Soil Dynamics and Earthquake Engineering 85 (2016) 31–43

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Seismic analysis of underground tunnels by the 2.5D finite/infinite element approach

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ARTICLE INFO

Article history:
Received 17 December 2015
Received in revised form
9 February 2016
Accepted 3 March 2016

Keywords:
Earthquake
Free field
Infinite element
2.5D approach
Tunnel
Wave transmission

ABSTRACT

A procedure for the seismic analysis of underground tunnels using *recorded free-field earthquakes* based on the 2.5D finite/infinite element approach is presented. The near and far fields of the half space are modeled by finite and infinite elements, respectively. Using the 1D wave theory, the nodal force and displacement on the near-field boundary are computed for each spectral frequency of the earthquake. Then, equivalent seismic forces are computed for the near-field boundary for the earthquake spectrum. By assuming the soil-tunnel system to be uniform along the tunnel axis, the 2.5D approach can account for the wave transmission along the tunnel axis, which reduces to the 2D case for infinite transmission velocity. The horizontal and vertical components of the 1999 Chi-Chi Earthquake (TCU068) are adopted as the free-field motions in the numerical analysis. The maximal stresses and distribution patterns of the tunnel section under the P- and SV-waves are thoroughly studied by the 2.5D and 2D approaches, which should prove useful to the design of underground tunnels.

1. Introduction

Underground tunnels are a kind of structures characterized by the fact that they are embedded in a half space with infinite domain, and that they are relatively long compared with their cross-sectional dimensions. To analyze the dynamic response of an underground tunnel to moving trains or earthquakes, it is necessary to consider the three-dimensional (3D) behaviors of wave propagation in the half-space medium, including wave transmission along the tunnel axis. Besides, the mechanism of excitation by an earthquake is different from that by a moving train. A moving train can be simulated as a *line load* moving along the invert of the tunnel, from which the waves radiate to all directions. However, the excitation by an earthquake on the tunnel structure is different, as the waves originating from the epicenter may transmit via various paths and reach asynchronously the boundary of the *near field* enclosing the tunnel due to the reflection and scattering effects.

Previously, many researchers have investigated the seismic responses of underground tunnels or cavities using different approaches, as will be briefly reviewed here. Hwang and Lysmer [1] analyzed the response of buried structures to traveling waves. Wong et al. [2] studied the scattering of elastic waves of an elliptical inclusion and cavity embedded in a half-space by the hybrid finite element and eigenfunction expansion method. Wolf [3] studied the problem of soil vibrations caused by incident seismic waves with inclined angles. Lee and Karl [4] studied the scattering and diffraction of plane SV waves by underground cavities at various depths in an elastic half-space by adopting the Fourier-Bessel series to satisfy the wave equation and boundary conditions. Luco and De Barros [5] solved the dynamic response of a cylindrical cavity embedded in a half-space subjected to various harmonic plane waves using an indirect boundary integral method based on the 2D Green's function for a viscoelastic half-space. Stamos and Beskos [6] used a special direct boundary element method (BEM) in the frequency domain to study the 3D seismic response of long lined tunnels in an elastic or viscoelastic half-space, which was reduced to a 2D problem by a coordinate transformation and integration of the full-space dynamic solution along the tunnel axis. Davis et al. [7] derived analytical solutions for the transverse response of unlined cavities embedded within

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http://dx.doi.org/10.1016/j.soildyn.2016.03.005
0267-7261/

an elastic half-space by using the Fourier–Bessel series and a convex approximation for the free surface of the half-space.

Kim and Yun [8] presented the earthquake response analysis in time domain for 2D soil-structure systems using analytical frequency-dependent infinite elements. Park et al. [9] presented a procedure for simulating the tunnel response for the case where the ground properties vary along the longitudinal direction. Their results indicated that spatially variable ground motions cause longitudinal bending of the tunnel, while inducing substantial axial stress on the tunnel lining. Hatzigeorgiou and Beskos [10] used the finite element method to investigate the importance of seismic soil–structure interaction in three-dimensional lined tunnels, assuming inelastic material behavior for both the concrete liner and the soil of soft rock type. Yu et al. [11] presented a multiscale method for the dynamic analysis of underground structures using the coarse-scale and fine-scale finite elements. By this method, the seismic response of the overall system was identified firstly by the coarse mesh, then the coarse mesh of the region of interest was replaced with a refined mesh.

Yang et al. [12] used the finite/infinite element approach to analyze the dynamic response of an elastic half-space with cavity subjected to P and SV waves, which was previously analyzed by Wong et al. [2], Luco and De Barros [5], and Davis et al. [7], but with different results. The results obtained by Yang et al. appear to agree closely with those by Luco and De Barros. Gomes et al. [13] investigated the effect of soil stratification on the seismic response of circular tunnels using a finite element plane-strain model. Alielahi et al. [14] evaluated the seismic amplification pattern of a linear elastic medium including a buried unlined tunnel subjected to incident SV and P waves using the time-domain BEM formulation. Their results indicated that the amplification of the ground underlain by a tunnel is increased in long periods.

As revealed by the above review, mainly 2D and 3D methods have been adopted by researchers in the seismic analysis of a half-space with embedded long tunnels. For an elastic half-space subjected to traveling loads or waves, a plane strain model that is two-dimensional (2D) may be used to generate simple and qualitative results for use in preliminary design, but it is incomplete because of the overlook of wave transmission along the tunnel axis. On the other hand, a full 3D model considering the length scale of the tunnel can account for the wave traveling effect, but the cost of computation is prohibitive for it to be used in routine design. To simulate the effect of wave transmission, the assumption of *uniform soil profiles* along the tunnel axis offers a simple and valuable aid. Such an idea was exactly the one behind the 2.5D approach [15] for treating the train-induced soil vibrations using the finite/infinite elements.

Both the 2D and 3D approaches are self-explanatory, which will not be elaborated herein. For readers who are interested in the 2D approach using the finite/infinite element approach, they should refer to the paper by Yang et al. [16]. Only some key aspects of the 2.5D approach will be summarized in the following.

By assuming the soil-tunnel system to be uniform along the tunnel axis, only a profile of the system needs to be considered in analysis. Such an approach is 2D in nature, but it allows us to simulate the 3D waves traveling effect, for which it was named the 2.5D approach [15]. Take the 8-node (Q8) plane element as an example. For the 2D analysis, each node of the element consists of two translational degrees of freedom (DOFs) of the profile. However, for the 2.5D analysis, a third DOF, i.e., the displacement normal to the profile, should be added to account for wave transmission along the tunnel axis. Previously, the assumption of uniform soil properties along the tunnel direction was also adopted by Hwang and Lysmer [1] in studying the seismic response of buried structures using the wave-transmitting elements. In their study, the region of the half space including the tunnel structure was modeled by finite elements, and the earthquake was simply assumed to act at the base of the soil model. Such an approach was extended by Hanazato et al. [17] to study the traffic-induced ground vibrations.

Specifically, Hwang and Lysmer's procedure [1] hinges on *condensation* of the 8-node solid elements to the 4-node plane elements on a 2D profile using the relation of displacement between two neighboring nodes along the tunnel direction. In contrast, the 2.5D approach by Yang and Hung [15] is based on the *Fourier transformation* of the traveling load function, which enables us to separate the wave transmission along the tunnel axis from the 2D profile. Owing to its conceptual elegance, the 2.5D approach or its variants have been widely used by researchers in studying the train-induced soil vibrations, for which a partial review can be found in Hung et al. [18] including the effect of rail irregularities. No effort will be made herein to review all the related previous works.

In this paper, the procedure of analysis will be briefed only for the 2.5D approach, since the 2D approach can be regarded as a special case. Three major steps are of concern herein: (1) The 2.5D finite/infinite element method [15] for modeling the soil medium is summarized. (2) For given displacements and tractions on the boundary of the near field, equivalent nodal loads on the boundary can be computed [19,20]. (3) For unit ground motions, the 1D theory of wave transmission is adopted to compute the displacement and traction at each point of the near-field boundary [21]. The last step provides a means for including all the spectral components of an earthquake via the spectrum. Based on the above procedure, analyses will be conducted for various parameters. It is believed that the maximal principal stresses and associated patterns computed of the tunnel section under the P- and SV-waves for the 2.5D and 2D cases are useful to tunnel designers.

2. Summary of 2.5D finite/infinite element method

Consider a force $f(x,y,z,t)$ of the form $\psi(x,y)\phi(z)$ and amplitude $Q(t)$ moving with velocity c at time t via point (x,y,z) of the z-axis of the soil-tunnel system in Fig. 1,

$$f(x,y,z,t) = \psi(x,y)\phi(z-ct)Q(t) \tag{1}$$

where $\psi(x,y)$ is the distribution function on the x–y plane and $\phi(z)$ is the distribution of the force along the z-axis. Applying twice the Fourier transformation to Eq. (1) yields the force $\tilde{\tilde{f}}$ in frequency (ω) and wave number (k_z) domain as

$$\tilde{\tilde{f}}(x,y,k_z,\omega) = \psi(x,y)\tilde{\phi}(k_z)\tilde{Q}(k_z c+\omega) \tag{2}$$

where $\tilde{Q}(\omega)$ is the Fourier transform of $Q(t)$ and $\tilde{\phi}(k_z)$ is the

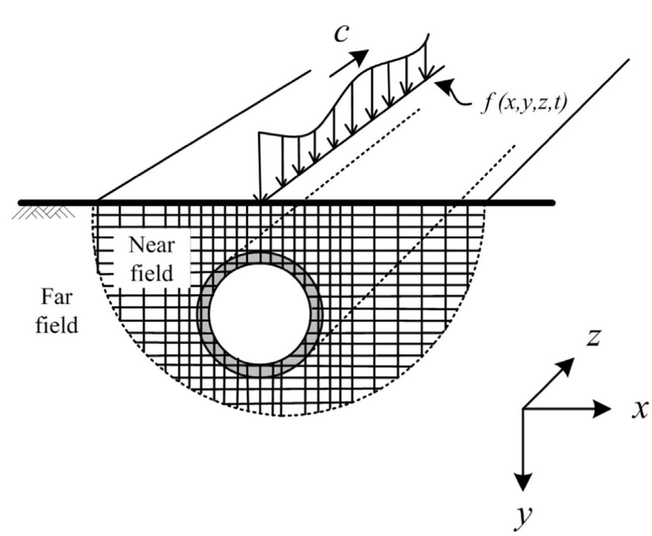

Fig. 1. Soil-tunnel system in Cartesian coordinates.