Seismic model test research on the combination of rigidity with flexibility of tunnel portal in high intensity seismic areas

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ABSTRACT
Taking the soft rock portal section of the Baiyunding Tunnel as the research background, it is proposed that the combination of rigid and flexible anti-vibration measures can more effectively improve the seismic performance of the tunnel. Through shaking table model test, the seismic effects of structural reinforcement, installation of shock absorbing joint, and the combination of rigid and flexible anti-vibration measures are compared and analyzed. The test data shows that: only structural strengthening measures are taken, the minimum increase percentage of the structural safety factor of the tunnel portal section is between 30.40% and 62.28%; only shock absorbing joint are installed, and the minimum increase percentage of the safety factor of the tunnel portal section is between 41.86% and 53.30%; the combination of rigid and flexible anti-vibration measures is adopted, the minimum increase percentage of the structural safety factor of the tunnel portal section is between 85.20% and 140.99%. The combination of rigid and flexible anti-vibration measures has a significant effect on resisting earthquake vibration and reducing forced displacement, and the effect of shock absorption is the best. The research results can provide a reference for improving the seismic performance of traffic tunnels in high seismic intensity areas.

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Introduction
As China’s transportation infrastructure projects continue to develop in the three high areas (high seismic intensity, high altitude, and high latitude), a large number of traffic tunnels have emerged in strong earthquake areas. The seismic fortification design of traffic tunnels in high seismic intensity areas has attracted more and more attention.

The portal section and the fault fracture zone are the key sections of the tunnel seismic fortification design (Japan Society of Civil Engineers 1997; Cui et al. 2011),
and the soft rock portal section is more affected by the earthquake than the hard rock portal section (Gao et al. 2009; Feng et al. 2012; Patil et al. 2018). In the Sichuan earthquake, there are even serious damages of lining collapse in the portal section of soft rock (Wang et al. 2012). Therefore, experts pay more attention to further improve the seismic performance of soft rock tunnel portal section in strong earthquake area.

At present, there are mainly two kinds of protection measures for tunnel in earthquake: anti-seismic measures and shock absorption measures. There are two kinds of anti-seismic measures for the tunnel: Structural strengthening and surrounding rock strengthening. The specific measures are as follows: strengthening the mechanical properties of the surrounding rock by using the system anchor bolt, improving the surrounding rock strength by using the surrounding rock grouting (full ring interval grouting, full ring contact grouting and local grouting), and improving the lining strength by using the concrete with higher strength (Bottelin et al. 2017). The shock absorption measures can achieve the shock absorption effect by setting the shock absorption layer and the shock absorption joint (Li 2014). Because the anti-seismic measures will increase the strength of the tunnel and surrounding rock, it has more advantages to resist the seismic inertia force. As the shock absorption measures will provide a certain amount of deformation margin for the lining (Huang 2012), which is more advantageous to reduce the forced displacement.

Due to the influence of earthquake, the seismic inertia force and forced displacement of the tunnel structure in the soft rock portal section are stronger than that in the ordinary section (Wang et al. 2017). Therefore, this article puts forward the seismic measures of combining rigidity with flexibility to fortify the portal section of soft rock (the second lining is strengthened and set the shock absorption joint). The shock absorption joint of the second lining is generally set according to the length of the formwork trolley (the shock absorption joint and the construction joint are set at the same section), the shock absorption joint is built with rubber waterstop, and the back surface of the shock absorption joint is filled with caulking paste, and the inside of the shock absorption joint is filled with asphalt sand mixture.

