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High performance of the scaled boundary finite element method applied to the inclined soil field in time domain

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ABSTRACT

An efficient method for modelling the wave propagation in semi-infinite domain is proposed. It is applicable to soil–structure interaction problems for complex inclined soil field. The scaled boundary finite element method is modified through the original scaling center substituting by a scaling line. Based on this scaling line, the dynamic stiffness equation is derived. Then, an accurate and efficient continued fraction method is firstly introduced for solving equation for the model with rigid bedrock. By using the continued fraction solution and introducing auxiliary variables, the equation of motion of unbounded domain is built. Coupling the far field modelling by modified scaled boundary finite element method with the near field modelling by the finite element method, the global time-domain equation is obtained, which is a standard equation of motion for the whole domain. As a key point, the precise time-integration method is firstly employed to solve global equation of motion. The advantages of this integration method are that the integral interval is divided into quite small piece. It makes sure the precision achieve to computer precision. Owning to adopting five terms Taylor expansion for each small integral interval, the computational precision is increased greatly. Applying precise time-integration method in this paper, it greatly improves the accuracy and computing speed of proposed method. By using the sub-structure method, the inclined soil field is modelled. Numerical examples demonstrate accuracy and high efficiency of the new method, especially for complex dip mediums.

1. Introduction

In practical, the interaction of soil–structure is attracting more and more attention of researchers. Considering the soil field is formed through a long-term sedimentation process, the soil always is multi-layered, even the inclined soil field. Therefore, it is more realistic and significant to study the dynamic response of inclined soil field. This subject is greatly importance in academia so that numerous researchers are concerned it. In order to describe the wave propagation in infinity, the radiation damping must be satisfied [1]. Other researches also are involved the radiation damping in soil–structure interaction subjects [2–4]. Earlier numerical and analytical studies on this field have been proposed. It is referred to those review references [5–8]. In a series studies, many methods have been applied in researching unbounded domain problems. However, the limitations on wave propagation in soil field for those methods are often encountered in engineering [9]. Over the last decades, a large amount of numerical methods have been developed in this area. Such as the finite element method (FEM) [10,11], the boundary element method (BEM) [12–14] and the thin layer method (TLM) [15–19]. The FEM employs the viscous-spring artificial boundaries to model wave propagate and in general decay slowly in unbounded domain. The range of bounded domain must be enough big for obtaining correct results. It consumes a large amount of computation times and human efforts. The BEM is a popular tool to model the wave propagation in soil–structure interaction. It can satisfy the radiation condition in infinity by using fundamental solution. The BEM has the advantages in meshing generation and nonlinear analysis problems, and it is widely used in soil systems. However, the fundamental solution for soil medium is based on Green's function, and it is a complex process for anisotropic problem. Especially in time domain, the convolution integrals have to be evaluated. It greatly reduces the computation efficiency. The TLM is suitable for solving dynamic analysis of horizontally layered media. It has analytical solution in the direction of layer by constructing exact non-reflecting boundary condition in wave/frequency domain. It is only available for simple geometry and homogeneous material. Recently, the precise integration method [20] has been developed. It has quite small integral interval. And the precision of the method can reach to computer precision.

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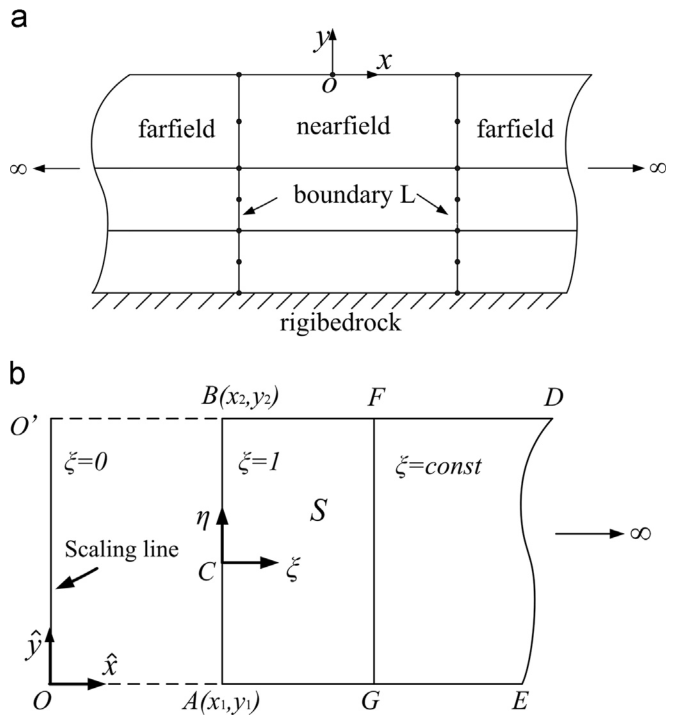

Fig. 1. Scaled boundary finite element method for 2D layered medium. (a) 2D layered medium and (b) coordinate transformation model.

