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A practical and efficient coupling method for large scale soil–structure interaction problems

Surong Huang [a], Ozgur Ozcelik [b], Quan Gu [c,d,*]

[a] Department of Aeronautics, Xiamen University, Fujian 361005, China
[b] Department of Civil Engineering, Dokuz Eylul University, Izmir 35397, Turkey
[c] Department of Civil Engineering, Xiamen University, Xiamen, Fujian 361005, China
[d] High-speed railway construction technology of the National Engineering Laboratory, China

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ABSTRACT

A practical and efficient coupling method for performing nonlinear static pushover or time history analysis for soil–structure interaction (SSI) systems is presented. The method combines the advantages of efficient analysis of a half-space soil medium represented as discrete filters and powerful modeling capabilities of finite element analysis (FEA) software for large scale nonlinear structural systems, thus is potentially useful for solving large scale realistic civil infrastructure problems. The boundary conditions of displacement continuity and force equilibrium between soil and structure are satisfied by using Newton's method. The coupling between the two substructures is based on a real-time data communication technique called the client–server (CS) integration technique. A comprehensive study is made regarding the newly developed coupling method by using a single- and a multi- degree of freedom structure and soil systems, as well as a real world SSI example. Several details are discussed, including the effect of simulation time step sizes, comparison of implicit and explicit methods, effects of increasing nonlinearity in the SSI system, and the nonlinear seismic responses of the SSI systems in cases of considering vs. not considering SSI effect. This paper proposes a practical and efficient method for nonlinear static pushover or seismic analysis of large scale SSI systems, and part of the research results provides valuable insight for engineering practice.

1. Introduction

Structural response to free-field earthquake motion is affected by soil structure interaction (SSI). SSI effect plays a very crucial role in nonlinear structural analysis [1]. The main effects of SSI on the structural responses are that SSI increases the dominant natural period of the system therefore modifies effective eathquake excitation, filters the high frequency components in the ground motion, and increases system damping due to wave radiation and damping in the soil [2]. Regardless of the presence of a structure, the local soil conditions may change significantly, and through their dynamic filtering effects the earthquake motion from the bedrock level to the ground surface may differ substantially. Past analytical and experimental research as well as field observations and measurements have shown that the response of a structure to earthquake motion on a deformable soil can be significantly different from the response of the same structure on a rigid foundation [3–11]. SSI may have beneficial or detrimental effects on the response of superstructures, depending on the characteristics of earthquake motion, soil, foundation and super structures. It is very hard to draw general conclusions about the SSI effect on the system during seismic motions [12–16]. Therefore, an accurate assessment of structural responses (e.g., inertial forces and deformations) requires a careful treatment of SSI effects.

Numerical formulations for SSI are various. Two- and three-dimensional finite-element analyses (FEAs) are capable of incorporating fully nonlinear dynamic modeling of SSI system where soil, foundation and structure are modeled as whole system and analyzed in a single step [17–21]; another class of methods include simplified nonlinear substructure approaches [22–24] and simplified linear substructure-based techniques suitable for use in design codes [25,26]. Many past research work on SSI are based on the substructuring approach where linear substructures (soil, foundation and structure) are formulated in the frequency domain. When compared with structure-only systems, the resonant frequency of linear soil—linear single degree of freedom (SDOF) structure system decreases and the peak response usually decreases due to a greater

* Corresponding author at: Department of Civil Engineering, Xiamen University, Xiamen, Fujian 361005, China. Tel.: +86 592 2188958; fax: +86 592 2186421.
E-mail address: quangu@xmu.edu.cn (Q. Gu).

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effective damping ratio [27]. The main disadvantage of the linear sub-structuring technique is that it cannot be used to simulate the real nonlinear structural responses.

In last decades, performance-based earthquake engineering (PBEE) has emerged as a new analysis and design philosophy in earthquake engineering requiring nonlinear analysis [28–30]. PBEE requires an in-depth understanding of the earthquake response of SSI systems. The superstructure and soil need to be modeled as realisticly as possible with material and possibly geometric non-linearities. However, advanced nonlinear models where surrounding soil, foundation and structure are all modeled as a whole system with realistic nonlinear constitutive models have big disadvantages that great amount of time is required for performing a nonlinear seismic analysis.

In this context, the paper provides a novel analysis framework based on sub-structuring method in time domain where the superstructure can be modeled as realistic as possible to meet the requirement by new design approaches such as PBEE using FEA software. The method combines the powerful modeling capabilities of FEA software with the simplicity of modeling the soil medium using discrete time recursive filters, and therefore is potentially useful to large scale linear/nonlinear SSI problems. The main contribution of the current paper is: (1) A novel coupling method for nonlinear SSI analysis is presented, with both implicit and explicit methods developed. (2) A matrix of coupled frequency dependent compliance functions are represented in time domain by a discrete recursive soil filter method. (3) Analytical solution to MDOF linear structure-rigid foundation-linear half space soil systems is derived in frequency domain. (4) A comprehensive study to the method is made by SDOF/MDOF structure–soil systems and a Millikan Library SSI example.

2. The coupling method based on substructure method

In this section, a novel practical analysis framework is presented for solving a wide class of SSI problems in time domain based on the sub-structure method. The analytically obtained frequency dependent compliance functions of a rigid foundation sitting on a uniform elastic half-space is modeled in time domain using discrete-time recursive filters [16]; and the superstructure is modeled by using finite element analysis (FEA) software, such as OpenSees [31]. OpenSees (Open System for Earthquake Engineering Simulation) is an open source FEA software used to model structural systems and simulates their earthquake responses. In the following sections, the coupling method is presented in details. Firstly, a time domain representation of the frequency dependent compliance matrix is obtained by using a discrete recursive soil filter. Secondly, an implicit algorithm based on Newton's method is designed to achieve the displacement continuity and force equilibrium between boundaries of the soil and structure. Thirdly, an efficient and practical integration technique for coupling FEA software and SSI framework (i.e., the client–server, or CS technique) is described briefly.

2.1. Time domain representation of the closed form solution of SSI systems in frequency domain

The coupling between the soil and structure is done in time domain using the sub-structure method. The total response $\mathbf{u}$ of the rigid foundation at a reference point can be written as

$$\mathbf{u}=\mathbf{u}_g+\mathbf{u}_s \tag{1}$$

where $\mathbf{u}_g$ is the free field input motion and $\mathbf{u}_s$ is the additional motion of the foundation due to the generalized forces and moments that the rigid foundation exerts on the soil. The motion $\mathbf{u}_s$ is given by

$$\mathbf{u}_s=\mathbf{C}(\omega)\mathbf{F}_s \tag{2}$$

where $\mathbf{C}(\omega)$ is the compliance matrix for a rigid foundation embedded in a soil medium. This matrix is frequency dependent, affected by the geometry of foundation and the characteristics of soil [4]. Notice that the compliance function is the inverse of the impedance matrix (i.e., $\mathbf{C}(\omega)=\mathbf{K}(\omega)^{-1}$). For different soil types and foundation geometry, analytical procedures are available in the literature for computation of impedance functions for rigid foundations [4,31,32]. $\mathbf{F}_s$ is the generalized force vector that the rigid foundation exerts on the soil. This force can be computed as follows:

$$\mathbf{F}_s=\mathbf{M}_0\ddot{\mathbf{u}}+\mathbf{F}_b \tag{3}$$

where $\mathbf{M}_0$ is the mass matrix of the rigid foundation and $\mathbf{F}_b$ is the generalized force vector that the superstructure exerts on the foundation. In the coupling method described in this paper, the generalized force vector $\mathbf{F}_b$ in time domain is computed by the FEA software, i.e., OpenSees in this paper.

In order to perform time domain analysis of the SSI system, it is necessary to transform the frequency domain compliance matrix $\mathbf{C}(\omega)$ into time domain, in order to incorporate SSI effects in standard time-history analysis. In this paper, the frequency dependent compliance functions (a matrix) are represented in time domain by extending the existing approach for representing soil as discrete recursive filters [16] which considers only one impedance function at a time. To illustrate the proposed method, a two dimensional (2D) analytical compliance functions for a rigid square foundation embedded in uniform elastic half-space is represented in time domain as follows:

$$\mathbf{u}_s=\begin{Bmatrix} u_B \\ a\theta_B \end{Bmatrix}=\frac{1}{Ga}\begin{bmatrix} k_{HH} & k_{HM} \\ k_{HM} & k_{MM} \end{bmatrix}^{-1}\begin{Bmatrix} H_S \\ \frac{M_S}{a} \end{Bmatrix}=\begin{bmatrix} C_{HH} & C_{HM} \\ C_{HM} & C_{MM} \end{bmatrix}\begin{Bmatrix} H_S \\ \frac{M_S}{a} \end{Bmatrix}=\mathbf{C}(\omega)\mathbf{F}_s \tag{4}$$

where a is the half-width of the foundation, u_B and θ_B are horizontal displacement and rotation of foundation, respectively; k_{ij} and C_{ij} (i, j=H, M for horizontal and rotational motions) are the frequency dependent impedance and compliance functions, respectively;H_s and M_s are the horizontal force and moment acting on the soil. Recursive discrete-time filters can be fitted using weighted least-squares method for each element of the compliance matrix $\mathbf{C}(\omega)$ for a range of dimensionless frequencies. By doing so, the compliance function $\mathbf{C}(\omega)$ can be represented in time-domain by specifying relationship between a displacement sequences and a force sequences as follows:

$$\begin{aligned} u_1(t)=&[b_0F_1(t)+b_1F_1(t-1)+\cdots\cdots+b_kF_1(t-k)]\frac{1}{Ga}\\ &+[c_0F_2(t)+c_1F_2(t-1)+\cdots\cdots+c_lF_2(t-l)]\frac{1}{Ga}\\ &-a_1u_1(t-1)-a_2u_1(t-2)-\cdots\cdots-a_mu_1(t-m) \end{aligned} \tag{5a}$$

$$\begin{aligned} u_2(t)=&[e_0F_1(t)+e_1F_1(t-1)+\cdots\cdots+e_rF_1(t-r)]\frac{1}{Ga}\\ &+[h_0F_2(t)+h_1F_2(t-1)+\cdots\cdots+h_sF_2(t-s)]\frac{1}{Ga}\\ &-d_1u_2(t-1)-d_2u_2(t-2)-\cdots\cdots-d_nu_2(t-n) \end{aligned} \tag{5b}$$

Where $u_i$and F_i are component of displacement and generalized force, respectively; a_j, b_j, c_j, d_j, e_j, h_j are estimated constant discrete filter coefficients, m, k, l and r, s, n denote numbers of the force or displacement sequences. Notice that the current output is a linear combination of current and past forces and past displacement responses. The functions $F(t-r)$ and $u(t-r)$denotes the generalized force and displacement at time $t-r$step. Using Fourier transformation and defining $Z=e^{i\omega\Delta}$ where Δ is the time interval between two sequential steps. Then