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Effect of twin-parallel tunnels on seismic ground response due to vertically in-plane waves

Hamid Alielahi [a,*], Mohammad Adampira [b]

[a] Department of Civil Engineering, Zanjan Branch, Islamic Azad University, Zanjan, Iran
[b] Department of Civil Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran

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ABSTRACT

In this paper, the effects of two long unsupported parallel tunnels on the seismic response of the ground surface are studied, using the boundary element method in the time-domain. The medium is assumed to have a linear elastic constitutive behavior subjected to vertically in-plane propagating incident SV and P waves. The ground surface amplification pattern above underground single and twin tunnels are examined based on the several effective parameters such as wavelength of the incident wave, buried depth, and spacing distance of the twin tunnels. It is evident that the seismic ground response above tunnels may be different from that of free-field motions during the seismic events. Moreover, the embedded depth and spacing distance of the twin tunnels have significant influences on the amplification patterns on the ground surface. Finally, some amplification coefficients are presented, which could be used while introducing simple preliminary ideas for modification of the standard design spectra in building codes.

1. Introduction

Due to population growth and transportation problems, underground structures are one of the most substantial infrastructures in developing countries. Hence, in recent years many tunnels have been designed or constructed in urban areas in order to develop or extend underground transportation systems. In some populous cities, underground tunnels usually require separate tunnels aligned horizontally for reducing the traffic load. Based on the experience gained from past earthquakes, it is evident that underground long structures, such as subway, tunnels, and also surface structures above them have great potential for destruction and disruption during earthquakes.[1] Furthermore, providing a safe way of transportation and reliable service in emergency situations such as earthquake conditions is of utmost importance. Thus, the seismic behavior of subsurface tunnels has increasingly become an important topic of research. Nevertheless, the presence of an underground structure and its effects on the seismic ground response and surface structures are the uncertainties and unknowns in the geotechnical earthquake engineering.

Nowadays, it has been established that the seismic ground response above tunnels and cavities may be different from that of free-field motions during earthquakes.[2] Heretofore, a number of investigations have been reported by several researchers to determine the seismic response of the ground surface due to individual (single) tunnels and underground openings. In this regard, many analytical and semi-analytical methods were presented extensively to study multiple scattering by a cavity, tunnel and inclusion.[3–7] Lack of flexibility and complexity of the analytical models formulation for solving complex geometric problems has necessitated the use of numerical methods. Accordingly, the effect of a single tunnel, cavity and crack on the surface response has been examined by different numerical approaches.[8–15]

In contrast, a little information is available in the literature to determine the seismic response of the ground surface because of twin side-by-side and parallel tunnels. Earlier, the two parallel tunnels of circular cross-section subjected to incident plane harmonic SH-waves were surveyed in closed form by Balendra et al.[16] In this study, the image technique was employed to account for the reflection of waves at the ground surface and to determine the influence of spacing between the tunnels on the shear stresses and displacements of the tunnel walls. Moore and Guan[17] investigated the response of a pair of lined cylindrical cavities located in a full-space subjected to incident seismic waves (SV and P). The method of successive reflections was employed in this study, where the twin lined tunnels were uncoupled and analyzed independently. Later, Hasheminejad and Avazmohammadi[18] investigated the dynamic interaction of time harmonic plane waves with a pair of parallel circular cylindrical cavities in a poroelastic medium. The

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[*] Correspondence to: Geotechnical Engineering Group, Department of Civil Engineering, Zanjan Branch, Islamic Azad University, Shahid Mansoori St., Moallem St., Zanjan 4515658145, Iran.
E-mail addresses: h.alielahi@iauz.ac.ir (H. Alielahi), m.adampira@srbiau.ac.ir (M. Adampira).

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analytical results are illustrated with numerical examples in which two empty cavities and lined twin tunnels are induced by compression or shear waves. Moreover, a theoretical method is presented by Li et al.[19] to predict underground tunnel behavior considering the peak particle velocity and the stress distribution. Lately, Fang et al.[20] evaluated the natural hazard resulting from the interactions between the imperfect interfaces of closely spaced double-tunnels under P waves using a semi-analytical method. Additionally, some numerical examples were given to analyze the interaction between the tunnels with different interface conditions. These above mentioned studies focus on the dynamic interaction of tunnels on each other, dynamic stress concentration, displacement distribution and determining the seismic response at circumference of twin tunnels.

Lately, Dravinski and Yu[21] investigated the scattering of a plane harmonic SH wave by a system of multiple inclusions of arbitrary shape and locations embedded within an elastic half-space by using a direct boundary integral equation approach. Afterward, Liu et al.[22] presented an analytical solution for scattering of harmonic plane P, SV waves by twin closely-spaced circular tunnels in an elastic full space. The numerical results show that the space between twin tunnels and the frequency of the incident wave have great effect on the dynamic response of the tunnels. Liang et al.[23] studied the three-dimensional diffraction of incident plane SH waves by twin infinitely long cylindrical cavities in half-space using the indirect boundary element method. It is shown that the surface displacement may be significantly amplified by twin cavities and surface displacement peaks become large when two cavities are close. Recently, Parvanova et al.[24,25] examined the seismic response of unlined and lined tunnels, as well as multiple buried inclusions within an elastic homogeneous half-plane with surface relief.

Despite the past studies performed on this issue, there are still some major shortcomings in this field as follows: (1) most applied investigations were either limited to propagate incident anti-plane SH waves or restricted to a single cavity or tunnel; (2) not applying compressive study on the effective parameters to identify seismic interactional behavior of twin tunnels yet; (3) lack of study in the interaction between the twin tunnels and their effect on the ground surface in periodic (or frequency) bands of engineering interest. Moreover, there are critical shortages in the demonstration of amplification patterns for different embedded depths of the twin tunnels; and (4) the shortage of considering the effect of underground cavities and tunnels, especially urban subsurface structures, such as twin-parallel tunnels, on the seismic amplification of the ground surface is observed in building codes and seismic microzonation studies.

In earthquake engineering, it is important to understand the seismic amplification of incident waves and characterize its pattern for the ground surface. In this regard, this research presents a two-dimensional analysis for the dynamic interaction of two long unsupported parallel tunnels aligned horizontally, buried in an elastic medium and subjected to vertically propagating in-plane SV and P incident waves. The primary aim is to study the effects of the spacing between the two tunnels, the depth of underground structures such as twin tunnels, the wavelength of incident wave, and the incident wave field on the seismic response of the ground surface. Finally, introducing simple preliminary ideas and tables for modifying the standard design spectra of structures which are found on the underground structures such as subway tunnels and circular cavities is the final purpose of this research.

2. Numerical formulation and verification

Generally, numerical methods used for the seismic analysis of the two-dimensional sites are divided into three main categories: volumetric methods such as finite element and finite difference methods, and boundary methods such as boundary element method, and hybrid methods that combine volumetric and boundary methods. Among the numerical methods, boundary element method (BEM) is frequently used for solving wave propagation problems in infinite and finite linear media. The two main advantages of the BEM are the reduction of the dimensionality of the problem and the high accuracy of the method for a wide class of problems, especially wave radiation in infinite domain. The mentioned advantages are more pronounced in linear elastodynamics, especially when the domain of interest is infinite or semi-infinite.[26]

Furthermore, BEM can be conducted in two domains of time and frequency. In comparison with the frequency-domain, time-domain provides a direct way of obtaining the time history of the response and it can be extended to the non-linear behavior when combined with volumetric methods. Mansur[27] and Antes[28] were the first who formulated a time stepping algorithm using two-dimensional kernels. But their traction kernels were very complicated, and appeared only implicitly in BEM formulation. In this regard, Israil and Banerjee[29–31] introduced a new formulation which included simple and explicit kernels. While this formulation was easier to apply and could be used to evaluate the response of a structure either in a step-by-step time marching manner or by the superposition of the impulse response, a step-by-step marching scheme could be extended to non-linear cases.[26] Afterwards, Kamalian et al.[32–34] implemented modified kernels in site response analyses of 2-D topographic features. Thus, these modified kernels are applied for analyses of the subsurface features in current research.

The governing differential equation of the dynamic equilibrium of elastic, isotropic and homogeneous body with a small amplitude displacement field is expressed using the following equation[29]:

$$(\alpha_1^2 - \alpha_2^2)\frac{\partial u_j(x,t)}{\partial x_i \partial x_j} + \alpha_2^2 \frac{\partial u_i(x,t)}{\partial x_j \partial x_j} + b_i(x,t) - \frac{\partial^2 u_i(x,t)}{\partial t^2} = 0 \tag{1}$$

where u_i indicates the displacement vector and b_i denotes the body force vector. α_1 and α_2 are the compression and shear wave velocities of the body, respectively. They are obtained using $\alpha_1^2 = (\lambda + 2\mu)/\rho$ and $\alpha_2^2 = \mu/\rho$ in which, λ and μ are Lame coefficients and ρ is mass density. In this paper, the soil behavior is assumed to be linear and the body forces are neglected.

In cases where the domain Γ contains holes, contours are more than one. In other word, a finite number of non-intersecting inner contours are enclosed by an outer boundary. This type of domain, in mathematical terms, is referred to as a multiple connected domain.[35,36] It is notable that the schematic form of the mathematical model is depicted in Fig. 1.

The governing boundary integral equation for the elastic, isotropic, and homogeneous half-plane domain Γ containing holes using the well-known weighted residual method, while ignoring contributions from initial conditions and body forces, can be written as: