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Analysis of transient wave scattering and its applications to site response analysis using the scaled boundary finite-element method

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ABSTRACT

In this paper, the problem of scattering and amplification of seismic waves by topographical and geological irregularities is addressed directly in the time domain through the scaled boundary finite-element method (SBFEM). The quadtree domain decomposition technique is utilized for the SBFEM discretization of the near field. The far field is rigorously modeled by the displacement unit-impulse response matrix. The computational cost of analyses is reduced through using local formulations in space and time. Considering incident fields of obliquely plane waves coming from far field, the seismic wave inputs are formulated as boundary tractions applied to the near field. Implementing all these aspects in the SBFEM, leads to an elegant technique for time-domain modeling of seismic wave propagation in heterogeneous media with topographical irregularities. Four numerical examples considering various site effects and wave patterns demonstrate the accuracy, versatility and applicability of the approach.

The approach is straightforwardly applicable to nonlinear and 3D wave scattering problems with complex site effects.

1. Introduction

Earthquakes have caused catastrophic consequences in densely-populated zones. The earthquake wave energy is generated in the far field and propagates toward the structures. One of the important research topics in earthquake engineering is the realistic prediction of earthquake motions. To gain a better understanding and prediction of the distribution of the earthquake motions, it is crucial to understand how seismic waves interact with the sites. Site conditions may include geological features (such as soil layering, potential soil non-linearity, crack and fault) and topographical features (such as structures, canyons, and ridges). They will result in scattering of incident waves and may lead to considerable amplifications and spatial variations in the ground motion. Therefore, the real response of structures such as buildings, dams, tunnels, walls and bridges may be influenced by the site effect.

To investigate the site effect of seismic loads, the problem domain extending to infinity is divided into a near field and a far field. The near field includes important features of the site. The remaining part of the problem domain is the far field. It is generally assumed to be homogeneous and linear elastic. The near field and far field are coupled at their interface. In the modeling of the far field, the radiation condition at infinity has to be satisfied. Rigorous approaches for satisfying radiation condition at infinity are spatially and temporally global and include convolution integrals in a direct time-domain analysis. In contrast, approximate methods are spatially or temporally local but they often suffer from insufficient accuracy. Since the source of an earthquake is typically far away from the site of interest, it is common to assume the seismic waves reaching the near field as plane waves. In analysing the scattering of the seismic waves by the near field and the response of the near field, it is necessary to convert the plane waves to an equivalent boundary condition and, at the same time, to permit the outgoing waves transmitted in the near field to propagate across the interface to infinity.

Closed-form analytical solutions have been developed in the literature for 1D, 2D and 3D wave scattering problems [1–4]. However, they are only applicable to simple material properties and geometries of the near field. Most of them have been derived for out-of-plane motions in the frequency domain. To handle complex site conditions, numerical simulations are employed. Various numerical approaches have been reported in the literature on seismic wave analyses [5].

The boundary element method (BEM), is often used for modeling far fields as the radiation condition at infinity is rigorously satisfied. The wave scattering problems can be solved straightforwardly in the

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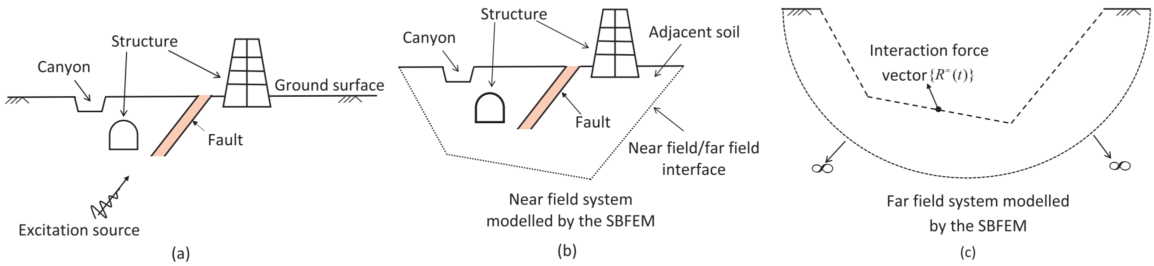

Fig. 1. Division of the problem domain for wave excitation analysis in an elastic medium (a) a general wave propagation problem (b) near field system (c) far field system.

frequency domain by converting the seismic wave input into an equivalent load to be enforced on the boundary [6,5,7,8].

The finite-element method (FEM) is the most commonly used numerical method for modeling near fields. It is efficient to represent complex geometries and non-linear material properties. Special boundary conditions need to be enforced on the near field/far field interface to avoid the reflection of outgoing waves back into the near field. Various local transmitting boundary conditions and infinite elements can be found in the literature [9–11]. Finite-difference method (FDM) is another domain type method which has been widely used for modeling seismic wave propagation [12–15]. The spectral-element method (SEM) using high-order shape functions has increasingly attracted the attention of researchers in wave propagation analysis in both 2D and 3D simulations [16,12] in recent years. Hybrid type methods have been also used in the literature for modeling wave propagation problems [17,18].

