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Experimental study on normal fault rupture propagation in loose strata and its impact on mountain tunnels

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ABSTRACT

Understanding earthquake fault rupture propagation is important in building and lifeline engineering, especially in the construction of mountain tunnels. Thus, studying rupture propagation in strata and tunnel failure with fault displacement is significant. For this purpose, an experiment has been designed to simulate normal fault displacements with different dip angles. The influence of normal faults on tunnels has been observed by examining the rupture and strata deformation and analyzing the shear zone, tunnel stain, position, and forms of tunnel cracks. The results show that more than one strata rupture appears when the normal fault moves, and at least one rupture reaches the ground surface as the vertical fault dislocation is approximately 4.4% of the covering depth. In general, those ruptures form an inverted triangle zone in which strata deform significantly. The range of the rupture shear zone increases as the fault dip angle decreases. Strata-tunnel -fault can be considered as a beam on an elastic foundation. The lining of the tunnel in the hanging wall and shear zones is subjected to sagging, and that in the foot wall zone is subjected to hogging. Failure modes appear to change with fault dip angle. The lining damage form is flexure failure occurring mainly in the foot wall with the circumferential cracks, when the dip angle is 75°. When the dip angle is 60° and 45°, the failures are caused by a combination of flexure and shear both in the shear and foot wall zones with a lot of circumferential and diagonal cracks. Furthermore, to guide design work reasonably, the calculation method in determining the weak parts of the tunnel and feasible reinforcement measures are discussed.

1. Introduction

Tectonic earthquakes have two main failure modes: strata vibrations triggered by seismic waves and permanent strata deformations caused by fault dislocation. The permanent deformations of strata have a significant effect on buildings and lifeline engineering because of differential movements on both sides of the faults, especially on linear structures such as underground pipelines and tunnels. The optimal solution is to select a proper site and avoid any potential fault structure. However, this solution is impractical because of the extension and width of tunnels (Lee and Hamada, 2005). For example, several tunnels of the Duwen highway near the earthquake fault zone were damaged during the Wenchuan earthquake. All the main bodies of 13 tunnels through adverse geological structures were seriously damaged, and some even collapsed. The vertical displacement and the dextral horizontal displacement reach are 5.0 m and 4.8 m, respectively, in the rupture zone of the Longmen Mountain, and the average dislocation reaches 23 m (Zhang et al., 2008) along the rupture zone. Understanding failure modes is crucial in designing tunnels in failure-prone locations.

Many scholars have studied propagations of active faults in bedrock overburdens. Scale model tests and centrifuge tests have been conducted using sand and clay samples (Bray et al., 1994a; Guo et al., 2001; Johansson and Konagai, 2007; Lin et al., 2006; Liu and Hamada, 2004; Roth et al., 1981). Propagations and geometric characteristics of ruptures have been identified. Numerical studies on strain field and plastic deformation caused by rupture propagations in severely deformed regions have been reported and compared with scale model experiments (Bray et al., 1994b; Johansson and Konagai, 2007; Lin et al., 2007). The effects of fault dip, formation material properties, overburden thickness, and displacement on the rupture propagation have been discussed as well.

Shear displacement caused by fault bedrock dislocation can propagate through the cover layer to the ground surface. Rupture propagation creates a severely deformed region in the bedrock

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cover layer and extends upward as bedrock displacement develops. More than one rupture (Lee and Hamada, 2005) can be formed through normal fault rupture propagation in general. Likewise, when the displacement of the reverse fault is large enough, a secondary rupture (Taniyama and Watanabe, 2002) can occur outside the primary sliding surface. Taniyama found that the rupture surface propagated through the alluvium if the vertical bedrock fault displacement reached 3–7% of the depth of the alluvium.

Burridge et al. (1989) conducted a series of scaled model experiments in a centrifuge to assess the effect of fault rupture movement on tunnels. Based on experimental results, a model was developed and used to calculate the vertical displacement, longitudinal bending moment, and shearing force of the infinitely long prototype tunnel under fault displacement of 0.61 m and 1.12 m, respectively. Johansson and Konagai (2007) used model test and numerical simulation to determine the structural design criteria based on fault displacement and failure strain. Field observations and numerical simulation results showed that the surrounding horizontal stress of the underground structures should be considered in the design. Lin et al. (2007) studied the deformation and the stability of strata and tunnels under different control factors using sand box experiment and numerical simulation for reverse faults with large dislocation distance. The influence of tunnel structure on the rupture propagation was also investigated based on observation data.

