Study on mechanics damage mechanism of arch surround reinforced structure under loose load

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Abstract. Lining crack is a typical disease of highway tunnels in operation, which affects the long-term operation safety of tunnels. The arch surround is suitable for strengthening tunnel projects with serious cracks due to its characteristics of significantly increasing structural bearing capacity and prolonging service life. However, at present, the damage evolution mechanism of arch surround reinforcement structures under loose loads based on the secondary stress mode is not well understood. Aiming at the above problems, in this paper, based on the load structure method, indoor 1:10 model test of arch surround reinforcement for Grade VI surrounding rock and damaged lining structure is carried out and the stress and deformation law, failure mode and ultimate bearing capacity of tunnel after arch surround reinforcement is explored. On this basis, finite element software is used to simulate the whole process of damage evolution of arch surround reinforced the structure, and to explore the mechanism of mechanical damage evolution of arch surround structure after reinforcement. The results show that the arch surround reinforcement can effectively repair the damaged tunnel and greatly improve its bearing capacity. When the residual bearing capacity of lining is 48.4%, the bearing capacity is increased by 164%. The original structure of the second lining and the reinforced structure of the arch surround are both in large eccentric compression failure. The main damaged parts are the vault and the haunch. The failure of the reinforcing structure of the arch surround is caused by the slip cracking of the combined surface between the second lining and the arch surround. Anchor bolts should be added to improve the shear bearing capacity of the combined surface.

1. Introduction

In the construction of expressway, tunnel engineering has the advantages of improving alignment, reducing slope, shortening mileage and driving time. Therefore, the tunnel scheme is widely used in highway construction. At the present stage, although considerable achievements have been made in the field of highway tunnel construction worldwide, there are still many problems. Due to the immature design and construction technology or the uneven management and organization ability,
more or less structural diseases have appeared in a large number of early-built tunnels (Inokuma et al., 1996; Wang et al., 2010; Sharifzadeh et al., 2013), such as lining structure cracking, leakage of water, lining deformation and peeling and voids between liners, in which lining cracking is the most common (Zhu et al., 2003; Kim et al., 2006; Hideto et al., 2006; Chiaia et al., 2009; Zhu et al., 2013; Xiao et al., 2014), not only reducing the bearing capacity of the structure, but also seriously affecting the safe operation of the tunnel.

Loose load is one of the main inducing factors of tunnel lining cracks. Under loose load, longitudinal tension cracks are easy to appear inside the vault, and oblique cracks appear outside the spandrel, posing great influence on the safety of the structure. Without timely and effective treatment of tunnel defects caused by loose loads, the lining structure will be further damaged, even the tunnel will be damaged to completely interrupt the whole traffic line, resulting in huge economic losses and adverse social effects.

At present, studies on the reinforcement of the highway tunnel in our country mainly focus on the reinforcement of the tunnel during construction. There are three reinforcement methods for tunnel lining in operation period: arch surround, paste steel plate and gumming carbon fiber (Toshihiro et al., 2003; Kiriyama et al., 2005; Sahranavard et al., 2006; Van Empel et al., 2006; Yang et al., 2011; Liu et al., 2015). Nowadays, there are relatively few studies on the timing and principle of arch surround reinforcement, especially on the damage of lining caused by the loose load of the vault. Therefore, it is necessary to study the reinforcement of arch surround for cracked tunnel lining caused by loose load in the operation period.

In this paper, the cracked lining is reinforced by the arch surround. The model test, numerical simulation, and theoretical analysis are combined. Firstly, the loading failure test of the second lining under the loose load of the vault is carried out, and the stress-deformation law, failure mode and ultimate bearing capacity of the second lining under the test conditions are obtained by analysis. Then, the tunnel lining with 48.4% residual bearing capacity is reinforced and loaded to failure, and the stress-deformation law, cracking process, strain distribution law, failure mode and ultimate bearing capacity of the reinforced structure of the arch surround are obtained. Finally, the finite element software is used to simulate the whole process of second lining and the stress-failure of arch surround reinforcement structure. The deformation process, ultimate bearing capacity, stress distribution, and variation characteristics, crack development process of the second lining and arch surround reinforcement structure are obtained, and the evolution mechanism of stress damage of arch surround reinforcement structure is analyzed.

