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Investigation and Rehabilitation of Lining Imperfections and cracks in an Operating Railway Tunnel

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ABSTRACT

The X.Z.Y. tunnel is a curved tunnel with single-rail track for the railway in southwest China. The construction was started in April 2003 and completed in August 2004. The tunnel crosses a hills area where the excavation was in a stratum of mudstone mixed with sand stone. The stratum was formed horizontally with developed joints. The tunnel was constructed using the conventional tunnelling method with an integral lining system.

During the operation, in March 2014, a inspection shows that the tunnel lining was found severe damaged and fractured in wide range sections. In typical damaged section, the tunnel lining was cracked symmetrically at the springline due to bulge and broke at the crown in a compression way. Similar trends were observed in other sections of the tunnel lining system. Nondestructive detection test shows that there were cavities and incompacted areas behind the tunnel lining.

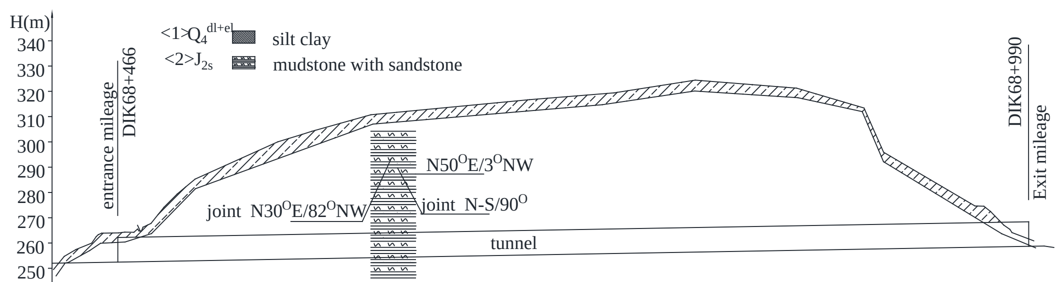
In this paper, a systematic method was proposed to rehabilitate the lining sections where the lining was fractured or showed a trend of fracture. Such method was based on a reinforced shotcrete technology together with anchors for fixation in the application. Numerical analysis was carried out to investigate the mechanical performance of the tunnel lining damage. Field investigation were conducted to monitoring the effectiveness of the applied measures. The results show a good performance of using the reinforced shotcrete for the rehabilitation of tunnel lining fracture.

1. Introduction

The lining imperfections will lead to damages to the tunnel lining during the operation stage. Such problem has been discussed in several studies [1-3]. It is kown that a void under the invert leads to decrease in the magnitude of bending moment, and for large void size, the moments can reverse sign [4]. However, if the void is behind the lining at the crown area, does similar results will be occurred? This paper presents a case studies on the investigation and rehabilitation of lining damges caused by lining imperfections, especially the void and uncompacted area behind the lining at the crown area. Then, a system scheme of using reinforce shotcrete to rehabilitate the lining damages and imperfections is presented.

2. Project overview

The X.Z.Y. tunnel is a curved alignment tunnel with single-rail track for the railway in southwest China. The construction was started in April 2003 and completed in August 2004. The tunnel crosses a hills area where the excavation was in a stratum of mudstone mixed with sandstone. The stratum was formed horizontally with developed joints. The tunnel was constructed using conventional tunnelling method with an integral lining system (C20 concrete). Wire mesh was used for the reinforcement of the shotcrete and lattice girder was used only when necessary. The design parameters for the tunnel lining system and reinforcement are presented in Table 1 and Table 2. The tunnel depth is varying between 30 m – 50 m. The tunnel span is 7.17 m and the high is 9.64m; the shape of the tunnel is kind of slim. Figure 1 shows the tunnel longitudinal cross section while Figure 2 presents the transvere cross section.



