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Evaluation of undrained shear strains in multi-directional horizontal shaking

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ABSTRACT

The evaluation of shear strains under multi-directional shaking is an important issue in interpreting dynamic soil behavior for both laboratory physical modeling and in situ monitoring. Shear strain components evaluated from Cartesian coordinates in undrained conditions have limitations to fully capture the coupled shear strain-pore pressure responses with an individual expression. In the present study, radial and rotational shear strain components derived from particle motions described with cylindrical polar coordinates are proposed. The proposed radial and rotational shear strains are verified with data from a bi-directional laminar shear box and a free field downhole array. Comparison results show that the proposed expressions of shear strain effectively capture the coupled strain-pore pressure responses in terms of the frequency content, amplitude variation, phase difference, and oscillation behavior. Comparison results reveal that the radial shear strain is the dominant shearing mode and the amplitude of the rotational shear strain is only 6.5–14.5% of the radial component. This provides quantitative data for the correction factor for multi-directional shaking and suggests that a simple shear system capable of inducing the radial shear strain on the vertical plane is a better approach than other shearing modes for physically modeling the behavior of soil subjected to undrained seismic loadings.

1. Introduction

Shear strain amplitude is an important variable in describing nonlinear soil properties and dynamic soil behaviors such as pore pressure generation and post-liquefaction settlement. Although subsurface soil strata under seismic shaking are always subjected to multi-directional loading conditions, the vertical component of seismic loading is often ignored and soils are generally assumed to be sheared by multi-directional upward-propagating shear waves. The complexity of multi-directional horizontal loading can be observed in the trajectories of horizontal acceleration time histories at the surface (FA1–5) and at a depth of 6 m (DHB6) of the downhole array data from the Lotung Large Scale Seismic Test (LLSST) shown in Fig. 1. Additionally, the undrained condition is generally assumed in dynamic physical modeling and seismic analyses of soil liquefaction due to the short duration of seismic loading. As a result, the coupled shear–dilatancy effects under drained conditions transfer to the coupled shear strain-pore pressure responses.

Due to its highly nonlinear and stress-dependent nature, the mechanical behavior of soil is loading-path dependent. Depending on the existence of a phase shift among stress/strain components, loading-paths described by the resultant vectors can be categorized into in-phase and out-of-phase patterns [1,2]. The phase shift alters the loading paths from line-type paths to loop-type paths, resulting in one-directional and multi-directional loading conditions, respectively.

Due to the limited availability of appropriate testing apparatus, most laboratory tests are performed under one-directional loading conditions with in-phase loading paths. However, researchers have shown that the out-of-phase loading components increase the accumulation rate of strain [1,2], accelerate the rate of pore pressure accumulation [3], reduce the cyclic resistance against liquefaction [4], and increase the post-liquefaction settlement [5]. Seed et al. [6] proposed using a reduction factor of 0.8–0.9 for the liquefaction resistance of soil to account for the effects of multi-directional loading in liquefaction analysis. Ishihara and Nagase [7] used a simple shear device capable of applying irregular and bi-directional shear stress on a soil specimen to study the effects of load irregularity and multi-directionality and concluded that the correction coefficient for multiplicity of load direction should be 0.83. Although empirical adjustment factors for applying one-directional testing results to multi-directional conditions have been proposed (e.g., [6,7]), the effects of multi-directional shearing on soil behaviors have not been not clearly quantified and discrepancies raise when comparing dynamic numerical results to physical modeling or filed monitoring data [8].

To properly model the field loading conditions, bi-directional shearing devices, such as a bi-directional simple shear device [3] and a bi-directional laminar shear box [9], are preferred.

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