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Nonlinear analysis of soil–structure interaction using perfectly matched discrete layers

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ABSTRACT

When nonlinear behaviors of soil are important in a soil–structure interaction system, radiation of energy into the infinity of the soil as well as the nonlinearity must be considered rigorously. In this study, perfectly matched discrete layers (PMDLs) are employed to represent the radiation of energy rigorously. A time-domain formulation for a soil–structure interaction is given using the layers. To represent a layered half-space effectively and accurately, a method to determine PMDL parameters for the half-space is proposed. It is demonstrated that the proposed PMDL system can be applied successfully to problems of nonlinear soil–structure interaction.

1. Introduction

Wave propagation is a research topic with many applications in a variety of areas including seismology, meteorology, oceanography, mechanical engineering, civil engineering, and naval engineering. Typical examples are subsurface imaging, weather prediction at local and global levels, non-destructive testing, dynamic fluid–structure interaction, dynamic soil–structure interaction, and underwater acoustics. Among these applications, the dynamic soil–structure interaction is one of the most complex physical phenomena because structural vibration and elastic wave propagation in soil are deeply involved. Therefore, many researchers have studied this phenomenon and developed various approaches to understand the physics that underlies it.

A typical soil–structure interaction system is shown in Fig. 1a. The structure is placed on or embedded in a layered half-space or layered soil on a rigid bedrock. As sketched in Fig. 1a, the soil can be divided into two regions, i.e., near- and far-field regions. Although a near-field region can have an irregular geometry and be inhomogeneous in elastic properties, a far-field region is assumed to be regular in geometry and has homogeneous elastic properties in the direction of infinity. Conventional finite elements are usually employed for an irregular and inhomogeneous near-field region. On the other hand, a regular and homogeneous far-field region must be represented by mathematical or numerical models that can radiate elastic waves into infinity. Consistent transmitting boundaries [1], boundary element methods [2,3], infinite elements [4], non-reflecting boundary conditions [5], and perfectly matched layers (PMLs) [6,7] are frequently-used models for an infinite far-field region.

When strong external forces are applied to the soil–structure interaction system, two kinds of nonlinear behaviors are expected in the system. The first one is nonlinear material behaviors of the structure and soil. The material nonlinearity can be represented by nonlinear constitutive equations of the materials. The other nonlinearity is associated with sliding and a partial uplift of the foundation and separation of its wall from the soil [8]. Contact elements can be employed for the nonlinearities on an interface between the foundation and soil. In the nonlinear soil–structure interaction analysis, the radiation of elastic waves into infinity must also be considered rigorously. Therefore, the soil is divided into the near- and far-field regions in the same way as mentioned above. Usually, nonlinear behaviors are confined within the near-field region, and the far-field region is assumed to be linear. Since the conventional finite elements for the near-field region can represent nonlinearities accurately, a rigorous model for the far-field region that can represent the radiation effect is required for an accurate nonlinear analysis.

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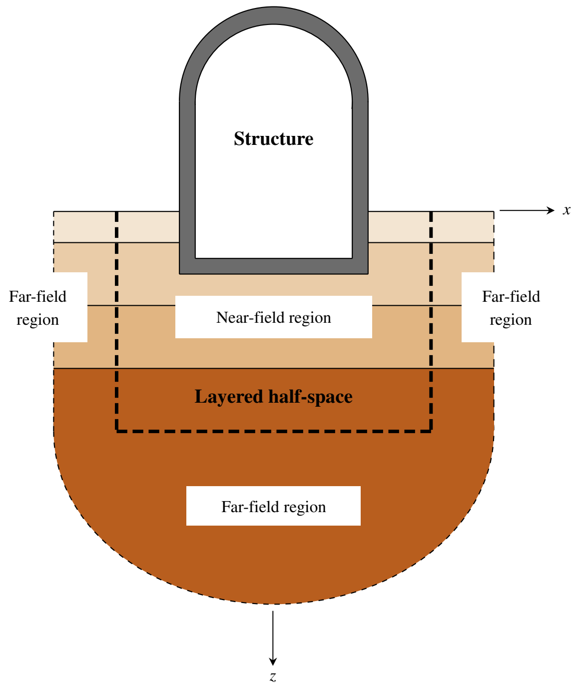
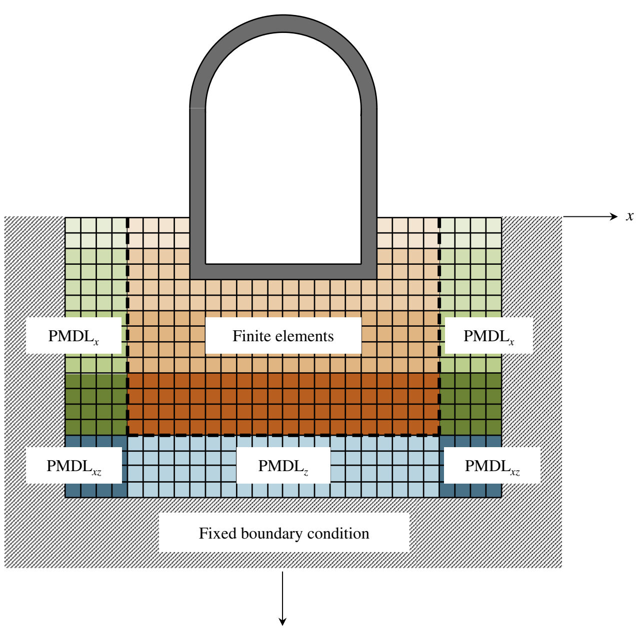


(a) Schematic view



(b) Numerical model

Fig. 1. Soil–structure interaction system in a layered half-space.

