A segmental shaking table test device for cross-fault tunnels under coupled strong ground motion and fault dislocation

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ABSTRACT: Precise simulation of active fault hazards remains a critical challenge in investigating the seismic failure mechanisms of tunnels crossing faults, particularly in achieving controllable coupling between strong ground motion and fault displacement. This contribution describes a novel experimental methodology based on a dual-array shaking table platform for coupled seismic–fault-displacement simulation. A tri-component test apparatus is developed, consisting of: (1) a Strong Ground Motion–Dislocation Coupling Loading System (SGDS) for integrated seismic excitation and fault displacement input, (2) a Detachable and Modular Linkage Device (DMLD) enabling flexible configuration of fault geometry and kinematic parameters, and (3) an Adjustable Deformation-Mode Segmented Box (ADMSB) serving as the soil container. The proposed apparatus allows controlled simulation of different fault deformation modes, including single-slip-plane and uniformly distributed dislocation. The applicability and reliability of the system are validated through free-field shaking table tests and three-dimensional numerical simulations under identical loading conditions. Good agreement in acceleration responses and residual displacement patterns demonstrates that the proposed apparatus can accurately reproduce coupled seismic–fault-displacement effects. The proposed methodology provides a reliable and repeatable experimental platform for studying the dynamic response and damage evolution of tunnels crossing active faults under strong earthquakes.

1 INTRODUCTION

Tunnels crossing active faults are highly vulnerable during strong earthquakes, and severe damage has been repeatedly reported in post-earthquake investigations (Wang et al., 2001; Yu et al., 2016, 2026). Physical model tests have therefore been widely used to investigate the seismic response of underground structures, as they allow controlled simulation of complex geological conditions and soil–structure interaction (Yuan et al., 2014).

Existing experimental devices for simulating tunnels crossing active faults can generally be classified into two categories: (i) devices considering fault dislocation only and (ii) devices considering both seismic excitation and fault dislocation. For example, Liu et al. (2013, 2015) developed model boxes that simulate normal fault dislocation through controlled relative movement between the hanging wall and footwall, while Liu et al. (2021) further investigated fault creep–slip behavior under three-dimensional stress conditions. Other studies attempted to incorporate both seismic excitation and fault displacement in shaking table tests (Shen et al., 2020; Wang et al., 2021). However, these devices typically apply seismic motion and fault dislocation sequentially or independently, rather than reproducing their simultaneous interaction during earthquakes.

Although these studies have improved the understanding of tunnel responses under fault movement and seismic loading, several limitations remain. Many existing devices use rigid boxes to represent the hanging wall and footwall, neglecting the mechanical effects of fault damage zones. Moreover, the loading schemes adopted in most studies essentially represent a superposition of ground motion and imposed fault displacement, rather than a truly coupled loading process. As a result, the spatiotemporal interaction between seismic excitation and fault dislocation cannot be realistically reproduced.

To address these limitations, this study develops a novel segmental model box for multi-point shaking table tests of tunnels crossing active faults. The proposed apparatus enables simultaneous transmission of strong ground motion and fault dislocation through a modular structural design. Numerical simulations and shaking table tests are conducted to validate the applicability and reliability of the developed experimental system.

2 DESIGN OF THE MODEL BOX

This section presents the design concept and physical realization of the proposed segmental model box for multi-point shaking table tests of tunnels crossing active faults. The design philosophy and associated constraints are first introduced, followed by a detailed description of the structural configuration and installation scheme developed to implement coupled strong ground motion and fault dislocation loading.

2.1 Design philosophy and constraints

The proposed model box consists of rigid boxes at both ends and a segmental shear box in the middle, as shown in Figure 1. It should be emphasized that the loading scheme implemented in this study differs fundamentally from the sequential or superposed loading strategies adopted in many previous shaking table experiments. In conventional approaches, seismic excitation and fault dislocation are typically applied independently or in separate stages, resulting in a simplified superposition of the two loading effects. In contrast, the proposed system employs a multi-point shaking table configuration to simultaneously input non-uniform seismic motions at the hanging-wall and footwall boundaries. This arrangement enables the spatiotemporally coupled development of strong ground motion and fault dislocation within the model ground, allowing their interaction to evolve naturally during testing rather than being imposed step by step.

(1) Structural integrity and safety.

The model box should possess sufficient structural strength, with reliable connections between adjacent segments. The segmental system should maintain overall stability during testing while allowing modular assembly and disassembly, thereby ensuring structural safety throughout the experimental process.

