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Shaking table tests on seismic measures of a model mountain tunnel

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ABSTRACT

A series of three dimensional (3D) shaking table tests were carried out to investigate the mechanism and effect of seismic measures of mountain tunnel using a scaled model based on a real tunnel. Key technical details of the experiment, including similarity relations, seismic measures simulation, boundary conditions, sensor layout, modeling methods, and ground motion input were presented. Main seismic measures, including reinforcing surrounding rock with anchors, increasing lining flexibility with steel wire mesh, and installing seismic isolation layer between reinforced surrounding rock and tunnel lining, were investigated in this study. Experiment results show that: (1) adding a layer of steel wire mesh in the tunnel lining can improve the flexibility and seismic performance and also may effectively prevent radial cracks from crossing the lining; (2) installing a geofoam isolation layer between the reinforced surrounding rock and the tunnel lining reduces dynamic earth pressure by 70–90% for the lining without a seismic isolation layer; (3) the flexible joints can effectively avoid global failures of tunnel lining for they reduce dynamic strain and bending force in the tunnel lining and decrease the seismic energy transmission along the lining in axial direction; (4) reinforcing surrounding rock with anchors significantly reduces dynamic earth pressure and strain of the lining by about 50%. In addition, the length of seismic reinforcement for general mountain tunnel portal is recommended to be 50 m from the tunnel portal along the axial direction.

1. Introduction

It is well known that many tunnels have experienced significant damage in recent large earthquakes, such as the 1995 Kobe earthquake in Japan, the 1999 Chi-Chi earthquake in Taiwan, the 1999 Kocaeli earthquake in Turkey, and the 2008 Wenchuan earthquake in China. Recently, an increasing number of researchers and engineers have carried out studies on the seismic damage and responses of tunnels and underground structures during large earthquakes (Wang et al., 2001; Yashiro and Kojima, 2007; Towhata, 2008; Sun et al., 2011; Li, 2012; Wang and Zhang, 2013). Seismic design methods and measures for tunnels have been proposed by many researchers (Kuesel, 1969; St John and Zahrah, 1987; Hashash et al., 2001). However, these seismic measures for tunnels are rarely used in practice mainly due to the lack of reasonable theoretical basis and having potential risks in the use of these measures in real tunnels.

Three main methods, including reinforcing surrounding rock, improving tunnel lining performance, and installing seismic isolation layer between the surrounding rock and the tunnel lining, have been proposed to improve the seismic performance of tunnels and underground structures. The first method is to reinforce the surrounding rock by grouting or anchors. It is the main seismic measure for tunnels for it can reduce the stiffness difference between surrounding rock and tunnel lining, and thereby reduce the differential deformation (Gao et al., 2005; Chen, 2011). The second method is to improve the tunnel lining performance, by increasing the flexibility of the tunnel lining to make its deformation compatible with that of the surrounding rock, and thereby reduces the seismic damage in the lining. For example, flexible joints between two sections lining along the longitudinal direction can reduce the longitudinal bending stiffness of the tunnel lining and avoid global damage of tunnel lining (Constantopoulos et al., 1979; Kiyomiya, 1995; Xiong et al., 2007). The third method is to install a seismic isolation layer between the surrounding rock and the tunnel lining. The seismic isolation layer reduces the dynamic loads transmitted from the surrounding rock to the tunnel lining, thus to reduce the deformation of the tunnel lining. At present, analytical and numerical approaches have been used by some researchers to verify the feasibility of using different materials such as foam concrete, geofoam and rubber for the seismic isolation layer (Kim and Konagai, 2001; Wang et al.,

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Table 1
The similarity ratio of the model to prototype.

Physical quantity	Symbol and relational expression	Similarity ratio	Physical quantity	Symbol and relational expression	Similarity ratio
Geometry	C_l	1/40	Cohesion	C_C	1/35
Unit weight	C_γ	1/0.85	Friction angle	Φ	1
Young's modulus	C_E	1/35	Poisson's ratio	μ	1
Stress	$C_\sigma = C_E C_\varepsilon$	1/35	Acceleration	$C_a = C_l C_t^{-2}$	1
Strain	$C_\varepsilon = C_l C_\gamma C_E^{-1}$	1	Time	$C_t = C_l^{1/2}$	0.158

2006; Hasheminejad and Miri, 2008; Xu and Li, 2011; Kiryu et al., 2012). In summary, theoretical and numerical analyses have been extensively conducted to verify these methods and measures for tunnel seismic design, while experimental studies are seldom carried out. Therefore, experimental studies are necessary for more understanding of the mechanism and effects of seismic measures on tunnels for a better application of these measures on real tunnels. Most previous studies mainly focused on seismic measures of shield tunnels, immersed tunnels, and cut and cover tunnels in soil medium; however, there have been few studies on mountain tunnels using NATM (New Austrian Tunnelling Method) in the rock medium.