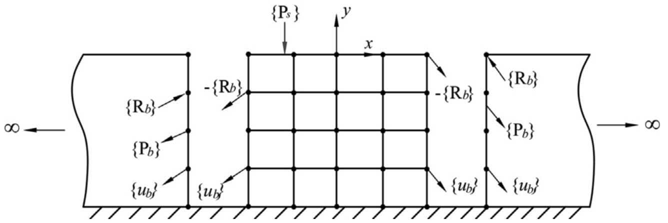

Fig. 2. Coupled model of finite element method and scaled boundary finite element method.

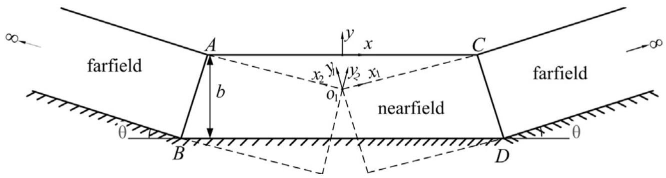

Fig. 3. The inclined soil model of the modified SBFEM.

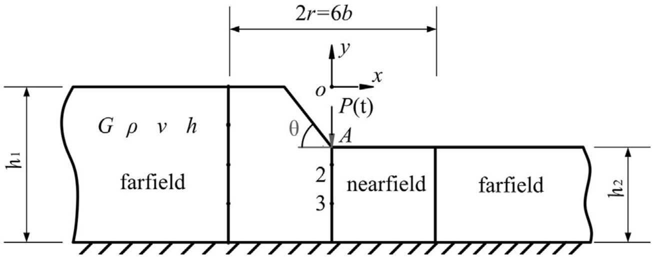

Fig. 4. Calculation diagram of one layer model.

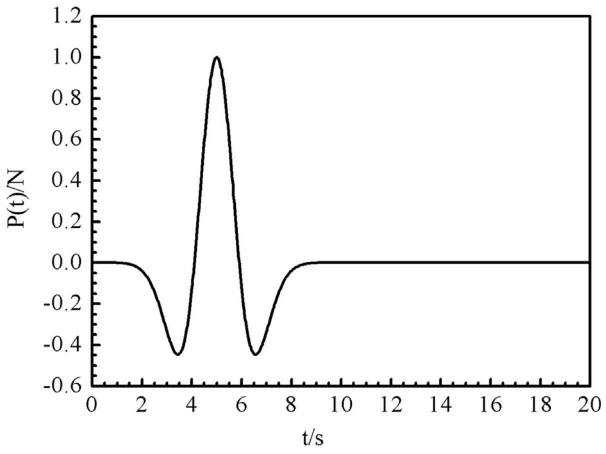

Fig. 5. Force history of the Ricker wavelet.

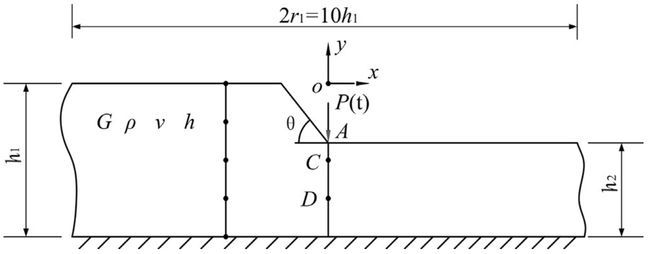

Fig. 6. Viscous-spring boundary model.

The scaled boundary finite element method (SBFEM) [21,22] is a novel method. It is suitable to model vector waves for soil medium in unbounded domain and singular problems in bounded domain. While no fundamental solution and no artificial boundary conditions are required. Only the boundary is discretized, thus, the spatial dimension is reduced by one. In a word, the SBFEM combines the advantages of the boundary element method and the finite element method. By using the weighted residual method or the principle of virtual work, the displacement equation of SBFEM is formulated. Since introducing the same displacement shape function, SBFEM can seamlessly couple with finite element model of near field. The model with anisotropic material can be modeled by SBFEM without any difficulty. SBFEM has been successfully applied to wave propagation problems in unbounded domain and singular problems in bounded domain [1,23].

Extensive literatures on the numerical solution of SBFEM governing equation in unbounded domain exist [23]. SBFEM is successfully applied to the dynamic analysis of soil–structure interaction. In the subsequent researches, most analyses were forced on solving the dynamic stiffness in frequency domain [24,25] and displacement in time domain [26–28]. The original SBFEM was employed integrating the unit impulse response in time domain, while the integral process consumed a lot of computer time. The computational cost increases with problem size increasing. Therefore, many researches' efforts have been devoted to improve the computational efficiency recently [29–32]. A novel SBFE solution method has been proposed recently with the continued fraction method. Song [33] introduced the continued fraction method for modelling bounded domain. Birk et al. [34,35] developed a high-order doubly asymptotic boundary by using doubly asymptotic continued fraction method in acoustic and diffusion problems. Chen [36,37] and Birk [38] proposed the continued fraction solution in time domain both in bounded and unbounded domains. Standard procedure in structural dynamic can be directly applied in time domain. The dynamic analysis of the soil medium is comparative complex, and the soil medium is not horizontal generally. However,