2. Stress-deformation characteristics and failure process of lining structure

2.1. Similar model test scheme

2.1.1. Test loading and testing system. The model test device consists of a loading system, measuring system, and reaction system, as shown in figure 1. The loading system is equipped with 11 independent jacks above the inverted arch of the tunnel. The front of the piston rod is connected with a helical cylinder spring, which simulates the formation constraints. The inverted arch part is equipped with a spring, without a jack, and is directly connected with the reaction system. The graded monotonic static full-cycle loading mode is used. Only Jack 5, 6 and 7, which simulate the loose load at the top, are actively pressurized. The other jacks, together with springs, play the role of simulating the passive resistance of formation. Loose loads are distributed in the range of 60°, and the applied load is 100N at each stage.

This test includes a group of unreinforced and a group of arch surround reinforcement conditions. When the reinforcement conditions simulate the moderate damage of the lining, the arch-cover reinforcement is adopted. Reinforced joints are 48.4% of the residual ultimate bearing capacity of the damaged lining and then loaded to failure.
2.1.2. Similar materials and measurement system. The standard cross section of two lanes is used for the lining section of the prototype tunnel. The outer dimension of lining is 50 cm in thickness, 1,186 cm in width and 953 cm in height. The reinforced arch surround is 20 cm in thickness. The model in 1/10 size is designed in figure 2. In the axial direction of the tunnel, the length of 300 cm is taken as the research object. Thus, the ring width of the model lining is 30 cm.

![Figure 2. Model tunnel section dimension.](image)

Geometric similarity ratio of 1/10 is used as the basic similarity ratio. Stress and elastic modulus similarity ratio are determined by mortar blocks. Other physical similarity ratios are deduced by dimensional analysis.

Mixed mortar is composed of cement, yellow sand, lime paste and water in a certain proportion. Two kinds of mortars M3 and M4 are made to simulate the strength of Concrete C30 and C40 respectively. M3 mortar is used to pour the second lining of the tunnel, M4 mortar is used to pour the arch surround. The fluidity of mortar is increased by adding naphthalene retarder to cement with 1% mass ratio and increasing the amount of lime paste. The quality mix ratio of mortar is shown in Table 1, and the mechanical properties of mortar obtained by the test are shown in Table 2.

| Mortar grade | Cement | Sand | Lime paste | Water | Water-reducing agent |
|--------------|--------|------|------------|-------|----------------------|
| M3           | 187    | 1450 | 113        | 330   | 0                    |
| M4           | 197    | 1450 | 163        | 330   | 1.97                 |

| Mortar grade | cube compressive strength (MPa) | Modulus of elasticity (GPa) |
|--------------|---------------------------------|-----------------------------|
| M3           | 3.1                             | 1.57                        |
| M4           | 4.0                             | 1.97                        |
The model wire mesh is made of galvanized iron wire, with wire spacing of 2.55 cm, a diameter of 0.9 mm and cross-sectional area of 0.636 mm². There are 12 main bars in the model lining section. The reinforcement ratio of the section is 0.056%, and the concrete protective layer is 5 mm. The arch surround is a reinforced concrete structure with a thickness of 2 cm. The form of interfacial reinforcement is single-layer reinforcement, with the thickness of the protective layer of 1 cm. The arch surround in this test is a composite arch surround. When pouring the arch surround, it is necessary to roughen the inner surface of the original lining to make the overlay surface rough enough, then drill holes and insert pins, and wrap the pin insertion part with epoxy resin. The pin spacing is 18 cm along the circumferential direction and divided into upper and lower layers. There are 36 sockets in the whole arch surround. The concrete arrangement is shown in figure 3.

Formation resistance is simulated by the passive application of resistance spring. There are three parallel I-springs at the front of Jack 5, 6 and 7 of vault. The total stiffness of this group is 245.22 N/mm. Elastic resistance devices in other parts have three parallel type II springs. The total stiffness of each group of springs is 515.25 N/mm. Resistance springs are in contact with the lining of the model. The distribution area of each jack is A= 6.21 cm². Therefore, the resistance coefficient of the formation in the model is:

\[
k = \frac{K}{A} = \frac{515.25N/m}{0.3 \times 0.15m^2} = 11.45 \text{ MPa/m}
\]

(1)

The load of the model test refers to the jacking force F of a single jack, and the loose load pressure intensity of the vault in the prototype is:

\[
\sigma_{p0} = \frac{F}{A} = \frac{100N}{0.3 \times 0.15m^2} \times 10 = 22.22 \text{ kPa}
\]

(2)

2.2. Lining failure process and ultimate bearing capacity
The failure modes of the structures under the two working conditions are large eccentric compression failure of the vault section and large eccentric compression failure of the reinforcing interface of the arch surround. For the unreinforced condition, when F=640N, the lining structure first cracks on the right side of the vault. When F=720N, the axial penetrating crack along the tunnel axis appears in the middle of the vault with the radial depth of 2.5cm, which develops into the main crack in the subsequent loading. In the stage of F=720–1400N, new cracks appeared inside the vault, outside the haunch, and at the inverted arch, one after another. In the stage of F=1400–2000N, the vault cracks are mainly developed in radial extension, and new lining cracks are mainly developed outside the haunch. In the stage of F=2000–2800N, the main crack of the vault bifurcates and the opening rate accelerates, the crack depth increases to 3.5cm, the width increases from 0.5mm to 1mm, accompanied by brittle
crack sound during the loading period, while new cracks continue to appear in the left and right haunches; in the stage of $F=2800\text{–}3200\text{N}$, the sinking of the lining vault accelerates, and under the influence of wider cracks, the steel bars gradually yield, and even part of the steel bars break. The concrete inside the right haunch shows signs of crushing, but the lining has not collapsed completely; When $F=3300\text{N}$, the deformation of the vault continues to increase, the crushing range of the concrete inside the haunch expands, an obvious brittle sound appears on the lining suddenly, a sudden change appears in the displacement of the vault, the steel bars on the cross-section of the vault are all broken, the steel bars (40° above the arch line) outside the haunch are all broken, and the lining completely loses the bearing capacity. The sketch of cracks in the unreinforced structure is shown in figure 4, and the final failure form of the tunnel is shown in figure 5.

For the reinforced condition of the arch surround, when $F=640\text{N}$, the lining structure first cracks on the right side of the vault. In the stage of $F=720\text{–}800\text{N}$, the mid-vault cracks and the radial depth increases gradually to 2 cm with the continuous development of the load. In the stage of $F=1200\text{–}1700\text{N}$, new cracks are generated inside the vault, outside the haunch, at the inverted position and on the left and right side walls. Many cracks already exist in the vault area before reinforcement, but the crack opening is not obvious. After reinforcement, in the stage of $F=1700\text{–}2415\text{N}$, the stiffness of the structure is obviously increased without any crack appearing. In the stage of $F=2415\text{–}5910\text{N}$, a crack appears inside the vault, outside the waist of the vault and at the inverted arch position successively, and increases and deepens with the increase of load. In the stage of $F=5910\text{–}6200\text{N}$, collapse appears outside of the vault, the opening rate of the inner main crack is accelerated, and the cracks on the haunch continue to increase. In the stage of $F=6470\text{–}8700\text{N}$, the combined surface of new and old concrete cracks, and the peeling aggravates with the increase of load; in the case of $F=8700\text{N}$, the cross-section of arch crown collapses, the arch surround is torn along the combined surface of concrete, the steel bar outside the left haunch is pulled apart, the inner concrete collapses, and the lining loses its load. The sketch of the cracks in the reinforcing structure of the arch surround is shown in figure 6.
Figure 6. Crackle sketch of arch surround reinforcement structure

The comparison of ultimate bearing capacity between unreinforced structure and arch surround reinforced structure is shown in Table 3. It can be seen from the figure that the original structure has an ultimate bearing capacity of 3300N. When the residual bearing capacity of the second lining structure is 48.4%, the ultimate bearing capacity of the structure is increased to 8700 N, which is 2.636 times that of the original structure. This shows that the bearing capacity of the reinforced structure has been significantly improved.

Table 3. Mortar ratio (Mass ratio).

| Specimen       | Percentage of residual bearing capacity | Failure load | Ultimate bearing capacity of prototype | Failure Load of Reinforced Structures/failure load of original structure |
|----------------|----------------------------------------|--------------|----------------------------------------|--------------------------------------------------|
| Unreinforced   | -                                      | 3300N        | 708.06                                 | -                                                |
| Reinforced     | 48.4                                   | 8700N        | 1866.65                                | 2.636                                            |

