Soil Dynamics and Earthquake Engineering 89 (2016) 85–90

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Boundary reaction method for nonlinear analysis of soil–structure interaction under earthquake loads

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ARTICLE INFO

Article history:
Received 30 May 2016
Received in revised form
26 July 2016
Accepted 27 July 2016

Keywords:
Nonlinear soil–structure interaction
BRM (boundary reaction method)
Base-isolated nuclear power plant
Hybrid frequency–time domain method
Nonlinear soil

ABSTRACT

This paper presents a boundary reaction method (BRM) for nonlinear time domain analysis of soil–structure interaction (SSI) under incident seismic waves. The BRM is a hybrid frequency–time domain method, but it removes global iterations between frequency and time domain analyses commonly required in the hybrid approach, so that it operates as a two-step uncoupled method. Specifically, the nonlinear SSI system is represented as a simple summation of two substructures as follows: (I) wave scattering substructure subjected to incident seismic waves to calculate boundary reaction forces on the fixed interface boundary between a finite nonlinear structure-soil body and an unbounded linear domain; and (II) wave radiation substructure subjected to the boundary reaction forces in which the nonlinearities can be considered. The nonlinear responses in the structure–soil body can be obtained by solving the radiation problem in the time domain using a general-purpose nonlinear finite element code that can simulate absorbing boundary conditions, while the boundary reaction forces can be easily calculated by solving the linear scattering problem by means of a standard frequency domain SSI code. The BRM is verified by comparing the numerical results obtained by the proposed BRM and the conventional frequency-domain SSI analysis for an equivalent linear SSI system. Finally, the BRM is applied to the nonlinear time-domain seismic analysis of a base-isolated nuclear power plant structure supported by a layered soil medium. The numerical results showed that the proposed method is very effective for nonlinear time-domain SSI analyses of nonlinear structure-soil system subjected to earthquake loadings.

1. Introduction

Generally, a soil–structure interaction (SSI) analysis finds a solution in the frequency domain to consider the radiation of elastic waves transmitted to infinite region [1]. Because the analysis methods in the frequency domain commonly use the superposition principle, linear elasticity is assumed for the structure and the soil. Accordingly, a typical SSI analysis program used to analyze the viscoelastic behavior seems to be inadequate for direct application in nonlinear SSI analyses such as seismic analysis of base-isolated nuclear power plant structures [2].

To consider nonlinear behavior in an SSI analysis, the equivalent linear frequency-domain analysis [3–5], hybrid frequency–time domain (HFTD) analysis [6], and hybrid time–frequency domain (HTFD) analysis [7] have widely been employed as well as time domain techniques such as direct approaches [8] and substructure methods [9–11]. However, both hybrid approaches cannot derive the numerical results at once, the HFTD method repeats the analysis until the error in the nonlinear restoring force is reduced and the HTFD method reiterates the analysis until the error in the interacting force becomes small. Likewise, direct procedure has a lot of degrees of freedom in the soil region resulting in significant running time. Recently, a method concurrently applying the domain reduction method (DRM) [10] and the perfectly matched layer (PML) [11,12] has been developed. However, there are still very few general-purpose finite element analysis programs providing such nonlinear SSI analysis function.

This paper proposes a boundary reaction method (BRM) based on the fixed boundary wave input method [4] as an uncoupled HTFD method, which operates in two steps without any need for iterative process and enables simultaneous consideration of the nonlinearity and the SSI. The BRM combines a linear SSI analysis in the frequency domain with a time domain finite element analysis program capable of executing the nonlinear analysis so as to conduct the nonlinear SSI analysis. The BRM is verified by comparing the numerical results obtained by the proposed BRM and the

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http://dx.doi.org/10.1016/j.soildyn.2016.07.020
0267-7261/

conventional frequency-domain SSI analysis for an equivalent linear SSI system. Finally, the proposed BRM is applied for the nonlinear SSI analysis of a base-isolated nuclear power plant (NPP) structure to demonstrate the accuracy and effectiveness of the method.

2. Boundary reaction method for nonlinear SSI analysis

Let us consider a structure–soil body that behaves nonlinearly and is supported by a linear elastic near- and far-field bodies subjected to incident seismic waves as shown in Fig. 1(a). If the nonlinear structure–soil body is separated from the linear soil parts, the corresponding equation of motion can be expressed as

$$\begin{Bmatrix} \mathbf{f}_s^{NL}(t) \\ \mathbf{f}_b^{NL}(t) \\ \mathbf{0} \\ \mathbf{0} \end{Bmatrix} + \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_{bb} & \mathbf{M}_{bn} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_{nb} & \mathbf{M}_{nn} & \mathbf{M}_{ne} \\ \mathbf{0} & \mathbf{0} & \mathbf{M}_{en} & \mathbf{M}_{ee} \end{bmatrix} \begin{Bmatrix} \ddot{\mathbf{u}}_s^t(t) \\ \ddot{\mathbf{u}}_b^t(t) \\ \ddot{\mathbf{u}}_n^t(t) \\ \ddot{\mathbf{u}}_e^t(t) \end{Bmatrix} + \begin{bmatrix} \mathbf{0} & \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{bb} & \mathbf{K}_{bn} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{nb} & \mathbf{K}_{nn} & \mathbf{K}_{ne} \\ \mathbf{0} & \mathbf{0} & \mathbf{K}_{en} & \mathbf{K}_{ee} \end{bmatrix} \begin{Bmatrix} \mathbf{u}_s^t(t) \\ \mathbf{u}_b^t(t) \\ \mathbf{u}_n^t(t) \\ \mathbf{u}_e^t(t) \end{Bmatrix} = \begin{Bmatrix} \mathbf{0} \\ \mathbf{0} \\ \mathbf{0} \\ \mathbf{r}_e^t(t) \end{Bmatrix} \tag{1}$$

