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Learning of pore pressure response and dynamic soil behavior from downhole array measurements

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ABSTRACT

Downhole arrays are deployed to measure motions at the ground surface and within the soil profile, with some arrays instrumented to also record the pore pressure response within soft soil profiles during excitation. The measurements from these arrays have typically been used in conjunction with parametric and nonparametric inverse analysis approaches to identify soil constitutive model parameters for use in site response analysis or to identify averaged soil behavior between locations of measurement. The self-learning simulations (SelfSim) inverse analysis framework, previously developed and applied under total stress conditions, is extended to effective stress considerations and is employed to reproduce the measured motions and pore pressures from downhole arrays while extracting the underlying soil behavior and pore pressure response of individual soil layers. SelfSim is applied to the 1987 recordings from the Imperial Valley Wildlife Liquefaction Array. The extracted soil behavior suggests a new functional form for modeling the degradation of the shear modulus with respect to excess pore pressures. The extracted pore pressure response is dependent on the number and amplitude of shear strain cycles and has a functional form similar to current strain-based pore pressure generation models.

1. Introduction

Understanding of local site conditions is necessary not only for seismic design, but also for interpretation of recorded ground motions at a site. Strong motion records from many earthquakes (e.g., 1957 San Francisco Earthquake, 1989 Loma Prieta Earthquake, and 1999 Chi-Chi earthquake) show significant differences between soil sites and nearby rock sites response. The 1985 Mexico City earthquake showed for the first time that soft soils can amplify weak ground motions and result in significant damage even at large distances from the earthquake source.

Site response analysis models are used to evaluate site response to strong ground shaking in terms of acceleration, velocity and displacement at ground surface and within the soil profile. The applicability of these models highly depends on both the representation of cyclic soil behavior and pore pressure response. Laboratory tests are often used to measure dynamic soil behavior and pore pressure response which is then used to develop cyclic soil constitutive and pore pressure response models for site response analysis. However, the loading paths from laboratory tests can be significantly different from those experienced by the soil in the field and are not necessarily representative of anticipated response.

Significant investments in downhole arrays have been and continue to be made to measure motions at the ground surface and within the soil profile, with additional pore pressure data measured throughout the same profile in some arrays. These arrays provide the real data necessary to better understand local site effects, in situ dynamic soil behavior and pore pressure response under earthquake loading.

Inverse analysis techniques have been applied to downhole array data to identify soil behavior via a variety of system identification procedures. Zeghal et al. [36] used a linear interpolation approach to estimate shear stress and shear strain seismic histories from downhole arrays via a nonparametric system identification procedure. Reduction of the stiffness of the soil at large strains and large excess pore pressures was identified, but the soil behavior identified by this method only represents averaged behavior between two points of measurements. Parametric system identification approaches such as the time–domain method [12] and the frequency domain method [8,17] have proven successful in providing better estimates of the soil dynamic properties, but are still limited in their capability of identifying soil behavior or in their implementation into a material

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constitutive model for use in future site response analysis. Although current approaches provide important insights from field observations, they do not fully benefit from these observations.

Downhole array data has similarly been used to find correlations in pore pressure response of soils, as well as to provide a check on the validity of site response analysis models. Using data obtained from the Lotung downhole array, Davis and Berrill [7] obtained good agreement between measured and calculated values of pore pressures via correlation of dissipated energy densities. Matasovic [25] evaluated the D-MOD site response analysis program and implemented cyclic-strain-based pore pressure generation model using data from the Imperial Valley Wildlife Liquefaction Array for comparison.

Tsai [29] and Tsai and Hashash [31] introduced a new self-learning inverse analysis algorithm, SelfSim, for total stress site response analysis. They applied the algorithm to synthetically generated data as well as field arrays from the Lotung and La Cienega arrays. Tsai and Hashash [31] showed that SelfSim applied to total stress site response analysis can learn and extract soil behavior from recorded events such as degradation of soil stiffness with increasing shear strain. Learning from multiple events was required to learn nonlinear soil behavior over a wide range of shear strains and to improve prediction of soil response in other events.