2.3. Lining deformation characteristics

The relationship between relative displacement from the vault to the arch line, the convergence of the side wall and a load of lining structure are shown in figure 7. For the unreinforced structure, from the initial state to the cracking stage of the lining vault (F=0–700N), the structural deformation basically develops linearly, and the structure mainly develops elastically. In the stage from cracking of lining vault to no new cracks at the vault interface (F=700–2000N), the decrease of overall stiffness of lining structure leads to the acceleration of structural deformation rate, which further leads to the generation of subsequent new cracks. In the stage from crack-free of vault to main crack steel bar breakage at vault interface (F=2000N–3200N), the cracks of lining at vault, haunch and inverted arch increased,
the structural damage is serious, the stiffness of vault and haunch is weakened obviously, and the rate of vault subsidence and convergence of side wall is accelerated obviously. In the stage from the breakage of the steel bar at the vault interface to the complete loss of the bearing capacity of the lining (F=3200~3300N), after the breakage of the main cracked steel bar, the crack tension angle increases rapidly, and the lining loses the bearing capacity. The relative displacement from the vault to the arch starting line is 12.44 mm under the failure load, and the side wall convergence is 11.68 mm.

For the reinforced structure, from the initial state to the pre-reinforcement stage (F=0~1700N), the displacement development includes two stages. The first stage is the elastic state of the structure, in which the displacement develops linearly, the second stage is the generation and development of lining damage, in which the displacement development rate accelerates. From the reinforcement point to the non-cracking stage (F=1700~2415N), the stiffness of the structure obviously increases after reinforcement, and the growth rate of deformation decreases and is less than that before reinforcement.

In the stage from non-cracking of arch surround structure to stripping of the combined surface between old and new concretes (F=2415~6470N), lining cracks successively inside the vault, outside the haunch, and at the inverted arch position. The increase of lining damage directly weakens the structural stiffness, while collapse appears outside the vault. Under the interaction of crack damage and deformation, the vault subsidence and the convergence rate of the side wall are obviously accelerated at this stage. The new and old concrete overlays are peeled off to the lining failure stage (F=6470~8700N).

The cracking of the arch's new and old concrete combined surface and its scope are gradually enlarged. The stiffness of the arch's cross-section is weakened and collapsed. The structural deformation increases until the structure is in failure the relative displacement between the vault and the springing line is 26.80 mm and the side wall convergence is 19.86 mm under the failure load.

3. Study on damage evolution mechanism of lining under stress

3.1. Computational model and parameters

![Sketch map and Model diagram]

Figure 8. Numerical calculation model.

The load-structure method is used as the analysis method, the tunnel lining structure is taken as the main bearing body, and the stratum resistance is simulated by the non-linear spring, which is only under pressure but not under tension. The numerical model is shown in figure 8. The specific parameters include:

a) Considering Grade VI surrounding rock, which has a formation resistance coefficient of 11.45 MPa/m, the stiffness of a single spring is calculated according to the principle of equivalent stiffness. At the same time, the stress concentration caused by sparse spring distribution should be avoided.

b) The material parameters of the lining structure are the same as those of the model test. The material parameters of M3 cement mortar are used for the second lining, and M4 cement mortar is used for the arch surround, the yield strength of the second lining steel bar is 350 MPa, and the yield strength of the cover steel bar is 300 MPa.

c) The maximum axial tensile stress criterion is adopted for crack propagation. The maximum axial tensile stress of the second lining is $\sigma_{\text{max}} = 0.8$ MPa, the fracture energy is $G_f^1 = G_f^2 = G_f^3 = 50$ N/m, the
maximum axial tensile stress of the arch surround is $\sigma_{\text{max}} = 1$ MPa, and the fracture energy is $G_f^I = G_f^{II} = G_f^{III} = 70$ N/m.

d) Irrespective of the bond slip between reinforcement and concrete, i.e. assuming the unique complete coordination and joint deformation between reinforcement and concrete, the effective bond between reinforcement and concrete can be achieved by embedded function in ABAQUS software.

The secondary force of this numerical simulation is realized through the birth-death element function of ABAQUS. In the first load step, the cover concrete and the cover steel bar structure are “killed” and the initial load is applied. The load is stopped when it reaches the reinforcement load. In the next load step, the cover concrete and the cover steel bar are activated and the load is continued to be applied until structural damage appears.

3.2. Evolution of lining damage

Based on the model test results, the development law of bearing capacity of lining components is obtained by numerical analysis, and the damage evolution process of lining structures is further analyzed. Figure 9a and figure 9b show the relationship curves of bearing capacity and loose load of unreinforced and reinforced structures, respectively.

![Figure 9. Relationship between convergent deformation and load of lining.](image)

| Damage characteristics | Stage of damage development |
|------------------------|----------------------------|
| Main crack occurs at vault | Cracking of concrete at arch waist | The inner steel of lining yields at vault | The outer steel of lining yields at arch waist |
| Load (N) | 711 | 1504 | 2026 | 3163 |
| Relative displacement between vault and arch line (mm) | 1.435 | 3.140 | 4.272 | 9.873 |
| Convergence of side wall | The depth of cracks at vault (mm) | The depth of the crack at the arch waist (mm) |
| 1.326 | 2.848 | 4.234 | 9.300 |
| 0.5 | 0.85 | 4.5 | 4.5 |
| 0 | 0.5 | 2 | 2 |
Table 5. Damage development of arch surround reinforced structures.

| Damage characteristics | Stage of damage development | I   | II  | III | IV   | V    | VI   |
|-------------------------|-----------------------------|-----|-----|-----|------|------|------|
| Main crack occurs at vault | Cracking of concrete at arch waist | Concrete of arch surround cracks at vault | The inner steel of secondary lining yields at vault | The steel of arch surround yields at vault | The outer steel of lining yields at arch waist |
| Load (N)                | 711                         | 1504| 2936| 6503| 7328 | 8962 |
| Relative displacement between vault and arch line (mm) | 1.435 | 3.140 | 5.173 | 12.595 | 15.581 | 24.589 |
| Convergence of side wall (mm) | 1.326 | 2.848 | 4.213 | 10.25 | 13.157 | 18.301 |
| The depth of cracks at vault (mm) | 0.5 | 1.5 | 1.5 | 4.5 | 4.5 | 4.5 |
| The depth of the crack at the arch waist (mm) | 0 | 0.5 | 0.5 | 2 | 2 | 2 |

The damage development process of the unreinforced structure is as follows: 1) when F=711N, the concrete inside the vault is yielded under tension, the tensile stress is 1 MPa, the main crack is generated, and the initial width of the crack is 0.5 cm; 2) when F=1,504N, the concrete outside the haunch is yielded under tension, and cracked, which is located at the 50° of the springing line, with the crack depth of 0.5 cm; 3) when F=2,026N, the steel bar inside the vault is yielded under tension, with the most principal stress of 350 MPa; 4) When F = 3,163N, the steel bar on the outer side of the haunch yields and the lining can no longer bear, leading to damages. Damage development process of arch surround reinforcement structure includes: I) before reinforcement, when F=711N, the main crack of the vault occurs, with the initial crack width of 0.5cm; II) when F=1,504N, the concrete outside the haunch achieves the tensile yield strength, the haunch cracks, which are located at 50° of the springing line, with the crack depth of 0.5cm; III) after reinforcement, when F=2,936N, the arch surround cross-section of the vault cracks with the crack depth of 0.5 cm; IV) when F = 6,503N, the inner steel bar of the second lining of the vault yields under tension; V) when F = 7,328N, the steel bar of the vault arch surround yields under tension; VI) when F = 8,962N, the steel bar outside the haunch yields under tension. The data characteristics of the damaged joints of the unreinforced structure and the arch-cover
structure are summarized in Table 4 and Table 5, respectively. The final failure modes of the reinforced structure and the arch surround structure are shown in figure 10a and figure 10b, respectively.

4. Comparison and analysis of results of model test and numerical simulation

4.1. Failure patterns and ultimate bearing capacity
In the model test, the failure mode of the second lining is that the inner steel bar of the arch crown is yielded and pulled apart, and then the outer steel bar of the haunch is pulled apart at 50°. The failure mode of the second lining in the numerical simulation is basically the same. In the numerical simulation, the failure mode of the reinforced structure of the arch surround is that the second steel bar of the arch surround first yields, then the steel bar of the arch surround yields, and finally the outer steel bar of the arch yields in failure; The failure order of reinforcing structure of arch surround is arch cross-section failure without measuring reinforcing steel stress in model test, then the reinforcement outside the haunch is pulled apart, and the lining can not continue to bear the load and fail. Unlike numerical simulation, when the load is large, circular shear cracks appear at the combined surface of arch surround concrete and second lining concrete at the vault. In the numerical simulation, it is considered the bond is good between new and old concrete, and there are no cracks on the combined surface.

