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# Interaction between strengthening and isolation layers for tunnels in rock subjected to SH waves

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ABSTRACT

The strengthening and isolation are two types of strategies to reduce seismic damages to tunnels in rock. However, few closed-form analytical solutions for their seismic responses when tunnels are subjected to SH waves have been proposed. Therefore, based on the Xianglu Mountain Tunnel in Western China, which is located in a very active seismic territory, a close-form analytical solution was presented for the scattering problem of SH waves by the strengthening layer-isolation layer-lining system using the wave-function expansion method. A parametric study was then conducted to study the effects of the isolation and strengthening layers on the dynamic responses of tunnels in rock. The results show that the isolation layer can remarkably reduce the stress in the lining, but at the same time may lead to an increase in rigid displacement; the strengthening layer can stabilize the rigid displacement and further reduce the stress in the lining, but this effect is limited by the construction technologies used in actual projects. For tunnels in high-intensity regions, the isolation layer may collaborate with the strengthening layer. Owing to the existence of the strengthening layer, a relatively large modulus and a relatively small thickness can be chosen for the isolation layer. As a result, the collaboration between the isolation and strengthening layers can not only effectively reduce the stress in the lining but also stabilize the rigid displacement.

## 1. Introduction

Tunnels are critical elements in transportation and utility networks (e.g. road tunnels, hydraulic tunnels and hydroelectric caverns, lifelines for transportation of water, oil, natural gas, etc.). Although tunnels are less vulnerable to earthquakes compared to above-ground structures, many tunnels have been severely damaged in recent major earthquakes such as the 1995 Kobe earthquake (Huo et al., 2005), the 1999 Turkey earthquake (Kontoe et al., 2008), the 1999 Chi-Chi earthquake (Wang et al., 2001) and the 2008 Wenchuan earthquake (Li, 2012). Moreover, even a low level of damage to tunnels may affect the serviceability of a wide network. Therefore, it is crucial to better understand the effects of anti-seismic measures on the dynamic responses of tunnels and then develop effective measures to mitigate seismic damages to tunnels.

The seismic response of a tunnel is dominated by the deformation of the surrounding ground and not the inertial properties of the tunnel structure itself. The seismic design of tunnels, therefore, focuses on the deformation of the ground and its interaction with the lining. Accordingly, the anti-seismic measures of tunnels can be divided into two categories: the strengthening (Liu and Song, 2005; Hashash et al., 2001; Power et al., 2004) and isolation. Strengthening strategies involve strengthening the lining (increasing the thickness and adding reinforcement or an internal steel liner) and the adjacent geologic materials (ground improvement, drainage, soil reinforcement, installing bolts, and grouting). Strengthening the lining does not always provide an acceptable solution, because it tends to result in an increased force. In contrast, strengthening the adjacent ground can improve the stiffness and may be effective in preventing large deformations. Thus, the strengthening mentioned in this paper only refers to the strengthening of the adjacent ground. While the seismic isolation for tunnels has been initiated by a few Japanese engineers (Shimamura et al., 1999; Suzuki et al., 2002; Kim and Konagai, 2000; Konagai and Kim, 2001; Kim and Konagai, 2001), and it is primarily implemented by installing a thin isolation layer between the rock and lining. The isolation material is much softer than the rock or the lining so that the isolation layer can weaken the ground-lining interaction and then reduce the imposed deformation on the lining.

In the past few decades, a number of studies have been conducted to examine the earthquake responses of tunnels and the effects of anti-seismic measures. Different kinds of methods have been employed to

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tackle this problem, such as dynamic tests (Cilingir and Madabhushi, 2011; Chen and Shen, 2014), numerical methods (Genis, 2010; Corigliano et al., 2011; Gazetas et al., 2005; Hasheminejad and Miri, 2008; Zhao et al., 2013), and analytical methods. Generally, numerical methods offer a more general approach to the solutions of most practical problems that involve nonlinear boundaries and material nonlinearities. In contrast, analytical schemes are limited to treating linearly elastic or visco-elastic media with simple geometries. However, analytical methods provide closed-form solutions with better accuracy and relatively less complex numerical implementation. In addition, analytical solutions still offer the best benchmarks to test and verify other approximate solutions. As for the seismic responses of tunnels, the wave function expansion method, as an analytical approach, is widely used. This method can reveal physically the nature of the wave scattering by local geometrical irregularities. Pao and Mow (1973) were the first to propose an analytical solution to the diffraction of elastic waves by a cylindrical cavity in the whole space. Using the imaging technique, Lee (1979) developed an analytical solution for an underground, circular, unlined tunnel subjected to incident anti-plane SH waves. Lee and Karl (1992, 1993) and Davis et al. (2001) used a large, circular, almost-flat surface to approximate the half-space surface, and they extended this method to the problem of diffraction of P and SV waves by cylindrical, unlined cavities. Liang et al. (2003) and Smerzini et al. (2010) used the same method to study the effects of underground cavities on surface ground motions. Liang et al. (2004) proposed an analytical solution for the scattering of incident SH waves by a circular-arc hill with a concentric circular tunnel. Later, Liang et al. (2010) further investigated diffraction of plane SH waves by a semi-circular cavity in half-space. Liu et al. (2016) extended this method to the scattering of plane SH waves by a rectangular cavity embedded at a shallow depth in an elastic half-space. Gao et al. (2016) used the same method for the diffraction of both plane and cylindrical SH waves induced by a horseshoe shaped cavity. Kara (2016) presented an analytical solution for the dynamic response of a cylindrical tunnel embedded in homogenous, isotropic, linear elastic quarter-space excited by plane harmonic SH waves.

However, most of these studies mainly focused on dynamic responses of tunnels without strengthening or isolation layers, and few studies have been conducted on the interaction between two types of countermeasures using analytical methods. Hence, in this paper, we extend the wave function expansion method to a more complex case of a tunnel with both strengthening and isolation layers, and propose a closed-form analytical solution for the dynamic responses of tunnels embedded in homogenous, isotropic and linear elastic half-space excited by incident anti-plane SH waves. In addition, based on the Xianglu Mountain Tunnel located in Western China, the influences of the strengthening and isolation layers on the dynamic response of the tunnel are investigated. The method described in this work can serve as a general method for studies of seismic responses of tunnels with composite linings. For practical purposes, this investigation may be helpful for the seismic design of tunnels in high seismic intensity areas and the verification of approximate numerical techniques.

## 2. Description of the Xianglu Mountain tunnel

The Xianglu Mountain Tunnel has been chosen as a case study because of the availability of its design data and the relevant seismicity of the region in which it is located.

### 2.1. Description of the tunnel

The goal of the Dianzhong Water-Transportation project, which is currently under construction, is to solve the problem of water shortage in central Yunnan province, China. The water is taken from the Jinsha River, and supplied to the Dali, Chuxiong, Kunming, Yuxi, and Honghe areas. The total length of the main canal is about 661.06 km, and the average water volume is about 3.4 billion cubic meters per year. The Xianglu Mountain Tunnel is an important part of the main canal. It is a long tunnel with a length of 63.4 km and a maximum rock cover of 1412 m.

### 2.2. Seismicity of the region

The project is located at the junction of several plates, and the tectonic movement is very active. The tunnel crosses three seismically active faults: the Longpan–Qiaohou Fault, the Lijiang–Jianchuan Fault, and the Heqing–Eryuan Fault. Several strong earthquakes ($Ms \geq 7.0$) have occurred in this region, with the most recent one being the Lijiang earthquake ($Ms = 7.0$), which occurred in 1996. This region is expected to experience a strong and destructive seismic event in the near future. According to the site-specific seismic hazard analysis report, the peak ground accelerations are 0.3 g (the probability of exceeding this is 10% in 50 years) and 0.6 g (the probability of exceeding this is 2% in 100 years).

### 2.3. Geological and geotechnical properties

According to the earthquake observation data, the seismic damages to tunnels mainly occur at the portals and the cross-fault areas. Therefore, the portal was chosen for this study. Owing to the active tectonic movement in the region, the geological environment is very complicated. At the portal, the surrounding rock within 50 m of the ground surface consists mainly of strongly weathered mudstone and shale, and the rock mass structure is loose and unstable. The grade of the rock mass is judged to be grade V according to the China standard (2008), and its elastic parameters are listed in Table 1.

### 2.4. Anti-seismic measures and the tunnel lining

At the tunnel portal, two anti-seismic measures are proposed. One is strengthening the surrounding rock by use of grouting, pipe roofs, anchors and shotcrete (thickness of 0.25 m, Grade C25: the uniaxial compression strength is not less than 25 MPa). The other is isolating the tunnel lining by adding an isolation layer between the surrounding rock and the final lining. The final lining, with an inside diameter of 4.2 m, is made up of reinforced concrete with a thickness of 0.6 m (Grade C30: the uniaxial compression strength is not less than 30 MPa), and its elastic parameters are shown in Table 1. A typical tunnel cross section at the portal is shown in Fig. 1.

Owing to the high-level of seismicity and complicated geological environment in this area, the seismic design of the tunnel is crucial to the overall project. Therefore, this paper first represents an analytical solution for the scattering problem of SH waves by the strengthening layer-isolation layer-lining system, and then investigates the interaction between the strengthening and isolation layers for the tunnel subjected to SH waves.

**Table 1**
Parameters of the rock and tunnel lining.

| Material | Thickness (m) | Shear wave velocity (m/s) | Shear modulus (GPa) |
|---|---|---|---|
| Rock | – | 542 | 0.5 |
| Reinforced concrete | 0.6 | 2236 | 12.5 |