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Research Paper

Identification of soil dynamic properties through an optimization analysis

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ABSTRACT

An identification technique is used to estimate the nonlinear dynamic properties of a soil deposit using the acceleration records provided by a vertical (downhole) array along with a nonlinear least squares optimization algorithm. The technique employs non-parametric estimates of the shear stresses derived from the recorded accelerations; therefore, it does not require the forward modeling of the whole soil deposit. Soil properties are described by a hyperbolic shear stress–strain relation. A multi-surface plasticity approach is used to model the stress–strain relation. Convergence and accuracy of the identification technique are assessed using numerical simulations. Two centrifuge experiments are used to validate and demonstrate the capabilities of the technique to estimate the stiffness and damping ratio profiles of a site subjected to base excitation. Performance of the technique is also evaluated using field data corresponding to the 1987 Superstition Hills earthquake recordings from the Wildlife Liquefaction Array at the Imperial Valley in Southern California. The identification results were found to be in good agreement with direct measurements of shear wave velocities.

1. Introduction

The seismic response of sites is strongly dependent on the dynamic properties of the associated soil layers. In turn, this response has significant effects on the performance of embedded or overlying structures. Identification and inverse problem techniques play an important role in estimating in situ soil parameters, and calibrating models of the dynamic response of soil systems. An increasing number of geotechnical system identification studies have been undertaken recently, motivated by the growing availability of high quality laboratory as well as field data [1–6]. In geotechnical earthquake engineering, noteworthy identification efforts were linked to the recent availability of high quality seismic records of sites equipped with vertical (downhole) accelerometer arrays [7–11]. The current state-of-the-art in centrifuge model testing also relies on vertical arrays of acceleration and pore-pressure sensors [13,14]. Oskay and Zeghal [15], and Hashash et al. [16] included comprehensive reviews of system identification approaches in geotechnical earthquake engineering problems.

This paper presents a technique to streamline the identification of the elastoplastic stiffness parameters and damping ratio of a soil deposit using acceleration records provided by a vertical array. The following sections provide an outline of the technique. Results of the identification analysis and validation of the technique are presented thereafter.

2. System identification technique

Several techniques have been developed in the past for the in situ identification of large-strain dynamic soil properties using downhole array seismogram recordings. Zeghal, Elgamal and co-workers [7,18,19], for instance, proposed a methodology for the direct evaluation of non-parametric estimates of the associated shear stresses and strains at several depth locations using the accelerations provided by vertical (downhole) arrays under conditions of vertical wave propagation. The estimates of stress and strain are then employed to determine the associated variation of stiffness and damping with the level of strain amplitude. These previous identification strategies [7,12,18] implemented an equivalent linear approach. Such an approach provides valuable information, but does not fully account for the nonlinear and path dependent soil response. Tsai and Hashash [42,41], on the other

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hand, and more recently Groholski et al. [40,11], implemented an inverse analysis framework, referred to as self-learning simulations (SelfSim), that uses downhole array data during the shaking of a site to develop a neural network-based material constitutive model. This technique has been successfully applied on field data for the identification of shear modulus degradation with respect to excess pore water pressures [11]. Additionally, Assimaki et al. [10], presented a full waveform inversion algorithm of downhole array seismogram recordings to estimate the inelastic soil behavior in situ during earthquake ground motion. That work incorporated previous developments by which a global optimization scheme was employed to estimate low-strain soil properties of instrumented sites [37–39].

This paper incorporates the methodology for estimation of shear stresses and strains proposed by Zeghal, Elgamal and coworkers [7,18,19], but it introduces an alternative nonlinear technique to characterize the shear stress–strain response. This methodology results advantageous in that it does not require the forward modeling of the whole soil deposit. The technique employs a hyperbolic relationship [24] to model the material shear stress–strain backbone curve along with the Masing criterion [17] to handle the cyclic response during dynamic excitations. Unlike previous works, this technique employs a multi-surface plasticity model. Such an approach provides high versatility in the description of the desired stress–strain curves. Furthermore, the implemented constitutive model characterizes both the low-strain and the nonlinear parameters of the soil. A gradient-based optimization algorithm iteratively searches for material model parameters that provide an optimal fit to the shear stress time histories obtained from the vertical array accelerations. The soil is characterized in terms of solely two parameters. This allows for a simpler and more intuitive representation of the soil's behavior and of the sensitivity of the fitness of the identification to the model parameters, compared to previous identification schemes. The identification process is shown schematically in Fig. 1. The different components of the algorithm are explained in the following sections.

2.1. Estimation of dynamic shear-strain histories

The equations of motion of a soil deposit experiencing only lateral displacements may be idealized using a shear beam model (Fig. 2):

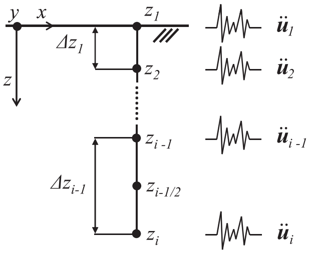

Fig. 2. Schematic of a vertical array of accelerometers.

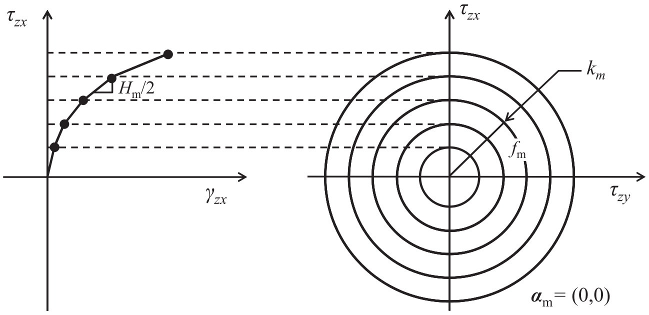

Fig. 3. Relationship between the backbone curve and initial parameters of the nested yield surfaces.

$$\frac{\partial \boldsymbol{\tau}}{\partial z} = \rho \ddot{\mathbf{u}}, \quad \text{with boundary condition } |\boldsymbol{\tau}(0,t)| = 0 \tag{1}$$

where t is time, z is depth, $\boldsymbol{\tau} = \boldsymbol{\tau}(z,t) = \{\tau_{zx}(z,t), \tau_{zy}(z,t)\}$ is horizontal shear stress vector, and $\ddot{\mathbf{u}} = \ddot{\mathbf{u}}(z,t) = \{\ddot{u}_x(z,t), \ddot{u}_y(z,t)\}$ is horizontal acceleration vector.

Integrating the equation of motion and using the stress free surface boundary condition (Eq. (1)), the shear stress at any level z may be evaluated using:

$$\boldsymbol{\tau}(z,t) = \int_0^z \rho \ddot{\mathbf{u}}\, dz \tag{2}$$

Employing linear interpolation between downhole accelerations, the discrete counterpart of shear stress at level z_i (of the ith accelerometer of a vertical array), reduces to:

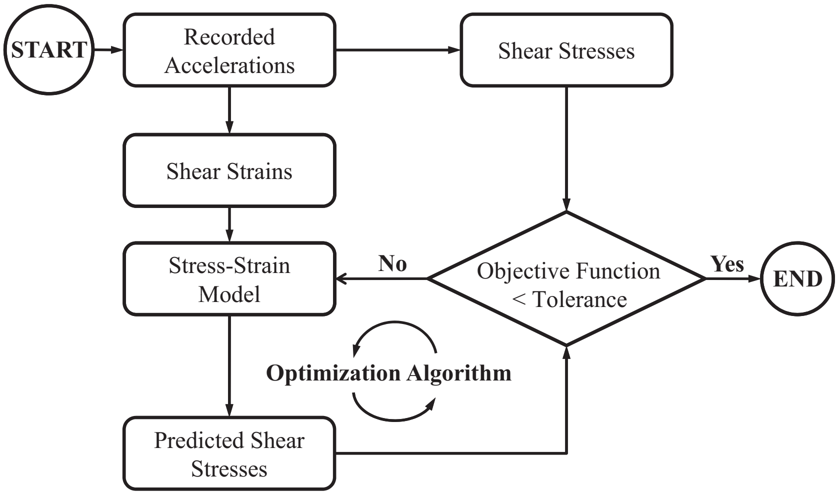

Fig. 1. Schematic of the employed identification algorithm (the objective function is a measure of the discrepancy between shear stresses estimated from acceleration records and shear stresses predicted by the employed soil model).