Test on Rigid-flexible Composite Anti-breaking Measure for Tunnels across Stick-slip Fault

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Research Article

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Abstract

In this paper, based on the F8 stick-slip fault section of Longxi Tunnel in China, the effect of the anti-breaking measure of rigid-flexible composite (reinforcement of the secondary lining & construction of the reducing dislocation layer between the primary support and the secondary lining) is studied by using the method of indoor model test in order to improve the anti-breaking performance of the tunnel across stick-slip fault in the actual tunnel engineering. The test results show that the anti-breaking effect is limited by adopting structural strengthening measures to resist the influence of stick-slip dislocation on the tunnel structure and the anti-breaking effect is obvious by adopting the measures of reducing dislocation layer only. However, the structural safety of the tunnel with stick-slip fault in the strong seismic intensity area can be greatly improved by adopting the anti-breaking measure of rigid-flexible composite, and the structural safety factor can be significantly improved. The research results of this paper can provide a reference for the anti-breaking design of the tunnel across stick-slip fault in the high seismic intensity area.

Introduction

The anti-breaking technology for the tunnel across the stick-slip fault has always been one of the most difficult problems in the field of tunnel engineering all over the world (Baziar, M. H., et al, 2014; Wang, Z. Z., and C. Chen., 2017). For example, in China, which is a vast country in territory, with the continuous and in-depth development of traffic infrastructure construction in the west, tunnels crossing the stick-slip fault continue to emerge, such as Jiudingshan Tunnel of Mianzhu-Maoxian Highway (crossing Longmenshan Fault), Erlangshan Tunnel of Yakang Expressway (crossing Baohuang Fault) and Chengdu-Lanzhou Railway Tunnels (crossing Longmenshan Faults), etc.

Through investigation, it is found that strong earthquake can induce the activation of the stick-slip fault, and the dislocation of the fault is the primary factor causing the serious damage of the tunnel across the stick-slip fault (Cui, G. Y., and Wang, X. L., 2019; (Baziar, M. H., et al, 2016; Ardeshiri-Lajimi, S., et al, 2015). Once the stick-slip dislocation occurs, it will cause the tunnel lining to be misplaced, collapse, and even severe earthquake damage such as collapse of surrounding rocks. Typical similar tunnels are such as the Sabzkouh tunnel in Iran, the Inatori Tunnel and Tanah Tunnel in Japan, the Longxi Tunnel and the Baiyunding Tunnel in China (Chermahini, A. G., and Tahghighi, H., et al, 2019; Yu, H., et al, 2016). Therefore, in the field of tunnel engineering worldwide, it is necessary to carry out systematic research on the anti-breaking technology of tunnels across stick-slip fault.

Experts and scholars in the field of tunnel engineering all over the world have done a plenty of research on the subject of anti-breaking technology of tunnels across the stick-slip fault. Wang, Z. Z., et al. (2017) used numerical simulation technology to study the disaster mechanism of the tunnel, damage mechanism of tunnel structure and surrounding rock under the action of stick-slip dislocation (Boming, Z., and Yang, L., 2009; Zhao, Y., 2016). Wang, M. N., and Cui, G. Y. (2010) used the method of model test to study the response of tunnel structure and surrounding rock under the action of stick-slip dislocation in

highly seismic area (Liu, X.Z., et al, 2013; Sim, W. W., et al, 2012). According to the previous research results, it is obviously found that shear force and forced displacement are the main causes of the structural damage of the tunnel across stick-slip fault. Therefore, based on this, the most common methods in the anti-breaking design of the tunnel can be summarized as anti-breaking measures and reducing dislocation measures. The anti-breaking measures mainly include strengthening the secondary lining and strengthening the surrounding rock, which can resist the shear force and forced displacement caused by stick-slip dislocation. Reducing dislocation measures mainly include the construction of reducing dislocation layer and the construction of reducing dislocation joint, which can reduce the transfer of shear force and forced displacement to the secondary lining. At present, more and more experts and scholars have done a lot of research on the anti-breaking measures and reducing dislocation measures. Relying on the tunnel project of Urumqi Metro Line 1 crossing the F2-3 section of Jiujiawan active fault, Cui, G. Y., et al. (2019) adopted the method of model test to make a comparative analysis of the different anti-breaking effects of the reducing dislocation layer under different construction position. Shahidi, A. R., and Vafaeian, M. (2005) carried out a series of studies on the Koohrangs hydraulic tunnel in Greece, and compared and analyzed the influence of the anti-breaking effect of the reducing dislocation joint with different spacing under the influence of the stick-slip fault. Liu, X.Z., et al. (2015) used numerical simulation technology to study both the anti-breaking measures and reducing dislocation measures of active fault tunnel in high intensity seismic area.

In conclusion, all the above studies prove that those measures can play a good anti-breaking role in the tunnel engineering crossing active faults. However, the current research is mainly focused on the single measures such as reducing dislocation joint in the secondary lining, reducing dislocation layer between the primary support and the secondary lining. There are few reports on the research of the combination of anti-breaking measures and reducing dislocation measures. Based on this, this paper puts forward a kind of anti-breaking measure called "Rigid-flexible composite", that is to say, two measures are adopted at the same time, i.e. strengthening the secondary lining and setting the reducing dislocation layer between the primary support and the secondary lining, so as to be used in the anti-breaking design for tunnels across stick-slip fault, which is of great significance for the further development of the anti-breaking technology.

Test Scheme Design

Background

In order to study the anti-breaking measure for tunnels across stick-slip fault, the method of model test was designed for research. This model test is based on the F8 stick slip fault section of Longxi tunnel located in Dujiangyan City, China. The F8 Fault is a compressional stick-slip fault with a dip angle of 82° to the north, which is mainly composed of molonite and fault gouge, with a width of about 10m and surrounding rock grade of grade V. The surrounding rock of upper and lower wall is grade IV.

The section of the tunnel is horseshoe-shaped with a span of 11.90m and a height of 10.14m. C20 shotcrete(GB50010-2010 2010) with a thickness of 20cm is used for the primary support, and C25

concrete with a thickness of 60cm is used for the secondary lining.

Test purpose and grouping

In order to study the response law and anti-breaking effect of rigid-flexible composite measure, the experimental groups were designed as shown in Table 1. In this experiment, the "rigid" part is simulated by the secondary lining of C25 ($E = 28\text{GPa}$) and C35 ($E = 31.5\text{GPa}$) concrete, and the "flexible" part is simulated by setting reducing dislocation layer between the primary support and the secondary lining, and the optimum thickness of the reducing dislocation layer is 10 cm.

Table 1. Test Grouping

Working condition	Test contents
1	The secondary lining concrete is C25, with no reducing dislocation layer.
2	The secondary lining concrete is C35, with no reducing dislocation layer.
3	The secondary lining concrete is C25, with 10cm thick reducing dislocation layer.
4	The secondary lining concrete is C35, with 10cm thick reducing dislocation layer.

Test equipment

The test was carried out with a self-designed test box (length $\times$ width $\times$ height = 2.5m $\times$ 2.5m $\times$ 2m). The test box consists of a fixed footwall and a movable hanging wall with a fault dip angle of 82°. The test box is shown in Figure 1.

The test measurement sensors mainly include: AVIC resistance strain gauge (BE120-5AA type) and Sanda micro pressure box (DYB-1 type), as shown in Figure 2. Donghua static strain collector is used for data acquisition.

Similar ratio design and similar materials

In order to eliminate the boundary effect of the test as much as possible, and considering the size of the test chamber and the tunnel model, the geometric similarity ratio of the test is set as 30. The secondary lining is simulated with gypsum mixture, and the similar ratio of gravity and elastic modulus is 1.5 and 45 respectively. Similar ratios of other physical quantities are shown in Table 2.

