Physical Simulation of 'Strong Ground Motion-Fault Displacement' Coupling Effects in Tunnels Crossing Active Faults (I): Experimental System and Methods

Authors: Mei Xiancheng, Cui Zhen, Sheng Qian, Chen Jian, Fei Yang, Tang Langzhou, Zhao Xu, Li Ruohan, Huang Jingqi, Cui Zhen

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Abstract

Tunnel damage cases from strong earthquake events such as the 2022 Menyuan earthquake have conclusively confirmed that tunnel sections crossing active fault zones are simultaneously subjected to fault displacement from the active fault zone and strong seismic forces, resulting in severe seismic damage phenomena. Correctly analyzing the "strong earthquake-fault displacement" coupling effect experienced by cross-fault tunnels during seismic events is currently the key to ensuring safe construction and operation of tunnels crossing active faults in strong earthquake regions. This paper proposes to conduct pioneering physical simulation research on the "strong earthquake-fault displacement" coupling effect for tunnels crossing active faults. First, a "strong earthquake-fault displacement" coupling physical simulation system for tunnels crossing active faults was independently developed, consisting of a twin shaking table array, a "ground motion-permanent displacement" non-uniform loading model box, and a follow-up sliding frame module. Additionally, an artificial ground motion synthesis method considering synchronous non-uniform "ground motion-permanent displacement" was proposed, forming a coupled input hybrid framework for "strong earthquake-fault displacement" , which realizes physical simulation of the coupled response between the seismic wave field and deformation displacement field in rock masses on both sides of the fault zone. A strong earthquake-fault coupling physical simulation test was conducted using the Daliang Tunnel, which was damaged in the Menyuan earthquake, as the background engineering case, successfully reproducing the failure phenomena of the Daliang Tunnel under the "strong earthquake-fault" coupling effect. The effectiveness of the test apparatus and methodology was verified through comparative analysis of the shaking table surface response characteristics, model test box response characteristics, and response characteristics of the surrounding rock and lining structure of the cross-fault tunnel. This paper will provide physical simulation research means for subsequent in-depth studies on the mechanism of the "strong earthquake-fault displacement" coupling effect for cross-fault tunnels and is expected to advance the development of seismic design practices for cross-fault tunnels.

Full Text

Physical Modeling of the Coupling Effect of Strong Shaking-Fault Movement on a Tunnel Crossing an Active Fault (Part I): Experimental System and Method

Mei Xiancheng[1],[2], **Cui Zhen**[1],[2], **Sheng Qian**[1],[2], **Chen Jian**[1],[2], **Fei Yang**[1],[2], **Tang Langzhou**[1],[2], **Zhao Xu**[3], **Li Ruohan**[4], **Huang Jingqi**[5]

[1]State Key Laboratory of Geomechanics and Geotechnical Engineering Safety, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China
[2]School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China
[3]Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing Key Lab of Earthquake Engineering and Structural Retrofit, Beijing University of Technology, Beijing 100124, China
[4]Institute of Future Civil Engineering Science and Technology, Chongqing Jiaotong University, Chongqing 400074, China
[5]Beijing Key Lab of Urban Underground Space Engineering, School of Future Cities, University of Science and Technology Beijing, Beijing 100083, China

Abstract: Tunnel damage cases observed during the 2022 Menyuan earthquake have provided conclusive evidence that tunnels crossing active fault zones are simultaneously affected by both fault displacement from active fault movement and strong seismic shaking, resulting in severe seismic damage. Properly analyzing the coupled "strong shaking-fault movement" effects experienced by fault-crossing tunnels during earthquakes is crucial for ensuring safe construction and operation of tunnels in seismically active regions. This study presents the first physical simulation investigation of the "strong shaking-fault movement" coupling effects on tunnels crossing active faults. We developed an innovative physical simulation system comprising a twin shaking table array, a "seismic motion-permanent displacement" non-uniform loading model box, and a co-moving sliding support module. Additionally, we proposed an artificial ground motion synthesis method that considers synchronous non-uniform "seismic motion-permanent displacement," establishing a hybrid input framework for "strong shaking-fault movement" coupling. This enables physical simulation of the mutual interaction between seismic wave fields and deformation-displacement fields on both sides of the fault zone. Using the severely damaged Daliang Tunnel during the Menyuan earthquake as a case study, we conducted a shaking-displacement coupling physical simulation test that successfully reproduced the tunnel' s failure phenomena under coupled effects. The validity of the experimental apparatus and methodology was verified through comparative analyses of shaking table response characteristics, model box responses, and the response characteristics of surrounding rock and lining structures of the fault-crossing tunnel. This study provides an innovative physical simulation approach for investigating the coupled mechanism of "strong shaking–fault movement" effects on fault-crossing tunnels and is expected to advance seismic design practices for tunnels intersecting active faults.

Keywords: fault-crossing tunnel; coupling effect of earthquake and dislocation; synchronous non-uniformity of seismic motion and permanent displacement; non-uniform loading model box; artificially synthesized seismic motion

1. Introduction

With the rapid development of infrastructure construction in China, numerous transportation projects are advancing into the western "Third Pole" region of the Qinghai-Tibet Plateau [1,2]. This region is characterized by high seismic intensity, active plate tectonics, and densely distributed active faults, making it a significant strong earthquake and tectonic activity zone [3,4]. Consequently, many tunnel projects in this high-intensity seismic region are constrained by route selection and must cross active faults. For such fault-crossing tunnels, the long construction and operation periods face severe threats from near-field strong ground motion, large fault displacement deformation, and their synergistic coupling effects [5,6]. The catastrophic damage to the Daliang Tunnel on the Lanzhou-Xinjiang high-speed railway during the M6.9 Menyuan earthquake on January 8, 2022, in Qinghai Province, exemplifies this problem [7]. To ensure safe construction and stable operation of strategic transportation tunnel projects, a clear understanding of the dynamic response characteristics and damage mechanisms of fault-crossing tunnels under "strong shaking–fault movement" coupling effects is urgently needed to support national strategic planning.

Shaking table model testing serves as an important research method for investigating seismic dynamic responses of tunnel engineering, capable of revealing seismic dynamic response mechanisms and reproducing seismic damage characteristics. Numerous scholars have conducted extensive research on tunnel dynamic response characteristics through shaking table model tests. Since tunnel engineering is constructed in various site conditions, researchers have investigated the seismic dynamic response characteristics of tunnel structures in soft soil [8-10], sand [11], compacted clay [12], loess [13], and bedrock [14,15] environments. Scholars including Zhang Jing [16], Cui Guangyao [17], Fan Kaixiang [18], and Lu Yaobo [19] have studied the seismic dynamic response characteristics of tunnels passing through soft-hard rock transitions and analyzed the influence of surrounding rock stiffness variations on tunnel structural dynamic responses. Research has also examined interaction mechanisms and seismic dynamic response patterns among different structural systems, including tunnel-surrounding rock/lining structure systems [20], tunnel-surface building systems [21], tunnel-foundation systems [22], and tunnel-soil-adjacent pile systems [23]. For tunnel portal sections—the critical "throat" engineering elements—scholars have investigated dynamic response influence patterns from aspects such as biased topography [24,25], ground motion input direction [26], ground elevation [27], and portal slope-tunnel interaction [28,29] through shaking table tests. Additionally, detailed studies have been conducted on seismic dynamic response characteristics of special complex tunnel structures, including large-section tunnels [30], orthogonal tunnels [31], oblique tunnels [32], three-dimensional crossing tunnels [33], complex connecting passage structures [34,35], and ultra-small clearance tunnels [32,36], while considering factors such as different burial depths [37], progressive damage states [38,39], and existing damage in tunnel linings [40] on tunnel structural seismic performance. Based on extensive research on tunnel seismic dynamic response characteristics, scholars have investigated the seismic performance of various mitigation measures through shaking table tests, including deep grouting reinforcement methods [41], polypropylene fiber concrete lining structures [42], and buffer layers of foam, damping materials, and rubber installed between surrounding rock and lining [43-46].

In recent years, shaking table tests investigating the seismic dynamic response of fault-crossing tunnels have gradually attracted widespread attention. Most existing research results treat the fault fracture zone as a geological condition by altering the similar materials of the corresponding range of surrounding rock [47-50], without considering the permanent displacement and large deformation problems induced by active fault rupture. Zhang Zhichao et al. [51,52] simulated the dynamic response characteristics of fault-crossing underground pipelines by dividing the active fault sides into two model boxes fixed on the ground and shaking table, respectively. Other scholars have simulated non-uniform seismic excitation using multiple shaking tables to analyze seismic dynamic response characteristics of underground engineering [53-55]. Xin Chunlei et al. [56,57] analyzed the seismic performance of different mitigation measures for active fault-crossing tunnels by placing the entire model box on a shaking table and setting up a fault displacement device inside the model box. Shen et al. [58] simulated the dynamic response characteristics of tunnels crossing normal active faults by placing the entire model box on a shaking table and controlling the movement of one side of the model box through a jack. However, the above shaking table model test studies on the dynamic response characteristics of active fault-crossing tunnels treat high-frequency strong ground motion and low-frequency fault permanent displacement as two independent events, without considering their synchronous non-uniformity and coupling effects, which is insufficient to realistically simulate the "strong shaking-fault movement" coupling effects on fault-crossing tunnels. Table 1 summarizes how various shaking table test methods consider the "strong shaking-fault movement" coupling effects.

This study presents the first physical simulation investigation of the "strong shaking-fault movement" coupling effects on active fault-crossing tunnels. We developed a novel physical simulation system comprising a twin shaking table array, a "seismic motion-permanent displacement" non-uniform loading model box, and a co-moving sliding support module. Additionally, we proposed an artificial ground motion synthesis method considering synchronous non-uniform "seismic motion-permanent displacement," establishing a hybrid input framework for "strong shaking-fault movement" coupling. This enables physical simulation of the mutual interaction between seismic wave fields and deformation-displacement fields on both sides of the fault zone. Using the severely damaged Daliang Tunnel during the Menyuan earthquake as a case study, we conducted a shaking-displacement coupling physical simulation test that successfully reproduced the tunnel' s failure phenomena under coupled effects. Comparative analyses of shaking table response characteristics, model box responses, and the response characteristics of surrounding rock and lining structures of the fault-crossing tunnel confirmed the validity and reliability of the proposed experimental system and methodology. This study provides an innovative physical simulation approach for investigating the coupled mechanism of "strong shaking-fault movement" effects on fault-crossing tunnels and is expected to promote the advancement of seismic design practices for tunnels intersecting active faults.

2.1 Research Background and Problem Description

The Daliang Tunnel is located in Menyuan County, Haibei Prefecture, Qinghai Province, and serves as a key control project on the Lanzhou-Xinjiang passenger dedicated line. The tunnel entrance is at mileage K1965+525.24, the exit at K1972+093.06, with a total length of 6,576.82 m, maximum burial depth of approximately 800 m, and maximum elevation of approximately 4,430 m. The tunnel is situated in the middle-high mountain region of the Qilian Mountains and features a double-track layout with a horseshoe-shaped cross-section. During the M6.9 Menyuan earthquake on January 8, 2022, the epicenter was approximately 4.5 km from the Daliang Tunnel, with a focal depth of 10 km. The seismogenic fault was the Lenglongling Fault (F5) in the western section of the Qilian-Haiyuan fault zone on the northeastern margin of the Qinghai-Tibet Plateau, characterized by left-lateral strike-slip movement, with the epicenter located about 3-4 km south of the F5 fault.

The F5 fault is a Holocene active fault with an average left-lateral slip rate of 3.5-6.6 mm/year. The strata on the two sides consist of Ordovician crystalline limestone interbedded with striped slate (hanging wall) and Permian light white to gray-white sandstone (footwall). Post-earthquake surface ruptures formed a main fracture approximately 21.5 km long crossing the tunnel exit, extending roughly east-west. The tunnel section crossing the active fault zone exhibited severe fiber offset, sidewall extrusion and dislocation, secondary lining crushing, track bed uplift, drainage system blockage, and damage to power and communication equipment. Post-earthquake tunnel clearance scanning revealed that tunnel structure dislocation was concentrated within approximately 21 m near the main rupture surface in the active fault zone (K1971+390.4~K1971+411.7). Within the tunnel' s passage through the F5 fault zone main rupture surface (approximately 21 m), obvious compression and dislocation occurred, with severe deformation and a relative dislocation of 2.8 m. In other sections, the tunnel structure showed overall offset, with maximum internal contour offset of approximately 1.92 m, though the structure itself did not exhibit obvious dislocation.

The seismic damage phenomena observed in the Daliang Tunnel during the Menyuan earthquake transcend the scope of traditional underground engineering seismic research. The damage indicates that the coupling effect of strong seismic ground motion forces and fault dislocation actions is the core cause of catastrophic structural failure [59], as shown by the purple segment in Figure 1 [Figure 1: see original paper]. The key to achieving "strong shaking–fault movement" coupling effects lies in creating an extremely special loading environment that incorporates both strong seismic forces causing structural inertia and fatigue damage, and fault dislocation causing large deformation and geometric instability.

2.2 Technical Approach and Implementation Process

To address the key scientific problem of dynamic response characteristics and damage mechanisms of fault-crossing tunnels under "strong shaking-fault movement" coupling effects, this study conducts relevant shaking table physical simulation tests based on the Menyuan earthquake Daliang Tunnel damage, which reveals that fault-crossing tunnels simultaneously experience high-frequency strong shaking from external seismic sources and low-frequency large displacement from fault movement (as shown in Figure 2 [Figure 2: see original paper]).

To achieve true physical simulation testing of fault-crossing tunnels under "strong shaking–fault movement" coupling effects, the research approach consists of five steps: (1) First, synthesize permanent displacement-containing ground motions based on an equivalent velocity pulse model [60], enabling the shaking table input ground motion to simultaneously reflect both high-frequency seismic energy components and low-frequency large deformation components, thereby achieving the special loading environment; (2) Second, conduct shaking table physical simulation tests using a twin shaking table array combined with a self-developed "seismic motion–permanent displacement" non-uniform loading model box. This achieves non-uniform seismic motion input on both sides of the model box through the twin shaking tables, while using dislocation layer frames to connect the two model box sides fixed on the shaking table surfaces to realize non-uniform responses of the two model box sides; (3) Third, determine the model test similarity ratio and surrounding rock-lining similar material proportions. Based on test conditions, model box dimensions, and prototype engineering parameters, an appropriate length similarity ratio is determined, from which similarity ratios for different dimensional parameters are derived. Indoor mechanical property tests are conducted to determine surrounding rock-lining similar material proportions that satisfy similarity conditions; (4) Fourth, implement comprehensive multi-target, multi-parameter monitoring using multiple monitoring devices for shaking table acceleration, velocity, and displacement; model box displacement; surrounding rock acceleration, stress, and surface rupture; lining structure acceleration, stress, deformation, and damage characteristics; and develop appropriate monitoring schemes based on tunnel-surrounding rock and lining structure characteristics; (5) Finally, after completing the aforementioned research and design preparations, conduct the "strong shaking–fault movement" coupling effect simulation test.

3. Physical Simulation Test System

The test apparatus system used in this study consists of three main modules: a twin shaking table array, a "seismic motion–permanent displacement" non-uniform loading model box, and a co-moving sliding support bracket. The twin shaking table array comprises two sub-tables from the nine-sub-table array three-direction six-degree-of-freedom high-performance shaking table test system at Beijing University of Technology. The "seismic motion–permanent displacement" non-uniform loading model box and co-moving sliding model box support bracket were jointly developed by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, and the Institute of Geotechnical and Underground Engineering at Beijing University of Technology. Figure 3 [Figure 3: see original paper] illustrates the physical model test system for the fault-crossing tunnel "shaking–dislocation" coupling effect.

The shaking table system operates as a twin table array in this test, with the two sub-tables spaced 80 cm apart, as shown in Figure 3(a) and 5(b). The main technical parameters of the two sub-tables are identical, with each sub-table featuring a table size of 1 m × 1 m, maximum load capacity of 5 t, maximum displacement of \$±\$7.5 cm, maximum velocity of 50 cm/s, full-load acceleration of 1.5 g in horizontal and 0.8 g in vertical directions, frequency range of 0.1-50 Hz, and acceleration and displacement control modes.

The "seismic motion–permanent displacement" non-uniform loading model box has internal net dimensions of 2.8 m × 1.4 m × 1.0 m (length × width × height). The two rigid side boxes each have a length of 1.0 m, connected in the middle by six dislocation layer frames (totaling 0.8 m) through four rows of bolts to both side boxes, as shown in Figure 3(c). The relative displacement within the fault zone is achieved by controlling the bolt pre-tightening degree. Three openings with a diameter of 20 cm are provided at both ends of the model box to serve as access channels for internal tunnel monitoring after test completion. During testing, 10 cm thick polyethylene foam boards are installed around the interior of the model box as flexible boundary conditions to absorb vibration energy propagating to the boundaries.

A co-moving sliding support bracket is designed in the space below the model box on the twin shaking table surfaces to enhance the load-bearing capacity of the twin shaking tables and address the problem of dislocation layer frames dropping down after bolt release, as shown in Figure 3(d). The six dislocation layer frames are placed on top of three rows of 30 universal rollers fixed on the support bracket, thereby reducing friction between the dislocation layer frames and support bracket to ensure effective displacement response of the surrounding rock-lining within the fault fracture zone range.

4.1 Artificial Ground Motion Synthesis Considering Synchronous Non-Uniform "Seismic Motion-Permanent Displacement"

When determining the shaking table loading scheme, it is necessary to input synchronous non-uniform ground motion time histories with "seismic motion-permanent displacement" on each of the two shaking table sub-platforms. Since no real ground motion data records currently meet this requirement, the research team proposed a method that synthesizes artificial base ground motion (without permanent displacement) and then synthesizes permanent displacement-containing ground motion based on this base motion to provide input loads for the physical simulation test.

Based on the ground motion attenuation relationship provided in the site seismic safety evaluation report for the prototype engineering project (the Daliang Tunnel project in the Menyuan earthquake case), as shown in Equation (1), and combined with the site seismic geological parameters, the peak ground acceleration is determined to be 460 gal. According to the prototype engineering site response spectrum shape (in this case, the "Code for Seismic Design of Railway Engineering" (GB50111-2006) (2009 edition) [61] with a characteristic period of 0.4 s), the base ground motion is generated, as shown in Figure 4 Figure 4: see original paper.

$$\log_{10} a = 2.457 + 0.388M - 1.783 \log_{10}(R + 0.612 \times 10^{0.457M})$$

Where: a is the peak ground acceleration amplitude in gal; M is the magnitude, taken as 6.9; R is the fault distance in km, taken as 10.

Based on the base ground motion, the ground motion is divided into low-frequency and high-frequency components using the reciprocal of the ground motion design response spectrum characteristic period, $1/T_p$, as the boundary. The two components are simulated through different forms to reflect their respective ground motion characteristics, then combined through translation, amplitude adjustment, and superposition to generate a permanent displacement-containing ground motion that reflects the regional seismic geological condition characteristics of the engineering site. The low-frequency component velocity pulse parameters are determined based on the engineering site seismic geological parameters and equivalent velocity pulse model, while the high-frequency component is based on the aforementioned base ground motion with Fourier spectrum bandwidth limited above $1/T_p$. The specific artificial synthesis method has been disclosed as an invention patent [60] and will not be elaborated here.

Using this method, this study artificially synthesized two ground motion time histories with permanent displacements of 3.6 m and 2.2 m, with specific time histories shown in Figures 4(b) and 4(c).

4.2 Similarity Ratios and Similar Materials

This test is conducted using a scaled model based on similarity relationships. Using Bukingham' s π theorem and dimensional analysis, with geometric dimensions, density, and acceleration as basic physical quantities, and considering test equipment dimensions and ensuring similarity between model and prototype values in main mechanical properties, a geometric dimension similarity ratio C_L of 70, density similarity ratio of 2, and acceleration similarity ratio of 1 were designed. Other parameter similarity ratios were derived through dimensional analysis. Table 2 provides specific similarity ratio values for various physical quantities including material characteristics and dynamic characteristics.

Table 2 Similarity ratios for various physical quantities

Parameter	Similarity Ratio
Geometric dimensions/C_L	70
Density/C_ρ	2
Elastic modulus/C_E	140
Strain/C_ε	1
Stress/C_σ	140
Internal friction angle/C_ϕ	1
Cohesion/C_c	140
Time/C_t	8.37
Frequency/C_ω	0.119
Displacement/C_u	70
Velocity/C_v	8.37
Acceleration/C_a	1

Based on the actual geological survey report of the prototype engineering project, the surrounding rock within the fault zone crossed by the tunnel is considered as Class V, the rock on both sides as Class IV, and the tunnel lining structure strength grade as C30 concrete. Combined with the geological survey report data and China' s "Standard for Engineering Classification of Rock Mass" (GB/T50218-2014) [62] and "Code for Design of Concrete Structures" (GB50010-2010) [63], the prototype values for surrounding rock and lining structures are taken as shown in Table 3 . According to China' s "Standard for Test Methods of Engineering Rock Mass" (GB/T50266-2013) [64] and "Standard for Geotechnical Testing Method" (GB/T50123-2019) [65], standard specimens of similar materials for surrounding rock and lining were prepared. Through orthogonal testing methods, uniaxial compression, triaxial compression, and direct shear tests were conducted on various proportioned similar material specimens to test multiple mechanical parameters.

Table 3 Prototype and model values of surrounding rock and lining similar materials

Material	Density (kg/m^3)	Elastic Modulus (MPa)	Cohesion (kPa)	Internal Friction Angle (°)
Class IV Surrounding Rock (Prototype)	2200	1500	300	35
Class V Surrounding Rock (Prototype)	2000	500	100	30
C30 Concrete Lining (Prototype)	2400	30000	-	-
Class IV Surrounding Rock (Model)	1100	10.7	2.14	35
Class V Surrounding Rock (Model)	1000	3.6	0.71	30
Lining Structure (Model)	1200	214	-	-

Considering fabrication feasibility, mechanical parameter similarity ratios, and differences between hard and soft materials, the final proportions were determined as follows: barite powder, low-strength gypsum, and water at a mass ratio of 3.5:1:2 to simulate the C30 concrete lining structure; fly ash, yellow sand, engine oil, and diatomite at a mass ratio of 1:1.5:0.25:0.47 to simulate Class IV surrounding rock on both sides; and fly ash, yellow sand, engine oil, diatomite, and sawdust at a mass ratio of 1:0.74:0.35:0.2:0.47 to simulate Class V surrounding rock in the fault zone. The specific mechanical parameters of the surrounding rock and lining similar materials are shown in Table 3.

4.3 Test Loading and Monitoring Scheme

This physical simulation test uses the artificially synthesized permanent displacement-containing ground motion described above, with specific time histories shown in Figure 4. The test loading scheme is designed as shown in Table 4 . The permanent displacement-containing ground motions A1 and B1, synthesized from the same base ground motion, are input to the shaking table sub-platforms on the hanging wall and footwall sides of the model test box, respectively, enabling the two independent shaking table sub-platforms to simultaneously simulate strong ground motion effects while achieving relative permanent displacement effects from post-earthquake active fault dislocation, thereby simulating the "strong shaking–fault movement" coupling effects on fault-crossing tunnels. A white noise test case with a peak acceleration of 0.1 g was also included, with a duration of 40 s to reduce interference from accidental factors and transient effects. The specific test case settings are shown in Table 5 .

Table 4 Ground motion input scheme

Input Location	Ground Motion Input
Rigid Box A (Hanging Wall)	Permanent displacement ground motion A1
Rigid Box B (Footwall)	Permanent displacement ground motion B1

Table 5 Test case settings

Case	Ground Motion	Fault Zone Width (cm)	Peak Acceleration (g)	Lining Structure
1	White Noise	20	0.1	Horseshoe-shaped complete structure

Case	Ground Motion	Fault Zone Width (cm)	Peak Acceleration (g)	Lining Structure
2	A1-B1	20	0.46	Horseshoe-shaped complete structure

This test employs multiple monitoring devices to measure various dynamic physical quantities of the shaking table surface, model box, surrounding rock mass, and lining structure, establishing a comprehensive multi-target, multi-parameter monitoring scheme.

Table 6 Test monitoring equipment

Equipment	Model	Specifications
Accelerometer	CA-YD-186	Measurement range: 10g, Frequency: 0.2-600Hz
Strain Gauge	BX120-10A	Resistance: 120.1$±0.1Ω, *Sensitivity* : 2.0±1×$5.7mm
Cable Displacement Sensor	-	Max displacement: $±$5cm, Frequency: 0-10Hz, Sensitivity: 0.1V/cm/V
Laser Displacement Sensor	-	Range: 0-100kPa, Voltage: 24V DC, Resolution: $ 0.3×$1080

Since this experiment focuses on the response characteristics of the surrounding rock structure within the fracture zone, a total of seven monitoring sections are arranged throughout the test. Sections 1# and 7# are located at the middle positions of the two side model boxes, sections 2# and 6# are near the junctions between the side boxes and dislocation layer frames, sections 3# and 5# are at the interfaces between the fracture zone and surrounding rock on both sides, and section 4# is at the middle of the fracture zone. Each monitoring section is equipped with accelerometers and strain gauges. Specifically, accelerometers are installed above the lining at each monitoring section, and accelerometers are also placed at the surface, middle, and bottom positions of the surrounding rock mass at sections 1#, 4#, and 7#, totaling 16 accelerometers. Circumferential and longitudinal strain gauges are installed at the left and right arch waists and arch feet of the lining structure at each monitoring section, with circumferential strain gauges at the arch crown and invert, totaling 70 strain gauge positions throughout the model. Cable displacement sensors are installed at sections 2#, 3#, 5#, and 6# to monitor lining structure displacement responses. Earth pressure cells are installed at the arch waist positions where the lining contacts the surrounding rock at sections 1#, 3#, 5#, and 7#. Laser displacement sensors are installed on the six dislocation layer frames within the fracture zone and at the middle positions of the side boxes. The specific monitoring arrangement is shown in Figure 5 [Figure 5: see original paper].

Due to the large number of sensors, two types of dynamic data acquisition instruments totaling nine units with 114 channels are used to meet the monitoring requirements. After completing the shaking tests, an industrial endoscope (Dellon-VT) and laser point cloud scanner (FX-S70(A)) are used to collect data on internal damage conditions and overall offset of the tunnel lining structure. The monitoring equipment information and specific measured physical quantities are shown in Table 6 .

4.4 Model Fabrication and Test Procedures

Based on the similarity ratios designed for this test and considering the prototype engineering tunnel structural parameters and model box size limitations, a three-centered circular tunnel cross-section lining mold was fabricated with a maximum internal height of 196.5 mm, maximum width of 200 mm, and thickness of 20 mm. The lining model was prepared using the aforementioned lining similar material proportion, with 配料 and casting followed by demolding and curing after material setting. The surrounding rock and fault zone similar materials were then prepared according to the determined proportions and backfilled within the ranges of 1.2 m width for side rock and 0.2 m width for the fracture zone. To ensure integrity and similarity of the surrounding rock mass similar material, layered backfilling was employed with compaction treatment after each layer, followed by a resting period before the next layer. Compaction effectiveness was controlled through compaction thickness and backfill material quantity.

Figure 6 [Figure 6: see original paper] illustrates the test procedures. During backfilling of the surrounding rock similar material, after reaching the 预埋 position of the tunnel lining model, the tunnel lining model installation and sensor placement were completed before subsequent backfilling and compaction of the overlying surrounding rock material. Grid lines were drawn on the surface to facilitate observation of post-earthquake surface rupture characteristics. After completing the surrounding rock-lining model fabrication and sensor layout, numerous monitoring device connection lines were carefully connected to the dynamic data acquisition instruments and signal validity was verified. Once all preparations were complete, the shaking table oil valve was opened to begin the non-uniform shaking test.

5. Validation of Shaking-Dislocation Coupling Test Results

To verify the rationality and effectiveness of the physical simulation test scheme design, this study analyzes and discusses the results from aspects of shaking table surface response, model test box response, surrounding rock mass dynamic response characteristics, and lining structure dynamic response characteristics.

5.1 Shaking Table Surface Response Characteristics

Shaking table surface response results directly reflect equipment reliability. Therefore, the monitored acceleration and displacement responses on the shaking table surface are compared with the input ground motion acceleration and displacement time histories, as shown in Figures 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper].

Figure 7 shows that under both white noise and input method 1 conditions composed of A1-B1 ground motions, the acceleration waveforms monitored on the shaking table surface maintain good consistency with the input ground motions. The input white noise has a peak acceleration of 0.1 g, while under white noise conditions (Case 1), the monitored peak accelerations on the hanging wall and footwall sides are 0.16 g and 0.13 g, respectively, with root mean square errors (RMSE) of 0.0389 and 0.0403. Input method 1 has a peak acceleration of 0.46 g, while under input method 1 conditions (Case 2), the monitored peak accelerations on the hanging wall and footwall sides are 0.49 g and 0.48 g, respectively, with RMSE values of 0.0379 and 0.0262.

Figure 8 compares the displacement responses on the shaking table surface with input ground motion displacement time histories under two different ground motion input conditions. The results show that under both white noise and input method 1 conditions, the monitored displacement waveforms maintain high consistency with the input ground motions. In Case 1 with white noise input, the input displacement peak is 5.79 mm for both sides, while the monitored displacement peaks are 5.73 mm (hanging wall) and 5.52 mm (footwall), with post-shaking displacements of 0.57 mm and 0.47 mm, respectively, essentially achieving repositioning after shaking. Under input method 1 conditions (Case 2), the input and monitored displacement time histories also maintain high consistency, with target permanent displacements of 51.43 mm and 31.43 mm, and monitored permanent displacement values of 54.20 mm and 33.80 mm, achieving displacement realization accuracies of 94.6% and 92.5% for the hanging wall and footwall, respectively.

Comprehensive analysis shows that considering both acceleration and displacement responses, the shaking table sub-platform outputs faithfully reproduce the input seismic motion data, achieving fidelity in seismic input data.

5.2 Model Test Box Response Characteristics

After verifying shaking table output reliability, the model test box response characteristics are crucial for test success. Given monitoring limitations and the rigid material consideration of the side boxes, no acceleration monitoring scheme was designed for the model boxes. The key to successfully achieving "strong shaking-fault movement" coupling effects and meeting test expectations is the displacement response of the model boxes. Therefore, laser displacement sensors 1# and 8# were installed at the middle positions of the hanging wall and footwall side boxes, respectively, while sensors 2# through 7# were sequentially installed at the middle positions of the six dislocation layer frames connecting the two side boxes along the direction from hanging wall to footwall.

Figure 9 [Figure 9: see original paper] shows the model box displacement response curves monitored by laser displacement sensors under two different test cases. Under white noise input (Figure 9(a)), the displacements of both side boxes and the six middle dislocation layer frames maintain high consistency with the input ground motion displacement time history, with displacement peaks at the eight monitoring points distributed between 4.4 mm and 6.61 mm. Compared with the input white noise displacement peak, the model box displacement response accuracy reaches 76%-86%. Under Case 2 conditions (Figure 9(b)), the displacement response trends of the hanging wall box and the three dislocation layer frames near the hanging wall side are consistent with the hanging wall shaking table input, while those of the footwall box and the three frames near the footwall side are consistent with the footwall input. This is achieved by completely releasing the middle column of bolts in the dislocation layer frames before shaking to ensure relative permanent dislocation between hanging wall and footwall after shaking. Due to the enormous weight of the model boxes and dislocation layer frames and the gaps between frames, other bolts cannot be fully pre-tightened, creating a flexible connection state between other frames during shaking.

Figure 10 [Figure 10: see original paper] shows the post-shaking displacement distribution of the model test box under Case 2 conditions. A permanent relative dislocation of 77.65 mm occurred between the layer frames on both sides of the fully released bolts after shaking. The displacement pattern shows a gradually increasing mode between the dislocation layer frames and side boxes, which forms the basis for successfully reproducing the fault zone dislocation pattern rather than simplifying it as a single rupture surface. This analysis demonstrates that the research approach and model test box design can ensure permanent relative dislocation between hanging wall and footwall under strong shaking while reproducing the fault zone dislocation pattern.

5.3 Surface Rupture Distribution Characteristics

After verifying the rationality and effectiveness of the shaking table and model test box design, the final validation of the test' s effectiveness in simulating "strong shaking-fault movement" coupling effects on fault-crossing tunnels is achieved by comparing the model surrounding rock and lining response characteristics under Case 2 conditions with actual seismic damage.

Figure 11 [Figure 11: see original paper] compares the post-shaking shear rupture and propagation effects on the model surface with actual surface ruptures after the Menyuan earthquake. Multiple ruptures can be observed on the model test surface, with two through-going main rupture surfaces developing at the soft-hard interfaces between the fracture zone and surrounding rock on both sides, accompanied by numerous branches during main rupture propagation, effectively reproducing the actual rupture surface development characteristics during earthquakes.

5.4 Lining Damage Pattern Characteristics

This study validates the effectiveness of simulating "strong shaking-fault movement" coupling effects on fault-crossing tunnels by comparing the overall lining displacement response characteristics and internal/external structural damage features with actual seismic damage.

Figure 12(a) [Figure 12: see original paper] shows the post-shaking cable displacement sensor monitoring results for the lining. The 1# sensor at section 2# within the hanging wall range monitored a permanent offset of 41.37 mm, the 2# sensor at section 3# at the fracture zone-hanging wall interface monitored 27.81 mm, the 3# sensor at section 5# at the fracture zone-footwall interface monitored 12.67 mm, and the 4# sensor at section 6# within the footwall range monitored 23.25 mm. This indicates a relative offset of 40.48 mm occurred within the fracture zone.

Figure 12(b) shows the horizontal relative displacement contour map from three-dimensional laser point cloud scanning inside the lining under Case 2 conditions. Using the portal section as a reference, a relative horizontal dislocation of 64.10 mm is observed across the rupture surface, demonstrating that the model box displacement response is transferred to the lining structure. Overall, the deformation mode of the lining structure within the fracture zone closely resembles the damage pattern of the severely damaged section of the Daliang Tunnel, effectively reproducing the lining structure dislocation deformation mode of fault-crossing tunnels under "strong shaking-fault movement" coupling effects.

Figure 13 [Figure 13: see original paper] shows the external damage characteristics of the lining structure under Case 2 conditions. The left sidewall of the lining at the fracture zone-hanging wall interface was sheared off, while the right sidewall at the fracture zone-footwall interface near the footwall side was significantly sheared, indicating that the severe damage range extends beyond the fracture zone boundaries. A wide longitudinal crack developed at the crown within the fracture zone, with severe damage at both crown and invert positions showing spalling and rebar exposure. Multiple shear cracks at oblique angles to the longitudinal direction are observed on the external lining structure within the fracture zone, with shear failure being the dominant damage mode. These external lining damage patterns are highly consistent with the phenomena revealed by the Menyuan earthquake Daliang Tunnel damage.

Figure 14 [Figure 14: see original paper] compares the internal damage characteristics of the lining structure within the fracture zone captured by industrial endoscopy with the actual Menyuan earthquake Daliang Tunnel damage features. Severe damage within the fracture zone includes large-area spalling and rebar exposure, bent and deformed reinforcement, development of diagonal or circumferential through-cracks, multiple parallel cracks, or intersecting crack networks. Specifically, the crown bottom uplift, large-area concrete spalling and rebar exposure at sidewall and arch shoulder positions, and circumferential and diagonal cracking at the crown effectively reproduce the damage phenomena observed in the Menyuan earthquake Daliang Tunnel.

Comprehensive analysis of the lining structure damage patterns demonstrates that the research approach and test methodology can effectively simulate the seismic damage characteristics of the Menyuan earthquake Daliang Tunnel under "strong shaking–fault movement" coupling effects, validating the rationality and effectiveness of the proposed fault-crossing tunnel "shaking–dislocation" coupling effect shaking table model test method.

6. Conclusions

Based on the independently developed fault-crossing tunnel "strong shaking–fault movement" coupling physical simulation system and the proposed artificial ground motion synthesis method considering synchronous non-uniform "seismic motion–permanent displacement," this study establishes a hybrid input framework for "strong shaking–fault movement" coupling and achieves physical simulation of the mutual interaction between seismic wave fields and deformation-displacement fields on both sides of the fault zone. Comparative analysis of physical simulation test results with seismic damage characteristics yields the following preliminary findings:

(1) A "seismic motion–permanent displacement" non-uniform loading model box was developed based on rigid model boxes and flexible dislocatable layer frames, combined with a twin shaking table array and co-moving sliding support bracket module to complete the fault-crossing tunnel "strong shaking–fault movement" coupling physical simulation system.

(2) An artificial ground motion synthesis method considering synchronous non-uniform "seismic motion–permanent displacement" was proposed. Using this method, two "seismic motion–permanent displacement" synchronous non-uniform ground motion time histories with permanent displacements of 3.6 m and 2.2 m were synthesized, achieving a special loading environment where the input ground motion simultaneously reflects both high-frequency seismic energy components and low-frequency large deformation permanent displacement components.

(3) Verification through shaking table surface and model test box dynamic response results demonstrates that the current test method can faithfully reproduce input seismic motion data and successfully achieve physical simulation of the mutual interaction between seismic wave fields and deformation-displacement fields on both sides of the fault zone, providing

assurance for reproducing seismic damage to surrounding rock and lining structures of fault-crossing tunnels under "strong shaking-fault movement" effects.

(4) Comparison of surface rupture and lining structure damage patterns with actual seismic damage shows good reproduction of the Menyuan earthquake Daliang Tunnel damage characteristics, while successfully reproducing the large deformation dislocation mode of the fault fracture zone within the fracture zone range.

(5) The test system and method described in this paper will provide a physical simulation research approach reference for subsequent in-depth studies on the "strong shaking-fault movement" coupling effect mechanism of fault-crossing tunnels. Due to space limitations, specific analysis results of the "strong shaking-fault movement" coupling effects will be presented in subsequent papers in this series.

The accurate loading of synchronous non-uniform "seismic motion-permanent displacement" by the twin shaking tables is the key to the successful first implementation of the fault-crossing tunnel "strong shaking-fault movement" coupling physical simulation test. The research team sincerely appreciates Mr. Ji Jinbao from Beijing University of Technology for his excellent calibration work on the twin shaking tables.

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Corresponding author: Cui Zhen, E-mail: zcui@whrsm.ac.cn

Author Contributions Statement:

Mei Xiancheng: Test scheme design, test implementation, data analysis, paper drafting
Cui Zhen: Research proposition and design, test implementation, paper drafting
Sheng Qian: Research concept development
Chen Jian: Research concept development
Fei Yang: Test scheme design
Tang Langzhou: Test scheme design
Zhao Xu: Test scheme design and implementation
Li Ruohan: Test scheme design and implementation
Huang Jingqi: Test scheme design

Author contributions can be categorized as: 1) Research proposition and design, including specific viewpoints or methods; 2) Research implementation, such as conducting tests or investigations; 3) Data acquisition, provision, and analysis; 4) Paper drafting or final revision. Each research paper can further detail author contributions based on research activity characteristics. Some research activities may involve other work and contributions that can be specifically described. For papers with multiple authors, each author' s specific contributions in the above four aspects must be indicated at the end of the paper.

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