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Experimental and Numerical Investigation of Cyclic Response of Dense Sand under Multidirectional Shaking

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ABSTRACT

The seismic performance of many nuclear power plant structures depends on the cyclic shear stress-shear strain-volumetric strain behavior of dense, compacted sands used to support their foundations. Current understanding of the constitutive behavior of dense sand is derived largely from unidirectional (1D) element tests, which may underestimate volumetric strains. In this paper, we describe a testing program that includes a unique set of multidirectional cyclic direct simple shear (I-mcDSS) and dynamic centrifuge tests. Preliminary results from I-mcDSS and one free-field dynamic centrifuge test are discussed. Both tests were performed on saturated dense Ottawa sand (Dr~95%) in which a unique set of unidirectional (1D) and multidirectional (2D) motions were applied. Preliminary results from 1D and 3D numerical modeling are compared to the centrifuge test results.

Introduction

A seismic deformation analysis is commonly part of the seismic assessment of nuclear power plants (NPPs) not founded on rock. Surficial soils are then excavated and replaced with compacted coarse-grained fill. However, the evaluation of the cyclic shear stress-shear strain-volumetric strain behavior of dense sands has been largely derived from unidirectional (1D) cyclic simple shear and cyclic triaxial tests, which may underestimate volumetric strains under multidirectional shaking (Pyke 1975; Kammerer 2002). A limited number of multi-directional element-level cyclic tests on dense coarse-grained soils are available in the literature (e.g., Kammerer 2002), and field case histories of the seismic response of saturated dense sands are scarce. As a result, validating existing constitutive models and developing alternative models and empirical correlations remains challenging.

Figure 1 summarizes an ongoing research program to enhance our understanding of dense sand response to multidirectional shaking. The research program consists of three elements: (a) unique

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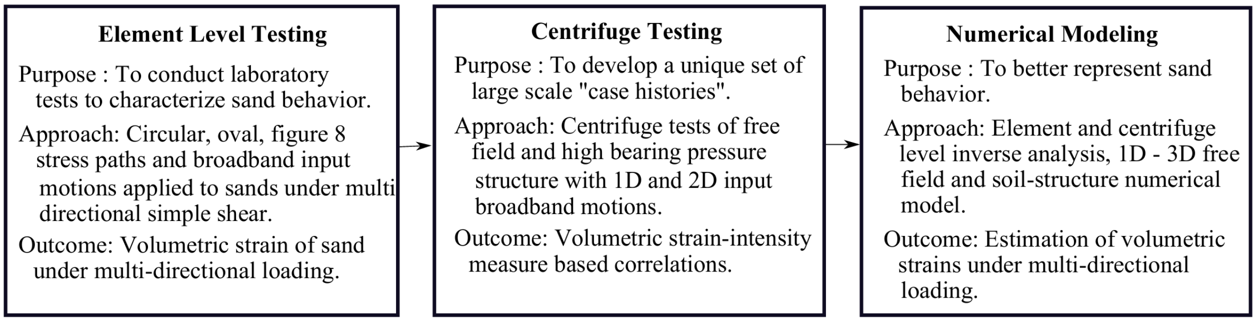
multidirectional cyclic direct simple shear (I-mcDSS) tests using oval, circular, figure-8 stress-strain paths, as well as broadband input motions to study cyclic loading-induced volumetric strains in various sandy soils (poorly-graded, well-graded, silty, and clayey sands); (b) bidirectional dynamic centrifuge tests performed under free-field conditions as well as with a structure that applies a high bearing pressure to the soil (similar to pressures applied by a NPP containment structure); and (c) numerical modeling to calibrate existing constitutive models and, if required, develop new models to better represent sand response under multidirectional cyclic loading.



Element Level Testing

Purpose : To conduct laboratory tests to characterize sand behavior.

Approach: Circular, oval, figure 8 stress paths and broadband input motions applied to sands under multi directional simple shear.

Outcome: Volumetric strain of sand under multi-directional loading.

Centrifuge Testing

Purpose : To develop a unique set of large scale "case histories".

Approach: Centrifuge tests of free field and high bearing pressure structure with 1D and 2D input broadband motions.

Outcome: Volumetric strain-intensity measure based correlations.

Numerical Modeling

Purpose : To better represent sand behavior.

Approach: Element and centrifuge level inverse analysis, 1D - 3D free field and soil-structure numerical model.

Outcome: Estimation of volumetric strains under multi-directional loading.

Figure 1. Overview of planned experimental and numerical testing programs.