geology	Tunnel underlying mudstone-sandstone, completely weathered about 2-4 m; stratum structure is simple, and occurrence of the rock is subhorizontal; joints is developed but not rich with groundwater.				
rock grade	Ⅴ	Ⅳ	Ⅲ	Ⅳ	Ⅴ
rock length	44	100	130	184	66
mileage	DIK68+466 – DIK68+510	DIK68+510 – DIK68+610	DIK68+610 – DIK68+740	DIK68+740 – DIK68+924	DIK68+924 – DIK68+990

Figure 1 Tunnel longitudinal cross section

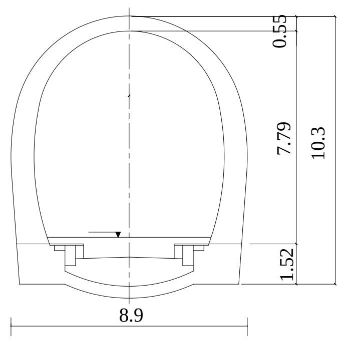


Figure 2 Tunnel transverse cross section (unit in meter)

Table 1 Parameters for lining system

Rock grade	Lining thickness (cm)		shotcrete		Wire mesh			
	arch	arch foot	position	thickness (cm)	position	Spacing (cm)	reinfocement logitudinal	reinfocement hoop
Ⅲ	45	45	arch and wall	7	--	--	--	--
Ⅳ	50	72	arch and wall	10	arch	25×25	Φ6mm	Φ8mm
Ⅴ	55	80	arch and wall	14	wall	25×25	Φ6mm	Φ8mm

Table 2 Parameters for ground and lining reinforcement

Rock grade	Bolt			Lattice girder		forepolling			note
	position	parameters spacing (m)	parameters length (m)	position	spacing (m)	position	form	spacing (m)	
III	arch (70%)	2.0	2.5	--	--	--	--	--	--
IV	arch and wall	1.2	3.0	arch and wall when necessary	1.0	arch in soft rock	bolt or small pipe L=3.5	Ring 0.4m	- -
V	arch and wall	1.0	3.0	arch and wall, when necessary for invert	1.0	arch	bolt or small pipe L=3.5	Ring 0.4m	fiber reinforcement 0.9kg/m^3

3. Tunnel imperfections and damages investigation

3.1. Vision observation

In March 2014, a vision inspection shows that the X.Z.Y. tunnel lining was found severe damaged and cracked in some sections, as shown in Figure 3 and Figure 4. Cracks have a maximum width 10 mm; maximum detective depth 15 cm; maximum longitudinal spread of crack 40 m. In typical damaged section, the tunnel lining was cracked symmetrically at the intrados of tunnel arch shoulder due to bulge (see Figure 3) and crushed at the crown in a compression way (see Figure 4). Water leakage occurred at some positions on the lining surface.

(a) mileage DKI68+340 right side (b) mileage DKI68+450 left side

Figure 3 longitudinal tensile crack at intrados of tunnel arch shoulder

(a) mileage DIK68+325 crown (b) mileage DIK68+349 crown

Figure 4 crushing at crown due to local compression (flaking and falling)

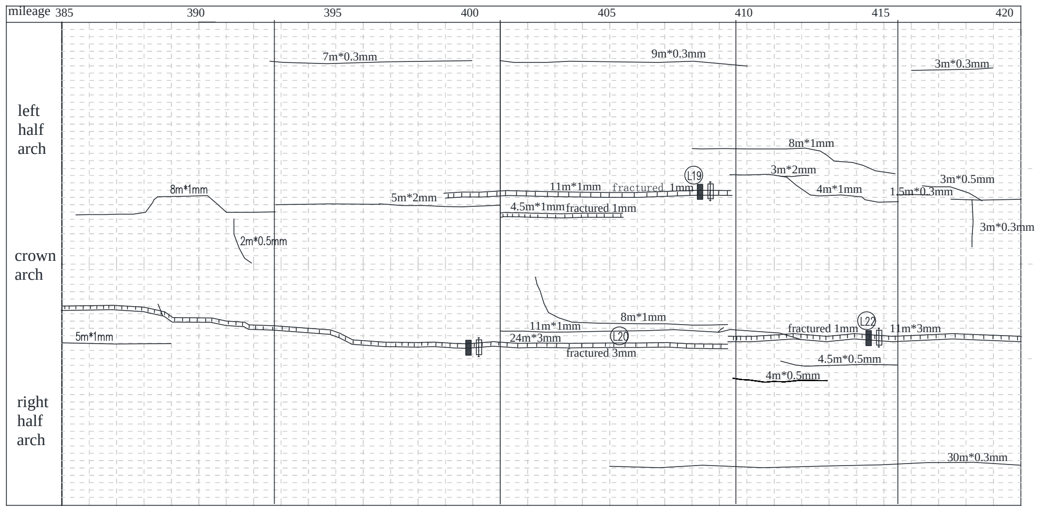


Figure 5 The distribution of imperfections and damages on tunnel lining at DIK68+385-420 (cracks are majorly longitudinal found at the intrados of tunnel arch shoulder)

3.2. Nondestructive detection test

Nondestructive detection test was used to investigate the lining imperfections and damages. This was done by using ground penetrating radar (GPR) to scan throughout the lining. Such nondestructive detection test shows that there were voids behind the tunnel lining and the filled materials were not compact. These lining imperfections majorly can be divided into three categories. The first is insufficient lining thickness in some positions, especially at the tunnel crown; the second one is that the material are not compact behind the tunnel lining; the third one is the void behind the tunnel lining. In this tunnel, about 19 places of totally about 95m in length are not compact behind the lining which is 3.63% of the total tunnel length. Three places about 10 m in length are found having void behind the lining which is 0.64% of the total length.

3.3. Check from grouting hole

Based on the results of the nondestructive detection test, a field check was carried out from those grouting holes left hollow which found that the lining only about 30cm～45cm. Such thickness is actually less than the designed thickness which wa 50 cm. This actually reveals that the void behind the lining may not only result from insufficient grouting behind the lining but it may also result from insufficient lining thickness. It seems that the lining was not compacted when pumping the concrete to the lining mould. Moreover, the waterproof membrane was found in a loose status and some local places of the lining were crushed. Such results is similar to the nondestructive detection results.

3.4. Detection of internal contour

Figure 6 shows the monitoring of the tunnel clearance. Seven points at each transverse cross section was measured to obtain the tunnel lining inner profile, as shown in Figure 6 (a). The measured results of a typical section was shown in Figure 6 (b). It was found most of points along the tunnel contour have sufficient surplus space compared with the required clearance while only individual points intrude in the required railway clearances. It is suggested that rehabilitation measures could be take place at the surplus tunnel space outside the clearances. However, attention should be also paid to those individual points already inside the clearance profile.

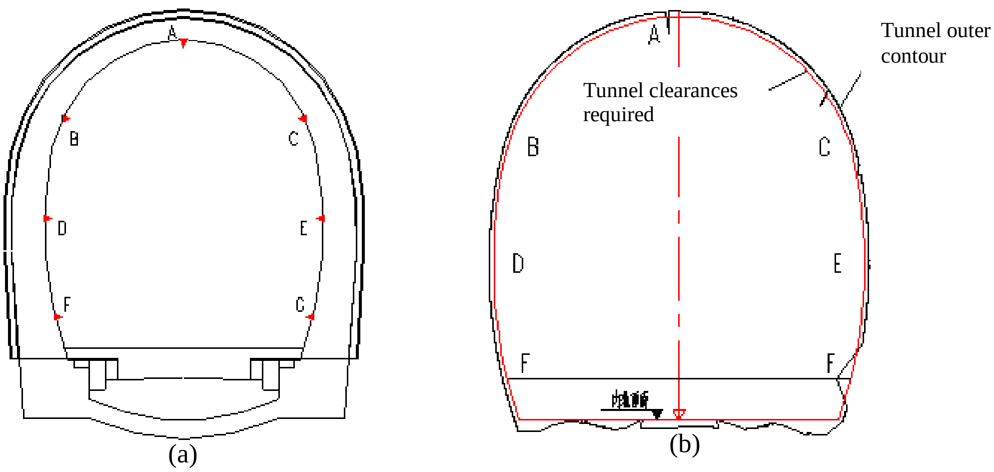


Figure 6 Monitoring of the lining clearance; (a) distribution of monitoring result; (b) measured lining profile

3.5. Safety assessment and damage cause analysis

The above investigations shows that there are many lining imperfections and damages observed, including insufficiency of lining thickness, voids behind the lining, uncompact are behind the lining, water leakage, cracks on lining and lining crush or flaking, etc.

Based on the distribution of lining imperfections and damages, surrounding rock grade, ground water condition and safety for operation, the lining damages can be divided into five categories: intact (A1), slight (A2), moderate (A3), severe (A4), very severe (A5). The evaluated tunnel damage categories at each element blocks were presented in Figure 8. It is clear that most of the tunnel lining has undergo a severe damage. Table 3 summarized the overall damage categories of X.Z.Y tunnel into very severe. There two block sections abot 110 m was assessed into the very severe damage category which is 38.4% of the total length. More than half of the tunnel overall length was categorized into severe damage. Hence, concrete rehabilitative measures should be took to reinforce the tunnel lining.

Simple FLAC2D numerical analysis was carried out to investigate the influence of void behind the lining on the lining mechanical performance, as shown in Figure 9. Generally tunnel damages may be influenced by many factors such as ground condition, imperfections in design and construction. Numerical analysis show that the insufficient lining thickness and void behind the lining are major causes of the lining crack. This is shown in Figure 10 that if a void at the corwn, the lining bening moment reverse at the crown. The computed results of the stress at the different position of the tunnel lining was presented in table 4. It found that at the shoulder of the intrados of the tunnel arch the bending moment change from compression to tensile, which is very easy to cause a tensile crack due to the low tensile strength of the lining concrete. This results highly coincides with observed result in Figure 3 and Figure 5.

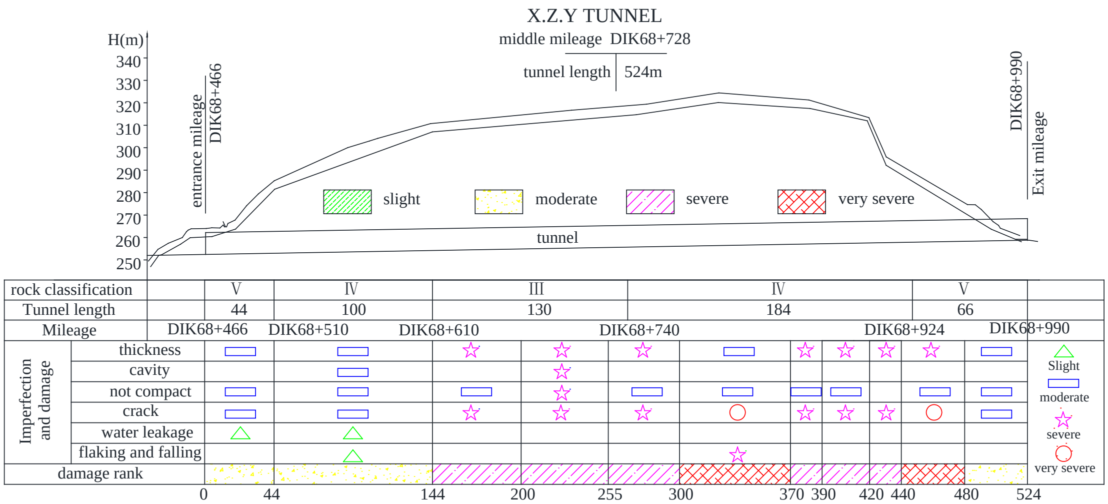


Figure 8 Damage categories along X.Z.Y tunnel longitudinal section

Table 3 Summary of damage categories of X.Z.Y tunnel

	element block	**length（m）**	**Percentage of tunnel length**
very severe	9	201	38.4%
severe	6	85	16.2%
moderate	13	238	45.4%

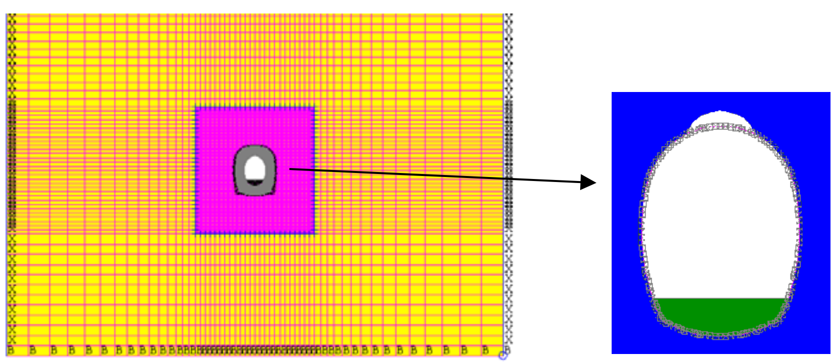


Figure 9 FLAC 2D Numerical model

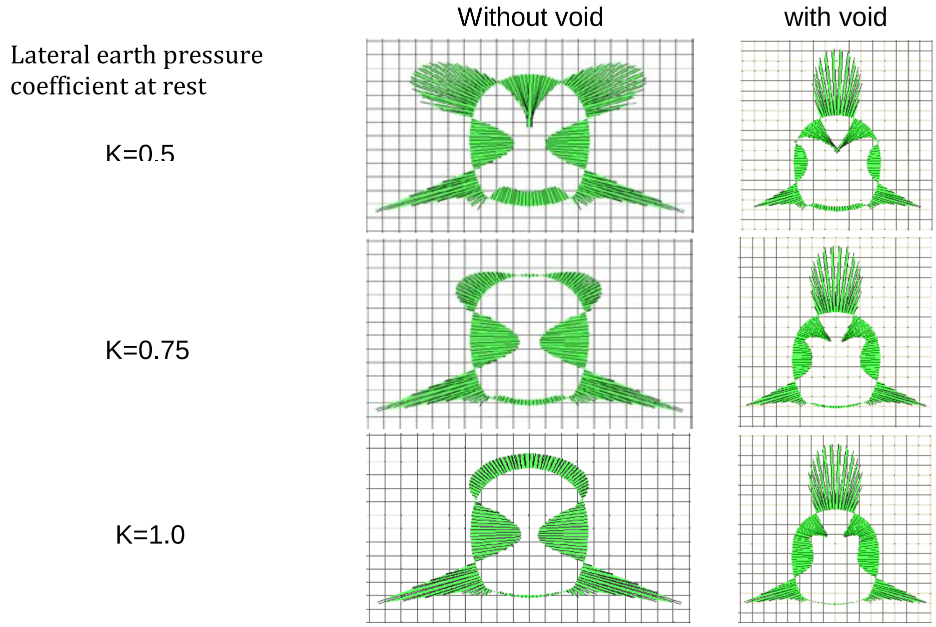
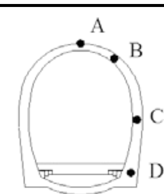


Figure 10 Bending moment distribution along the lining profile

Table 4 stresses at a typical section with void behind the lining

case			A	B	C	D	
k=0.5	**without void**	extrados	5.56	2.35	6.12	1.11	
		intrados	0.52	5.09	2.73	2.5	
	with void	extrados	-2.0(-3.3)	7.3	3.19	0.73	
		intrados	12(17)	-0.38(-1.2)	1.93	1.34	

The cause of the tunnel lining damages should be complicated. Generally, the following causes are the major contribution of the tunnel lining damages. They are: 1) the tunnel located in a horizontally layered strata of mudstone mixed with sandstone, the relaxation of ground pressure shows a time dependent effect; 2) Due to technique limitation at the time of construction, the used lower strength concrete (C20) is more easy to crack; 3) To meet for two layers of containers transportation, the tunnel section has a relatively larger high than width, which lead to a complex structure internal force; 4) In some place, voids behind the lining (especially at the crown) causes a non-uniform distribution ground pressure which is negative to the lining mechanical performance; 5) Insufficient lining thickness, un-grouted grouting hole shows the lining thickness locally only 30 cm ~45 cm, and normally it should be 50 ~ 120 cm; 6) Possible complex ground stress condition, which results in crush at the crown and tensile crack at the intrados of the arch shoulder.

4. Rehabilitation using reinforced shotcrete

Two stages of measures were carried out to rehabilitate the tunnel lining imperfections and damages. In the first stage, the running speed of the railway was reduced to 80km/h ; and then temporary steel-rib archs were placed for supporting tunnel lining where were evlauated as very severe damaged (mileage of DIK68+324-370 and 440-480). Figure 11 shows the photoes of the steel-rib archs taken on site. This temporary support ensures the safety of railway operation during day time and the rehabilitation work in the night time.

Figure 11 Temporary steel-rib arch for supporting vert severe damaged lining section

In the second stage of rehabilitation, at first grouting was carried out to fill the void behind the lining and the uncompacted material, as shown in Figure 12. Non-shrinkage grout was used to back fill the void, each layer of grouting less than 40 cm. The grouting was processed layer by layer to ensure the exsiting void to be fully back filled and the uncompacted area to be compacted. Then, when close the tunnel for a long time is impossible, and there are sufficient surplus space outside the tunnel clearances, reinforced shotcrete were used to form a shell arch to rehabilitate and reinforce the tunnel lining.

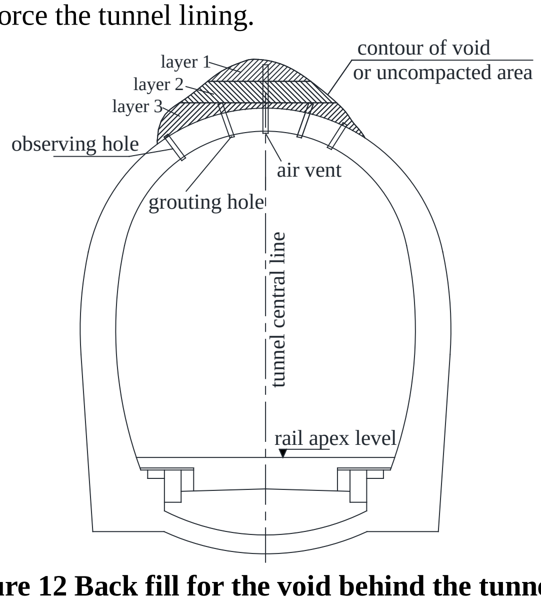
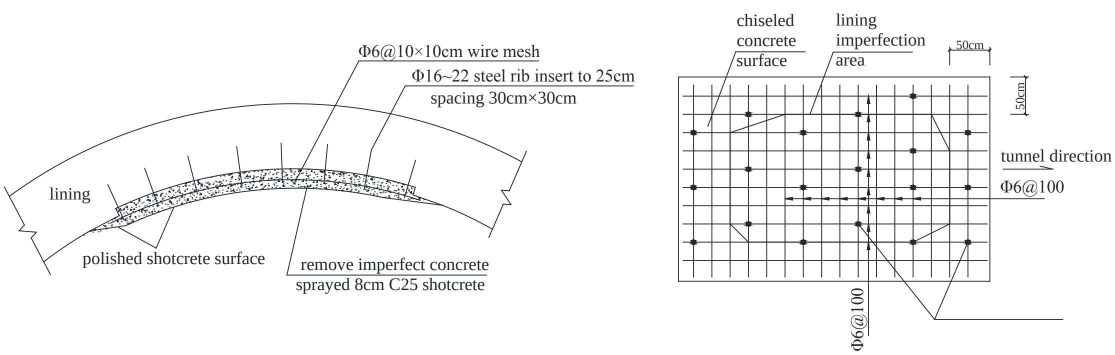


Figure 12 Back fill for the void behind the tunnel lining

For lining with moderate or not very severe damages, such as concrete flaking off and crack net occurred at the crown area of the tunnel lining. First, the lining surface was removed and chiselled to be rough, and then the steel bar and wire mesh were installed accordingly. Finally, the shotcrete was sprayed with the surface brushed after the early strength stage. Such rehabilitating scheme was presented in Figure 13.

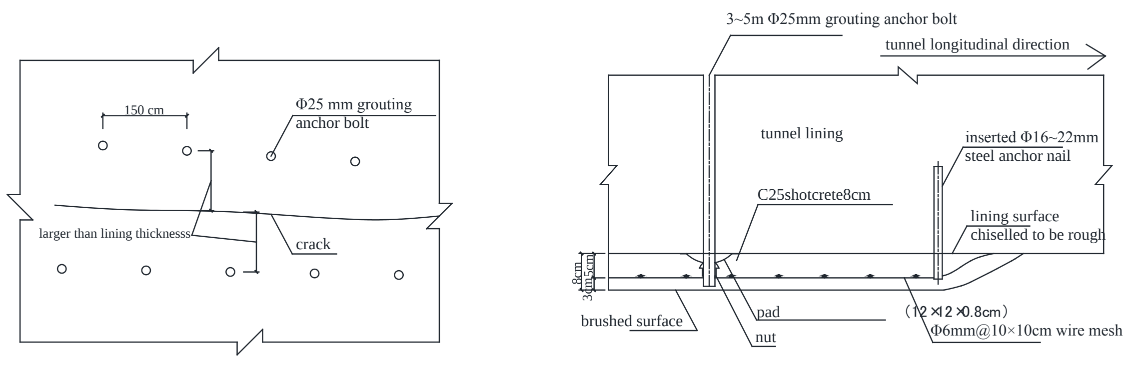
However, if lining crack larger than 1.5 mm, or cracks are severely developed to be net distribution and staggered, and there are more than 10 cm surplus clearance. Hollow grouting anchor bolt should be used to cross over the cracks, as shown in Figure 14. Hence, the shorcrete geneally was reinforced by the grouting anchor bolt together with the wire mesh.

Figure 15 shows the field application of the rehabilitation scheme. It clear show the three difference surfaces at the different stages. From the right to the left, they are the old lining surface, the surface of the sprayed shotcrete, and the surface placed with wire mesh. The possible smooth transition between the three surfaces indicates that the proposed scheme could work effectively to rehabilitate the lining imperfections and damages.



shotcrete reinforced with stell rib and wire mesh　　　　Layout of the wire mesh

Figure 13 The design chart of shotcrete reinfoced with steel bar and wire mesh



Distribution of grouting bolt cross cracks　　　　Schematic reinforcement

Figure 14 The design chart of shotcrete reinforced with anchor bolt and wire mesh

Figure 15 The field application of the rehabilitation scheme

5. Concluding remarks

A systematic method was proposed to investigate and rehabilitate the tunnel lining imperfections and damages. Such method was based on a reinforced shotcrete technology together with anchor bolts for position fixation and a grouting technique for fill the void behind the lining and to compact the material behind the lining.

It has been revealed that the insufficient lining thickness and void behind the lining at the crown area are major causes of the lining crack. Void and uncompacte area behind the lining would lead to decrease in the magnitude of bending moment and reverse sign, which could cause cracks at the intrados at the shoulder of the tunnel arch on the inner lining surface.

If surplus tunnel space outside the railway clearance is enough, shotcrete reinforced by anchor bolt and wire mesh are an effective way to form a shell arch for rehabilitating and reinforcing the tunnel lining, compared with closing the tunnel to replace the lining. Field case study shows a good performance of using the reinforced shotcrete for the rehabilitation of crushed or cracked tunnel lining.

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