(2) Dynamic compatibility.

Resonance between the model box and the contained soil should be avoided, so that the dynamic response of the model soil closely approximates that of the prototype ground under seismic excitation.

(3) Load capacity compliance.

The total mass of the model box and the enclosed soil should remain within the allowable load capacity of the shaking table system.

(4) Coupled loading capability.

The model box should be capable of transmitting coupled strong ground motion and fault-dislocation loads.

To implement the above design philosophy and satisfy the associated constraints, the shaking table test device is composed of four functional subsystems, as schematically illustrated in Fig. 1.

(i) Strong ground motion–fault dislocation coupled loading system (SGDS).

Based on the multi-point shaking table platform at Tongji University, the SGDS enables non-uniform seismic excitation across the fault zone, thereby reproducing the coupled effects of strong ground motion and fault dislocation and capturing the key seismic hazard characteristics associated with active faults.

(ii) Detachable and modular linkage device (DMLD).

The junction between the hanging wall and footwall is constructed using prefabricated, detachable modular components. This configuration allows flexible adjustment of fault width and dip angle, enabling the simulation of different fault geometries and satisfying the loading requirements under various experimental scenarios.

(iii) Adjustable deformation-mode segmental box (ADMSB).

The interaction mode between adjacent shear frames can be flexibly adjusted, allowing controlled simulation of various fault deformation patterns, including single-slip-plane, multi-slip-plane, and uniformly distributed fault deformation modes.

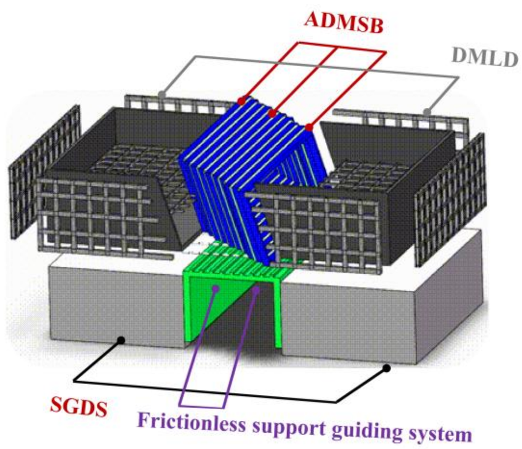

Figure 1. Diagram of the shaking table test device for cross-fault tunnels.

2.2 Design and Installation of the Model Box

This section presents the structural configuration and installation scheme of the segmental model box, with emphasis on how the proposed design enables coupled transmission of strong ground motion and fault dislocation while satisfying dynamic compatibility and experimental constraints.

The shaking table tests were conducted using the multi-point shaking table system at the State Key Laboratory for Disaster Reduction in Civil Engineering. Each shaking table has a plan dimension of 4 m × 6 m, and the tables can be independently controlled to achieve non-uniform seismic excitation (Yuan et al., 2018). In the tests, equal-magnitude but opposite-direction coupled strong-motion–fault-dislocation ground motions were simultaneously input at two individual tables, serving as the loading boundaries for the hanging wall and footwall of the fault.

The overall dimensions of the segmental model box are 8 m × 6 m × 2 m (length × width × height). The model box consists of two rigid boxes at both ends and a shear box composed of ten shear frames positioned in the middle. Each rigid box is composed of three side walls and a bottom plate. The side walls are constructed with an inner 10 mm thick steel plate and externally welded HW150 steel sections, while the bottom plate is a 20 mm thick steel plate bolted directly to the shaking table, as shown in Figure 2. During testing, the two rigid boxes are placed separately on two dividual tables. To satisfy the dynamic compatibility requirement and reduce boundary effects, a 500 mm thick foam layer is installed along the inner side walls of the rigid boxes, allowing the deformation mode of the model soil to better approximate that of the prototype ground.

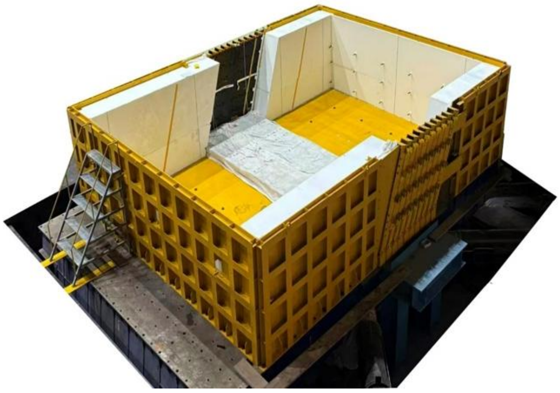

Figure 2. Layout of the Segmental Model Box.

The shear box consists of ten individual shear frames. Each frame is assembled from four steel sections connected by bolts, with a frame width of 175 mm and an overall sectional dimension of 6 m × 2 m. The spacing between adjacent frames is 25 mm. By disassembling and rotating the side steel members, the inclination angle of the fault can be flexibly adjusted. A 10 mm thick rubber layer is installed inside each frame to ensure stable inter-frame connections while accommodating transverse shear deformation as well as longitudinal tensile and compressive deformation during testing. The entire shear box is supported by a bottom support frame and is allowed to slide through spherical hinges at the connections.

To evaluate the dynamic characteristics of the model box and avoid resonance during testing, white-noise scanning tests were conducted for both the empty model box and the soil-filled model box. The identified fundamental frequencies were approximately 25 Hz and 10 Hz, respectively, indicating a clear separation from the dominant frequencies of the input motions and ensuring dynamic stability during the experiments.

The core structural configuration of the model box consists of two main components: a detachable modular linkage device and a segmental shear-frame system with adjustable deformation modes. The modular linkage device is arranged at the interface between the hanging wall and footwall and is composed of standardized prefabricated components connected through bolts and positioning pins. This configuration allows adjustment of fault width and dip angle. The segmental shear-frame system forms the central part of the model box and enables controlled relative deformation between adjacent segments.

Meanwhile, the overall model box adopts a segmental, deformable structural design. The connection stiffness and constraint conditions between adjacent shear frames can be precisely adjusted according to specific experimental schemes. By controlling the interaction among segments, the model box can simulate various fault deformation modes in a controlled manner, including single-slip-plane mode, multi-slip-plane mode, and uniformly distributed slip mode. This design enables a more realistic representation of slip distribution characteristics within active fault zones and provides experimental support for investigating strong-motion propagation paths and soil dynamic responses in faulted ground.

3 APPLICABILITY ANALYSIS OF THE MODEL BOX

To verify the mechanical applicability and functional reliability of the proposed segmental model box under coupled strong ground motion and fault-dislocation loading, this section combines numerical simulations with shaking table tests. The dynamic response characteristics and load-transfer performance of the model box are systematically evaluated.

3.1 Loading Scenarios

Both numerical simulations and physical tests employed harmonic waves and artificially synthesized seismic motions as input excitations. The harmonic wave had a peak acceleration of 0.1 g and a frequency of 25 Hz, while the artificially synthesized seismic motion had a peak acceleration of 0.5 g with a dominant frequency of 25 Hz. To evaluate the applicability of the proposed model box in shaking table tests of tunnels crossing active faults under coupled strong ground motion and fault-dislocation loading, two loading scenarios were considered:

Case A: harmonic wave input applied in the horizontal transverse direction;

Case B: artificially synthesized seismic motion applied in the horizontal transverse direction, with opposite movements imposed at the hanging-wall and footwall tables to reproduce fault dislocation.

In this study, the coupling effect refers to the simultaneous occurrence of seismic excitation and fault dislocation generated by the opposite movements of the hanging-wall and footwall shaking tables. During the tests, two adjacent shaking tables were simultaneously excited to reproduce non-uniform seismic input across the fault. The two tables move with equal magnitude but opposite directions, representing the hanging wall and footwall of the fault. A total of 16 accelerometers were installed in the model box: three accelerometers were mounted on one rigid box, and one accelerometer was installed on each shear frame to measure horizontal transverse acceleration responses. The layout of the acceleration sensors is shown in Figure 3

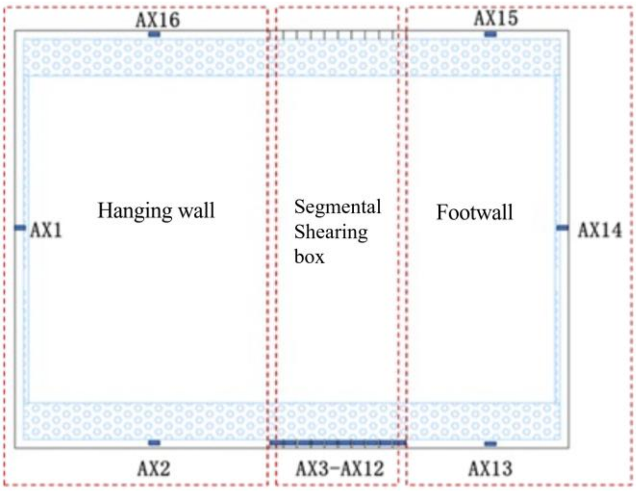

Figure 3. Layout of Acceleration Sensors in the Model Box.

