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Three-dimensional numerical analysis for the longitudinal seismic response of tunnels under an asynchronous wave input

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ABSTRACT

The numerical analysis of the longitudinal seismic response of tunnels to the spatial variation of earthquake ground motion is an important issue that cannot be ignored in the design and safety evaluation of tunnel structures. In this paper, numerical modelling techniques for the analysis of the longitudinal response of tunnels under an asynchronous seismic wave are extensively studied. The free field wave motion is calculated using the 1D time-domain finite element method and is then extended to 3D. Based on the theory of wave input, three-dimensional numerical simulation techniques for a site response to an asynchronous earthquake are developed. Then, a 3-D soil–tunnel structure interaction model is established to simulate the longitudinal response of the tunnel when subjected to an asynchronous earthquake. These numerical modelling techniques are discussed in detail, and the analysis results prove their validity. The proposed method is applied to analyse the longitudinal seismic response of a tunnel under the oblique seismic incidence of P, SV and SH waves from a semi-infinite foundation. The influence of the incident angle and incident direction on the longitudinal seismic response is discussed. The study outcome will be beneficial to further research on refined nonlinear numerical analysis and seismic response mechanisms of tunnel structures that experience asynchronous earthquake motion.

1. Introduction

Underground facilities are an integral part of the infrastructure of modern society and are used for a wide range of applications. During recent strong earthquakes, especially during the 1989 Loma Prieta, 1994 Northridge and 1995 Kobe earthquakes, a number of underground structures experienced significant damage [1], and since then, there has been a general understanding that the seismic design and analysis of underground structures are of great importance.

A tunnel structure is usually very long, passes through different soils, and may be built using multiplex construction methods, all of which make the dynamic analysis of tunnels a sophisticated problem. Numerical methods such as the Finite Difference Method, Finite Element Method and Boundary Element Method have been widely used for soil-structure interaction problems due to their versatility and reliability. With the aid of these methods, the dynamic response can be solved reasonably well under realistic conditions [2]. Currently, the numerical analysis and simplified design methods for the transverse dynamic behaviours of tunnel structures are relatively mature [3–6]. In contrast, less systematic and thorough work has been reported on the numerical analysis of the longitudinal seismic response of tunnels under an asynchronous earthquake input. It has been noted that appropriate considerations should be given to travelling waves [7], especially for extended or embedded structures with a large span or size such as tunnels, because spatial variation of earthquake motion has dramatic effects [8]. Consequently, it is of great importance to carry out numerical analyses on the longitudinal seismic response of tunnels, which will greatly facilitate the evaluation of the influence of the wave-passage effect on the safety of tunnel structures.

For the analysis of longitudinal axial and bending deformations of tunnel structures, several simplified design approaches have already been proposed [9], such as the free field deformation approach, the soil structure interaction approach and the mass-spring system model [10]. The free field deformation method is a simple and effective design tool. However, in many cases, especially in soft soils, this method provides an overly conservative design. Although the soil structure interaction approach treats the tunnel as a beam on an elastic foundation to account for the interaction effects, the spring coefficients of the foundation are not easy to determine. Both these methods depend on the selection of the apparent velocity of the earthquake wave.

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In the mass-spring system model, the surrounding soil is divided into several strips, and each strip is considered to be a lumped mass [10]. The lumped masses are connected to one another and connected to the bedrock. Meanwhile, the tunnel beam is connected to the lumped masses of the soil. All the connections mentioned above are composed of a spring and a viscous damper connected in parallel. The parameters of each strip are obtained from the basic shear formation of the soil layers. The vertical shear force cannot be transmitted between adjacent strips, which indicates the model's imperfection in modelling the cooperative work of the foundation. Moreover, the wave input from the bedrock is also difficult to simulate.

Because the above simplified approaches all have their shortcomings, it is desirable and most appropriate to utilise numerical soil–tunnel structure interaction models that take into account the wave-passage effect. Several studies have been performed on this aspect. Stamos and Beskos [11] proposed a frequency domain boundary element method to analyse the dynamic response of three-dimensional large underground structures to external or internal dynamic forces or to seismic waves. Then, assuming the underground structure to be infinitely long with a uniform cross-section, they employed a special direct BEM in the frequency domain for both the structure and the soil, which effectively reduces the three-dimensional problem to a two-dimensional one [12]. Yang and Hung [13] proposed a 2.5D method finite/infinite element procedure in the frequency domain for dealing with the ground vibrations induced by moving loads, which can be used in computing the steady-state responses of a tunnel embedded in a half-space subjected to moving loads. These methods are performed in the frequency domain; therefore, they cannot be used directly with time-step integration techniques in solving nonlinear problems. Park et al. [14] computed the spatially variable ground motion displacement time histories in terms of the coherency function and evaluated the longitudinal tunnel response by performing a series of pseudo-static three-dimensional finite element analyses. Yu et al. [2] proposed a time-domain multi-scale method for the dynamic analysis of underground structures, which couples FEM calculations with coarse and fine meshes. Ding et al. [15] have also performed a three-dimensional large-scale seismic finite element analysis for an immersed tube tunnel in Shanghai. In these analyses, however, specific issues such as the asynchronous earthquake wave input, tunnel boundary treatment, as well as the tunnel wave-passage characteristic are not addressed systematically.

In light of this, the present study aims to develop a 3-D time-domain simulation model that is based on a well-developed finite element framework to provide a feasible computational modelling technique for the longitudinal seismic response of tunnels under an asynchronous earthquake wave input. The ground is assumed to be a horizontally layered half-space. The procedure starts with the computation of the free field wave motion and the realization of wave input into the finite domain to be analysed. By compiling a FORTRAN program with the finite element software ANSYS, 3-D numerical simulations of an elastic layered half space site response under oblique seismic incidence of plane body waves (P, SV or SH wave) are achieved. The accuracy and validity of the predictions are proven by numerical examples. Based on this, a 3-D soil–tunnel structure interaction model is established to simulate the longitudinal response of tunnels when subjected to asynchronous earthquakes, which display the wave-passage effect on the tunnel. The treatment of the tunnel boundary in the numerical model is proposed, and its efficiency is demonstrated. Based on these numerical examples, the influences of the incident angle and incident direction on the tunnel's longitudinal seismic response are also discussed.

2. Computational modelling technique for the soil-structure interaction

2.1. Problem statement

This paper studies a numerical modelling technique for the analysis of the longitudinal response of tunnels under asynchronous seismic waves. Several assumptions are made for the analysis. First, the foundation is assumed to be a horizontally layered half-space that can reflect the stiffness inhomogeneous feature in the vertical direction. Second, the asynchronous seismic wave field is induced by oblique seismic incidence of body waves (P, SV or SH wave). In fact, for the near field seismic problems, the incident direction is never vertical when the seismic waves arrive at an engineering site because the earthquake wave does not experience enough refractions during its propagation. As a result, the wave-passage effect occurs, which is a key factor among the four distinct phenomena that give rise to the spatial variability of earthquake-induced ground motions [16]. Third, at a certain distance away from the source, the earthquake wave can be seen as a type of plane wave because the source distance is much larger than the scale of the source dimension [17].

Consider the idealised model drawn out for a practical engineering problem in which a tunnel of infinite length is buried in a horizontally layered half-space foundation and the whole system is set into motion by an oblique incident plane body wave propagating from the infinite foundation. The last assumption is that the material and geometric properties of the tunnel structure are uniform along the tunnel axis, which is similar to the assumption made in several previous analyses [12,13] performed in the frequency domain.

When the finite element method is used to solve the wave propagation problems, a finite computational area is truncated from the unbounded media, and the proper artificial boundary designed to eliminate wave reflections is imposed on the truncated boundary. To simulate the 3-D longitudinal response of tunnel structures under an asynchronous seismic wave, the asynchronous free field ground motion must be properly solved and the wave input must also be correctly modelled.

2.2. Calculation of the free field motion

There have been several approaches to calculate the free field motion excited by an oblique body wave incidence. The earliest approaches were the transfer matrix method and the stiffness matrix method [18–20], which are performed in the frequency domain. These methods can be directly used to calculate the steady-state wave field, while for transient wave propagation problems, Fourier transformation is needed. Several studies have also been performed on time-domain earthquake analysis in a stratified soil foundation, such as the finite-difference method proposed by Alterman and Karal [21], Boore [22] and Jean [23]. Note that Joyner and Chen [24] also presented a method for calculating the seismic response of a system of horizontal soil layers that considers the nonlinear stress–strain behaviour of soils. To avoid the precision inconsistency of the frequency-domain analysis with those obtained from the widely used time-domain method, a 1D finite element method in the time domain was recently proposed by Liu [25,26] to calculate the free field wave motions excited by an anti-plane SH wave or in-plane P-SV wave oblique incidence in an elastic layered half-space. Numerical results have demonstrated that the 1D time-domain method is highly accurate and has good stability. Zhao [27] proposed an accurate artificial boundary for the in-plane P-SV wave oblique incidence problem to improve the method.