where $\mathbf{f}^{NL}(t)$ is a dynamic resultant force vector acting on nodes in the nonlinear structure–soil region including inertia force, damping force, nonlinear restoring force, and so on; $\mathbf{u}^t(t)$, $\dot{\mathbf{u}}^t(t)$, and $\ddot{\mathbf{u}}^t(t)$ are respectively total displacement, velocity, and acceleration vectors as measured from a fixed reference; $\mathbf{r}^t(t)$ denotes the interacting force vector at the interface of two adjacent bodies; $\mathbf{M}$ and $\mathbf{K}$ are respectively mass and stiffness matrices in the linear body; the superscript NL stands for the contribution of the nonlinear structure–soil body; and the subscripts s, b, n, and e represent the degrees of freedom at nodes in bodies or on interface boundaries as depicted in Fig. 1(a). Note that the damping force in the linear region is neglected in Eq. (1) for simplicity. If the nonlinear force vector $\mathbf{f}^{NL}(t)$ in Eq. (1) is approximated as a linear combination of the total response vectors ($\mathbf{u}^t(t)$, $\dot{\mathbf{u}}^t(t)$, and $\ddot{\mathbf{u}}^t(t)$), the solution of Eq. (1) can be obtained by standard SSI techniques, such as boundary element method [13], and finite element method coupled with transmitting boundary element [3] or with dynamic infinite element [4,5], either in the frequency domain or in the time domain.

The nonlinear SSI problem in Fig. 1(a) can be described by the superposition of substructure (I), whose nodes on the nonlinear–linear interface are fixed as shown in Fig. 1(b), and substructure (II) of Fig. 1(c), which is defined as a subtraction of the substructure (I) from the nonlinear SSI problem in Fig. 1(a). Thus, the total solution can be obtained by simple summation as

$$\mathbf{u}^t(t) = \mathbf{u}^i(t) + \mathbf{u}^{ii}(t) \tag{2}$$

where the superscripts i and ii stand for the substructure (I) and the substructure (II), respectively, and the motions within the nonlinear body in the substructure (I) are zero, i.e.,

$$\mathbf{u}_s^i(t) = \mathbf{0} \quad \text{and} \quad \mathbf{u}_b^i(t) = \mathbf{0} \tag{3}$$

As a result of the superposition of the two substructures, the equations of motion for the substructures can be expressed as

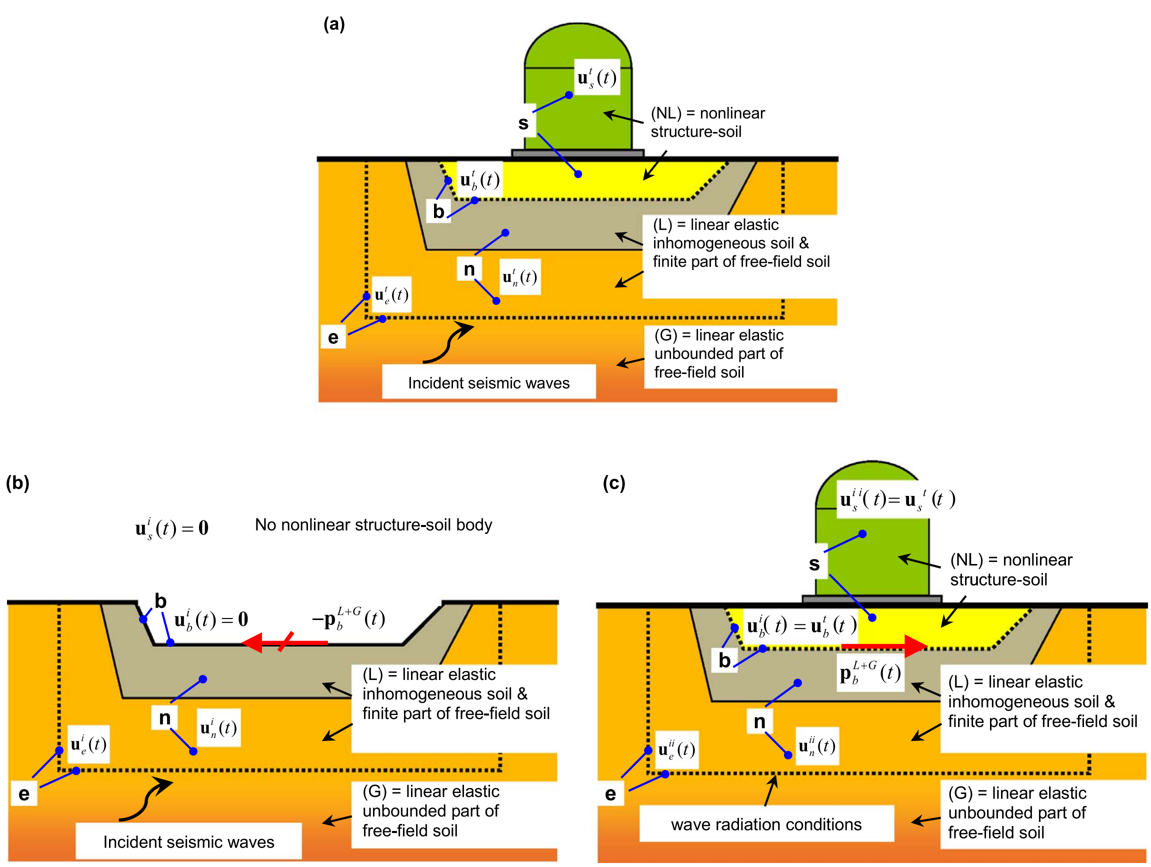

Fig. 1. Concept of boundary reaction method proposed in this study.