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Efficient time-domain deconvolution of seismic ground motions using the equivalent-linear method for soil-structure interaction analyses

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ABSTRACT

Deconvolution is the process that evaluates the seismic motion at depth of a soil profile, which can then be used as input excitation in soil-structure interaction (SSI) analyses. Clearly, the reliability of the SSI analysis depends on the precision of the derived deconvolved motions at depth. In this paper, the phase-amplitude modification procedure is presented to deconvolve both horizontal and vertical target (design) surface ground motions in multi-layered, equivalent-linear viscoelastic media for use in finite element time-domain structural analyses. The aim is to determine the seismic motions at the appropriate depth in the soil profile by modifying the target surface ground motions based on the mathematical model of the system, which is assessed by analyzing input-output data. The nonlinear behavior of the soil layers is approximated by employing the equivalent soil properties in the finite element model. The exact solution of vertical wave propagation, obtained with the SHAKE software, is used as a guide to obtain the equivalent properties of the soil layers, and evaluate the damping ratios. The procedure is validated using a multi-layered soil profile. The numerical results demonstrate that the convolved surface ground motions from the finite element analysis and the target ones are in almost perfect agreement, indicating that the approach can be used for reliable SSI evaluation in finite element time-domain analyses. Furthermore, the results indicate that the use of the deconvolved base motions resulting from SHAKE and applied directly in the finite element time-domain analysis may result in considerable error. In addition, the examination of different models of Rayleigh damping suggested that the optimized Rayleigh damping can decrease the frequency-dependency of the damping at high frequencies, which is more compatible with the frequency-independent behavior of soils, as verified experimentally by several researchers.

1. Introduction

The accurate evaluation of the seismic ground response is one of the most important issues in both geotechnical and structural engineering problems, the later involving SSI analyses [1]. Several methods have been developed to evaluate the seismic ground response by analyzing the one-dimensional propagation of shear (S-) waves in horizontally layered media. These methods can be categorized into two main groups: frequency- [2] and time-domain analyses [3].

In the frequency-domain techniques (e.g. SHAKE [2] and SHAKE91 [4] codes), the seismic ground response is computed based on the closed form solution of vertical shear wave propagation in a layered continuous medium (Fig. 1a). The soil nonlinearity is considered by employing the equivalent-linear approach in the frequency domain [2]. The soil damping is assumed to be hysteretic, strain-compatible, and frequency-independent. These methods can be used for both the convolution (i.e. propagation of seismic motion from a location at depth to the ground surface), and the deconvolution (i.e. inverse propagation of the surface ground motion to a location at depth). Their main limitation is the assumption of constant soil properties (shear modulus and damping within each layer). Some studies suggested that when the material parameters are selected to be strain-compatible (SHAKE-like approaches), the damping [5] and maximum shear strength [6] at high frequencies are over-estimated.

In the time-domain analysis methods, the soil column is discretized into multi-degree-of-freedom lumped models or finite elements, the dynamic equations of motion are solved [7] and, hence, the nonlinear behavior of soils can be modeled precisely. Several codes generated for this purpose (e.g. DESRA [8]; DEEPSOIL [9]; D-MOD2000 [10]), as well as general purpose finite element method (FEM) software, are available to perform one-dimensional (1-D) nonlinear time-domain response analyses. However, these approaches can be used only for the convolution of seismic motions.

Kramer [24] indicated that, in many cases, the predicted ground response by 1-D analyses is in reasonable agreement with recorded motions. Nonetheless, recent studies [11,12] on seismic downhole-

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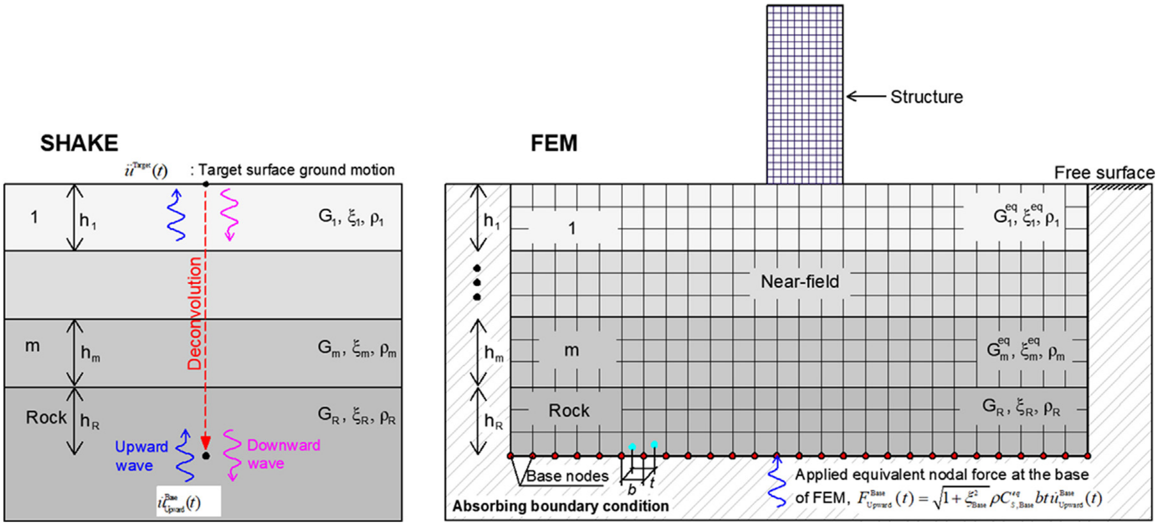

