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Research Paper

On numerical computation of impedance functions for rigid soil-structure interfaces embedded in heterogeneous half-spaces

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ABSTRACT

We present fully-discrete procedures for computing the impedance functions of rigid massless soil-structure interfaces that are embedded in arbitrarily heterogeneous half-spaces. The finite element method (FEM) is used for obtaining the wave responses of (visco-)elastic half-spaces truncated by Perfectly Matched Layers (PMLs), which provide the wave absorbing boundary conditions. The devised FEM-PML approach is verified in both time and frequency domains by using various benchmark solutions. Requirements on the prescribed input excitations for obtaining accurate impedances in the time domain as well as the relative computational cost of time- and frequency domain solutions are investigated. Accuracy of the implemented PMLs in extracting the impedance functions is also examined in comparison to Lysmer–Kuhlemeyer dashpots; and it was found that this simplified boundary treatment is generally inadequate. The utility of the proposed method is demonstrated by extracting the impedance matrix of rectangular and circular voids embedded in a linearly stiffening half-space. Impedance functions for such complex soil-structure systems are shown to be highly coupled and frequency-dependent due to wave reflections and interference caused by the soil heterogeneity and interface geometry. Fully discrete approaches, such as those proposed herein, are necessary to adequately capture these effects.

1. Introduction

Accurate quantification of dynamic soil-structure interaction (SSI) effects, induced by strong ground shaking, is critical in designing earthquake-resistant structures [1]. If SSI effects are neglected or poorly estimated, then critical response measures of a structure can be over- or under-estimated, which in turn can lead to unsafe or overly conservative designs. In general, SSI analyses are carried out by means of either the *direct* or the *substructure* methods (Fig. 1). In the direct approach (Fig. 1a), the near-field soil, the structure, and its adjacent soil are all discretized, and wave-absorbing boundary conditions (WABCs) are employed to truncate the semi-infinite far-field soil[1] [2,3]. Moreover, special considerations are needed to prescribe far-field input motions within the computational domain rigorously or approximately [see, for example, 3]. The computational cost of the direct method is often too high to be routinely utilized in the, invariably iterative, design procedures of the supported structures. The substructure method (Fig. 1b), on the other hand, is a computationally efficient approach where a reduced-order model (e.g., macro-elements comprising springs and dashpots) replaces the soil media. This method requires two ingredients: (i) the impedance function of the near-field soil and the foundation system, which is the complex-valued[2] frequency-dependent stiffness matrix relating the steady-state displacements and their corresponding reactions along the boundary of the foundation interface of the structure and the near-field soil, and (ii) the so-called foundation input motion, which is the motion that the soil-structure interface would experience in the absence of the mass of the structure under the considered seismic excitations. This motion can be computed by using the reciprocity theorem [5,6], which requires knowing the impedance functions of the soil-structure system in advance. Therefore, the substructure method relies significantly on the evaluation/knowledge of the impedance functions.

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[1] In the present study, the terms *near-field* and *far-field* refer to the soil domains inside and outside the computational domain truncated by absorbing boundaries, respectively.

[2] The real part of an impedance function corresponds to the stiffness and mass inertia effect of the soil and the imaginary part accounts for radiation damping [4].

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0266-352X/

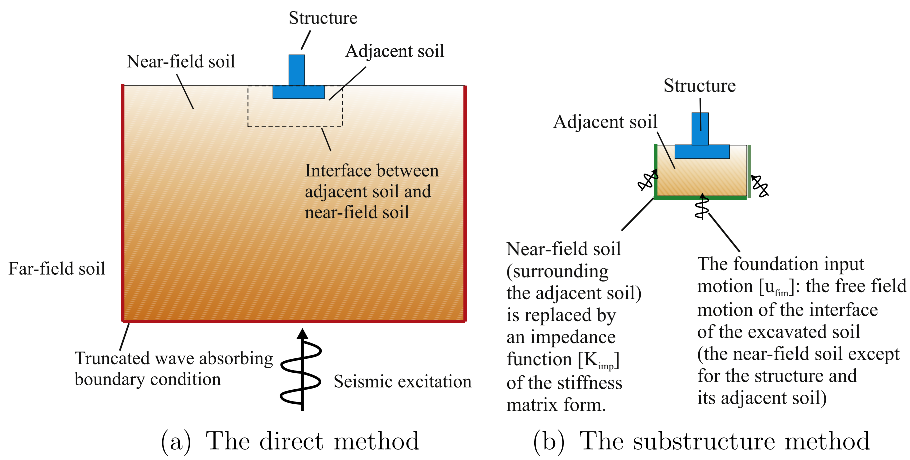

Fig. 1. The direct and substructure methods of analysis of SSI.

Table 1
A list of theoretically-obtained impedance functions available in open literature.

Authors	Analysis method	Soil profile	Foundation type	Motion
Karasudhi et al. [7]	Analytic	Homogenous elastic halfspace	Rigid, surface	V, H, R
Luco and Westmann [8]	Analytic	Homogeneous elastic halfspace	Rigid, surface	V, H, R
Gazetas [9]	Semi-analytic	Non-homogenous elastic halfspace	Rigid, surface	V, H, R
Hryniewicz [10]	Analytic	Homogeneous elastic halfspace	Rigid, surface	V, H, R
Rajapakse and Shah [11]	BEM	Homogeneous elastic halfspace	Rigid, embedded	V, H, R
Israil and Ahmad [12]	BEM	Viscoelastic layer on a viscoelastic halfspace	Rigid, embedded	V
Ahmad and Bharadwaj [13]	BEM	Viscoelastic layered halfspace	Rigid, embedded	H
Bharadwaj and Ahmad [14]	BEM	Viscoelastic layered halfspace	Rigid, embedded	R
Spyrakos and Xu [15]	BEM-FEM	Elastic layered halfspace	Flexible, embedded	V, H

In the 5-th column, V, H, and R stand for, respectively, vertical, horizontal, and rotational movements.

Quite a number of studies have been carried out since the late 1960s to compute the impedance functions for different types of soil-foundation systems (a non-exhaustive list of these studies for plane strain problems are summarized in Table 1). In these efforts, various modeling techniques were employed, including analytical and semi-analytical approaches, the boundary element method (BEM), and the coupled boundary and finite element method (BEM-FEM). As seen in Table 1, most of the available impedance functions are for relatively simple soil profiles and interface geometries. While there is a fairly large set of theoretically obtained impedance functions, along with *some* validation experiments [e.g., 16,17], it appears necessary to develop a robust and generalized method that can yield impedance functions for *any* soil profile, interface type, or geometry (rigid, flexible, surface, embedded, void, piled, etc.). Such a tool would extend the reach of the substructure method to a broader array of SSI problems, which is far more efficient, computationally, than the direct method.

In this paper, we devise a numerical approach for extracting impedance functions of general soil-structure systems, which comprises a finite element (FE) wave solver and Perfectly Matched Layers (PMLs). We employ the FEM, because it can handle interfaces with arbitrary geometries, embedded in arbitrarily heterogeneous soil media. We use the PMLs to represent the semi-infinite far-field soil—i.e., the truncated remote boundary—because they can absorb both propagating and evanescent waves, regardless of their incidence angles and frequency content. Through the use of various benchmark solutions, we also investigate the performance of this fully discrete approach. Specifically, we seek answers to the following questions:

- Is it possible to accurately extract impedance functions using an FEM-PML wave solver for a broad range of frequencies?
- Is it better to carry the computations in the time- or the frequency-domain?
- What is the best input signal for extracting the impedance function when the time-domain wave solver is used?
- What is the performance, as WABC while extracting the impedance functions, of the PML as compared to the widely used Lysmer–Kuhlemeyer (LK) [18] dashpots?

While the focus here will be on rigid interfaces and two-dimensional (2D)—i.e., plane-strain—problems, the proposed approach and the findings from the present study should apply equally well to flexible interfaces and three-dimensional problems.

The remainder of this manuscript is organized as follows: In Section 2, we describe the finite element modeling procedures to obtain the wave response in a PML-truncated elastic solid domain. In Section 3, we delineate the steps of a general procedure to evaluate the impedance functions in both time and frequency domains. In Section 4, we verify the proposed numerical approach using various existing (semi-)analytical solutions, and in Section 5, we investigate the efficiency and accuracy of PMLs against LK dashpots. Finally, in Section 6, we present a set of results for rectangular and circular voids embedded in a soil domain with a linearly depth-dependent stiffness to explore the effects of interface geometry and soil heterogeneity on impedance functions. Concluding remarks are provided in Section 7.

2. Finite element modeling of the forward problem

PMLs are used to serve as WABCs for modeling wave propagation in an elastic heterogeneous semi-infinite solid medium (soil). The central idea in the PML formulation is to use a finite-sized