Groholski and Hashash [15] extended the SelfSim framework to effective-stress considerations and further applied the expanded algorithm to synthetically generated data. Groholski and Hashash [15] showed that the extended SelfSim framework applied to effective-stress site response analysis can learn and extract both soil behavior and pore pressure response from recorded motions and pore pressures during seismic events. Learning from multiple events was required to learn nonlinear soil behavior and pore pressure response over a wide range of shear strain and various levels of excess pore pressures. This paper applies the extended SelfSim algorithm to the 1987 recorded events from the Imperial Valley, California Wildlife Liquefaction Array. The results will demonstrate that SelfSim is able to learn significant characteristics of soil behavior and pore pressure response including shear modulus reduction and damping increase with increasing shear strain, the effect of increasing excess pore pressures on shear modulus degradation, and the nature of excess pore pressure generation with respect to shear strains without the need to specify nonlinear soil parameters.

2. Self-learning simulations (SelfSim) applied to 1-D seismic site response – effective-stress consideration

The SelfSim methodology is an extension of the autoprogressive algorithm originally proposed by Ghaboussi et al. [10]. With the use of a continuously evolving neural network (NN) based material model, the autoprogressive method is used to extract stress–strain material behavior using global load and deflection measurements. SelfSim has previously been implemented for static laboratory tests [26,28], deep excavations [19], and one-dimensional (1-D) seismic site response under total stress consideration [30,31]. Groholski and Hashash [15] extended the application of SelfSim to 1-D seismic site response under effective-stress consideration using synthetically generated downhole array data of motions and excess pore pressures.

Fig. 1 illustrates the application of the SelfSim framework to downhole array measurements of ground motions and pore pressure response. In Step 1, a downhole array measures the accelerations and pore pressures at selected locations in a profile as seismic waves propagate through a soil column. The deepest recorded motion in the profile is treated as the input base excitation for the overlying soil layers. The input base excitation and corresponding recorded motions within the soil profile represent complementary sets of field observations.

In Step 2, SelfSim uses these measurements to extract the underlying dynamic soil behavior by performing two complementary site response analyses. SelfSim first uses the base excitation and measured pore pressures to conduct an analysis where force boundary conditions are imposed (Step 2a). The measured motions within the soil profile are imposed as a displacement boundary condition in a parallel analysis, Step 2b. In these

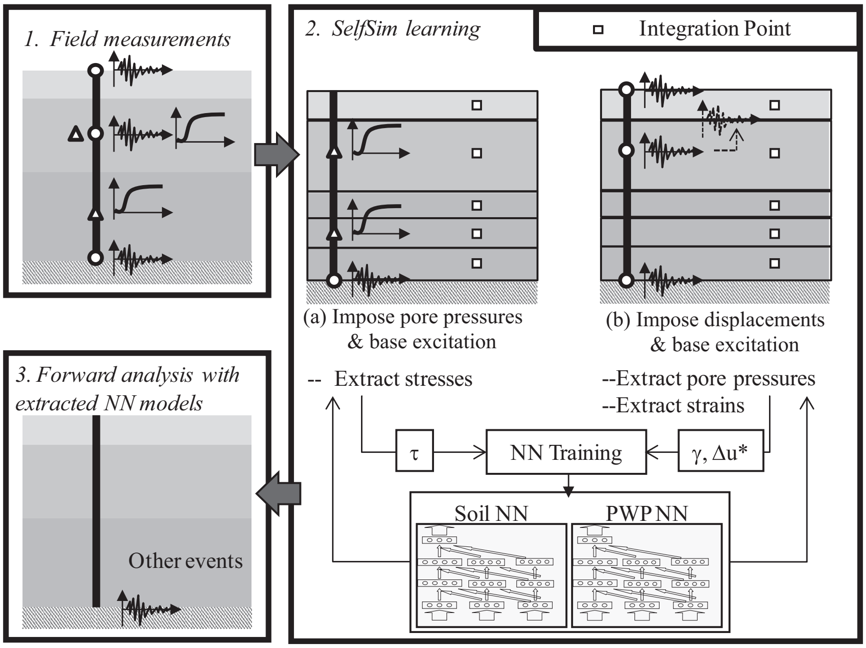

Fig. 1. SelfSim inverse analysis algorithm applied to vertical array with pore pressure measurements. O represents acceleration measurements, and Δ represents pore water pressure measurements.