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Transient SH-wave scattering by the lined tunnels embedded in an elastic half-plane

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ABSTRACT

A direct half-plane time-domain boundary element method (BEM) was developed and successfully applied to analyze the transient response of ground surface in the presence of arbitrarily shaped lined tunnels, embedded in a linear elastic half-space, subjected to propagating obliquely incident plane SH-waves. To prepare the model, only the interface and inner boundary of the lining need to be discretized. The problem was decomposed into a pitted half-plane and a closed ring-shaped domain, corresponding to the substructure procedure. After computing the matrices and satisfying the compatibility as well as boundary conditions, the coupled equations were solved to obtain the boundary values. To validate the responses, a practical example was analyzed and compared with those of the published works. The results showed that the model was very simple and the accuracy was favorable. Advanced numerical results were also illustrated for single/twin circular lined tunnels as synthetic seismograms and three-dimensional frequency-domain responses. The method used in this paper is recommended to obtain the transient response of underground structures in combination with other numerical methods.

1. Introduction

According to the extensive development of urban texture and the vital necessity of lifelines, infrastructure and underground openings have found an important role in human societies. A full understanding of the behaviors of underground tunnels including tunnels for transportation, water, and facilities, can assist in presenting an optimum layout. The importance of this issue has increased because of the complex performance of the tunnels against seismic loads. The seismic analysis of underground tunnels has been used by the researchers for almost half a century. A complete review up to 1981 can be found in Ariman and Muleski [1] about the methods employed for analyzing the ground with underground tunnels. Apart from experimental and field approaches, solution methods can be divided into three categories: analytical, semi-analytical, and numerical [2].

To analyze the ground response in the presence of unlined and lined tunnel cases, analytical and semi-analytical methods were developed as well. Lee [3], Datta and Shah [4], Lee et al. [5], Tsuar and Chang [6], and Gao et al. [7] investigated the unlined tunnels subjected to seismic waves by analytical approaches. The seismic analysis of a single-phase medium including a lined tunnel was presented in the analytical studies of Lee and Trifunac [8], Balendra et al. [9], Smerzini et al. [10], Zhang et al. [11], Li et al. [12], Min and Bing-Yu [13], Liu et al. [14], Xu et al. [15], and Yi et al. [16]. In the use of analytical procedures, the problem of lined tunnel embedded in a multi-phase medium was explored by Shi et al. [17], Hasheminejad and Kazemirad [18], and Jiang et al. [19]. In this regard, some studies can be found in the literature on modeling the embedded lined tunnels with the help of semi-analytical approaches which include Datta et al. [20], Wong et al. [21], Chin et al. [22], Moore and Guan [23], Manoogian [24], Davis et al. [25], Yeh et al. [26], Liao et al. [27], and Liu et al. [28] in a single-phase medium, and Zhou et al. [29] in a multi-phase medium.

According to what is observed in the nature, although the responses of analytical or semi-analytical methods have a high accuracy, various types of arbitrarily shaped topographic features cannot be applied for modeling in reality. It results in the development of numerical methods with a good flexibility. Generally, these methods can be divided into two types of volumetric and boundary methods. Despite the development of volumetric methods such as finite element method (FEM) or finite difference method (FDM) and their simple formulations, the whole body including the inside and boundaries must be discretized in order to model unlined/lined underground tunnels and topographies (e.g. Besharat et al. [30]; Esmaeili et al. [31]; Faccioli et al. [32]; Gelagoti et al. [33]; Huang et al. [34]; Narayan et al. [35]; Rabeti and Baziar [36]; Yiouta-Mitra et al. [37]). As a result, special attention has been paid to the boundary element method (BEM) among the various existing numerical methods in the recent three decades. Full reviews of BEM and its application can be respectively found in Beskos [38] and Stamos and Beskos [39] for underground structures.