To date, neither physical modeling nor its effect on mountain tunnels has been performed to investigate the rupture propagation in loose strata. However, this study should be important because fault structures are unavoidable in building tunnels. A clear understanding of the stress and deformation mechanism of tunnel crossing fault is necessary.

This paper presents an experimental study that focuses on the loose bedrock overlay because tunnels in fault zones often undergo weathering or fracturing. Fault rupture propagation with different normal fault dips is simulated and geometric features are identified. When a shallowly buried tunnel crosses the fault orthogonally, it is affected by the severe deformation of the shear zone. A large fault displacement could even cause structural damage. Fault dislocation (induced structural deformation) and internal force variation are analyzed based on strains, and tunnel ruptures and failure features after loading are identified.

2. Experimental method and apparatus

2.1. Model geometry and apparatus

A schematic of the experimental setup is shown in Fig. 1. The length, width, and height are 2.0, 0.8, and 1.1 m, respectively. The sand box is composed of 8 mm thick steel plates. The bottom plate of the box is composed of a hanging wall (movable) and a foot wall (fixed) based on normal faults. A photograph of the test apparatus is shown in Fig. 2. The hanging wall can be moved up or down to simulate the fault displacement, which is achieved by manipulating the oil jack underneath the sand box. The bearing is arranged between the loading system and hanging wall bottom plate so that the fault dip angle can vary between 30° and 90°. During site observation, the normal fault dip is relatively large. Therefore, in our test, the fault dip-angles are 75°, 60°, and 45°, respectively. During the test, a digital camera is mounted on one side of the model box to record the rupture propagation.

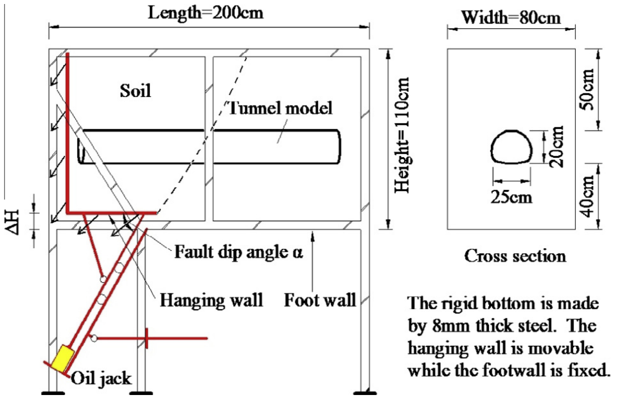

Fig. 1. Schematic of the test apparatus.

In the test, a prescribed displacement is applied at the bottom to simulate the fault dislocation. The bottom plate of the box simulates the fault bedrock, whereas the sand soil simulates the loose cover layer. The simulated tunnel is buried at a designated distance above the bedrock. The ruptures induced by the displacement of bedrock propagate upward in the cover layer, which simulates the mechanism of fault dislocation. When the bottom plate on the hanging wall side is moved down, an obvious rupture occurs in the overlay.

The loading procedure is conducted as follows. Given the aforementioned displacement of the Longmen Mountain rupture zone, the hanging wall is raised by 10 cm ($\Delta H = 100$ mm) prior to the experiment. The model box is filled with multiple layers of sand with 10 cm height intervals, and white powder is filled between layers as markers. The thickness of the sand is 90 cm for the elevated hanging wall and 100 cm for the foot wall. A lifting height of $\Delta H = 100$ mm is used in the scaling experiment, which corresponds to the maximum vertical displacement of the prototype of 5 m. In fact, a vertical displacement of several meters did occur during the earthquakes in Chi-Chi, Taiwan (Wang et al., 2000) and Wenchuan, Sichuan (Zhang et al., 2008).

2.2. Sample preparation

The model tunnel is constructed using brittle gypsum reinforced with steel mesh to simulate a road tunnel that runs through the mountain. The geometric similarity ratio is 1:50 and the bulk density similarity ratio is 1:1. The original simulated structure

Fig. 2. Photograph of the test apparatus (original state).