Table 2. Similar ratios of other physical quantities

Type	Physical quantity	Similarity ratio
Material properties	Stress / cohesion	45
	Strain / Poisson's ratio / internal friction angle	1
Geometric characteristics	angular displacement	1
	Area	900
Load type	Load	40500
	Moment	1215000

The secondary lining is simulated with gypsum mixture and finished steel wire mesh (double layer). The water-paste ratio is 0.676 for C25 and 0.599 for C35, respectively. The physical and mechanical

parameters of lining model are shown in Table 3. Gypsum is used to simulate the primary support. The surrounding rock is simulated with fly ash, river sand and waste engine oil. Sponge rubber plate with thickness of 1.7mm is used to simulate the reducing dislocation layer. Polyethylene film is used to simulate the waterproof board (between the primary support and the secondary lining) (see Figure 3). The dislocation effect of stick-slip fault is realized by two layers of PVC plastic plates set at the fault, and the butter is evenly applied between the two layers of PVC plastic plates (see Figure 4).

Table 3. Physical and mechanical parameters of lining model

Material name		Elastic modulus/MPa	Bulk density / (kN·m-3)	Poisson's ratio
C25	Prototype lining	29500	25	0.2
	Similar material	657.4	16.8	0.21
C35	Prototype lining	31500	25	0.2
	Similar material	696.3	16.7	0.206

Test measurement section and layout of measuring points

The measuring section and the layout of measuring points are shown in Figure 5-6 respectively. The transverse strain gauge (Y) is arranged inside and outside the secondary lining, the longitudinal strain gauge (ZY) is arranged outside the secondary lining, and the miniature pressure box (T) is arranged between the primary support and the secondary lining.

Test process

(1) The jack (5t, see Figure 7) at the bottom four corners of the upper plate of the test box was used to lift the upper plate of the test box by 5cm (in Wenchuan earthquake, the dislocation of fault surface of F10 Fault of Longxi Tunnel was 1.5m).

(2) Similar materials of surrounding rock were filled and compacted layer by layer with each layer of 0.2m, and the secondary lining model was installed at the bottom elevation of the tunnel. Then the waterproof board, damping layer and the test sensor were laid.

(3) After the above steps are completed, the surrounding rock similar materials were continuously compacted layer by layer to the surface elevation. After the test instrument were debugged, the four jacks at the bottom of the upper plate of the test box were put down at the same time, so that the upper plate rock mass would slip and move along the fault plane. After the final test data was collected, the test was completed.

Test data and analysis

Longitudinal strain

After the test, the test data of the longitudinal strain on the measuring points of the arch crown of each measuring section under each working condition were extracted. Take sections III and IV that were greatly affected by dislocation as examples, as shown in Table 4. The increment of longitudinal strain was calculated as shown in Figure 8. The positive part of the abscissa is the hanging wall, and the negative part of the abscissa is the footwall.

Table 4. The longitudinal strain of vault

Working condition		1/ $\mu\epsilon$	2/ $\mu\epsilon$	3/ $\mu\epsilon$	4/ $\mu\epsilon$
Section III	Before dislocation	2.72	1.82	3.64	2.85
	After dislocation	1117.45	641.35	36.61	22.65
Section IV	Before dislocation	1.96	2.11	1.76	2.11
	After dislocation	95.60	82.87	5.89	5.56

It can be seen from Table 4 and Figure 8 that:

(1) After the test, the increment of longitudinal strain of the vault of the hanging wall is obviously greater than that of the footwall tunnel, and the influence of the stick-slip dislocation of the hanging wall is greater than that of the footwall.

(2) The increment of longitudinal strain along the longitudinal structure of the tunnel changes from violent change to more uniform change.

The maximum values of the increment of longitudinal strain under each working condition were extracted, and the anti-breaking effect of longitudinal strain under each working condition was calculated, as shown in Table 5.

Table 5. The anti-breaking effect of longitudinal strain

Working condition	The maximum value of the increment of longitudinal strain	Anti-breaking effect/% (Relative to working condition 1)	Anti-breaking effect/% (Relative to working condition 2)
1	1114.73	—	—
2	639.53	42.63	—
3	32.97	97.04	94.84
4	19.8	98.22	96.90

According to Table 5:

(1) The anti-breaking effect of longitudinal strain under working condition 2 with structural strengthening measures only (compared with working condition 1) is 42.63%, which shows that the effect of structural strengthening measures on the longitudinal strain of tunnel structure is limited.

(2) The anti-breaking effect of longitudinal strain under working condition 3 (relative to working condition 1) and working condition 4 (relative to working condition 2) are 97.04% and 96.90%, respectively, which

shows that the influence of stick-slip fault on the longitudinal strain of tunnel structure can be reduced by using the measures of reducing dislocation layer, and the anti-breaking effect is more than 96%.

(3) Anti-breaking measure of rigid-flexible composite (working condition 4) has the best anti-breaking effect of longitudinal strain, which is 98.22%.

Contact stress

After the test, the test data of the contact stress on the measuring points of the arch crown of each measuring section under each working condition were extracted. Take sections III and IV that were greatly affected by dislocation as examples, as shown in Table 6. The increment of contact stress was calculated as shown in Figure 9.

Table 6. The contact stress of vault

Working condition		1/kPa	2/ kPa	3/ kPa	4/ kPa
Section III	Before dislocation	-1.97	-2.04	-2.24	-1.99
	After dislocation	60.09	66.62	16.48	18.39
Section IV	Before dislocation	3.12	2.85	-2.79	-2.81
	After dislocation	49.14	50.42	8.14	10.52

According to Table 6 and Figure 9:

(1) After the test, the increment of contact stress of the vault of the hanging wall tunnel is obviously greater than that of the footwall tunnel, and the influence of the dislocation of stick-slip fault of the hanging wall tunnel is greater than that of the footwall tunnel.

(2) After installing the reducing dislocation layer, the increment of contact stress along the longitudinal structure of the tunnel changes from violent change to more uniform change.

The maximum values of the increment of contact stress under each working condition were extracted, and the anti-breaking effect of contact stress under each working condition was calculated, as shown in Table 7.

Table 7. The anti-breaking effect of contact stress

Working condition	The maximum value of the increment of contact stress	Anti-breaking effect/% (Relative to working condition 1)	Anti-breaking effect/% (Relative to working condition2)
1	58.12	—	—
2	64.58	-11.11	—
3	14.24	75.50	77.95
4	16.40	71.78	74.61

According to Table 7:

(1) For the maximum value of contact stress increment, working condition 2 is increased relative to working condition 1, and working condition 4 is also increased relative to working condition 3, which

shows that the release of surrounding rock stress is further limited after the structural strengthening measures are adopted.

(2) The anti-breaking effect of contact stress under working condition 3 (relative to working condition 1) and working condition 4 (relative to working condition 2) is 75.50% and 74.61% respectively, which shows that the influence of stick-slip fault on the contact stress of tunnel structure can be reduced by using the anti-breaking measures, and the anti-breaking effect is more than 74%.

Structural internal force

After the test, the measurement data of the transverse strain gauge of each monitoring section measurement point under each working condition were extracted, and the axial force, bending moment and safety factor of the structure were calculated according to the Equations (1) - (4) (GB50157-2013 2013; JTGD70-2004 2004), as shown in Figure 10 (taking the measurement point of the arch crown as an example).

The axial force and bending moment of lining are:

$$N = \frac{1}{2} E(\varepsilon_{inside} + \varepsilon_{outside})bh \quad (1)$$

$$M = \frac{1}{12} E(\varepsilon_{inside} - \varepsilon_{outside})bh^2 \quad (2)$$

Safety factor of lining is:

$$KN \leq \varphi \alpha R_a bh \quad (3)$$

$$KN \leq \varphi \frac{1.75 R_l bh}{6e_0 / h - 1} \quad (4)$$

In the equations: The width of the section is expressed by b, and the width of the section is 1m. The thickness of section is expressed by h. The modulus of elasticity is expressed in E. The internal and external strain of the structure is expressed by ε_{inside} and $\varepsilon_{outside}$, respectively. Structural axial force is expressed by N. The bending moment is expressed by M. The ultimate compressive strength of concrete is expressed by R_a . The ultimate tensile strength of concrete is expressed by R_l . The safety factor is expressed by K. The longitudinal bending coefficient of components is expressed by φ . The influence coefficient of axial force eccentricity is expressed by α .

It can be seen from Figure 10 that the safety factor of the tunnel structure in the hanging wall part is smaller than that in the footwall part under each working condition after stick-slip dislocation. After the minimum values of safety factor of each working condition were extracted, the increase multiples of the minimum value of safety factor of each working condition were calculated, as shown in Table 8.

Table 8. Increase multiple of the minimum value of the safety factor

Working condition	Minimum value of safety factor	Increase multiple (Relative to working condition 1)	Increase multiple (Relative to working condition2)
1	0.19	—	0.49
2	0.55	2.06	—
3	3.42	17.54	8.53
4	4.13	21.16	10.29

According to Table 8:

(1) Compared with working condition 1, the increase multiple of the minimum value of safety factor of working condition 2 is only 2.06, which shows that the effect of structural strengthening measures to resist the influence of stick-slip dislocation on the internal force of tunnel structure is limited.

(2) The minimum increase times of safety factor of working condition 3 (relative to working condition 1) and working condition 4 (relative to working condition 2) are 17.54 and 10.29 respectively, which shows that the effect of reducing the influence of the stick-slip dislocation on the internal force of the tunnel structure is obvious, and the minimum value of the safety factor is increased by more than 10 times.

(3) When the anti-breaking measure of rigid-flexible composite (working condition 4) is adopted, the minimum value of safety factor increases by 21.16, which is the biggest.

Conclusions

(1) After installing the reducing dislocation layer, the increment and increase times of longitudinal strain and contact stress along the longitudinal structure of the tunnel change from violent change to more uniform change.

(2) By adopting structural strengthening measures to resist the influence of stick-slip dislocation on the tunnel structure, the anti-breaking effect of longitudinal strain is 42.63%, and the minimum safety factor increases by 2.06 times so that the effect is limited.

(3) By adopting the measures of reducing dislocation layer to reduce the influence of stick-slip dislocation on the tunnel structure, the anti-breaking effect of longitudinal strain is more than 96%, the anti-breaking effect of contact stress is more than 74%, and the minimum safety factor is increased by more than 10 times so that the effect is obvious.

(4) Through adopting the measures of rigid-flexible composite to deal with the influence of stick-slip dislocation on the tunnel structure, the anti-breaking effect of longitudinal strain and contact stress is 98.22% and 69.70% respectively, and the minimum safety factor is increased by 21.16 times so that the effect is limited.

(5) To sum up, the structural safety of the tunnel can be greatly improved by adopting the anti-breaking measure of rigid-flexible composite (reinforcement of the secondary lining & Construction of the reducing dislocation layer between the primary support and the secondary lining). This measure is of great

significance for the further development of the anti-breaking technology of the tunnel across the stick-slip fault.

Declarations

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Ethics approval: This article does not contain comments on morality.

Consent to participate: Agree to participate in related research

Consent for publication: If this article is accepted, we agree to transfer the copyright to this journal.

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Figures

Figure 1

Test box for stick-slip dislocation of normal fault.

(a) Strain gauge

(b) Micro pressure box

Figure 2

Measuring sensors

(a) Secondary lining model

(b) Reducing dislocation layer

(c) Waterproof board

(d) Primary support

Figure 3

Test similar material

Figure 4

Simulation of dislocation effect of stick-slip fault

Figure 5

Measuring section (unit: mm)

Figure 6

Arrangement of measuring points

Figure 7

Dynamic device of stick-slip fault dislocation

(a) Working condition 1-4

(b) Working condition 3-4

Figure 8

The increment of longitudinal strain

Figure 9

The increment of contact stress

Figure 10

Safety factor of vault