The object of this paper is to present experimental results for further references for seismic design of tunnels and seismic measurements in field tunnels. In this study, a series of 3D shaking table model tests were carried out to investigate the seismic response and the mechanism of seismic measures by using a variety of input ground motions of different intensity and incident directions. The tunnel model is based on Huangcaoping tunnel No. 2 located in a high-intensity earthquake area in the southwest of China. Main seismic measures investigated in this study include reinforcing surrounding rock with anchors, increasing lining flexibility with steel wire mesh, setting flexible joints, and installing seismic isolation layer between the reinforced surrounding rock and the tunnel lining. Key technical details of the experiment, including similarity relations, seismic measures simulation, boundary conditions, sensor layout, modeling methods, and ground motion input were presented. The mechanism and effects of seismic measures were evaluated based on accelerations, earth pressures and strains in the tunnel lining during earthquake excitation.

2. Model test setup

2.1. Experiment design

The model was built by a 1/40 scale down from the actual topography of the Huangcaoping Tunnel No. 2. The modeled part

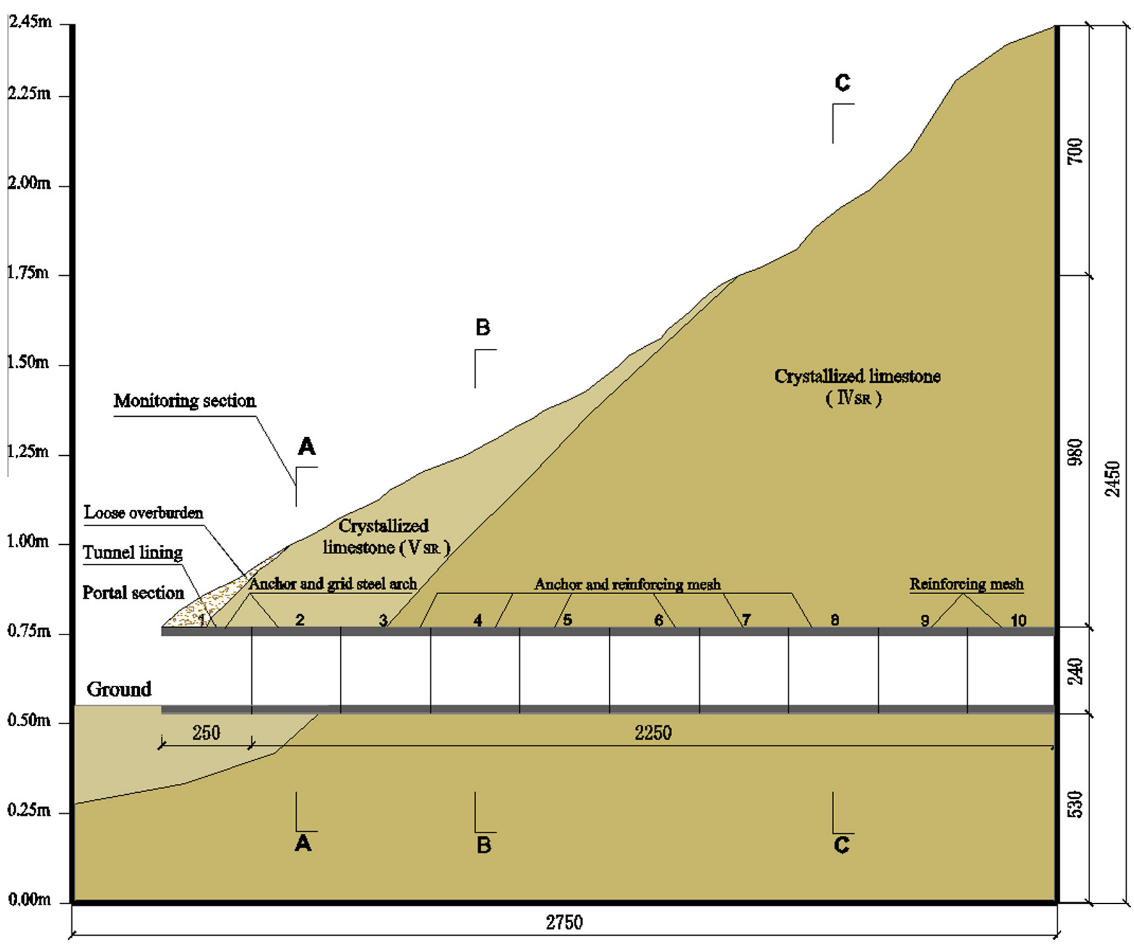

Fig. 1. Longitudinal cross-section of the model (mm).