Several techniques for the input of seismic waves originating from the far field have been reported. To model the seismic wave propagation in a system of horizontal soil layers, Joyner and Chen [19] used the viscous boundary condition to model the far field. They transformed the incident waves into equivalent forces for the near field. Clough et al. [20], Wolf [21] and Zienkiewicz et al. [22] presented the free-field input approach which has been widely used in the research and practice. In this method, the so-called free-field motions are defined on the near field/far field interface which are solved in parallel with the near field model. A fixing releasing boundary approach by adopting infinite elements was suggested in [23]. Liu and Lu [24] presented an input method based on a spring-dashpot boundary condition representing the far field using the FEM in time domain. Plane wave with different patterns and arbitrary incident angles can be converted to equivalent nodal forces to be applied on the near field/far field interface. Based on the idea of Liu and Lu [24], Huang et al. [25] used the FEM to analyze non-linear seismic response of tunnels with normal fault ground subjected to obliquely incident *P*- waves.

This paper presents an approach of the seismic wave inputs for use with the scaled boundary finite element method (SBFEM). The SBFEM is a semi-analytical technique developed by Wolf and Song [26] in the 90s for dynamic stiffness of unbounded domains. Only the boundary is discretized and no fundamental solution is required. Anisotropic and non-homogeneous materials satisfying similarity can be modeled without additional efforts. The radiation condition at infinity is rigorously satisfied. It has been successfully applied in wave propagation [27–30], fracture mechanics [31,32], structural dynamics [33], seepage analysis [34], electromagnetism [35], heat transfer [36], fluid-structure interaction [37] and elasto-plasticity [38]. Recently, flexible and efficient domain decomposition techniques have been employed for the SBFEM modeling of bounded domains. Polygon elements with arbitrary number of edges based on triangulation were used for fracture mechanics and elasto-plastic analyses [39,38]. More recently quadtree meshes were utilized for domain decomposition in the analysis of crack propagation [32].

In the proposed approach, the idea presented by Liu and Lu [24] is followed for the wave input. The near field is decomposed using the quadtree meshes [40]. The displacement unit-impulse response matrix [28] with a new efficient time discretization approach is employed to allow the scattering waves to travel to infinity without any reflection. Spatial approximation by sub-structuring the far field [41,30] and temporal local formulation based on truncating the displacement unit-impulse response matrix are conducted to reduce the computational time. The seismic input wave motions are converted to surface tractions to be enforced on the near field/far field interface. The formulations can be applied to both in-plane and out-of-plane motions with arbitrary incident angles. These features implemented in the SBFEM leads to an elegant technique for modeling general wave scattering problems in the time domain. The approach can be directly applied to 3D general soil-structure interaction problems of arbitrary geometry and site effects.

The structure of the paper is as follows. In Section 2 the fundamentals of the SBFEM for wave excitation problems are briefly presented. Section 3 states the wave input formulations for the scattering wave problems. In Section 4, the accuracy and applicability of the SBFEM in modeling the wave scattering problems is demonstrated by using four numerical examples. The major conclusions drawn from this study are summarized in Section 5.

2. The scaled boundary finite-element solution of wave excitation problems

In this section only the fundamentals of SBFEM for wave excitation analysis are discussed. Its developments and detailed formulations can be found in [26,42,28]. To perform a wave excitation analysis with the SBFEM, the problem domain (Fig. 1a) is decomposed into a bounded near field system (Fig. 1b) and an unbounded far field system extending to infinity (Fig. 1c). These two systems are connected at the near field/far field interface.

The near field includes the structure and the near field soil with topographical and geological irregularities. It can exhibit non-linear behavior. In this work, the far field system is assumed to be homogeneous and have a linear elastic behavior. Both systems are modeled by the SBFEM in this study. Once the property of both systems was defined, they are coupled on the near field/far field interface. The resulting equations of motion of the coupled problem can be integrated step-by-step. Here, first the formulation and concept of the SBFEM is briefly described followed by the modeling procedures of the near field and far field systems.

2.1. Scaled boundary finite-element method formulation

A generic polygon element for modeling the near field system using the SBFEM is shown in Fig. 2a. A scaling center is selected inside the polygon element from which the entire element boundary must be visible.

This satisfies the similarity or visibility criterion for the near field elements. For convenience, the origin of the Cartesian coordinate system is chosen at the scaling center. The boundary of the polygon element is scaled towards the scaling center, so that the entire polygon is covered. The one-dimensional line elements can be used for discretization of polygon edges (see Fig. 2b). The scaled boundary coordinate system is defined by a radial coordinate ξ and a circumfer-