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In order to model underground tunnels using BEM approaches, the surrounding boundaries must be discretized. If the two-dimensional BEM formulation was established based on a full-plane scenario, the circumference of the unlined/lined tunnel, smooth ground surface, and enclosing boundary must be meshed [40]. In this regard, full-plane BEM was statically used by Crouch and Starfield [41], Yang and Sterling [42], Xiao and Carter [43], Panji et al. [44], Wu et al. [45], and Panji et al. [46] for modeling underground tunnels. Also, this method was dynamically utilized to analyze the seismic behavior of the ground including unlined/lined tunnels in the transformed domains (e.g. Kattis et al. [47]; Liu and Liu [48]; Luco and de barros [49]; Manolis and Beskos [50]; Parvanova et al. [51]; Yu and Dravinski [52]).

When the stress-free boundary conditions on the smooth ground surface are satisfied and applied in the formulation, the half-plane BEM scenario is obtained [53]. Although the formulation became more complex, the accuracy and modeling were improved. In the use of this method, only the boundaries around the unlined/lined tunnel need to be discretized. Similar to the full-plane case, half-plane BEM was developed in both static and dynamic states. Some researchers statically utilized this method to analyze half-plane problems in the presence of underground tunnels as well as inhomogeneities (e.g. Dong et al. [54]; Dong and Lo [55]; Panji and Ansari [56]; Telles and Brebbia [57]; Ye and Sawada [58]). In the frequency domain, half-plane BEM was dynamically applied to obtain the seismic ground response with unlined/lined tunnels (Ba and Yin [59]; Benites et al. [60]). Despite the fact that the formulation of the method in the time-domain is more difficult, analyzing the problems with time-dependent geometry and the ability to combine with other numerical approaches can be only achieved in the use of transient responses. Most studies carried out using time-domain BEM were not only formulated in the full-plane, but also applied to investigate surface topographies and unlined tunnels (e.g. Alielahi et al. [61]; Kamalian et al. [62–64]; Takemia and Fujiwara [65]). To the best knowledge of the present authors, in the few studies using half-plane time-domain BEM, the lined tunnel problem embedded in a half-plane has not been studied so far (Belytschko and Chang [66]; Hirai [67]; Panji et al. [53,68,69]; Rice and Sadd [70]).

This paper develops a half-plane time-domain BEM for analyzing seismic ground response in the presence of arbitrarily shaped underground lined tunnels subjected to propagating obliquely incident SH-waves. By the assistance of an appropriate substructuring process, the model was decomposed into a half-plane with a cavity and a closed ring-shaped medium. After applying the method for each domain and obtaining the influence coefficients of the matrices, continuity and boundary conditions were used to determine the assembled coupled equation. The method was successfully implemented in a developed algorithm previously called as DASBEM [53]. The capability and efficiency of the method as well as the prepared computer code were investigated by solving a practical example and comparing the results with those of the published works. With considering some intended parameters, a numerical study was eventually conducted to obtain the ground surface response including single/twin circular lined tunnels. Displaying a powerful approach for preparing simple models of underground lined tunnels, determining accurate results in the use of the proposed method, and presenting some applicable graphs to complete the results were the main purposes of the present paper.

2. Statement of the problem

Consider a homogeneous linear elastic half-plane including an arbitrarily shaped underground lined tunnel as shown in Fig. 1. It is assumed that the lining and surrounding domain have a perfect interaction. The governing scalar wave equation and existing boundary conditions on the smooth ground surface are respectively as follows [71]:

$$\frac{\partial^2 u(x,y,t)}{\partial x^2} + \frac{\partial^2 u(x,y,t)}{\partial y^2} + b(x,y,t) = \frac{1}{c^2}\frac{\partial^2 u(x,y,t)}{\partial t^2} \tag{1}$$

and:

$$\mu\frac{\partial u(x,y,t)}{\partial n}|_{y=0} = 0 \tag{2}$$

where $u(x, y, t)$ and $b(x, y, t)$ are antiplane displacement and body force at point (x, y) and current time t, respectively; c is shear wave velocity given by $\sqrt{\mu/\rho}$, with μ as shear modulus and ρ as mass density; and $\boldsymbol{n}$ is the normal vector for the ground surface. As can be seen in Fig. 1, the model is decomposed into two domains, a uniform half-plane with arbitrarily shaped unlined cavity, and a closed ring-shaped medium. To solve the problem, half-plane time-domain BEM must be applied for each domain, using the image source approach to define a complementary area. Moreover, Fig. 1 depicts the meshing form using the proposed method located only on the surrounding boundaries.

3. Half-plane time-domain BEM

The key parameters of BEM approaches are the solutions obtained from basic equations. Transient half-plane fundamental solutions can be achieved by the singular solution of Eq. (1) and considering Eq. (2). These solutions can be found in Panji et al. [53]. If the problem is statically solved, fundamental solutions are adequate for the formulating process. An application of elastostatic half-plane BEM in modeling lined tunnels can be found in Panji and Ansari [56].

3.1. Boundary integral equation (BIE)

The original form of the direct time-domain boundary integral equation (BIE) can be obtained by applying the weighted residual integral to Eq. (1) and ignoring the contributions from initial conditions and body forces [72,73]. If the problems include incoming waves, the original BIE must be modified [74,75]. The modified form of BIE is as follows:

$$c(\xi)u(\xi,t) = \int_\Gamma \left\{ \int_0^t \left[u^*(\boldsymbol{x},t;\xi,\tau).q(\boldsymbol{x},\tau) - q^*(\boldsymbol{x},t;\xi,\tau).u(\boldsymbol{x},\tau)\right] d\tau \right\} \times d\Gamma(\boldsymbol{x}) + u^{ff}(\xi,t) \tag{3}$$

u^* and q^* are half-plane time-domain displacement and traction fundamental solutions at position $\boldsymbol{x}$ and time t due to a unit antiplane impulsive force in position ξ and preceding time τ, respectively [53]; u and q are displacements and tractions of boundary, respectively; $\Gamma(\boldsymbol{x})$ denotes the boundary of the body; $c(\xi)$ is the geometry coefficient; and u^{ff} is the free field displacement of ground surface without surface irregularities.

3.2. Discretizing BIE

To solve BIE and carrying out the integrations, the time axis and the boundary of the body must be discretized. By discretizing the time axis using N equal increments with duration Δt ($t = N\,\Delta t$), temporal integration can be analytically accomplished. With assuming a linear variation for the temporal shape functions, the following form of BIE can be obtained:

$$c(\xi)u^N(\xi) = \sum_{n=1}^{N}\int_\Gamma \begin{pmatrix} \left[U_1^{N-n+1}(\boldsymbol{x},\xi) + U_2^{N-n}(\boldsymbol{x},\xi)\right] q^n(\boldsymbol{x}) \\ -\left[Q_1^{N-n+1}(\boldsymbol{x},\xi) + Q_2^{N-n}(\boldsymbol{x},\xi)\right] u^n(\boldsymbol{x}) \end{pmatrix} \times d\Gamma(\boldsymbol{x}) + u^{ff.N}(\xi) \tag{4}$$

where $u^n(\boldsymbol{x})$ and $q^n(\boldsymbol{x})$ are displacement and traction fields, respectively; $u^{ff.N}$ stands for the free field displacement at time $t = N\,\Delta t$; and $U_1^{N-n+1}(\boldsymbol{x},\xi) + U_2^{N-n}(\boldsymbol{x},\xi)$ and $Q_1^{N-n+1}(\boldsymbol{x},\xi) + Q_2^{N-n}(\boldsymbol{x},\xi)$ denote the half-plane displacement and traction time-convoluted kernels, respectively. These closed-form responses can be found in Panji et al. [53] and Panji et al. [68]. All the processes were completely analytically carried out up to now. After discretizing the necessary boundaries of the body by M quadratic elements, spatial integration can be numerically