International Journal of Rock Mechanics & Mining Sciences 79 (2015) 172–182

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

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

Dynamic interaction of two circular lined tunnels with imperfect interfaces under cylindrical P-waves

Xue-Qian Fang[a,*], He-Xin Jin[a], Bao-Lin Wang[b]

[a] *Department of Engineering Mechanics, Shijiazhuang Tiedao University, Shijiazhuang 050043, PR China*
[b] *Institute for Infrastructure Engineering, University of Western Sydney, NSW 2751, Australia*

ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form
19 June 2015
Accepted 3 August 2015

Keywords:
Two circular tunnels
Imperfect interfaces
P waves
Wave function expanded method
Dynamic stress

ABSTRACT

A semi-analytical method is used to characterize the interacting effects of imperfect interfaces around two circular lined tunnels under cylindrical P-waves. The spring interface model separating the tunnels from the rock mass is introduced to analyze the interface effect. To express the wave fields in different regions, the wave function expand method is applied, and the expanded coefficients are determined by satisfying the boundary conditions with imperfect interface effect. The dynamic stress concentration factors around the tunnels are evaluated and analyzed. The effects of incident wave's frequency, imperfect interface conditions and the distance between the two tunnels are examined. It is found that the imperfect interface effect increases significantly due to the interaction between the two tunnels, especially at the positions adjacent to another one. The high-frequency loading leads to a lower dynamic stress; however, the interacting effect is greater. The imperfect interface effect will increase significantly due to the interaction between the two tunnels. The imperfect interface effect at different positions of tunnels is also examined.

1. Introduction

Underground tunnels are widely used for highway transportation, powerhouses and in other national defense areas such as underground cables. During service, it is fundamental for these underground structures to possess adequate safety under different loadings. So, the strength of underground tunnels is attracting lots of interests, especially for those tunnels storing large amount of toxic and flammable substances [1,2]. Due to the existence of underground tunnels, the response of the surrounding rock mass to the static or dynamic loadings will show great variation, especially when the dynamic interaction between the tunnels is considered. Because of the large dynamic stress resulting from the interaction between the tunnels, many rock tunnels have been damaged by earthquakes in recent years [3,4].

Knowledge of the distribution of stress around the tunnels is important for the design and construction of deep underground tunnels. Liner is the primary structure used to endure the pressure around the tunnels. It has been of high interest for determining the stress distribution in the liner and rock medium under static overburden and dynamic loadings. The analytical methods including the wave function expansion [5–8] and the series expansion techniques [9] have been widely used to simulate the displacement potentials around the circular tunnels embedded in the rock medium. By using wave function expansion method, the seismic dynamic response of piecewise liners embedded in the porous medium was investigated [5]. The scattering of waves around a semi-circular canyon in an elastic half-space subjected to seismic plane and cylindrical waves was studied by Lee and Liu, and the dynamic stress around the canyon was analyzed [6]. The numerical methods including the finite element method and the boundary element method were also introduced to examine the response of tunnels under dynamic excitations. By using the indirect boundary element method in the frequency domain, Liang et al. studied the scattering of SV waves by a canyon in a fluid-saturated, poroelastic layered half-space [10]. Jiang and Yin presented the stress redistribution in the surrounding soil and the earth pressure acting on the shield tunnel, and the principal stresses was discussed in detail [11]. Pakbaz and Yareevand investigated the interaction between the ground and the tunnel lining under earthquake excitation by a finite difference method [12]. The dynamic finite element method was also used to investigate the seismically induced stress increments in the lining of a circular tunnel subjected to harmonic P- and S-waves [13]. Chen et al. [14] investigated the seismic response of a tunnel in mono-layer rock subjected to harmonic P-, S-, and R-waves by numerical simulation, and it was found that the seismically induced stress is significantly related to the tunnel depth and the wavelength of incident wave.

---

[*] Corresponding author.
E-mail address: stduxfang@yeah.net (X.-Q. Fang).

http://dx.doi.org/10.1016/j.ijrmms.2015.08.016
1365-1609/

In the reviewed literatures, the boundaries between the tunnel and the surrounding medium are all assumed as perfect interfaces for convenience of derivation, which means that the traction and displacement at the interfaces are both continuous. In practical engineering, the boundary is not always perfect due to the existence of microcracks or interstitial media in the interface. This imperfect boundary may result in the local failure around the tunnels. Thus, the imperfect interface should be introduced to analyze the effect of microcracks or interstitial media on the response of tunnels. Recently, the imperfect interface has been introduced to analyze the dynamic response of a circular lined tunnel under cylindrical P-waves, and it was found that the imperfect interface exhibits great effect on the dynamic stress [15]. In engineering application, the tunnels are sometimes built closely [16], and the interactions between the imperfect interfaces will make the dynamic stress more complex. So, new techniques should be developed to precisely solve the complex interactions. Up to present time, no one has dealt with this complex phenomenon.

The main objective of this paper is to evaluate the natural hazard resulting from the interactions between the imperfect interfaces of closely spaced double-tunnels under P waves, and the analytical solutions of dynamic stresses are derived. The wave function expansion method is used to describe the wave fields in different regions, and the imperfect interface is modeled with a spring model. To transform the wave fields around one tunnel into another one, the addition theorem is introduced. To solve the expanded coefficients, the boundary conditions with spring models around the two closely spaced tunnels are presented. Some numerical examples are given to analyze the interaction between the tunnels with different interface conditions.

2. Governing equations and general solutions

Two infinitely long circular tunnels (denoted by 1 and 2) parallel to each other embedded in the infinite rock mass are considered, as depicted in Fig. 1. Two local coordinate systems are set, and the centers of them are located at o_1 and o_2, respectively. The outer and inner radii of these identical tunnels are denoted by a and b, respectively. The Láme constants and Poisson's ratio of the rock mass are λ_r, μ_r, ν_r and those of the tunnels are λ_t, μ_t, ν_t. A harmonic P wave with circular frequency ω is located at o_0, which is at a distance d_i from o_i $(i=1,2)$, see Fig. 1. The relationship between ω and the angular frequency f is $\omega = 2\pi f$, and so the displacements in the mediums will be basically steady. It is assumed that the rock mass is elastic, homogenous, isotropic and linear. To express the displacement vectors $(\boldsymbol{u})$ in the medium, the wave function expansion method is applied.

2.1. Wave fields around the two tunnels

According to the Helmholtz decomposition of displacement vectors, two potentials φ and ψ are introduced. Then, the displacement vectors are expressed as

$$u_r = \frac{\partial\varphi}{\partial r} + \frac{1}{r}\frac{\partial\psi}{\partial\theta}, \quad u_\theta = \frac{1}{r}\frac{\partial\varphi}{\partial\theta} - \frac{\partial\psi}{\partial r}. \tag{1}$$

The incident waves can be represented, in the two local coordinate systems, as

$$\varphi_q^{(in)} = \varphi_0 \sum_{n=0}^{\infty} (-1)^n \varepsilon_n H_n^{(1)}(\alpha_1 d_q) J_n(\alpha_1 r_q)\cos(n\theta_q) e^{-(i\omega t + n\phi_q)}, \quad q = 1, 2, \tag{2}$$

where φ_0 is the amplitude of the incident waves, $\varepsilon_0 = 1$, and $\varepsilon_n = 2$ for $n \geq 1$, α_1 is the wave number of the P waves in the rock medium, ϕ_q is the incident angle of P waves in the two local coordinate systems, and $J_n(\cdot)$ is the nth Bessel function of the first kind. The superscript (in) represents the potentials corresponding to incident waves.

Due to the presence of the closely-spaced tunnels, the multiple scattering of incident waves will come into being. The scattered waves around the two tunnels can be expressed as

$$\varphi_q^{(sc)} = \sum_{n=0}^{\infty} A_{nq} H_n^{(1)}(\alpha_1 r_1)\cos(n\theta_q), \ q = 1, 2, \tag{3}$$

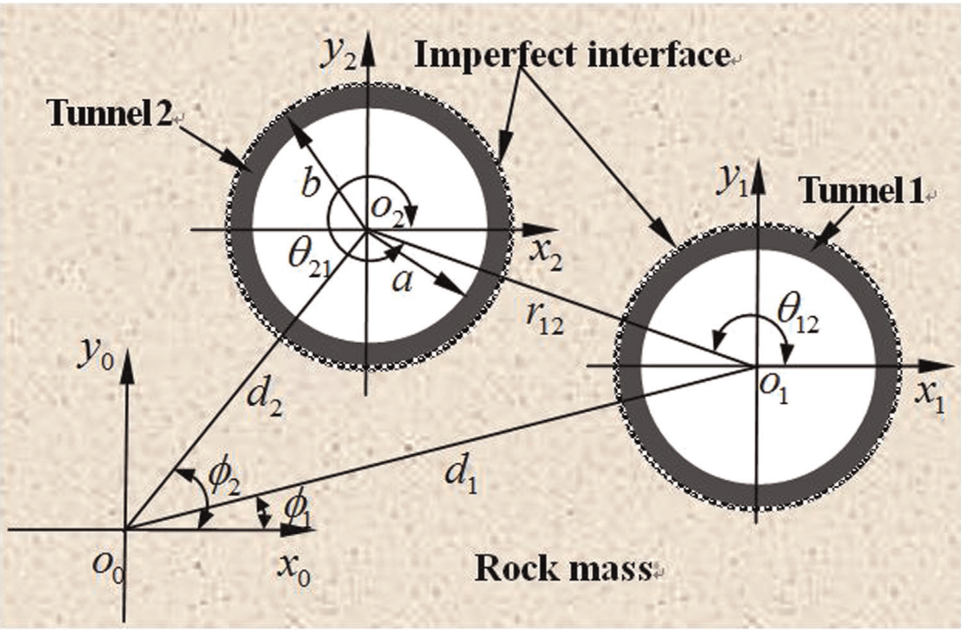

Fig. 1. Two infinitely long circular tunnels with imperfect interfaces in the rock mass under P waves.