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Response of a tunnel in double-layer rocks subjected to harmonic P- and S-waves

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ABSTRACT

The combination of tunnel depth and incident wavelength has been numerically revealed as a key factor dominating seismic responses of a tunnel in a homogenous rock layer. To investigate further the seismic response of a tunnel in double-layer rocks and to clarify the effect caused by the layered rocks, this study applies the dynamic finite element method and investigates seismically induced stress increments in the lining of a circular tunnel subjected to an incident harmonic P- and S-wave. Analysis results reveal that the normalized seismically induced stress increments are maximal when normalized tunnel depth is 0.25 multiplying an odd number. Additionally, normalized seismically induced stress increments are minimal when normalized tunnel depth is 0.25 multiplying an even number. Further, the impedance ratio links the seismic responses of upper and lower rock layers subjected to incident harmonic waves, which may significantly amplify incident stress in the upper rock layer, thereby affecting the seismically induced stress increments in a tunnel lining.

1. Introduction

Rock tunnels are regarded as both strong and durable. However, many rock tunnels have been damaged by earthquakes in recent years [1–4]. Tunnels are often the fastest routes between two traffic points, or in some cases, the only routes. Once a tunnel has been severely damaged by an earthquake, repair typically takes a long time, adversely affecting traffic flow or water flow. Thus, rock tunnels damaged by earthquakes have attracted considerable attention [5–14].

Dowding and Rozen [15] indicated that one main reason for damage to rock tunnels by earthquakes is their shallow depth. Sharma and Judd [16] concluded that shallow tunnels are damaged more severely by an earthquake than deep tunnels. Wang et al. [1] investigated the damage to 57 rock tunnels after the Chi-Chi Earthquake, which hit Taiwan in 1999, and summarized damage patterns in tunnel lining. Asakura et al. [2] and Yashiro et al. [3] reviewed historical reports for mountain tunnels damaged by earthquakes. Ji et al. [4] and Wang et al. [17] investigated the damage to rock tunnels after the China's Wenchuan Earthquake in 2008. These reports underscore the importance for assessing seismic damage to rock tunnels. Furthermore, statistical analysis of seismic damage to rock tunnels in last two decades indicates that both the damage ratio and severity increase as the distance of a rock tunnel to the earthquake epicenter decrease; however, no direct relationship exists between the amount of damage and tunnel depth.

Chen et al. [18] applied numerical simulation to investigate the causes of damage to the one-year-old Sanyi No. 1 Tunnel by the 1999 Chi-Chi Earthquake. Analytic results indicated that the combination of shallow tunnel depth and rock mass characteristics amplified the tunnel's response to seismic waves reflected by the free ground surface and the scattering effect of the tunnel, leading to considerable seismic damage. Chen et al. [19] and Chen et al. [13] then investigated the seismic response of a tunnel in monolayer rock subjected to harmonic P-, S-, and R-waves by numerical simulation. They found that the seismically induced stress is strongly correlated with tunnel depth and the wavelength of the incident wave. When tunnel depth is 25% of the wavelength, amplification of seismically induced stress is pronounced. The seismically induced stresses in the lining of a tunnel in a monolayer rock are influenced by the amplification of incident waves, free-surface reflection, and the tunnel scattering effect. However, are earthquake effects on a tunnel in multi-layer rocks similar to those of a tunnel in monolayer rock? What is the seismic response of a tunnel in different locations in multilayer rock? What

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characteristics of a rock mass dominate the seismic response of a tunnel? These questions remain unanswered.

This study uses a tunnel in double-layer rock as an example tunnel and applies dynamic analysis in the time domain using the finite element method. Numerical models are first validated by comparing simulation results with the corresponding analytical solutions. The seismically induced stress in the lining of a tunnel that is subjected to harmonic, vertically propagating incident P- and S-waves are determined and discussed. The influence of tunnel location, relative stiffness of double-layer rocks, and incident wave frequency are also investigated.

2. Numerical model and verification

This study applies ABAQUS, a two-dimensional finite element code, to simulate seismically induced stress increments in a tunnel lining under the plane-strain condition to investigate the seismic response of a tunnel. Fig. 1 presents the numerical model. The numerical model considers a circular tunnel with a diameter of 8 m subjected to an incident wave caused by harmonic sinusoidal displacement along the bottom boundary. The upper boundary of the model is a free surface, while the left and the right boundaries are set as absorbent boundaries, which can move to minimize wave reflection. The rock mass and lining are considered homogenous elastic materials. No slipping is allowed between the rock mass and lining. The lining is 0.3 m thick; has a density of 23.54 kN/m^3; an elastic modulus of 23.5 GPa; and a Poisson ratio of 0.2.

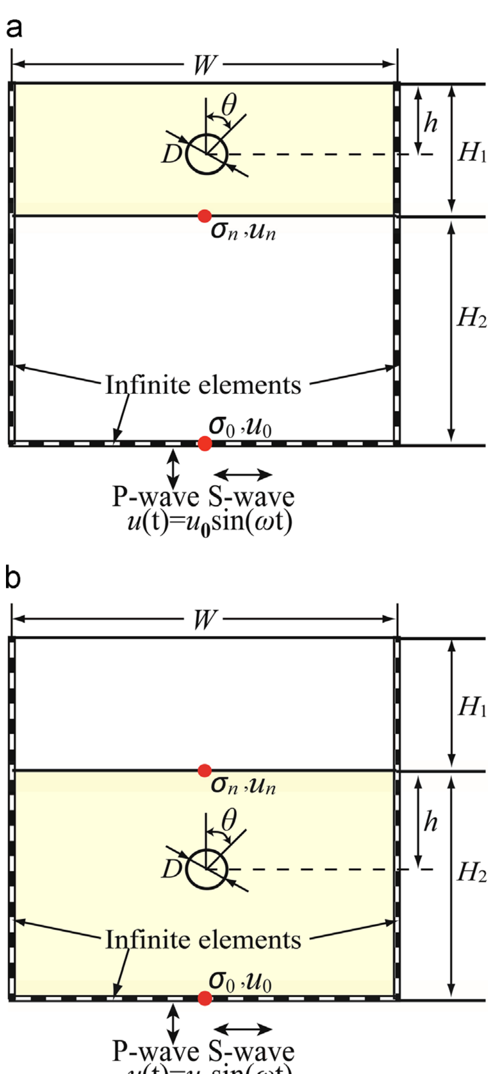

Fig. 1. Configurations of numerical models. (a) The tunnel is located in the upper rock layer, and (b) the tunnel is located in the lower rock layer.

Verification of the numerical simulation for a tunnel subjected to seismic impact is divided into two stages. First, dynamic analysis of a free field, i.e., without a tunnel, is conducted. The simulated displacement of the center point on the ground surface, which is the point directly above the tunnel considered subsequently, is compared with the analytical solution for the semi-infinite domain. The main purpose of verification is to ensure that the range of the numerical mesh is sufficient, and error at the center point on the surface caused by wave reflection from lateral boundaries is acceptable. Second, dynamic analysis of a tunnel is conducted. To avoid the influence of wave reflection, dynamic analysis continues until the propagating wave from the bottom boundary has been reflected from the free ground surface, but not reached the tunnel. Consequently, the influence of the incident and refracted waves is only considered. The analytical solution indicates that the simulated displacement near the tunnel should converge to a steady state. The element size in numerical simulation is then confirmed as appropriate. Verification results for numerical simulations for the absence or presence of a tunnel are as follows.

2.1. Absence of a tunnel

A harmonic P- or S-waves is generated and propagates vertically upward from the bottom boundary by a sinusoidal displacement of $0.01\sin(2\pi tf)$, where $f = 3$ Hz, which is the frequency of the sinusoidal displacement; and t is time (displacement is in meters). The boundary ranges of the numerical model and element size are adjusted, and the displacement of the center point on the free

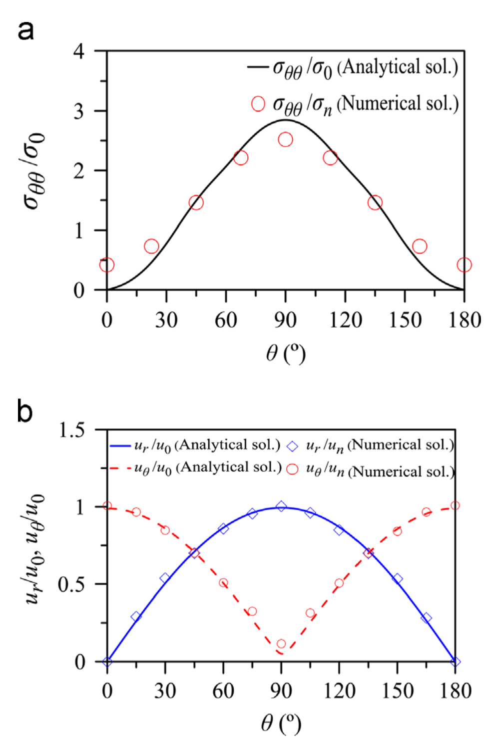

Fig. 2. Verification of the numerical model. (a) Normalized seismically induced stress increments in the tangential direction ($\sigma_{\theta\theta}/\sigma_n$) obtained by numerical simulation and Pao's analytical solution [20], and (b) seismically induced displacements along a tunnel wall obtained by numerical simulation and Mow's analytical solution [21].