulation model and material properties

The aforementioned case with construction deficiencies in an operating railway tunnel was numerically simulated by ABAQUS software (Dassault Simulia International Inc.

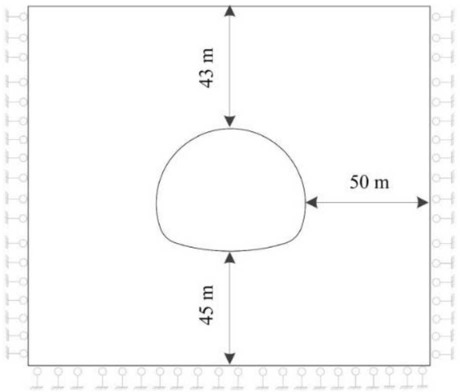


Fig. 8 Numerical model and boundary condition (unit: m)

2004), and the damage to the concrete lining induced by the construction deficiencies of the cavity and the insufficient lining thickness were investigated.

The numerical model and the boundary conditions used in investigating the damage to the concrete lining are shown in Fig. 8, and 18696 elements are meshed in the simulation model (including whole concrete lining with 1450 solid elements are set enrichment shape function). The longitudinal calculation range of the numerical model was 112 m, and the vertical calculation ranges of both lateral sides were 100 m, including a vertical range of 43 m from tunnel top to the upper boundary. The surrounding rocks and concrete lining in the numerical model were simulated using solid elements CPE4R (4-node bilinear, reduced integration with hourglass control) in the ABAQUS with a 2-D model considering the stress state of plane strain. In addition, some assumptions were adopted for the boundary conditions of the numerical model. The displacement of the lower boundary was constrained in both the longitudinal and vertical directions, both lateral boundaries were only restricted in the longitudinal direction, and the upper boundary was free in both longitudinal and vertical directions. The surrounding rocks were considered to be an ideal elastic-plastic material met with the Mohr-Coulomb yield criterion, which also can reflect the behaviours of the surrounding rocks during tunnelling. The secondary lining was considered to be an ideal elastic material to simulate the lining failure of cracking and spalling (Zhao *et al*. 2019). The damage criterion for the traction-separation laws was used for the lining-damaging evolution, according to the ultimate tensile strength of concrete of 1.42 Mpa (MOT 2001), and evolution law of energy damage is used in cracking propagation stage with fracture energy 19.58 N/m. Moreover, the effect of the steel arch in the primary lining was converted to shotcrete by the following Eq. (4) (Zhao *et al*. 2019)

$$E' = E_0 + S_g E_g / S_c \tag{4}$$

where E' is equivalent Young's modulus; E_0 and E_g are Young's moduli of the shotcrete and the reinforcement, respectively; S_g and S_c are the section areas of the steel arch and the shotcrete, respectively.

The physical properties of the composite lining and the surrounding rock are listed in Table 1, which are based on the site test data and design documents. Besides, the parameters of the cavity are based on Zhao *et al*. (2019)'s work.

Table 1 Physical properties of surrounding rocks and tunnel structure

Material	Physical and mechanical parameters
Surrounding rock	E=800 MPa, ρ=2200 kg/m^3, μ=0.32, c=500 kPa, φ=30°
Cavity	E=80 MPa, ρ=220 kg/m^3
Spring around cavity	k=1N/m
Primary lining concrete	E=26 Gpa, ρ=2500 kg/m^3, f_c'=9 MPa, f_t=1.0 MPa, μ=0.23
Secondary lining concrete	E=31.5 Gpa, ρ=2500 kg/m^3, f_c'=14.3 MPa, f_t=1.42 MPa, μ=0.2

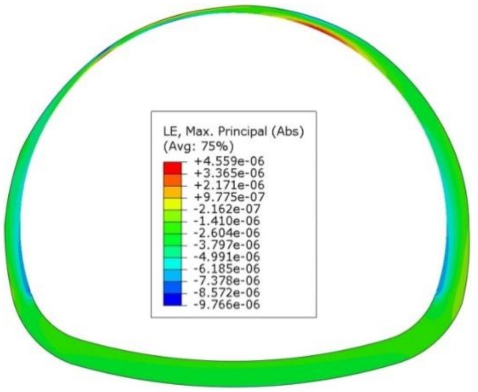


Fig. 9 Strain distribution of concrete lining

4.4 Numerical results

The contour of the true strain on the lining under the condition of geometric nonlinearity is shown in Fig. 9, which demonstrates that the dominant strains are distributed within the right vault and left hance regions. The maximum tensile strains on both dominant regions exceeded the ultimate value of concrete, which means that the lining structure was already damaged in these two locations. The results are similar to the illustrated lining failure forms in Fig. 3, which proves the effectiveness of the numerical analysis considering the impacts from two different construction deficiencies on the tunnel structure.

Moreover, the evolution of lining failure can be presented visually through the iso-surface for the signed distance function PHILSM by XFEM, and the outcomes of numerical calculation are shown in Fig. 10. A tensile-type crack was generated around the left hance region of lining, which corresponds to the vertical crack from the field investigation. Another crack generated around the right-arch region of the lining, which propagated in the vertical-circumferential direction of the lining and ended at another part of the inner surface. For this reason, the continuously propagated crack caused an individual part of the concrete lining to be partitioned from the whole structure, which corresponds to the spalling region found in the field investigation. The locations and forms of damaging behaviours in the model were similar to the field conditions, validating the numerical model's simulation of the damage process.

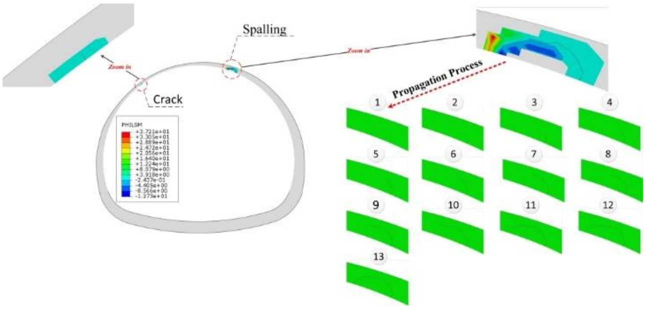


Fig. 10 Evolution process of lining failure

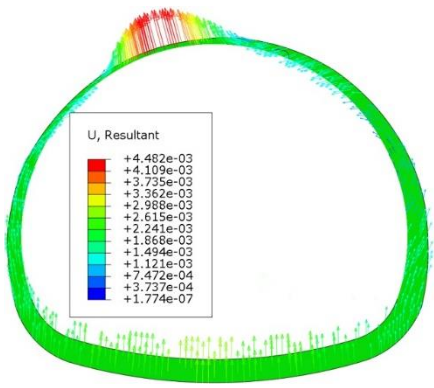
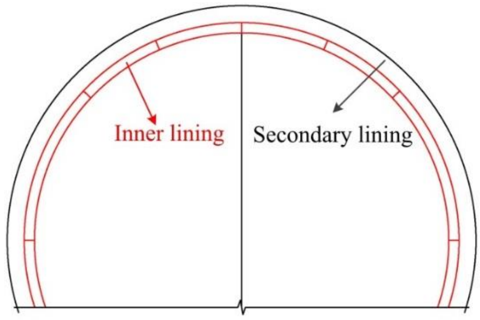
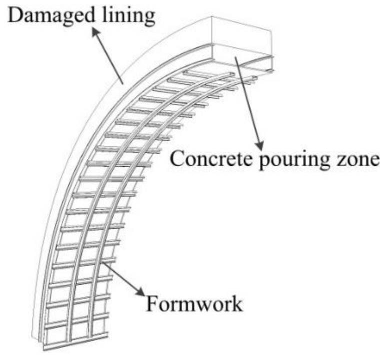


Fig. 11 Resultant displacement of the lining



(a) Schematic inner lining



(b) Technical schemes

Fig. 12 Maintenance work of damaged lining

The contour of resultant displacement can demonstrate the mechanical response of the tunnel lining with the investigated construction deficiencies. The evident asymmetric deformation of the secondary lining can be observed in Fig. 11. There is a specific region under compressive force around the arch region, resulting from the insufficient lining thickness and the cavity. Additionally, the vertical crack and spalling regions are in tension-failure zones around the edges of the location subjected to the compression force. The existence of the two construction deficiencies leads to unusual stress distributions on the lining structure, which can be verified as the direct inducements of lining failure.

5. Specific maintenance design

After the implementation of the field investigation and the numerical simulation, the insufficient lining thickness and the cavity are the confirmed inducements of the lining failure. Thus, maintenance will need to be designed regarding each construction deficiency. The cavity behind the primary lining will need to be backfilled by the grouting method prior to the maintenance on the lining structure.

The damaged tunnel is still in operation because of the railway system's strict management policy to protect the growth of the national economy. For the aforementioned reasons, convenient construction, time efficiency, and structural safety are the three key factors in maintaining the lining structure. As shown in Fig. 12(a), the damaged lining could be reinforced by connecting it to an inner lining. Because the concrete fracture was determined to be caused by the cavity and insufficient lining thickness, an inner lining could enhance the bearing capacity of the tunnel structure after backfilling the cavity. As shown in Fig. 12(b), erecting a formwork and pouring concrete is a convenient construction technical scheme without the need of any other large construction machinery. In addition, the maintenance can be implemented during regular inspection periods overnight, which does not affect the railway operations.

Therefore, the maintenance of the inner lining could effectively meet the requirements of convenient construction, time efficiency, and structural safety and could be an effective method for similar engineering projects.

6. Conclusions

The topic of serious lining damage in an operational tunnel has been brought into the forefront. After investigating lining failures by observing the graphical model, vertical crack propagation and serious lining spalling were selected as the research emphasis of this study. Multiple construction deficiencies were investigated by geological radar, an effective method to align a numerical model with realistic site conditions. Additionally, the results verify the rationality of the simulation model and the impact of the construction deficiencies. The following points outline the case study's outcomes:

- The field investigation thoroughly illustrated the construction deficiencies of the cavity and the insufficient lining thickness. These findings were then used as the parameters for the materials and the geometrical model in the numerical simulation.

• The construction deficiencies of the cavity and insufficient lining thickness, leading to unusual stress distributions, played an important role in the stability of the tunnel structure.
• The comparison between the field investigation and the numerical results verified that the construction deficiencies were the direct causes of the lining fracture, providing the design basis for appropriately strengthening the damaged tunnel structure.
• An inner lining could be used as effective maintenance in an operational railway tunnel with the aforementioned construction deficiencies.

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