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Nonlinear soil-structure interaction analysis in poroelastic soil using mid-point integrated finite elements and perfectly matched discrete layers

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ABSTRACT

A numerical approach for a nonlinear analysis of soil-structure interaction in poroelastic soil is proposed. Nonlinear behavior in the near-field region of soil is considered by conventional finite elements. The far-field region of soil is represented by mid-point integrated finite elements and perfectly matched discrete layers (PMDLs) in order to consider the energy radiation into infinity. The mid-point integrated finite elements can be formulated identically to conventional finite elements. Thus, PMDLs for poroelastic media are formulated in this study. A means by which to represent a layered poroelastic half-space with conventional finite elements, mid-point integrated finite elements, and the developed PMDLs is proposed. The proposed numerical approach is verified from various perspectives. The approach is applied to a nonlinear analysis of the earthquake responses of a structural system on poroelastic soil. It is demonstrated via the application that the proposed approach can be applied successfully to nonlinear dynamic soil-structure interaction problems.

1. Introduction

Wave propagation in poroelastic media has many applications in various areas of civil engineering and mechanical engineering. Typical examples are nonlinear dynamic analyses of structures built on a poroelastic half-space, a liquefaction analysis of layered soil, subsurface imaging to understand deep geologic structures and explore hydrocarbon deposits, and the non-destructive testing of structures composed of porous materials. Because wave propagation in poroelastic media has a very wide range of applications in various branches of engineering in addition to those mentioned above, many studies have been conducted in an effort to understand the underlying physics in poroelastic dynamics and wave propagation in poroelastic media [1].

Among the many different applications, the nonlinear dynamic soil-structure interaction (SSI) and liquefaction analyses are the most complex because both nonlinear material behaviors and energy radiation into infinity must be considered simultaneously in the applications. The nonlinear material behaviors can be best considered using nonlinear finite elements in the time domain. On the other hand, the energy radiation into infinity can be taken into rigorous consideration in the frequency domain. The mechanical models for the radiation derived in the frequency domain must be combined with the nonlinear model in the time domain. Thus, the accuracy and efficiency of nonlinear dynamic soil-structure interaction and liquefaction analyses depend on how the radiation of energy can be modeled accurately and efficiently in the time domain. Accurate and efficient numerical representations of the phenomena in the time domain have presented great challenges to researchers.

Various numerical models have been developed in order to represent the energy radiation into infinity. Typical examples are consistent transmitting boundaries [2], boundary element methods [3,4], infinite elements [5], high-order non-reflecting boundary conditions (NRBCs) or absorbing boundary conditions (ABCs) [6], and perfectly matched layers (PMLs) [7,8]. As mentioned above, numerical models for the radiation of energy must be able to be combined accurately and efficiently with nonlinear finite-element models in the time domain for nonlinear dynamic soil-structure interaction and liquefaction analyses. Thus, the models must be represented in terms of local temporal operators in the time domain. Among the aforementioned models, high-order ABCs and PMLs can meet these requirements by adjusting their parameters [9].

In this study, a numerical approach for the nonlinear analysis of soil-structure interaction in poroelastic soil is proposed. In this approach, the energy radiation into infinity is taken into consideration using mid-point integrated finite elements and perfectly matched discrete layers (PMDLs). Because PMDLs preserve both the advantages of high-order ABCs and PMLs [10,11], they have been applied successfully to various wave-propagation problems [10,12–19]. Specifically, the numerical models have been successfully applied to nonlinear soil-structure interaction problems in plane strain [20] and to general three-dimensional problems [21]. In these studies, the parameters of the PMDLs for an effective and accurate representation of a layered half-space were proposed. The proposed models were applied to various

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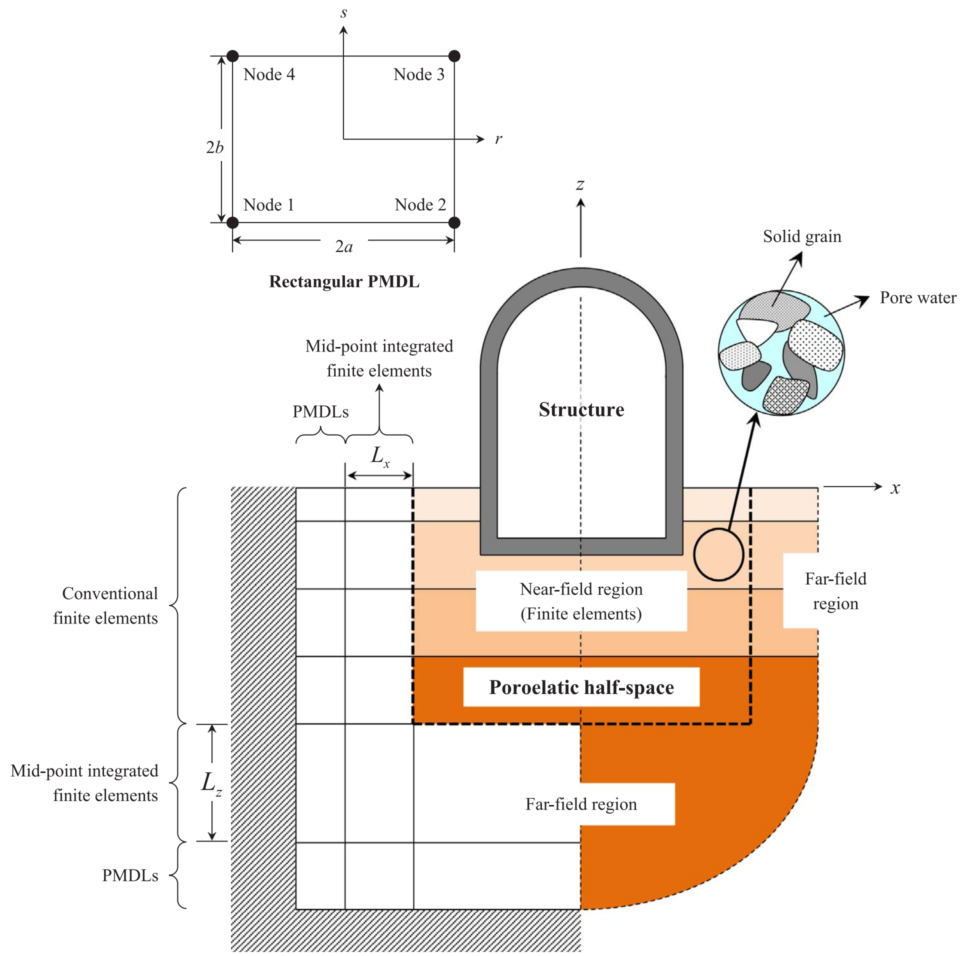

Fig. 1. Representation of a poroelastic half-space.

nonlinear soil-structure interaction problems, confirming their capabilities. In this study, this approach is extended to wave-propagation problems in a poroelastic half-space in plane strain and applied to nonlinear dynamic analyses of structures built on poroelastic soil. Specifically, the PMDLs for poroelastic media are combined with mid-point integrated finite elements because it has been shown that the combined model can represent a layered half-space in an accurate and effective manner [22]. Mid-point integrated finite elements can be formulated in the same manner as conventional finite elements. Thus, the PMDLs for a poroelastic half-space in plane strain are developed for time-domain analyses of soil-structure interactions in this study. A means of determining their parameters for an effective and accurate representation of a layered half-space is proposed while considering the dynamic characteristics of poroelastic media. The proposed numerical approach is verified from various perspectives and applied to a nonlinear analysis of earthquake responses of a structural system built on poroelastic soil.

2. Perfectly matched discrete layers for a poroelastic half-space in plane strain

In this section, dynamic properties of poroelastic media are reviewed briefly and dynamic stiffness matrices of PMDLs for a poroelastic half-space in plane strain are derived.

2.1. Brief review of dynamic behaviors of poroelastic media

The governing equations for poroelastic media in plane strain can be written in rectangular Cartesian coordinate systems as follows [23–26]:

for $i, j = x$ or z

$$\mu u_{i,jj} + (\lambda + \mu + Q\alpha^2)\, u_{j,ji} + Q\alpha w_{j,ji} - \rho \ddot{u}_i - \rho_w \ddot{w}_i = 0 \tag{1a}$$

$$Q\alpha u_{j,ji} + Q w_{j,ji} - \rho_w \ddot{u}_i - \frac{\rho_w}{n}\ddot{w}_i - f\dot{w}_i = 0 \tag{1b}$$

where u_i denotes the displacement of the solid skeleton; w_i is the relative displacement of the fluid with respect to the solid skeleton multiplied by the porosity; λ and μ are the Lamé constants of the solid skeleton; Q and α are parameters accounting for the compressibility of the poroelastic media; ρ_w is the density of the fluid; $\rho = (1 - n)\rho_s + n\rho_w$ denotes the averaged density of the mixture in which ρ_s is the density of the solid; n represents the porosity; and $f = 1/\kappa$, in which κ is the permeability.

The displacements u_i and w_i in Eq. (1) can be expressed in terms of four potentials, i.e., two potentials for dilatational waves and two potentials for rotational waves. Given that the two rotational waves for the solid and fluid phases are linearly related to each other, there are three independent potentials. It can easily be shown that the governing equations can be expressed in terms of the three potentials as follows when motions in poroelastic media have $\exp[i(\omega t - k_x x - k_z z)]$ dependence:

$$\left(k^2\begin{bmatrix} \lambda + 2\mu + Q\alpha^2 & Q\alpha \\ Q\alpha & Q \end{bmatrix} - \omega^2\begin{bmatrix} \rho & \rho_w \\ \rho_w & \frac{\rho_w}{n} \end{bmatrix} + i\omega\begin{bmatrix} 0 & 0 \\ 0 & f \end{bmatrix}\right)\begin{Bmatrix} \phi_u \\ \phi_w \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix}$$

for P1 and P2 waves (2a)