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Mechanisms causing seismic damage of tunnels at different depths

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ABSTRACT

This study investigates the influence of the depth of a tunnel on its seismic damage. Dynamical finite element analysis based on a numerical model of rock mass and tunnel lining is carried out and the incident waves are modeled as harmonic *S*- and *P*-waves. The analysis reveals that seismically induced stress is strongly correlated with the depth and the wavelength of the incident wave: when the depth is one quarter of the wavelength, the amplification of the seismically induced stress is particularly pronounced. The amplification is caused by the reflection of waves from the free surface and the scattering effect of the tunnel. A case history of a seismically damaged tunnel is considered to confirm this amplification phenomenon. Damage potential to a tunnel is greatest when the tunnel is at a depth that is close to 0.25 times to the wavelength, so shallow tunnels in weak rock and deep tunnels in competent rocks are particularly vulnerable.

1. Introduction

The relevant literature indicates that earthquakes can damage tunnels. Many instances of noticeable seismic tunnel damage were reported in Japan between 1923 and 2007, including 82 instances associated with the 1923 Kanto earthquake (Okamoto, 1973), 20 with the 1995 Kobe earthquake (Asakura and Sato, 1998), more than 50 with the 2005 Niigataken-Chuetu earthquake (Asakura et al., 2007) and six with the 2007 Niigataken Chuetu-Oki earthquake. In Taiwan, the old Sanyi railway tunnels were damaged in the 1935 Hsinchu-Taichung earthquake, and 49 tunnels were damaged in the 1999 Chi-Chi earthquake (Wang et al., 2001; Hwang and Lu, 2007). Seismic damage to tunnels has been reported in other countries, including the USA and Turkey (Brandl and Neugebauer, 2002; Hashash et al., 2001). Global databases of seismic damage to tunnels are available. For example, Dowding and Rozen (1978) collected 71 cases of seismic damage to tunnels, while Sharma and Judd (1991) collected 192 cases of damage to underground structures in 85 countries. These records reveal the need to investigate seismic damage to tunnels in rock.

The potential damage to a tunnel by an earthquake depends critically on its depth. Dowding and Rozen (1978) identified shallowness as one cause of seismic damage. Sharma and Judd (1991) pointed out that more tunnels at lower depths are damaged than are tunnels at large depths. The literature includes few numerical comparisons of tunnels at different depths. Fotiva et al. (2005) concluded that the maximum stress in the lining of a tunnel decreases as tunnel depth increases, based on three case histories of tunnels at different depths. The case histories collected in this present investigation (Section 4) reveal that in weak rock, shallow tunnels area damaged relatively more frequently. In contrast, in competent rock, deep tunnels are damaged more frequently. This finding has rarely been discussed or analyzed in the literature.

Although the mechanism by which depth influences damage has not been systematically examined, some related analyses have been performed. First, accelerations are high at lower depths (Okamoto, 1973; Hashash et al., 2001), and the amplitude of seismically induced stress decays with depth after it reaches a maximum close to the ground surface (Krammer, 1996; Madabhushi and Zeng, 2006; Chen and Han, 2009). Additionally, the geometry of a free surface may modify seismic waves. These factors may be important for tunnels at shallow depths, although the degree of their effect has not been explicitly studied. A systematic study of the effect of depth on possible damage to tunnels is highly desirable.

This study investigates the behaviors of tunnels at various depths when they are subjected to seismic excitation, to determine the effect of depth on seismically induced stress, including normalized axial stress, shear stress and flexural stress in the lining. The analysis aims to address the particular finding that tunnels at shallow depths in weak rock and those at large depths in competent rock are damaged relatively more frequently than others. In particular, both the tunnel depth and the wavelength of incident waves are correlated with seismically induced stress increments. Dynamical finite element analysis is used to model numerically the rock mass and tunnel linings, with the incident waves modeled as harmonic *S*- and *P*-waves. The effects of important factors, such

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as the damping ratio of the rock mass, the shape of the cross-section of the tunnel and the rigidity of the lining, are examined. Finally, the results of the analysis are compared to the damage to the San-I No. 1 tunnel in Taiwan during the 1999 Chi-Chi earthquake.

2. Numerical model and verification

2.1. Setup of numerical model

Fig. 1 presents the configuration of the numerical model. The depth of a tunnel, H, is the vertical distance from the free surface to the center of the tunnel; H' denotes the vertical distance from the bottom boundary to the center. An incident wave causes harmonic sinusoidal displacements along the bottom boundary. The upper boundary of the model is a free surface, while the left and right boundaries are set to "absorbent" boundaries, which are allowed to move to minimize the reflection of waves. Even when these boundaries are absorbent in this way, a minor reflection may propagate back and interfere with the central part of the model. Therefore, properly setting the width of the model is essential to prevent interference from the two lateral boundaries. The ratio of the size of the elements to the wavelength of the incident wave λ is set to less than 1/10 to ensure the accuracy of the simulated displacements and stresses. A series of preliminary tests reveal that, given the range of λ used, the width of the model should be more than 20 times the diameter of the tunnel. To study the effect of H, the H/λ ratio is varied from zero to one to cover all typical tunnel depths. Likewise, H' should be sufficiently large to prevent interference from the bottom boundary. The ratio H'/λ is found to have to exceed one to yield consistent results. The analysis is terminated whenever the wave that is reflected from the free surface reaches the bottom boundary, to prevent disturbance of the stress state of the tunnel by further reflection from the bottom boundary.

A seismic wave that is emitted from a deep focus is composed of mainly P- and S-waves; when it reaches the ground, a surface wave can be induced. Since this study is concerned with the effects of P-wave and S-wave on the structure of a tunnel, these waves are generated from the bottom boundary by vertical and horizontal boundary displacements, respectively. The effect of the surface wave is not considered here and the surface wave is suppressed using a free horizontal top surface.

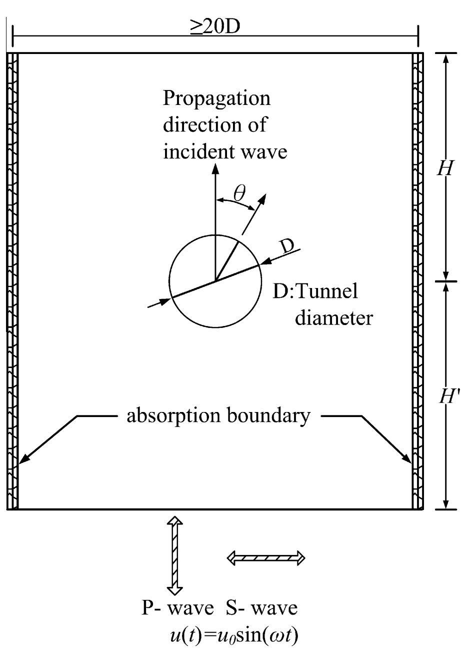

Fig. 1. Numerical model.

The rock mass and tunnel linings are assumed to be linearly elastic. In the elastic domain, the response is proportional to the amplitude of the incident wave, provided that the amplitude is not too large. Therefore, the response of the system will be normalized to the input amplitude in subsequent analyses, and the amplitude of the incident wave is fixed at 0.01 m. The predominant frequencies in rock strata are 1–5 Hz (IEA-AS and CEER-NTU, 1992; Krammer, 1996). Accordingly, the frequencies of the incident wave are set to 3 and 5 Hz herein.

This study considers the responses (stress and moment) of the lining to seismic action only: stress that is induced by the gravity of the surrounding rock mass is neglected. The tunnel is circular with a diameter of 8 m. No slipping is allowed between the lining and the rock mass. The lining is 0.3 m-thick and has a density (ρ_l) of 2400 kgf/m^3, a compressive strength (f'_c) of 24.5 MPa, an elastic modulus of the lining (E_l) of 23.48 GPa, and a Poisson ratio (υ_l) of 0.2. The rock mass has a density (ρ_m) of 2700 kgf/m^3, an elastic modulus (E_m) of 969.9 MPa, and a Poisson ratio (υ_m) of 0.3.

The velocities of the S-wave and the P-wave in the rock mass are selected to be 371.7 m/s and 695.4 m/s, respectively, representing wave velocities within weak rock strata, in which many instances of damage by earthquakes have been identified (Asakura and Sato, 1998; Asakura et al., 2007; Wang et al., 2001). For the chosen input frequencies of 3 and 5 Hz, the ratios of the wavelength to the tunnel diameter are 15.49 and 9.29 for the S-wave and 28.97 and 17.38 for the P-wave. Following Peck et al. (1972) and Hashash et al. (2001), the flexibility ratio F is

$$F = \frac{E_m(1-\upsilon_l^2)R^3}{6E_lI(1+\upsilon_m)} \tag{1}$$

where E_m and E_l are the elastic moduli of the ground and lining, respectively; I is the moment of inertia of the lining; R is the radius of the tunnel, and t is the thickness of the lining.

The flexibility ratio F is thus determined to be 144.6. Since the stiffness of the ground relative to that of tunnel lining exceeds one, the lining is flexible, according to Hashash et al. (2001). The effects of variations of axial stress, shear stress, and flexural stress in the lining are investigated here for design purposes.

2.2. Adjustment and validation of model

The effectiveness of the adopted model is firstly confirmed by comparing the results of an analysis of seismically induced stress in the absence of a tunnel to that of analytical solutions. Krammer (1996) indicated that the amplitudes of displacement at the free surface are double the amplitude of the incident wave. The boundaries of the model and the sizes of the associated elements can thus be adjusted in order that the analysis results match the analytical solution. The analytical solutions for the relationship between the absolute normalized stress $|\sigma/\sigma_0|$ and the normalized depth H/λ are derived in Appendix A, where σ_0 represents the maximum stress amplitude of the incident wave, while σ is the maximum seismically induced stress in the rock mass, which is normal stress for a P-wave and shear stress for an S-wave. The analytical solutions are used to verify the relationship between $|\sigma/\sigma_0|$ and H/λ that is obtained by the numerical analysis using the model in both P- and S-wave scenarios. Fig. 2 plots the variation of $|\sigma/\sigma_0|$ as versus H/λ obtained from analytical solutions and the numerical simulation for a semi-infinite domain without a tunnel that is subjected to a 3 Hz harmonic S-wave. The results of the numerical simulation are closely consistent with the analytical solution.

Following the aforementioned verification, the application of the model to an unsupported tunnel that is subjected to harmonic