In this study, the far-field region of soil is represented by perfectly matched discrete layers (PMDLs), and the representation is applied to a nonlinear analysis of soil–structure interaction. Guddati and Tassoulas [9] presented a new absorbing boundary condition based on a continued-fraction approximation for a scalar wave equation. The new absorbing boundary condition is referred to as a continued-fraction absorbing boundary condition (CFABC). Guddati [10] developed arbitrary wide-angle wave equations (AWWEs) applicable for general heterogeneous, anisotropic, porous, and viscoelastic media, and showed that the AWWEs are equivalent to the continued fraction approximation. Because the CFABC is closely related to the complex coordinate stretching idea of the PML and does not reflect waves from an exterior region even after discretization [11], the CFABC is referred to as a PMDL. PMDLs have been applied successfully to a variety of problems: scalar wave propagation [11], dispersive acoustic wave propagation [12], elastic wave propagation [13], statics [14], wave propagation in anisotropic media [15,16], and wave propagation in a discretized domain [17]. For practical applications, the PMDLs were employed in a soil–structure interaction analysis [18]. As shown in previous studies, PMDLs are easy to be implemented and effective in modeling the wave propagation in various unbounded domains. Therefore, nonlinear problems in the area of soil–structure interaction are solved using the PMDLs in this study.

The outline of this paper is as follows. In Section 2, the dynamic stiffness of PMDLs is given, and an equation of motion for a soil–structure interaction system is formulated. To represent a layered half-space effectively and accurately, a determination of the PMDL parameters is suggested in Section 3. In Section 4, the proposed PMDL system is applied to various nonlinear soil–structure interaction problems in a layered half-space. The paper is summarized in Section 5.

2. Perfectly matched discrete layers for time-domain analysis

A time-domain formulation of PMDLs is given when they represent the far-field region of the soil. Usually, three kinds of PMDLs are employed for a representation of the half-space (Fig. 1b). One is a PMDL for the vertical edge, another is for the horizontal edge, and the other is for the corner. In this study, the PMDLs will be referred to as PMDL$_x$, PMDL$_z$, and PMDL$_{xz}$ because they represent the far-field regions that are infinite in the x-direction, z-direction, and both directions, respectively. It is assumed in this study that the vertical and horizontal edges form a right angle. Therefore, the PMDLs are rectangular in shape. The same approach can be applied when the boundaries make any convex polygon and the PMDLs in a parallelogram are employed [11]. The dynamic stiffness of the rectangular PMDLs shown in Fig. 2 can be obtained [13]:

$$\mathbf{S} = \int_{-1}^{1}\int_{-1}^{1}\Big[\frac{b}{a}\mathbf{B}_{rr}^T\mathbf{D}_{rr}\mathbf{B}_{rr} + \frac{a}{b}\mathbf{B}_{ss}^T\mathbf{D}_{ss}\mathbf{B}_{ss} + \mathbf{B}_{rs}^T\mathbf{D}_{rs}\mathbf{B}_{rs} + \mathbf{B}_{sr}^T\mathbf{D}_{sr}\mathbf{B}_{sr} - ab\rho\omega^2\mathbf{N}^T\mathbf{N}\Big]drds \tag{1a}$$

$$\mathbf{N} = \begin{bmatrix} N_1 & 0 & \cdots & N_4 & 0 \\ 0 & N_1 & \cdots & 0 & N_4 \end{bmatrix} \tag{1b}$$

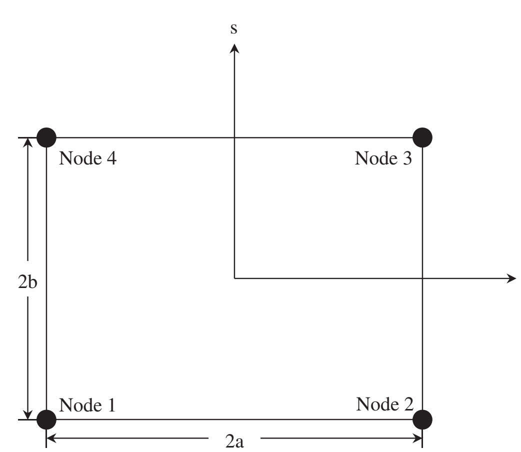


Fig. 2. Rectangular PMDL element.