| Table 6. Damage development of arch surround reinforced structures. |
|---------------------------------------------------------------|
| Ultimate Bearing Capacity of Secondary Lining (N) | Indoor model test | Numerical simulation | Ratio (test/simulation) |
|---------------------------------------------------------------|
| Ultimate bearing capacity of arch surround reinforced Structure (N) | 8700 | 8962 | 0.971 |

Table 6 shows the comparison of ultimate bearing capacity between model test and numerical calculation. It can be seen from the table that the ultimate bearing capacity of the second lining in the model test is slightly larger than that of numerical simulation. The results of the model test are 1.043 times as much as that of numerical simulation, The numerical simulation is slightly smaller than that of model test possibly due to the frictional force at the bottom of the lining and the elastic-plastic of the reinforced concrete. In the case of arch surround reinforcement, the numerical simulation results are larger than the model test results. The ratio of the model test to the numerical simulation ultimate bearing capacity is 0.971, which is quite close to 1. The numerical simulation results are rather large possibly due to the slip between the old and new concrete combined surfaces and the bond slip between the reinforcement and concrete.

4.2. Fracture distribution characteristics
In model tests, cracks are mainly distributed inside the vault, outside the haunch, and inside the inverted arch, and a small number of cracks are also distributed outside the side wall. Cracks inside the vault and outside the haunch are relatively numerous and dense; there are key cracks in the inner surface of the vault and outside of the haunch to control structural failure, which are located in the middle of the vault and 50° above the springing line, respectively, with deep depths and large width. Other cracks are smaller in depth and width. In the numerical simulation, no random crack appears as in the numerical simulation. In the whole loading process, only one crack is generated at the vault, one crack is located both at the left and right haunches and two cracks at the inverted arch position are distributed in piles, in which the vault crack and the haunch are the key cracks to control the failure of the lining structure, with basically the same distribution of the key cracks and the model test.
4.3. Comparisons of ultimate deformation values

Table 7 shows the comparison of the ultimate deformation between the model test and numerical simulation. From the analysis, it can be seen that the deformation result of the model test is slightly larger than that of numerical simulation. The ratio difference of unreinforced structure is about 0.25, and the difference of reinforcing structure is about 0.09. Due to the small elastic modulus of mortar material in the model test, the deformation result is larger.

|                          | Unreinforced structure | Reinforced structure with arch surround |
|--------------------------|------------------------|----------------------------------------|
|                          | Indoor model test      | Numerical simulation                   | Ratio (test/simulation) | Indoor model test | Numerical simulation | Ratio (test/simulation) |
| Relative displacement    | 12.440                 | 9.873                                  | 1.260                    | 26.80            | 24.589               | 1.090                    |
| between vault and arch    |                        |                                        |                          |                  |                      |                          |
| line (mm)                |                        |                                        |                          |                  |                      |                          |
| Convergence of side wall  | 11.680                 | 9.800                                  | 1.192                    | 19.86            | 18.301               | 1.085                    |
| (mm)                     |                        |                                        |                          |                  |                      |                          |

5. Conclusions

(1) The failure model of the second lining structure is the large eccentric compression failure of the vault section, which can be divided into four stages: the stage from the initial state to the vault cracking, the stage of enlarging overall stiffness of the structure and slowing deformation; the stage from the vault cracking to the haunch cracking, in which the pressure of the lining extends to the haunch, the structural cracks increase and the overall stiffness weaken, the tensile stress is mainly borne by the reinforcement, and the deformation increases rapidly; the stage of the steel bar inside the vault yielding to the steel bar outside the vault yielding, in which the reinforcing bars inside and outside the vault are subject to tension and yield successively, finally forming a three-hinged arch system, resulting in the failure.

(2) When the residual bearing capacity is 48.4%, the failure mode of the reinforcing structure of the arch surround is large eccentric compression. The failure is mainly caused by the slip cracking of the combined surface between the arch surround and second lining. At the same time, the cracks of arch surround converge with the existing cracks of second lining, the steel bars yield under tension or are even pulled apart, and the rigidity of the vault section is seriously weakened. Finally, the concrete of the outer compression area of second lining vault collapses and the structure loses its bearing capacity.

(3) The arch surround reinforcement can effectively repair the damaged tunnel and greatly improve its bearing capacity. When the residual bearing capacity of the lining is 48.4%, the ultimate load of the reinforced tunnel is 8,700N, which is 2.64 times that of the unreinforced second lining structure, increasing the bearing capacity by 164%. When the structure is failed, the relative displacement is 26.804 mm from the vault to the springing line, and the convergence of the side wall is 19.86 mm.

(4) Under the loose load, both the unreinforced second lining structure and the reinforced arch surround structure are damaged by large eccentric compression, and the key control interface is the vault and the arch springing. The vault is in large eccentric bending. Thus, it is suggested to increase the longitudinal reinforcement inside the arch crown so as to increase the tensile bearing capacity. For the compression-shear failure of the arch springing, the stirrup should be equipped to improve the shear bearing capacity. In addition, the failure of the reinforcing structure of the arch surround is caused by the slip cracking of the combined surface. Anchor bolts should be added to improve the shear bearing capacity of the combined surface.

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References
[1] Inokuma, A., Inano, S. (1996) Road tunnels in Japan: deterioration and countermeasures. Tunn. Undergr. Sp. Tech., 11 (3): 305-309.
[2] Wang, T.T. (2010) Characterizing crack patterns on tunnel linings associated with shear deformation induced by instability of neighboring slopes. Eng. Geol. 115 (1-2): 80-95.
[3] Sharifzadeh, M., Tarifard, A., Moridi, M.A. (2013) Time-dependent behavior of tunnel lining in weak rock mass based on displacement back analysis method. Tunn. Undergr. Sp. Tech. 38: 348-356.
[4] Zhu, W.S., Li, S.C., Li, S.C., et al. (2003) Systematic numerical simulation of rock tunnel stability considering different rock conditions and construction effects. Tunn. Undergr. Sp. Tech. 18 (5): 531-536.
[5] Kim, H.J., Eisenstein, Z. (2006) Prediction of tunnel lining loads using correction factors. Eng. Geol. 85 (3-4): 302-312.
[6] Hideto M., Nobuharu I., Tsutomu K., Takuo E. (2006) Effect of fiber reinforced concrete on shrinkage crack of tunnel lining. Tunn. Undergr. Sp. Tech. 21: 382-383.
[7] Chiaia, B., Fantilli, A.P., Vallini, P., (2009) Combining fiber-reinforced concrete with traditional reinforcement in tunnel linings. Eng. Struct. 31 (7): 1600-1606.
[8] Zhu, H.H., Ye, B., Cai, Y.C., Feng Z. 2013. An elasto-viscoplastic model for soft rock around tunnels considering overconsolidation and structure effects. Comput. Geotech. 50: 6-16.
[9] Xiao, J.Z., Dai, F.C., Wei, Y.Q., Min, H., Xu, C., Tu, X.B., Wang, M.L. (2014) Cracking mechanism of secondary lining for a shallow and asymmetrically-loaded tunnel in loose deposits. Tunn. Undergr. Sp. Tech. 43: 232-240.
[10] Toshihiro, A., Yoshiyuki K. (2003) Tunnel maintenance in Japan. Tunn. Undergr. Sp. Tech. 18: 161-169.
[11] Kiriyma, K., Kakizaki, M., Takabayashi, T., Hirosawa, N., Takeuchi, T., Hajohta, H., Yano, Y., Imafuku, K. (2005) Structure and construction examples of tunnel reinforcement method using thin steel panels. Nippon Steel Tech. Rep. (92): 45-50.
[12] Sahranavard, H., Aghanoori, R. (2006) Use of new technology in repair and renovation of Haji Abad tunnel. Tunn. Undergr. Sp. Tech. 21(3-4).
[13] Van Empel, W.H.N.C., Sip, J.W., Haring, F.P. (2006) Design of repair measures of a damaged shield driven tunnel. Tunn. Undergr. Sp. Tech. 21(3-4): 338-339.
[14] Yang, C.Z., T W., Yan J., Chen, Y.L. (2011) The application of carbon fiber reinforcement in tunnel second lining cracks. Adv. Eng. Mater. 194-196: 865-898.
[15] Liu, X.Z., Wang, X.L., He, B.G., Sang, Y.L. (2015) Model test of cracked tunnel lining reinforced with umbrella arch based on secondary loading. J. Sichuan Univ. 41(3): 22-28. (in Chinese)
[16] Liu, X.Z., Wang, X.L., He, B.G., Sang, Y.L. (2015) Comparative experiment of reinforcement of lining under different damage states with arch surround for tunnel. J. Cent. South. Univ. 46(12): 4611-4617. (in Chinese)