Shaking table test of Large-scale double track tunnel under fault rupture geological condition

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Abstract: fault rupture is extremely adverse geological condition in the construction of mountain tunnels, especially for the earthquake fault rupture propagation. In this manuscript, a series of three dimensional shaking table tests were conducted to investigate the seismic response and effect of composite shock absorbing layer (CSAL) of mountain tunnel using a large-scaled model in the fault zone. The experimental results show that the existence of fault rupture makes the dominant frequency range of the tunnel model transfer from low frequency to high frequency, and the CSAL cannot change the dominant frequency of acceleration. The maximum longitudinal tension and compressive strain of model tunnel is located at the interface between the fault rupture and surrounding rock, and the strain value decrease as the tunnel far from fault zone. The longitudinal strain and hoop strain of the model tunnel with CSAL can reduce more than 30% and 25% when compared the model tunnel without CSAL, which means the CSAL can effectively reduce the deformation of the model tunnel in longitudinal and hoop direction.

Keywords: Fault rupture; tunnel; composite shocking absorbing layer; seismic response

1 Introduction

In seismically active areas, tunnels are subject to earthquake induced risks. Many tunnel seismic disasters show that tunnel with better geological conditions has relatively good seismic performance, and tunnel seismic damage generally occurs in poor quality geological conditions, such as fault fracture zone (Wang, et al. 2009).

The seismic response of the tunnel in the fault rupture has been investigated by many scholars using various methods, including theoretical analysis, numerical simulation and physical model tests (Cividini et al 2010; Tolga Yilmaz and Paolucci, 2007; Anastasopoulos et al. 2007, 2008; Anastasopoulos and Gazetas, 2010; Mirko et al., 2011). In this paper, a large-scale model tunnel (the inside width and height are 93 cm and 82 cm) with surrounding soft rock in a large-scale rigid box (the length, width and height are 9.3m, 3.7m and 2.5m) were established firstly and then a series shaking table tests were carried out. Finally, summarized and discussed the main experimental data obtained from the tests, such as the concrete strain and frequency.

2 Shaking table tests

2.1 Shaking table test system

The tests were conducted using the Laboratory Multi-Function Shaking Table System (LMSTS) in the National Engineering Laboratory of High Speed Railway Construction Technology in Central South University, China. The LMSTS consists of three 6-Dofs mobile stations (4 m × 4 m) driven by electro-hydraulic servos, in which can be controlled independently to simulate single or multiple three-directional ground motions. Each table had a dynamic capacity of 350 kN and the maximum acceleration of the horizontal and vertical direction are 1.0 g and 1.6 g. The layout of LMSTS and the horizontal and vertical actuators are shown in Fig.1, and only Tables A and B were used in this tests.

Fig. 1. Laboratory Multi-Function Shaking Table System.

2.2 Model container

2.2.1 Structure of model container

The model container is a rigid box with the dimensions of 9.3 m (length) × 3.7 m (width) × 2.5 m (height), including the box wall, the inner framework, and the outer framework, as shown in Fig. 2. The model box is composed of steel plates and is equipped with steel frame structure to ensure the rigidity of the box. Two transverse ribs were welded onto the top of the model container. The model container was bolted firmly onto tables A and B using a total of 64 high-strength bolts.
Fig. 2. The model container.

2.2.2 Boundary condition

Boundary effect is crucial for model tests, which directly influence the reliability of experimental data. There are two ways to diminish the boundary effect of the model tunnel: one considers the length/height ratio of the container and the other considers flexible materials of the inner sides of the model container (Whitman and Lambe, 1986; Fishman, 1995). For the first method, numerical studies conducted by Whitman and Lambe (1986) and Fishman (1995) have demonstrated that if the length/height ratio of the container is greater than 3, the influence of rigid boundary can be minimized. As for the second method, flexible materials are usually polystyrene foam boards and sponge rubber (Lombardi et al. 2015; Ha et al. 2011). In this study, the length/height ratio of the model container is 3.72, a 10 cm thick polystyrene foam board was attached to the container walls, a 5 cm thick sponge rubber boards was attached to the end walls and a 2.5 cm thick sponge rubber boards was attached to the side walls. The requirement of reducing boundary effect proposed by both methods can be satisfied, so the boundary effect of this experiment is very small.