Materials tested

The testing program involves a range of sand gradations, including a poorly-graded fine sand (SP), a well-graded sand (SW-SM), a nonplastic silty sand (SP-SM), and a low-plasticity clayey sand (SC) (Figure 2b). Testing described here involves the poorly-graded sand, a subrounded Ottawa 40/70 sand (SP) from U.S. Silica with a median particle size D_{50} of 0.28mm (Figure 2). The SP has a minimum void ratio (e_{min}) of 0.50±0.03 as determined by the Japanese method (Yee et al. 2013) and the modified Proctor method (ASTM D1557); a maximum void ratio (e_{max}) of 0.82±0.01 as determined by the Japanese and the dry tipping method (ASTM D4254); and a specific gravity of 2.67 (ASTM D854), with all limiting density tests being performed at least 5 times.

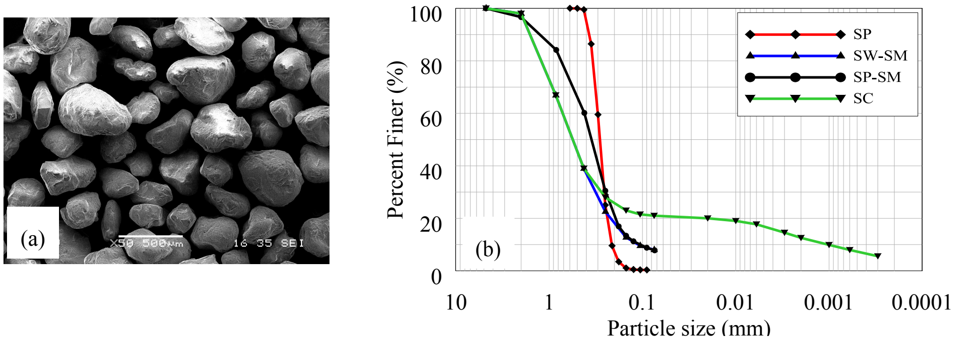


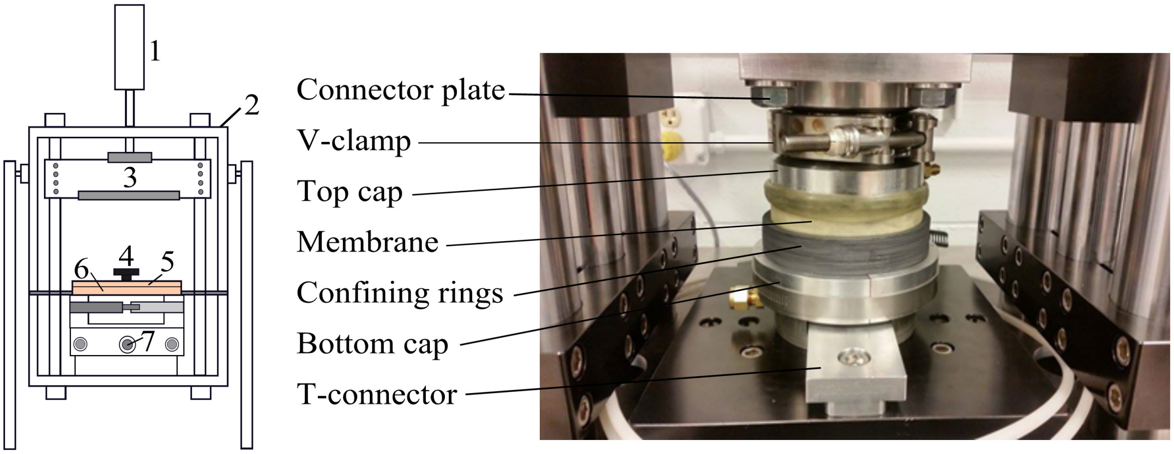
Figure 2 (a) Scanning Electron Microscope image for SP and (b) gradation curve for SP, SW-SM, SP-SM and SC.

Element-level Testing

Idealizing seismic shaking as vertically-propagating, horizontally-polarized shear waves, the soil is subjected to cyclic simple shear. This stress path subjects the soil to a smooth rotation of the principal stress/strain directions under plane strain conditions and is best simulated through a cyclic direct simple shear device.

Illinois multidirectional cyclic direct simple shear device (I-mcDSS)

Element-level multidirectional cyclic tests on the dense granular material are being performed using a newly constructed Illinois multidirectional cyclic direct simple shear device (I-mcDSS; Figure 3). The device can apply loads/strains along three independent axes, in the vertical (z) and two mutually orthogonal horizontal (x, y) directions. Stress- and strain-control tests can be conducted using monotonic, cyclic (e.g., sine or square wave) and user -defined broadband loading along the x, y, and z directions. Unique features of the I-mcDSS include: (1) reduced rocking by employing a four-column support frame with intermediate guide rods for the top assembly; (2) a chamber that uses air pressure to confine the sample to a maximum pressure of about 200kPa (30psi), allowing back-pressure saturation; (3) pressure transducers to measure excess porewater pressure and volume change during testing; and (4) a specialized multidirectional load cell that directly measures force and torque in three mutually perpendicular directions to increase accuracy and reduce compliance. The device can accommodate a sample up to 152.4 mm diameter.



(a) (b)

1- Vertical actuator
2- Pressure chamber
3- Top assembly
4- Sample position
5- Horizontal x-table
6- Horizontal y-table
7- Horizontal load cell

Figure 3. (a) Schematic of I-mcDSS device; and (b) installed sample.

Test description and preliminary results from I-mcDSS tests

Saturated undrained tests were conducted on dense Ottawa sand (Dr = 95%) at an effective vertical stress of 100 kPa using a circular strain path with 1% single amplitude strain at a frequency of 0.1 Hz. The sample diameter (D) and height (H) height were 10.16 cm and 1.91 cm, respectively. A D/H ratio of greater than 5 was used to minimize stress non-uniformity at the center of the sample (Franke et al. 1979). Stacked rings with low friction (Figure 3b) were used to maintain a constant cross-sectional area during shear. Different sample preparation methods (compaction, air pluviation) are to be investigated to study potential soil fabric effects on soil behavior. Here, the sample was prepared by air pluviation and tapping with a rubber hammer to obtain the required density, and back-pressure saturated until Skempton's B value of at least 0.95 was obtained. Figure 4 presents a sample strain path and soil response for a circular strain path.

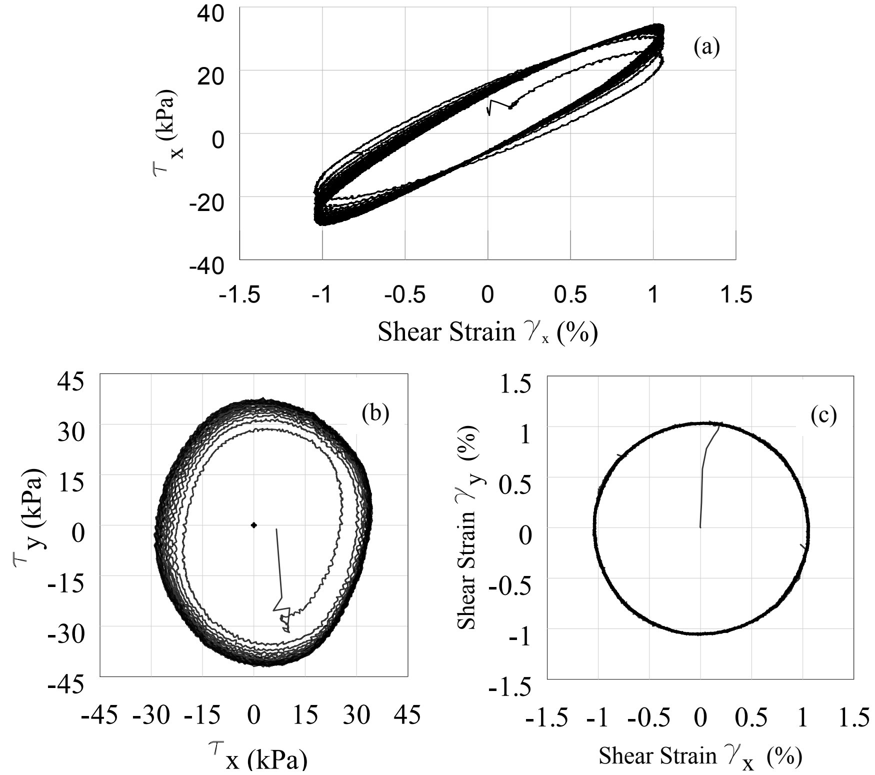


Figure 4. (a) Shear stress-shear strain response in x-direction; (b) shear stress response in x- and y-directions; and (c) imposed shear strain path.

Centrifuge Testing

As a result of the limited number of field case histories that document dense sand response to cyclic loading, unique centrifuge tests will be performed to develop "case histories" that will be used to validate and develop empirical and constitutive models in combination with laboratory test data. The centrifuge tests will utilize the two-dimensional (2D) shaker and 2D laminar container available at the Rensselaer Polytechnic Institute (RPI) geotechnical centrifuge facility. The 2D laminar container consists of a stack of aluminum rings connected by roller bearings, designed to allow multi-directional displacement with minimal frictional resistance (Figure 5c). Models will be subjected to 2D motions at centrifugal accelerations of 60g and 30g to simulate different compacted fill thicknesses.

