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Identification of soil dynamic properties of sites subjected to bi-directional excitation

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ABSTRACT

Accurate evaluation of soil dynamic properties is essential for seismic response analyses of sites. In a number of studies, site properties have been identified using one-dimensional analyses. Such analyses uncouple the two-dimensional (horizontal) response of soil deposits, which is inherently coupled. This paper presents a system identification technique that takes into account the coupled two-directional response of soil deposits. The technique employs non-parametric estimates of the shear stresses derived from acceleration records provided by a vertical (downhole) array. A multi-yield surface plasticity approach is used to model the multi-dimensional stress-strain relation. The identification technique is first verified using finite elements computational simulations. This technique was then used to assess the coupled response of the Wildlife liquefaction research site (Imperial Valley, California). The identified shear moduli and shear wave velocities were found to be in a very good agreement with those measured in the field using crosshole seismic testing.

1. Introduction

Evaluation or identification of soil dynamic properties is essential in geotechnical earthquake engineering applications, including site response and soil-structure analyses. 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 [16,17,23,28,29,38,41]. 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 [10,14,34,43,5]. In the last few decades, researchers have developed several system identification and inverse problem techniques. Zeghal et al. [42], 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 using an equivalent linear approach. The estimates of stress and strain are then employed to determine the associated variation of stiffness and damping with the level of strain amplitude. 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 [2–4]. Tsai and Hashash [36,37], on the other hand, and more recently Groholski et al. [13,14], 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. Most recently, Mercado et al. [26] incorporated the methodology for estimation of shear stresses and strains, proposed by Zeghal et al. to introduce an alternative nonlinear technique to characterize the shear stress–strain response. This methodology employed a hyperbolic relationship [20] to model the material shear stress–strain backbone curve along with the Masing criterion [24] to handle the cyclic response during dynamic excitations.

The techniques mentioned above performed one-dimensional (1D) site response analyses, neglecting the coupling effects of the orthogonal (horizontal) response. A bi-directional (2D) analysis is needed to more accurately characterize the soil response, which is inherently affected by the coupling effects of the two horizontal acceleration components. The importance of 2D site response analysis in dynamic problems has been highlighted by many researchers since the 1970s. The problem was first targeted by Pyke et al. [32], which conducted multi directional shaking table tests by mounting two shaking tables on top of each other. As expected, the settlement due to multi-directional shakings

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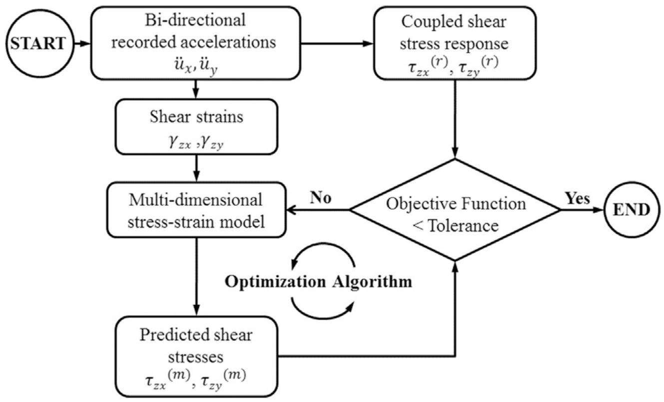

Fig. 1. Schematic of the employed identification algorithm.

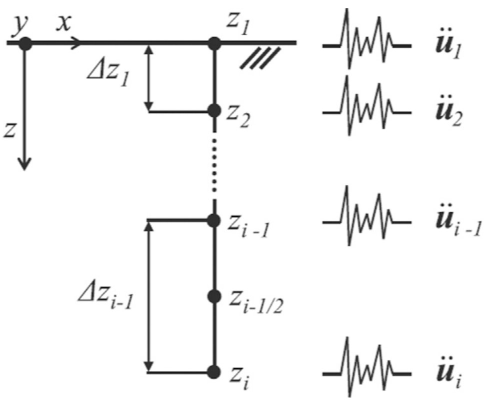

Fig. 2. Schematic array of accelerometers locations (after [42]).

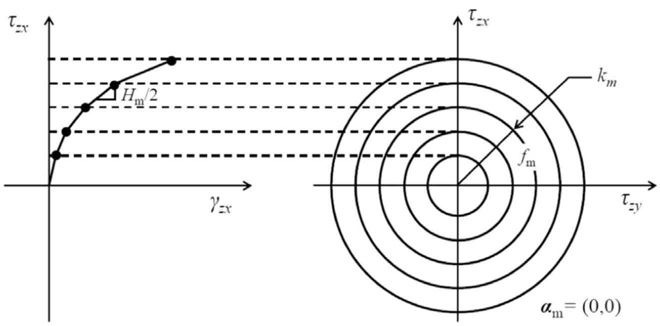

Fig. 3. Relationship between the backbone curve and initial parameters of the nested yield surfaces on a τ_{zx}-τ_{zy} plane (after [30,38]).

was found to be larger than that of the unidirectional. Later, Seed et al. [33] estimated the difference in liquefaction resistance between a sand deposit subjected to 20 cycles of unidirectional shakings and that of the

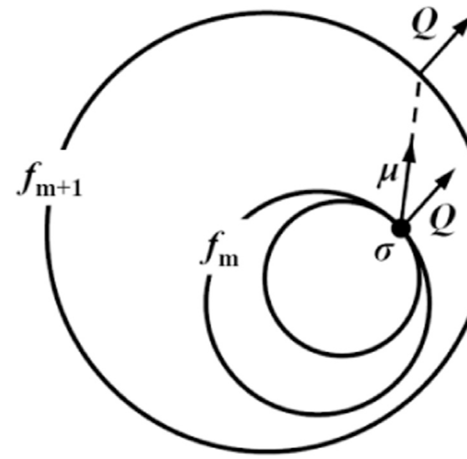

Fig. 5. Definition of translation direction (after [31]).

same sand subjected to a gyratory shaking. The resistance of the sand subjected to gyratory shaking was shown to be about 15% less than that subjected to uniaxial shaking. Ishihara and Yamazaki [19] conducted a series of multi-directional simple shear tests on loose saturated sand. In their experiments, they employed several phase differences between the main shaking and the secondary shaking, which was orthogonal to the main shaking. Again, as expected, it was found that a larger amplitude of the secondary shaking is associated with a decrease in stress required to induce a specific shear strain in the specimen. Borja et al. [8] presented a multi-dimensional nonlinear finite element model capable of predicting nonlinear ground response due to strong motion. The presented model allowed for a more accurate prediction of peak acceleration values, in comparison to one dimensional model predictions. In 2002, Zeghal and Oskay [41] introduced a multi-dimensional local system identification technique of soil systems. The proposed methodology allows for the analysis of a local soil domain monitored by a cluster of closely spaced accelerometers. The proposed technique was shown to be successful in the identification of soil characteristics of centrifuge tests of a soil-wall system, based on the analysis of the recorded multi-directional seismic response of the system. Most recently, Anantanavanich et al. [1] performed a finite element analysis of the behavior of submarine slopes under earthquake motions subjected to both uni and multi-directional shakings. The ground motions used for their study were recorded during the Loma Prieta earthquake from two outcropping rock sites with scaled ground motion having a PGA ranging from 0.17 g to 0.35g. The ground motions implemented in their analyses in the two orthogonal directions were characterized by relatively comparable PGAs. The results of their analysis indicated that when a multi-directional shaking was incorporated, the displacement and pore pressures developed were 20–30% higher than for the uni-directional shakings. This suggests that the current methods and procedures that implement unidirectional ap-

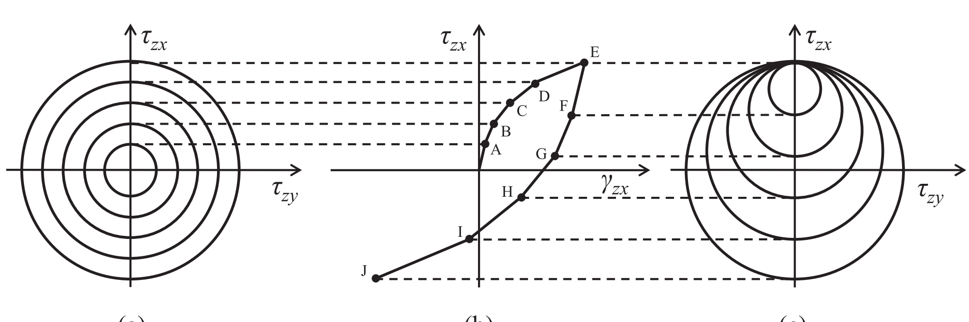

Fig. 4. Relationship between the backbone curve and the yield surfaces during cyclic loading: (a) initial configuration of the yield surfaces, (b) approximation of the shear stress strain curve upon initial loading (A–E) and loading reversal (E–J), and (c) configuration of the translated yield surfaces upon reaching point E during loading. (After [26]).