A three-dimensional numerical model of the segmental model box was established in Abaqus, as shown in Figure 4. All components were modeled using solid elements. Vertical constraints were applied at the base, and dynamic loads were imposed at the bottoms of the two rigid boxes on both sides to reproduce the actual loading conditions of the shaking table tests.

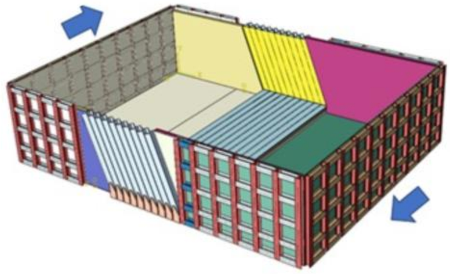

Figure 4. Three-Dimensional Numerical Model of the Segmented Model Box.

3.2 Acceleration Response Comparison of the Segmental Model Box

Figure 5 presents the peak acceleration responses of the rigid boxes and shear frames under horizontal transverse harmonic-wave excitation. As shown in Figure 5, the experimentally measured results agree well with the numerical simulation results. The peak acceleration responses of the rigid boxes are identical to the input acceleration at the shaking table, indicating that the imposed excitation is effectively transmitted to the model box without significant distortion. Meanwhile, the peak acceleration responses of the shear frames are close to those of the rigid boxes, suggesting that the segmental connections do not introduce noticeable attenuation or amplification of acceleration response under harmonic excitation.

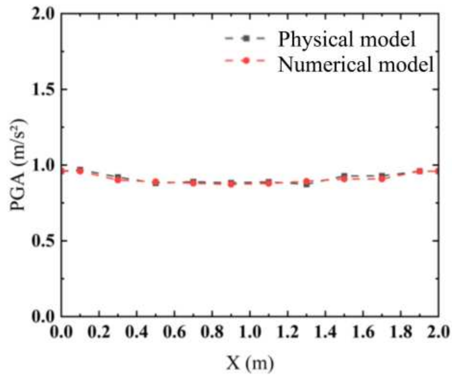

Figure 5. Peak Acceleration of the Hanging Wall, Footwall, and Shear Frames of the Model Box under Harmonic Wave Input.

Figure 6 shows the peak acceleration responses of the rigid boxes and shear frames under horizontal transverse seismic excitation. Similar to the harmonic-wave case, good agreement is observed between the experimental and numerical results. The peak accelerations of the rigid boxes coincide with the shaking table input, while the shear frames exhibit acceleration responses comparable to those of the rigid boxes. These results demonstrate that the proposed segmental model box is capable of reliably transmitting dynamic excitation under both harmonic and seismic loading conditions, without inducing adverse dynamic filtering effects.

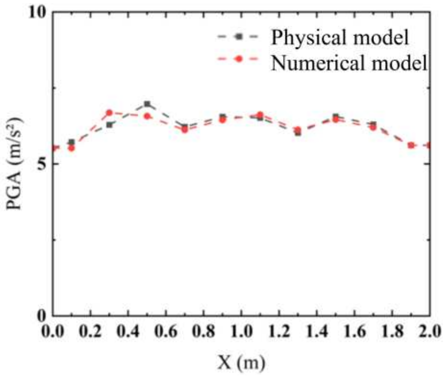

Figure 6. Peak Acceleration of the Hanging Wall, Footwall, and Shear Frames of the Model Box under Seismic Motion Input.

The residual displacement deformation pattern under uniform fault dislocation was first examined. Figure 7 compares the residual displacements obtained from the numerical simulation and experimental measurements. The results indicate that the residual displacement of the rigid boxes is consistent with the imposed displacement at the shaking table, while the residual displacement distribution of the shear frames exhibits an overall “S-shaped” pattern. This deformation profile is characteristic of uniform fault dislocation and indicates that the segmental shear box can effectively reproduce continuous fault-induced displacement transfer.

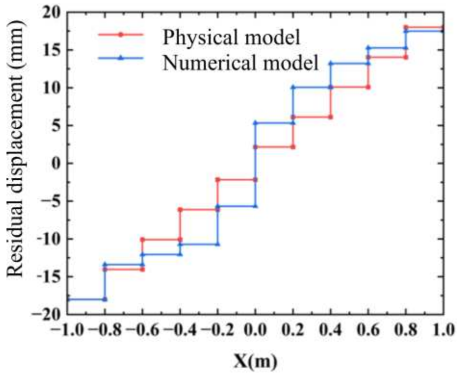

Figure 7. Residual displacement of the segmental model box under uniform fault dislocation.

To further verify the displacement characteristics under a single fault-dislocation plane, adjacent shear frames were rigidly connected using bolts to restrict their transverse relative displacement, leaving only one active dislocation plane. Figure 8 shows the residual displacement pattern of the model box under artificially synthesized seismic excitation. It can be observed that the imposed constraints between adjacent shear frames are effective, resulting in a clear concentration of displacement at the single dislocation plane. This confirms that the proposed model box can flexibly simulate different fault deformation modes through adjustment of inter-segment constraints.

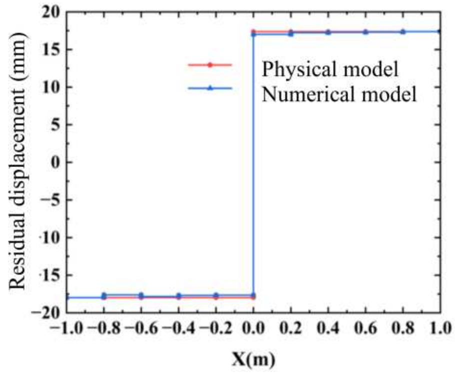

Figure 8. Residual displacement of the segmental model box under a single fault-dislocation plane.

Overall, the numerical simulations and shaking table test results consistently demonstrate that the proposed segmental model box can realistically reproduce the continuous transmission of coupled strong ground motion and fault-dislocation loading. Moreover, the model box is shown to be applicable for simulating different fault deformation modes and is well suited for shaking table tests of tunnels crossing active faults under coupled seismic and fault-dislocation effects.

4 CONCLUSIONS

A novel segmental model box capable of transmitting coupled strong ground motion and fault-dislocation loads was developed in this study. The proposed model box adopts a combined structural configuration consisting of rigid boxes at both ends and a shear box in the middle, addressing the limitations of conventional experimental devices in synchronously simulating the coupled effects of seismic motion and fault dislocation. With overall dimensions of 8 m × 6 m × 2 m and supported by a multi-point shaking table system, the model box enables coupled load input and provides a reliable physical testing platform for investigating the seismic response of tunnels crossing active faults under realistic earthquake loading.

A modular, detachable, and multi-mode adjustable design was achieved through the integration of a detachable modular linkage device and a segmental shear-frame system. This configuration allows flexible adjustment of fault width, dip angle, and dislocation direction. The incorporation of rubber layers and spherical hinges ensures deformation compatibility and boundary adaptability during dynamic excitation, enhancing reusability and experimental efficiency while extending applicability to faults with different geometric characteristics and kinematic modes.

The functionality and applicability of the proposed model box were validated through systematic numerical simulations and shaking table tests. Under different input motions, including harmonic waves and artificially synthesized seismic motions, the model box effectively transmitted acceleration responses and reproduced representative deformation patterns, such as S-shaped uniform dislocation and single-slip-plane behavior. Good agreement among experimental measurements and numerical simulation confirms the mechanical consistency and structural stability of the model box under coupled strong-motion–fault-dislocation loading.

Overall, the proposed model box provides an effective experimental methodology for studying tunnels crossing active faults under coupled seismic and fault-dislocation effects. It fills a key gap in existing shaking table experiments related to coupled load simulation and offers a controllable and repeatable testing approach for investigating soil–structure interaction mechanisms and evaluating tunnel seismic performance in fault zones. The findings provide practical technical support for improving the seismic safety of tunnel engineering in active fault regions. Future studies will utilize the developed apparatus to conduct systematic shaking table tests on tunnel models, with particular emphasis on tunnel–soil interaction mechanisms and seismic damage evolution under coupled strong ground motion and fault dislocation.

ACKNOWLEDGEMENTS

The research was supported by the National Key Research and Development Program of China (No. 2025YFE0125500).

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