(a) 1-D soil profile model in SHAKE

(b) Application of deconvolved base motion from SHAKE in the FEM

Fig. 1. Deconvolution procedure using the frequency-domain solution (SHAKE) and its application in FEM.

array data suggested that, in some cases, the 1-D analyses reproduce poorly the observed ground motions.

For a realistic time-history structural response evaluation including SSI, the seismic excitation needs to be applied at the base of the finite domain of the soil profile (Fig. 1b). Seismic ground motions at depth are rarely available. Alternatively, the appropriate base motion can be determined by deconvolving the target surface motion using frequency-domain analyses or data processing techniques.

Conventionally, the frequency-domain solution (SHAKE program [2,4]) is used to deconvolve the surface ground motions for the dynamic analysis of structures, including nuclear power plants [13,14], concrete dams [15,16], bridges [17,18], etc. There are a number of issues regarding the use of SHAKE to deconvolve the surface ground motions for subsequent use in a finite element time-domain analysis. The main issues are that the damping formulation and the solution approach in the FEM and SHAKE programs are quite different. As a result, if the deconvolved motion is applied at the base of the discrete finite element model, discrepancies between the convolved motion from the FEM analysis and the target one are expected. The inconsistently of the boundary conditions between the FEM and SHAKE programs is another source of discrepancy. An additional issue is that the SHAKE program can be used only for the deconvolution of the horizontal component of the seismic motion [2]. However, the vertical component should be also considered in certain structural response evaluations, and, thus, needs also to be deconvolved.

Data processing techniques are alternative methods to deconvolve the seismic motions. Reimer [19] suggested that the deconvolved base motions for linear systems can be determined by adjusting the Fourier transform of the surface ground motion applied at the base of the foundation to obtain the appropriate response at the free surface. Similarly, Ju [20] applied this concept to nonlinear systems and recommended an iterative scheme to deconvolve the seismic motions. Since the Drucker–Prager elasto-plastic criterion was used to model the soil nonlinearity, several iterations were required to obtain suitable results. Rajasankar et al. [21] also used the concept of transfer functions to transform the input target excitation at the surface level to a corresponding one at a specified depth of an elastic half-space. Sooch and Bagchi [22] showed that the adjustment of the Fourier amplitude is not effective for all types of seismic records, and suggested that the adjustment of the response spectrum can yield better results. Such analyses can be easily performed in the frequency domain, but become very difficult in the time domain [23].

In this paper, a phase-amplitude modification procedure is proposed which is suitable to deconvolve both horizontal and vertical seismic components in linear viscoelastic media by means of FEM. The method can be extended to nonlinear soil response problems by means of equivalent linearization. In addition, an efficient optimization methodology is presented to minimize the variation of the frequency-dependent Rayleigh damping, utilized in FEM formulations, to the more realistic frequency-independent one over the frequency range of interest.

2. Deconvolution of shear waves in the frequency domain (SHAKE)

The frequency-domain solution has been widely used to deconvolve seismic motions. The basic idea of the deconvolution process in the frequency domain is to generate motions at a given depth in the soil profile by utilizing the concept of inverse transfer functions [24]. A transfer function relates the surface ground motion to the motion at any given depth, and is computed based on the closed form solution of vertical shear wave propagation in a layered, continuous medium. It is further assumed that the soil behaves as a Kelvin-Voigt solid. The governing equation of motion for vertically propagating SH-waves can be expressed as [24]:

$$\rho\frac{\partial^2 u}{\partial t^2} = G^*\frac{\partial^2 u}{\partial z^2} \tag{1}$$

where $G^* = G\ (1\ +\ 2\,i\,\xi)$ is the complex shear modulus, and ρ and ξ are the density and damping ratio, respectively. For a time-harmonic excitation, the solution of Eq. (1) becomes:

$$u\ (z\ ,\ t)\ =A\ \exp\ (i\omega t\ +\ ik^*z)\ +\ B\ \exp\ (i\omega\ t\ -\ ik^*z) \tag{2}$$

where ω and t are the angular frequency and time, respectively, and $k^* = \sqrt{\rho\ \omega^2/G^*}$ represents the complex wavenumber. The first term in Eq. (3), $A\ \exp\ (\,i\omega t\ +\ ik^*z)$, expresses an incident (upward traveling) harmonic wave with amplitude A, whereas the second term, $B\ \exp\ (\,i\omega\ t\ -\ ik^*z)$, expresses a reflected (downward traveling) harmonic wave with amplitude B.

For harmonic waves, the shear stress can be defined as: