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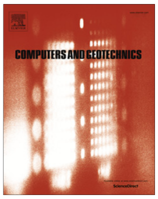

Research Paper

Characterization of the contractive and pore pressure behavior of saturated sand deposits under seismic loading

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ABSTRACT

This paper presents an identification technique to characterize the contractive and pore pressure behavior of loose sandy soils under seismic excitation. The technique relies on acceleration and pore pressure records provided during excitation by vertical arrays of accelerometers and pore pressure sensors. The technique employs non-parametric estimates of shear stresses and strains. A multi-surface plasticity approach is used to model the soil response. A reduced scale centrifuge model and a large scale experiment are used to demonstrate the capabilities of the developed technique. The technique allows for a more complete interpretation of the coupled shear–volume behavior of a soil deposit.

1. Introduction

Earthquake induced liquefaction of sandy soils has been the cause of severe damage to buildings and other structures all over the world, as shown again by recent earthquakes in Haiti (2010), Chile (2015), Japan (2011) and New Zealand (2010). Earthquake shaking generates cyclic shear loading which leads loose sand to contract, resulting in a transfer of normal stresses from sand grains to pore water. This is particularly true if the sand is fully saturated and unable to drain rapidly during shaking. This results in an overall reduction in the effective stress and hence, reduction in the shear stiffness and shear strength of the sand resulting in large deformation of the soil deposit and the damage or even destruction of supported structures [1]. Extensive efforts have been exerted by researchers and practitioners trying to predict the liquefaction behavior of sandy deposits for the purpose of assessment of safety and integrity of new and existing structures.

Along these lines, several researchers have developed a variety of system identification techniques in order to characterize the dynamic soil behavior and the associated pore pressure response. These developments have been possible due to the recent availability of high quality seismic records of sites equipped with vertical (downhole) arrays of accelerometers and pore-pressure sensors (e.g., [2–6]). The current state-of-the-art in centrifuge model testing and large scale testing of soil deposits also relies on vertical arrays of acceleration and pore-pressure sensors (e.g., [7–11]).

Developed inverse analysis techniques for identification of dynamic soil behavior include efforts by Zeghal et al. [2,12] for the direct evaluation of non-parametric estimates of shear stresses and strains using the accelerations provided by vertical (downhole) arrays. Additionally, Assimaki et al. [5], presented a full waveform inversion algorithm of downhole array seismogram recordings to estimate the inelastic behavior of soil deposits during earthquake ground motion. This work used a global optimization scheme to estimate low-strain soil properties of instrumented sites [13–15]. Tsai and Hashash [16,17] introduced a self-learning inverse analysis algorithm (SelfSim), that can learn and extract soil behavior from recorded events using neural networks.

Downhole array data has also been used to explore the pore pressures generation during earthquake events, and to evaluate the validity of site response analysis models. Matasovic [18], for instance, evaluated the performance of the computer program DMOD in predicting site response and pore pressure generation using data from the Imperial Valley Wildlife Liquefaction Array.

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Yang and Elgamal [19] applied an optimization analysis for the calibration of a multi-surface plasticity soil model that handles the coupling effects of soil behavior and pore pressure buildup. More recently, Groholski and Hashash [20], and Groholski et al. [6] extended the SelfSim framework to effective-stress considerations in order to extract both soil behavior and pore pressure response from recorded motions and pore pressures during seismic events.

This paper presents a technique to identify the coupled shear–volume response of sand deposits that can lead to significant generation of pore water pressures. The technique incorporates pore pressure records, as well as shear stress and strain estimates of a soil deposit subjected to dynamic excitation, along with a multi-surface constitutive model. The selected material model, based on previous models presented by Prevost [21], and Yang and Elgamal [19], is capable of handling the cyclic mobility response mechanism and associated pore pressure buildup of soils. This model controls the contractive response of the soil through a single calibration constant, which can be adjusted in order to capture the coupled volumetric response induced by shear loading. The proposed identification technique is first tested for convergence and accuracy using numerical simulations. The technique is then applied to experimental data from a centrifuge test and a large scale experiment.

2. System identification approach

The employed identification technique uses non-parametric estimates of shear stress and strain histories obtained directly from vertical arrays of acceleration records, and recorded excess pore pressure histories, to estimate a constitutive parameter defining the contractive behavior of the associated soil. The developed local identification technique is briefly described below:

(1) Shear stress and strain histories estimates are obtained using a methodology proposed by Zeghal, Elgamal and co-workers [2,12]. This methodology allows 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 shear wave propagation.
(2) Estimated strain time histories are used along with a constitutive (stress-strain) model to evaluate the corresponding (parametric) stress response.
(3) An objective function is evaluated based on discrepancies between the computed stress response and the recorded behavior of the soil as follows: shear stresses predicted by the employed soil model are compared to shear stresses estimated from acceleration records, and the reduction of the modeled effective vertical stress is compared to the recorded increase in excess pore water pressure.
(4) An optimization algorithm is implemented to determine optimal values of a constitutive parameter (defining the contractive behavior of the soil) that minimizes the objective function.

The implemented stress-strain constitutive model calculates the stress response using the prescribed (non-parametric) strain time history. This is advantageous as it does not require the forward modeling of the whole soil deposit. Even though the model does not deal with the pore pressure response directly, the reduction in the modeled effective vertical stress obtained for a given shear strain time history should coincide with the increase in pore water pressure that the corresponding actual soil deposit would experience for the same strains (this is further discussed within the context of the numerical simulations in Section 3). In practice, however, vertical strains at different depths of the soil deposit are difficult to measure and this information is often not available. Because of this, vertical strains are assumed to be zero in the presented identification analysis, thus ignoring the volumetric changes that take place due to water flow and consolidation during the shaking that typically occurs during seismic excitation. This may result in some bias in the identified parameters, especially for very high permeability soils. Nevertheless, the conducted identification analyses for soils with a permeability comparable to that of sandy soil showed that the employed technique leads to a reasonably good agreement with the soil's actual contractive parameters.

In this paper, the shear stress-strain relation of the soil profile in the absence of pore pressure buildup is assumed to be a priori known. This relation can be expressed in terms of a small-strain shear modulus, G_{max}, and reference shear deformation, γ_{ref}. A methodology for the estimation of these parameters was previously proposed by the authors [22]. Additionally, values of G_{max} can be inferred from direct shear wave velocity measurements, if these are available.

It should be also mentioned that the technique does not require the forward modeling of the whole soil deposit, since the analysis can be performed for a particular depth of the deposit using estimations of shear stresses, shear strains, and excess pore pressure at that particular depth. The identification process is shown schematically in Fig. 1. The different components of the algorithm are explained in the following sections.

2.1. Stress and strain estimates

Zeghal, Elgamal and co-workers [2,12] proposed a methodology for the estimation of shear stress and strain time histories based on acceleration records provided by a downhole array (Fig. 2). A one-dimensional shear beam idealization is used to describe the lateral response of the deposit along a vertical array: $\partial\boldsymbol{\tau}/\partial z = \rho\ddot{\mathbf{u}}$, with boundary condition $\boldsymbol{\tau}(0,\ t) = 0$, where t is time, z is depth, $\boldsymbol{\tau} = \boldsymbol{\tau}(z,t) = \{\tau_{zx}(z,t), \tau_{zy}(z,t)\}$ is the horizontal shear stress vector, and $\ddot{\mathbf{u}} = \ddot{\mathbf{u}}(z,t) = \{\ddot{u}_x(z,t), \ddot{u}_y(z,t)\}$ is the horizontal acceleration vector.

Integrating the equation of motion and using a stress free surface boundary the shear stress at any level z may be evaluated using:

$$\boldsymbol{\tau}(z,t) = \int_0^z \rho\ddot{\mathbf{u}}\, dz. \tag{1}$$

Discrete expressions for shear stresses at certain depths may be derived employing linear interpolation between downhole accelerations. These stress estimates are second-order accurate [3].

The corresponding shear strain is given by:

$$\boldsymbol{\gamma} = \partial\mathbf{u}/\partial z, \tag{2}$$

where $\boldsymbol{\gamma} = \{\gamma_{zx}(z,t), \gamma_{zy}(z,t)\}$, and $\mathbf{u} = \{u_x(z,t), u_y(z,t)\}$ is displacement vector. Second-order accurate shear-strain estimates at certain depth locations may be derived from linear interpolations [3].

2.2. Soil stress-strain model

A multi-surface plasticity technique is used to idealize the nonlinear and path dependent stress-strain soil response [23,24]. Relevant aspects of the model are outlined below. More details of the multi-surface plasticity models may be found elsewhere (e.g., [21,23,25]).

The model assumes that the total strain rate $\dot{\boldsymbol{\varepsilon}}$ can be expressed as the sum of elastic $\dot{\boldsymbol{\varepsilon}}^e$ and plastic $\dot{\boldsymbol{\varepsilon}}^p$ strain rates; therefore the constitutive equation is written as: