Computers and Structures 165 (2016) 34–47

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Perfectly matched discrete layers for three-dimensional nonlinear soil–structure interaction analysis

Jin Ho Lee [a], Jung Han Kim [b], Jae Kwan Kim [c,*]

[a] R&D Strategy Division, Future Strategic Center, Korea Railroad Research Institute, 176 Cheoldo Bangmulgwan-ro, Uiwang-city, Gyeonggi-do 16105, Republic of Korea
[b] Integrated Safety Assessment Division, Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon 34057, Republic of Korea
[c] Department of Civil and Environmental Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea

ARTICLE INFO

Article history:
Received 3 June 2015
Accepted 10 December 2015
Available online 5 January 2016

Keywords:
Nonlinear analysis
Material nonlinearity
Soil–structure interaction
Wave propagation
Perfectly matched discrete layer
Layered half-space

ABSTRACT

The dynamic behavior of structures established in flexible ground can be greatly influenced by soil–structure interaction. The challenge with regard to soil–structure interaction is to model the nonlinear behavior of soil in the vicinity of the foundation, including the boundary nonlinearity at the interface and the radiation of energy into infinity simultaneously. In this study, a three-dimensional time-domain formulation of perfectly matched discrete layers (PMDLs) is developed. It can be combined with a detailed finite-element model of the near-field region surrounding the foundation. The developed PMDL formulation can minimize the modeling region. A procedure to determine the parameters of the three-dimensional PMDLs to model a layered half-space effectively and accurately is proposed. Green's functions are calculated in half-spaces with the developed method and found to agree well with existing solutions. The developed PMDL formulation is applied to a nonlinear three-dimensional soil–structure interaction analysis, confirming its capability.

1. Introduction

With the rapid progress in engineering and technology, built structures such as long-span bridges and high-rise buildings are becoming ever larger and taller. The demand for the construction of safety–critical facilities such as nuclear power plants and large liquid storage tanks is increasing. Facilities such as offshore wind turbines and platforms are becoming larger and taller. These structures and facilities should be cost-effective and sufficiently safe at the same time. To achieve these goals, apparently conflicting, we must know very accurately the responses of these structures to various types of loading. These loadings in many cases are dynamic in nature. Among the many important factors that must be considered is the dynamic interaction between soil and structures. In particular, structures that are built in flexible soil can be affected greatly due to the soil–structure interaction. Hence, the dynamic behaviors of the system cannot be accurately predicted without considering the soil–structure interaction [1].

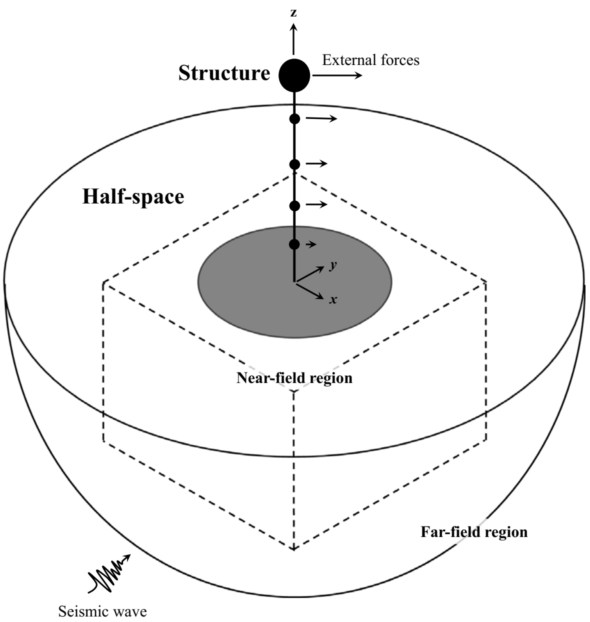
The accurate modeling of soil–structure interaction is a great challenge mainly due to two areas of difficulty related to mechanical modeling. The first area involves material and boundary nonlinearities in the soil and in the interface [2]. The second is the accurate treatment of the radiation of energy into the infinite boundary. The nonlinear behavior can be handled best by means of finite element modeling in the time domain. On the other hand, the radiation of energy in the layered half-space can be treated rigorously in the frequency domain. However, nonlinear soil–structure interaction analysis requires these two models be combined in the time domain. Thus, the accuracy and efficiency of a nonlinear soil–structure interaction analysis depend on whether the radiation of energy can be modeled accurately and efficiently in the time domain.

A typical example of a soil–structure interaction system is shown in Fig. 1a. The structure is assumed to be founded in soil modeled as a half-space. The half-space can be divided into the near- and far-field regions as shown in Fig. 1a. The near-field region can be defined as the soil region near the foundation where the geometry and material properties are heterogeneous and the responses are nonlinear. This region may be modeled best by finite element method which can handle both material and boundary nonlinearities. The far-field region is considered as the infinite soil region where the layer geometry is regular, the material properties are homogeneous, and the response is linearly elastic. A mathematical model of the far-field region should be able to radiate elastic waves into infinity efficiently. Various models have been developed for this purpose. Typical examples are consistent transmitting

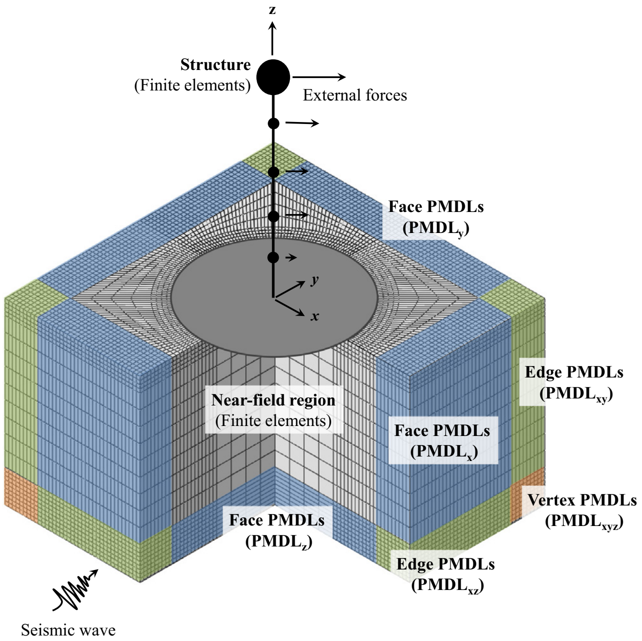
---

* Corresponding author.
E-mail addresses: ohnij2@krri.re.kr (J.H. Lee), jhankim@kaeri.re.kr (J.H. Kim), jkwankim@snu.ac.kr (J.K. Kim).

http://dx.doi.org/10.1016/j.compstruc.2015.12.004
0045-7949/© 2015 Elsevier Ltd. All rights reserved.



(a) Schematic view



(b) Numerical model

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

boundaries [3], boundary element methods [4,5], infinite elements [6], high-order non-reflecting boundary conditions (NRBCs) or absorbing boundary conditions (ABCs) [7], and perfectly matched layers (PMLs) [8,9]. For a nonlinear analysis, the far-field model should be able to be combined easily and efficiently with the near-field finite-element model in the time domain. Therefore the model must be expressed by local temporal operators in the time domain. Among the models mentioned above for the far-field region, the consistent transmitting boundary, boundary element methods, and infinite elements result in global temporal operators that are expressed in convolution integral in the time domain. However, the other models such as high-order ABCs and PMLs can satisfy the requirement by adjusting their parameters. The high-order ABCs can approximate accurately the exact dynamic stiffness of an infinite domain with rational expressions that can be implemented easily in the time domain using auxiliary variables. Because of the rational approximation, the effects of computational parameters in the high-order ABCs on their performance can be revealed through mathematical manipulations [10]. On the other hand, the PMLs are artificial absorbing-media based on complex-coordinate stretching. They are much easier to implement than the high-order ABCs. Besides, corners in the near-field region can be treated without difficulty for the PMLs. However, it is difficult in practical calculations to determine computational parameters that will guarantee high accuracy [10]. Therefore, it is hard to determine which model is better between high-order ABCs and PMLs. It depends on special requirements of a specific problem to be solved.

In this study, a newly developed high-order ABC based on continued-fraction approximation for a vector wave equation is developed in order to represent a far-field region of a half-space [11,12]. It was shown that an element which has a length of h in a direction normal to a boundary can be a perfect absorber for waves with a wavenumber of $-2i/h$, where i is the imaginary number, when displacements in the element are assumed varying linearly and the mid-point integration rule is used for the evaluation of element stiffness in the normal direction [12]. Since a successive application of the elements leads to a continued-fraction approximation of dynamic stiffness of a half-space, this ABC is called as a continued-fraction absorbing boundary condition (CFABC). In order to absorb propagating waves, the element must have a purely imaginary thickness since the waves have real wavenumbers in the propagating directions. This is similar to the complex-coordinate stretching that is the basic idea of the PML. Because of the underlying links between CFABC and PML [13], the CFABC can be viewed as a particular version of PML. Thus, the CFABC is also referred to as perfectly matched discrete layer (PMDL) in the literature. The PMDL preserves the both advantages of the high-order ABCs and PMLs which are mentioned above [12,14–16] and has been applied successfully to various wave-propagation problems: scalar wave propagation [11,14], dispersive acoustic wave propagation [15], elastic wave propagation [16], statics [17], wave propagation in anisotropic media [18,19], and wave propagation in a discretized domain [20]. As shown in the studies, the PMDL can be easily combined with domain-based numerical approaches such as the finite element method or finite difference method which are very powerful numerical methods for various wave propagation problems. Also, the accuracy of PMDL system can be improved to any desired degree simply by increasing the number of elements in normal directions to boundaries. Therefore, the PMDL is very effective and versatile for modeling wave propagations in various unbounded domains. Recently, it was applied to a two-dimensional soil–structure interaction analysis [21]. Specifically, the approach has been successfully applied to nonlinear soil–structure interaction problems in a plane-strain condition [22].

In this study, the PMDL system in plane strain [22] is extended further to three-dimensional nonlinear soil–structure interaction problems. A suite of three-dimensional PMDLs is developed, verified and applied to three-dimensional nonlinear problems. The dynamic stiffness from the three-dimensional PMDLs is derived and the equation of motion for a three-dimensional soil–structure interaction system is formulated in the time domain in Section 2. Section 3 describes the procedure used to determine the parameters of the three-dimensional PMDLs to represent a layered half-space effectively and accurately. In Section 4, the three-dimensional PMDLs are verified and applied to an earthquake response analysis of a typical soil–structure interaction system. The paper is summarized in Section 5.