2.3 Model tunnel and surrounding rock materials

The similarity relations and conditions between the model tunnel and the prototype is derived based on law of similarity for the model experiment in geotechnical engineering. The model tunnel was built by a 1/12 scale down from the actual double track tunnel of standard high-speed railway. Taking into consideration the dimension limits and bearing capacity of the shaking table, setting up the similarity ratios of geometry $C_l$, density $C_\rho$, Elastic module $C_E$ as the basic parameter to derived the other similarity ratios. The similarity ratios of model tunnel are shown in Table 1.

<table>
<thead>
<tr>
<th>Physical parameter</th>
<th>Similarity relationship</th>
<th>Similarity ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>$C_l$</td>
<td>1/12</td>
</tr>
<tr>
<td>Density</td>
<td>$C_\rho$</td>
<td>1/0.8</td>
</tr>
<tr>
<td>Elastic module</td>
<td>$C_E$</td>
<td>1/15</td>
</tr>
<tr>
<td>Strain</td>
<td>$C_\varepsilon$</td>
<td>1</td>
</tr>
<tr>
<td>Stress</td>
<td>$C_s = C_E \times C_\varepsilon$</td>
<td>1/15</td>
</tr>
<tr>
<td>Acceleration</td>
<td>$C_a$</td>
<td>1</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$C_\gamma$</td>
<td>1</td>
</tr>
<tr>
<td>Friction angle</td>
<td>$\Phi$</td>
<td>1</td>
</tr>
<tr>
<td>Frequency</td>
<td>$C_f = C_l^{-1} (C_E / C_\rho)^{1/2}$</td>
<td>3.464</td>
</tr>
<tr>
<td>Time</td>
<td>$C_t = C_l^{1/2}$</td>
<td>0.288</td>
</tr>
</tbody>
</table>

On the basis of equivalent stiffness principle, the model tunnel is made of micro-concrete with an inside wide of 93 cm and an inside high of 82 cm and a thickness of 4 cm. It is reinforced with steel mesh (6 mm diameter) at the radial ring spacing of 10 mm, as shown in Fig.3. The mechanical properties of the model tunnel used in the tests are listed in Table 2. The tests focus on the seismic response of the tunnel through the fault rupture in the soft surrounding rock, according to Code for Design of railway Tunnel in China [TB10003-2016]. The intensity range of soft rock are from 5MPa to 30MPa. The surrounding rock is made of micro-concrete (cement: sand : aggregate : water= 1: 2.68: 4.56: 0.82) and the mechanical parameters of them are shown in Table 3.

Table 2. Mechanical properties of the model tunnel and prototype tunnel (Lanzano et al., 2012).

<table>
<thead>
<tr>
<th></th>
<th>Unit weight(kg/m³)</th>
<th>Elastic modulus, $E_t$ (GPa)</th>
<th>Poisson’s ratio, $\nu$</th>
<th>Yield strength, $f_y$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model tunnel</td>
<td>1900</td>
<td>2.67</td>
<td>0.23</td>
<td>6</td>
</tr>
<tr>
<td>Prototype tunnel</td>
<td>2500</td>
<td>30</td>
<td>0.234</td>
<td>38.5</td>
</tr>
</tbody>
</table>

Table 3. Rock mechanical properties of the model and prototype.

<table>
<thead>
<tr>
<th></th>
<th>Unit weight $\rho_t$(kg/m³)</th>
<th>Elastic modulus,$E_t$ (GPa)</th>
<th>Friction angle $\phi$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock prototype</td>
<td>2320</td>
<td>16.75</td>
<td>23.5</td>
</tr>
</tbody>
</table>
2.4 Composite shock absorbing layer (CSAL)

The shaking table tests revealed that the strains of lining are reduced by the CSAL (Yamada et al., 2004; Chen and Shen, 2014). In this paper, the CSAL is a composite material, which includes 5cm thickness foam board and 5cm thickness foam rubber. The CSAL was used to wrap a section of the model tunnel (see Fig. 4) in order to investigate the effect of the CSAL on the tunnel response under seismic loading. Table 4 shows the mechanical properties of the foam board and table 5 shows the mechanical properties of the foam rubber.

![Fig. 4. Composite shock absorbing layer](image)

**Table 4. Mechanical properties of foam board.**

<table>
<thead>
<tr>
<th>Density $\rho_f$ (kg/m$^3$)</th>
<th>Young’s modulus $E_f$ (kPa)</th>
<th>Poisson’s ratio $\nu_f$</th>
<th>Damping $\xi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>16</td>
<td>0.29</td>
<td>24</td>
</tr>
</tbody>
</table>

**Table 5. Mechanical properties of rubber.**

<table>
<thead>
<tr>
<th>Density $\rho_f$ (kg/m$^3$)</th>
<th>Young’s modulus $E_f$ (kPa)</th>
<th>Poisson’s ratio $\nu_f$</th>
<th>Damping $\xi$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>2.5</td>
<td>0.13</td>
<td>34</td>
</tr>
</tbody>
</table>

2.5 Instrumentation

There are three cross-sections were installed accelerometers, transducers, strain gauges and pressure cells in order to monitoring the seismic response of model tunnel through the fault rupture. The angle between the fault rupture and the horizontal plane is 60° and the width of fault rupture is 40cm. The first one is the cross section #III, in which the model tunnel was wrapped by CSAL and three sets of transducers were installed. The accelerometers were installed to measure horizontal and vertical components of acceleration of the model tunnel. The longitudinal strain gauges and hoop strain gauges are installed to measure the deformation of the axial direction and hoop direction of the model tunnel. In addition, the dynamic earth pressure cells were installed to measure the interaction between the model tunnel and the surrounding rock, as shown in Fig.5 (c). The second one is the cross-section #IV, in which the model tunnel through the fault rupture and the transducers layout of is the same as the cross-section #III, as shown in Fig.5 (d). The third one is the cross-section #V and the transducers layout of model tunnel is the same as the cross-section #III, as shown in Fig.5 (b). Meanwhile, the accelerometers were also installed at the base of model container, in the surrounding rock and the top of surrounding rock, as shown in Fig. 5 (a).
2.6 Test procedure and experimental program

2.6.1 Experimental Program

There are two real earthquake records from the Kobe earthquake measured in 1995 at Nishi-Akashi Station and the Turkey earthquake measured in 1999 at the Lzmit station were used as input motions in the shake table tests, which came from the similarity geological conditions of peer strong motion database. Duration and frequency of the earthquake records were scaled for model input motions by a scale factor of 8, as shown in Fig. 6. The input motions were scaled up to different peak accelerations during the testing program. Four cases of peak acceleration were considered, scaled to 0.12gand 0.483g, as tabulated in table 6.

Table 6. Input motion characteristics.

<table>
<thead>
<tr>
<th>Number</th>
<th>Type of seismic motion</th>
<th>Peak acceleration/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>EQ1</td>
<td>Turkey</td>
<td>X: 0.12 Y: 0.085 Z: 0.045</td>
</tr>
<tr>
<td>EQ2</td>
<td>Kobe</td>
<td>X: 0.483 Y: 0.345 Z: 0.265</td>
</tr>
</tbody>
</table>

3. Test results and discussion

3.1 Spectrum time histories

It can be seen from Fig. 7(a)-Fig. 8(a) that the tunnel model has approximately the same acceleration time history curve and spectrum curve with CSAL, no CSAL and faults, because the bottom of the model is the first to be subjected to ground motion. However, when the seismic wave reaches the upper part of the tunnel model, the acceleration value changes. The acceleration value of the tunnel section with SAL is relatively smaller than that of the SAL-free and fault-free (Fig. 7(b)-8(b)), which indicates that the SAL has a sticky boundary. Without CSAL and with faults, the seismic waves of tunnel model are quite magnified relative to the initial wave (Figure 6). For seismic wave frequencies, when there is a fault, the dominant spectrum shifts from low frequency to high frequency, which is the result of repeated superposition of seismic waves near the fault. The acceleration time history curve and the spectrum curve law of the tunnel model with SAL and no SAL are approximately the same, indicating that the SAL cannot change the dominant frequency of seismic wave propagation.
no SAL are approximately the same, indicating that the CSAL cannot change the dominant frequency of seismic wave propagation.

\[ \text{Fig. 7. Comparison of spectrum time history of model tunnel with CSAL, without CSAL and fault rupture subjected to Turkey motion. (a) the bottom of the model tunnel, (b) the crown of the model tunnel.} \]

3.2 Tunnel deformation

3.2.1 Longitudinal deformation

Longitudinal strain gauges were arranged in model tunnel sections with fault rupture, CSAL and without CSAL, and each section bottom and crown was installed six gauges, as shown in the Fig.5 (d), (e) and (f).

Fig.9 describes the longitudinal strain variation curves of the bottom and crown of the model tunnel with EQ1, and EQ2 excitation, respectively. It should be noted that the positive strain represents tensile strain and the negative strain represents compressive strain. The deformation characteristics of the model tunnel under different input motions are different, the feature of model tunnel deformation with the Turkey excitation is under tension. With the acceleration of input motion increasing, the longitudinal deformation of model tunnel with fault rupture, with CSAL and without CSAL cross-section also increase and the maximum tension strain (321.13 µε) of model tunnel is located at the interface between the fault rupture and surrounding rock. The longitudinal tension strains of model tunnel with SAL are obviously lower than that of model tunnel without CSAL. The maximum values of longitudinal tension strain of model tunnel with CSAL and without are 127.25 µε and 189.41 µε, respectively.

Compared to the longitudinal deformation of the bottom of model tunnel, the same phenomenon happened on the crown of model tunnel, the maximum longitudinal tension and longitudinal compressive strain of model tunnel is located at the interface between the fault rupture and surrounding rock. The maximum value of longitudinal tension strain is 678.56 µε and the maximum value of longitudinal compressive strain is 324.87 µε. In addition, the longitudinal tension strain of model tunnel with CSAL is obviously lower than that of model tunnel without CSAL. The maximum values of longitudinal tension strain of model tunnel with CSAL and without are 267.89 µε and 378.87 µε, respectively.

In summary, the maximum longitudinal tension strain of the bottom of the model tunnel with CSAL can reduce more than 32.81% when compare with the model tunnel without SAL. The maximum longitudinal tension strain of the crown of model tunnel with CSAL can reduce 29.36% compared to the model tunnel without CSAL. This shows that CSAL can effectively absorb seismic waves and weaken its superposition on the free surface.

\[ \text{Fig. 9. Longitudinal strain of the model tunnel under different motion excitation. (a) the bottom of the model tunnel, (b) the crown of the model tunnel.} \]
3.4.2 Hoop deformation

Hoop strain gauges were arranged in model tunnel sections with fault rupture, CSAL and without CSAL, and each section bottom and crown was installed six gauges, as shown in the Fig. 5 (b), (c) and (d).

Fig. 10 show the hoop strain variation curves of the bottom and crown of the model tunnel with EQ1 and EQ2 excitation, respectively. From these figures can seen that. With the acceleration of input motion increasing, the hoop tension strains of the model tunnel also increase. The maximum hoop tension strains are located at the interface between the fault zone and the surrounding rock and the maximum value (564.88 με) of tension strain of model tunnel is located at the right foot of model tunnel.

Fig. 11 describe the hoop strain variation curves of the model tunnel section with CSAL and without hoop strain under EQ1 and EQ2 excitation. It can be seen that the maximum tension strain of the model tunnel without CSAL is obviously larger than that of model tunnel with CSAL. The positions of maximum tension strain are located at the right and left shoulder and the right and left foot.

In order to evaluate the anti-seismic effect of CSAL, the maximum tension strains were selected to get the reduction factor. The maximum hoop tension strain of the model tunnel with CSAL can reduce more than 39.76% and 32.63% when compared with the model tunnel without CSAL under the Turkey and Kobe excitations. It explained that the CSAL can reduce the strain of model tunnel with the different excitation.

Fig. 11 the hoop strain of the model tunnel with and without SAL under different motions excitation. (a) Turkey, (b) Kobe.

4. Conclusions

The paper discussed the seismic response of model tunnel in the fault zone and investigated the seismic effect of the composite shock absorbing layer to the model tunnel. The key findings of this study are summarized in the following:

- The dominant frequency of acceleration in the fault rupture has transferred from the low dominant frequency to high dominant frequency, which mainly caused by the energy released by seismic waves in the fault fracture zone. The CSAL cannot change the dominant frequency of acceleration.

- The maximum longitudinal tension and compressive strain of model tunnel is located at the interface between the fault rupture and surrounding rock, far away from the fault zone, the value of the strain get smaller.

- The longitudinal strain of the model tunnel for the CSAL can reduce more than 30% that of the model tunnel without in the main X excitation, however, the hoop strain of the model tunnel with the CSAL also can reduce more than 25% that of the model tunnel without, which means the CSAL can effectively reduce the strain of the model tunnel in longitudinal and hoop direction.

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References