The research on seismic measures of tunnels has been continuing. Li et al. (Li et al. 2009), carried out shaking table model tests on the anti-seismic measures for strengthening the surrounding rock and the shock absorption measures for setting shock absorption joints, respectively, and the research shows that the distance of 48–60 m from the entrance to the tunnel should be the key area of seismic protection. ZHAO et al. (Zhao et al. 2013), was used to study the material properties of high performance foam concrete shock absorption materials by indoor tests. The shock absorption material with high mechanical properties and economy was found for the shock absorption layer of the portal section of the Galongla Tunnel. The measures of strengthening surrounding rock and setting shock absorption joints are usually studied by numerical analysis (Chen et al. 2013; Wang et al. 2019). The seismic measures to improve the stiffness of the supporting structure are generally studied by simulation tests (Cui et al. 2018), and the longitudinal dynamic response characteristics of the tunnel are generally studied by establishing vibration equations (Zheng et al. 2014).
In the past research, there are few studies on the comprehensive seismic measures of tunnel portal section by using anti-seismic measures combined with shock absorption measures, and there are few reports on this aspect by using shaking table model test (Wang et al. 2015). Based on the research background of the portal section of Baiyunding Tunnel, this article studies the shaking table model test of the tunnel portal section by adopting the measures of combining rigidity with flexibility, which is of great significance to the development of the anti-seismic technology of the portal section of the traffic tunnel in the high intensity earthquake area.

### 2. Background and test scheme design

#### 2.1. Geological conditions of tunnel

The overburden at the portal of Baiyunding Tunnel is quaternary colluvium, mainly composed of gravelly soil and filled with a small amount of sandy silt, with lithology grade of V. Under the overburden, there is grade II surrounding rock, mainly composed of sandstone and limestone, with hard lithology and weak weathering.

#### 2.2. Structural design

The tunnel adopts composite lining and the section shape is horseshoe, span × height = 11.30 m × 9.65 m. The first support is C20 shotcrete with a thickness of 25 cm, and the second lining is C25 moulded reinforced concrete with a thickness of 60 cm.

#### 2.3. Test group

Since the shock absorption joint is usually set according to the length of the formwork trolley, this test takes the 9 m formwork trolley as an example, and the width of the shock absorption joint is 6 cm. C25 (modulus of elasticity is 28 Gpa) and C35 (modulus of elasticity is 31.5 Gpa) concrete were used to study the mechanics of the secondary lining structure.

In order to study the dynamic characteristics and anti-seismic effect of the seismic measures of combining rigidity with flexibility adopted for the tunnel portal section in the high intensity earthquake area, the test grouping is shown in Table 1.

| Working condition | Test contents |
|-------------------|---------------|
| 1                 | The second lining is made of C25 concrete and there is no shock absorption joint |
| 2                 | The second lining is made of C35 concrete and there is no shock absorption joint |
| 3                 | The second lining is made of C25 concrete and shock absorption joints with a distance of 9 m are set here. |
| 4                 | The second lining is made of C35 concrete and shock absorption joints with a distance of 9 m are set here. |
2.4. Test equipment

The test was carried out on a large shaking table with three directions and six degrees of freedom. Table size: length and width are 6 m, maximum load is 60t, frequency range is 0.1–100 hz. The shaking table is shown in Figure 1, and the basic parameters of the shaking table are shown in Table 2.

At present, layered shear test chamber and rigid test chamber are mainly used in dynamic test of underground structure. Layered shear test box can realize the shear deformation of soil layer and simulate the dynamic boundary conditions of soil better. It is mainly used in the dynamic test of underground structures in soft soil. Because the project of this test is mountain tunnel, the shear deformation of rock stratum is very small and can be ignored. Therefore, the self-made rigid test box is used in this test. The test box is made of steel plate with angle steel as lateral support.

The self-made model test box is used for the test, and the size of the test box: 2.5 m (length) × 2.5 m (width) × 2 m (height). In order to minimize the relative sliding between the bottom of the test box and the surrounding rock in the shake process, a layer of gravel is cemented at the bottom of the box to increase the friction force. In order to eliminate the boundary effect as much as possible and reduce the friction between the side wall and the surrounding rock in the shake process, 15 cm thick molded polystyrene foam board is laid on the side wall of the test box, and 6020 film (PVC film) is adhered to the inner surface. As shown in Figure 2.

Dynamic strain data acquisition instrument and dynamic strain data conversion instrument are used for data acquisition in the test, as shown in Figure 3. The main test sensors: accelerometer, micro earth pressure box and resistance strain gauge.
2.5. Similar design and similar materials

Considering the boundary effect of the test and the size of the test box, the geometric similarity ratio of this test is taken as 30. Referring to the relevant literature (Hua et al. 1997; Wang et al. 2019; Shen et al. 2020), it is finally determined that the acceleration similarity ratio is 1, the similar ratio of elastic modulus is 45, and the similar ratio of other parameters are shown in Table 3.

![Figure 2: Model test chamber and boundary processing.](image1)

![Figure 3: Test data acquisition system.](image2)

| Parameter name | Similarity ratio |
|----------------|------------------|
| Frequency      | 0.18             |
| Internal friction angle / Strain / Poisson’s ratio | 1     |
| Density        | 1.5              |
| Time / Speed   | 5.477            |
| Stress         | 45               |
| Damping        | 7394             |
| Load / Mass    | 40500            |
| Torque         | 1215000          |

Table 3. Similarity relation of main physical variables.
The surrounding rock is mainly simulated by sand, fly ash, barite powder, quartz sand, Vaseline, rosin and engine oil, and the proportion of each material is determined by orthogonal test. The first support and the second lining are simulated by gypsum admixture, and the waterproof board is simulated by polyethylene film. Gypsum admixture is used to simulate the primary support and secondary lining, and polyethylene membrane is used to simulate the waterproof board. The paste water ratio of the secondary lining structure is 1.48 (C25) and 1.67 (C35), respectively. The thickness of the initial support is 8.3 mm, and the thickness of the secondary lining is 2 cm. The space between the shock absorption joint is 0.3 m, and the width of the shock absorption joint is 2 mm. As shown in Figure 4.

### 2.6. Test dynamic load

In this test, the measured wave of Wenchuan earthquake (Wolong station) is used, the seismic wave duration is 164.6 s and the recording interval is 0.005 s. After amplitude modulation (9 degrees), similarity transformation, filtering and baseline correction. The acceleration time history curve taking the east-west direction as an example is shown in Figure 5.
2.7. Layout of monitoring section and measuring points

In order to study the dynamic characteristics and anti-seismic effect of the seismic measures of combining rigidity with flexibility, a monitoring section-A is set in the
soft rock section of the portal, and a monitoring section E is set in the hard rock section of the portal. Three monitoring sections are set in the soft and hard surrounding rock transition sections, which are Section B (the transfer position is the inverted arch), Section C (the transfer position is the side wall) and Section D (the transfer position is the vault), as shown in Figure 6.

The unidirectional accelerometer (J) is arranged on the inner side of the middle inverted arch of each monitoring section; The miniature earth pressure box (T) and the longitudinal strain gauge (ZY) are arranged on the outside of the vault; Transverse strain gauges (Y) are arranged in pairs on the inside and outside of the vault, side walls and the middle of the inverted arch. The layout of measuring points is shown in Figure 7.

3. Test data and analysis

3.1. Peak ground acceleration (PGA)

The acceleration time history curve of each measuring section under each working condition is extracted as shown in Figure 8 (take section C under condition 3 as an example).

The PGA (peak ground acceleration) is extracted from the acceleration time history curve of each measurement point, as shown in Figure 9. The percentage of PGA increase or decrease at each measuring point under each operating condition is calculated, as shown in Table 4.

According to Figures 8 and 9 and Table 4:

1. When the seismic measures only adopt structural strengthening (condition 2 contrast condition 1). The increase percentage of PGA in the hard rock section of the portal is very small, the maximum is only 1.95%; with the increase of the range of soft rock, the increase percentage in PGA is increasing, and the maximum increase percentage of soft rock section is 7.59%.

2. When the seismic measures only adopt the shock absorption joint (condition 3 contrast condition 1, condition 4 contrast condition 2). After setting the shock absorption joint, the change of PGA at each measuring section of the tunnel portal is very small, the
maximum is only 1.55%. This shows that the setting of shock absorption joint at the second lining has little effect on reducing the seismic inertia force.

3. When the measures of combining rigidity with flexibility are adopted (condition 4 contrast condition 1). The increase percentage of PGA in the hard rock section of the portal is also very small, and the maximum is only 1.05%; with the increase of the range of soft rock, the percentage increase in PGA is increasing more significantly, and the maximum is 9.26%.

### 3.2. Longitudinal strain

Similarly, extract the longitudinal strain time history curve of each monitoring point under each working condition, as shown in Figure 10 (take section B under condition 2 as an example).

Take the peak value of each longitudinal strain time history curve to draw a comparison diagram, as shown in Figure 11. According to the comparison data, the reduction percentage of the maximum value of the longitudinal strain under each working condition is calculated, as shown in Table 5.

According to Figures 10 and 11 and Table 5:

1. When the seismic measures only adopt structural strengthening (condition 2 contrast condition 1). The peak value of the longitudinal strain in the hard rock section of the tunnel portal decreases slightly, and the maximum decrease value is
6.19%; with the increase of the range of soft rock, the reduction percentage of the longitudinal strain peak decreases continuously, and the maximum reduction is 13.36%.

2. When the seismic measures only adopt the shock absorption joint (condition 3 contrast condition 1, condition 4 contrast condition 2). After setting the shock absorption joint, the increase/decreased percentage of PGA is shown in Table 4.

| Monitoring section | Condition 2 (contrast condition 1) (%) | Condition 3 (contrast condition 1) (%) | Condition 4 (contrast condition 1) (%) | Condition 4 (contrast condition 2) (%) | Condition 4 (contrast condition 3) (%) |
|--------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
| A                  | +7.59                                | +1.30                                | +9.26                                | +1.55                                | +7.86                                |
| B                  | +5.95                                | +0.58                                | +7.29                                | +1.27                                | +6.68                                |
| C                  | +3.93                                | +0.87                                | +4.59                                | +0.63                                | +3.68                                |
| D                  | +1.95                                | -0.49                                | +0.73                                | -1.19                                | +1.22                                |
| E                  | +0.52                                | -0.52                                | +1.05                                | -0.52                                | +1.58                                |

Note: The comparison of the experimental data of various conditions can directly reflect the seismic effect of the optimal conditions of the tunnel portal section.

Figure 10. Longitudinal strain time history.

Figure 11. Longitudinal strain peak.
absorption joint, the longitudinal strain peaks of the each measuring section of the tunnel portal decreases basically the same, and the reduction percentage is between 19.76% and 29.36%. This shows that the shock absorption joint of the second lining has a significant effect on reducing the longitudinal strain of the structure.

3. When the measures of combining rigidity with flexibility are adopted (condition 4 contrast condition 1). The reduction of the peak value of the longitudinal strain at each measuring section of the tunnel portal section is basically the same, and the reduction percentage is between 30.52% and 36.77%. This shows that the seismic measures of combining rigidity with flexibility have obvious effect on reducing the longitudinal strain of the structure.

### 3.3. Contact stress

Extract the contact stress time history curve of each measuring section under each working condition, as shown in Figure 12 (take section A under condition 4 as an example).

Take the peak value of each contact stress time history curve to draw a comparison diagram, as shown in Figure 12. According to the comparison data, the percentage increase or decrease of the longitudinal strain peak at each working condition is calculated, as shown in Table 6.

| Monitoring section | Condition 2 | Condition 3 | Condition 4 contrast condition 1 | Condition 4 contrast condition 2 | Condition 4 contrast condition 3 |
|--------------------|-------------|-------------|---------------------------------|---------------------------------|---------------------------------|
| A                  | -13.36      | -19.76      | -31.27                          | -20.67                          | -14.34                          |
| B                  | -12.59      | -22.15      | -31.78                          | -21.95                          | -12.37                          |
| C                  | -10.49      | -28.16      | -36.77                          | -29.36                          | -11.98                          |
| D                  | -6.19       | -26.82      | -30.52                          | -25.93                          | -5.06                           |
| E                  | -2.85       | -26.65      | -30.08                          | -28.02                          | -4.68                           |

*Note*: The comparison of the experimental data of various conditions can directly reflect the seismic effect of the optimal conditions of the tunnel portal section.
According to Figures 12 and 13 and Table 6:

1. When the seismic measures only adopt structural strengthening (condition 2 contrast condition 1). The peak value of the contact stress in the hard rock section of the tunnel portal increases greatly, and the maximum increase value is 14.72%; with the increase of the range of soft rock, the increase percentage in the contact stress peak increases continuously, and the maximum increase is 24.90%. When the supporting structure is strengthened, the rigidity of structure can be improved, and its effect of limiting the stress release of surrounding rock is enhanced.

2. When the seismic measures only adopt the shock absorption joint (condition 3 contrast condition 1, condition 4 contrast condition 2). After setting the shock absorption joint, the peak value of the contact stress in the hard rock section of the tunnel portal decreases slightly, with the maximum reduction value of -9.36%; with the increase of the soft rock, the reduction percentage of the contact stress peak decreases continuously. The reduction rate of contact stress in soft rock section is the largest, and the maximum reduction rate is -17.89%. After the shock absorption joint is set at the second lining, the longitudinal stiffness of the structure decreases, resulting in the overall decrease of the contact stress of the structure. The reduction percentage of peak contact stress is between 4.37% and 17.89%.

Table 6. Increase or decrease percentage of contact stress.

| Monitoring section | Condition 2 contrast condition 1 (%) | Condition 3 contrast condition 1 (%) | Condition 4 contrast condition 1 (%) | Condition 4 contrast condition 2 (%) | Condition 4 contrast condition 3 (%) |
|--------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| A                  | +24.90                              | -17.89                              | +6.07                               | -15.08                              | +29.19                              |
| B                  | +21.49                              | -16.04                              | +7.37                               | -11.62                              | +27.88                              |
| C                  | +17.55                              | -11.22                              | +4.97                               | -10.70                              | +18.24                              |
| D                  | +14.72                              | -9.36                               | +5.69                               | -7.87                               | +16.61                              |
| E                  | +4.99                               | -5.39                               | +0.40                               | -4.37                               | +6.12                               |

Note: The comparison of the experimental data of various conditions can directly reflect the seismic effect of the optimal conditions of the tunnel portal section.

Figure 13. Contact stress peak.
3. When the measures of combining rigidity with flexibility are adopted (condition 4 contrast condition 1). The increase of the peak value of the contact stress at each measuring section of the tunnel portal is less than 7.37%.

Figure 14. Internal force time course.
3.4. Internal force of structure

Firstly, the measurement data are obtained from the transverse strain gauge of the second lining at each measuring point under each working condition, and then the axial force, and bending moment of each measuring point are calculated according to Formula (1) and Formula (2), and the structural safety factor can be calculated according to Formula (3) and Formula (4) (TB 10003-2016, 2017). As shown in Figure 14 (take the measurement point of vault of section C under condition 2 as an example).

Axial force calculation of lining structure:

\[ N = \frac{1}{2} E(\varepsilon_i + \varepsilon_e)bh \]  

(1)

Bending moment calculation of secondary lining structure:

\[ M = \frac{1}{12} E(\varepsilon_i - \varepsilon_e)bh^2 \]  

(2)

Compressive strength of axial and eccentric compression members of rectangular section:

\[ KN \leq \phi x R_a bh \]  

(3)

Tensile strength of eccentric compression member with rectangular section:

\[ KN \leq \phi \frac{1.75R_l bh}{6e_0/h - 1} \]  

(4)

In the formula: \( E \)- Modulus of elasticity; \( \varepsilon_i, \varepsilon_e \)--- Internal and external strain of structure; \( M \)- bending moment; \( K \)-safety factor; \( N \)-axial force (KN); \( b \)-section width (m); \( \phi \)- longitudinal bending factor of member; \( x \)-eccentric influence factor of axial force; \( R_a \)-compressive ultimate strength of concrete or masonry; \( R_l \)- tensile ultimate strength of concrete; \( h \)-section thickness (m).

Extract the minimum value of the time history curve of the safety factor at each measuring point of the vault, as shown in Figure 15. According to the minimum safety factor data of each vault measuring point, the increase percentage of the minimum safety factor is calculated, as shown in Table 7.

According to Figures 14 and 15 and Table 7:

1. When the seismic measures only adopt structural strengthening (condition 2 contrast condition 1). After the structure is strengthened, the seismic inertia force and forced displacement of the hard rock section of the tunnel portal vary little, and the percentage increase of the minimum value of the safety factor of the supporting structure is large, between 57.99% and 62.28%; with the increase of the soft rock area of the section, the seismic inertia force of the support structure increases rapidly. As a result, the internal force of the structure increased rapidly,
and the increase rate of the structural safety performance starts to slow down, and finally fell to 30.40% at section A of the soft rock section.

2. When the seismic measures only adopt the shock absorption joint (condition 3 contrast condition 1, condition 4 contrast condition 2). After setting the joint, the increase of minimum safety factor of each measuring section is basically the same, the increase percentage is between 41.86% and 53.30%. This shows that the construction of shock absorption joint in the second lining has an obvious effect on improving the safety of tunnel portal structure.

3. When the measures of combining rigidity with flexibility are adopted (condition 4 contrast condition 1). After the measures are taken, the increase percentage of the minimum safety factor of each measurement section is between 85.20% and 140.99%. This shows that the measures of combining rigidity with flexibility have significant effect on improving the safety of tunnel portal structure.

4. Conclusions

When only strengthening the strength of the secondary lining, the PGA of each measurement section has a small change, the maximum is 7.59%; the reduction percentage of the longitudinal strain peak value is between 2.85% and 13.36%; the increase percentage of the contact stress peak value is between 4.99% and 24.90%; the minimum increase percentage of safety factor is between 30.40% and 62.28%. Structural

Table 7. Increased percentage of minimum safety factor.

| Monitoring section | Condition 2 contrast condition 1 (%) | Condition 3 contrast condition 1 (%) | Condition 4 contrast condition 1 (%) | Condition 4 contrast condition 2 (%) | Condition 4 contrast condition 3 (%) |
|--------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| A                  | +30.40                              | +45.20                              | +85.20                              | +42.02                              | +27.55                              |
| B                  | +31.25                              | +48.80                              | +87.02                              | +42.49                              | +25.69                              |
| C                  | +33.71                              | +42.26                              | +89.68                              | +41.86                              | +33.33                              |
| D                  | +62.28                              | +140.99                             | +48.50                              | +63.77                              |
| E                  | +57.99                              | +124.68                             | +42.21                              | +46.56                              |

Note: The comparison of the experimental data of various conditions can directly reflect the seismic effect of the optimal conditions of the tunnel portal section.

Figure 15. Minimum safety factor.
strengthening has a significant effect on resisting seismic inertial force, and the seismic effect is obvious. When the shock absorption joint is installed (the secondary lining has the same strength). The PGA of each measuring section has a small change, the maximum is only 1.55%; the reduction percentage of the longitudinal strain peak value is between 19.76% and 29.36%; the reduction percentage of the contact stress peak value is between 4.37% and 17.89%; the safety factor is the smallest. The value increase percentage is between 41.86% and 53.30%. The shock absorbing joint play a significant role in reducing the forced displacement, and the damping effect is obvious. When strengthening the strength of the secondary lining and installing shock absorption joints (combining rigidity and flexibility). The increase percentage of the PGA of the entire tunnel section is below 9.26%; the reduction percentage of the peak longitudinal strain is between 30.08% and 36.77%; the peak increase percentage of the contact stress is below 7.37%; the minimum increase percentage of the safety factor is between 85.20% and 140.99%. This shows that the combination of rigid and flexible anti-vibration measures has a significant effect on improving the safety of the tunnel portal section.

Disclosure statement

The authors declare that there is no conflict of interest regarding the publication of this paper.

Author contributions

Conceptualization, Guang-yao Cui and Bo-han Song; methodology, Guang-yao Cui and Dao-yuan Wang; investigation, Guang-yao Cui and Bo-han Song; data curation, Guang-yao Cui and Dao-yuan Wang; writing—original draft preparation, Guang-yao Cui and Bo-han Song; writing—review and editing, Bo-han Song; project administration, Guang-yao Cui; funding acquisition, Guang-yao Cui and Dao-yuan Wang.

Data availability

The data used to support the findings of this study are included within the article.

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