Centrifuge tests will be performed for free-field conditions and for models that include a structure that applies a high-bearing pressure to the dense sand. The centrifuge test described here was performed to calibrate 2D input motions. Ottawa sand (D_r ~ 95%) was air-pluviated in lifts, instrumented using accelerometers, pressure transducers, and side and vertical LVDTs (Figure 5), and saturated with methylcellulose fluid (viscosity = 60cst). Vertical LVDT settlement plates were placed within the model to measure vertical strain with depth. Prototype fill thicknesses of 20.5 and 10.25 m apply to centrifugal accelerations of 60 and 30g, respectively. Additionally, pairs of bender elements (Figure 5a) were used measure small-strain shear stiffness with depth. A suite of eight historical seismic events with two horizontal orthogonal components were selected from the PEER and the Chilean (RENADIC) strong motion databases to include both crustal and subduction rupture mechanisms. The motions contain a wide range of energy content (e.g., Arias intensity) to ensure that moderate (~0.5 – 1.0%) strains are induced in the dense sand models.

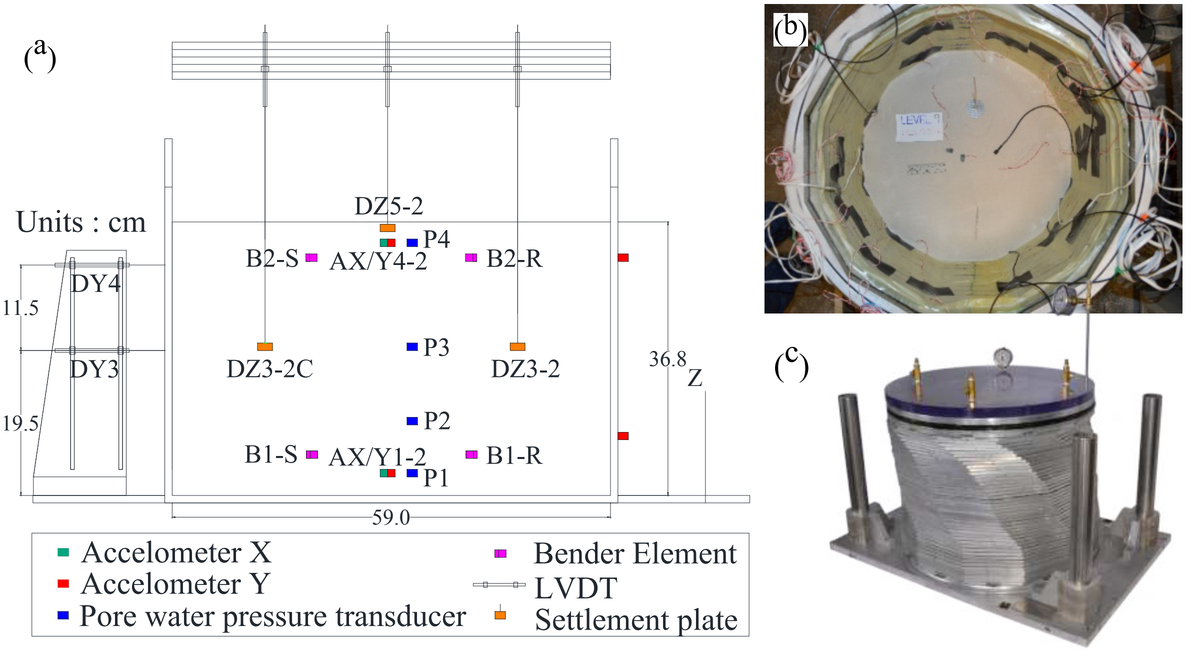


Figure 5. (a) Instrumentation layout for calibration test; (b) Instrumentation placed at “Layer 1” in model; and (c) 2D laminar container used for testing program.

Figure 6 shows sample cyclic soil response for the 20.5-m thick centrifuge model subjected to a moderately strong input motion. Here, the model amplified the ground motions in both the x- and y-directions. Recorded porewater pressure ratios ($r_u = \Delta u/\sigma'_{vo}$ = excess porewater pressure/initial effective vertical stress) were generally less than 0.3, and decreased with depth. During the strongest portion of the motion (~ 20s), slightly negative r_u values were recorded, indicating that sufficient straining occurred to mobilize the dilative tendency of the dense sand. This dilative tendency was suppressed with depth. Interestingly, settlement measurements indicated a non-uniform strain distribution with depth, with the measured vertical strain in the upper 10m being approximately twice as large as the vertical strain measured in the lower 10m, although all strains were quite small (<0.05%) during this motion. Lastly, we note that nearly all of the settlement occurred during shaking, and reconsolidation settlements in the dense sand were minor.

After the model was subjected to six 2D input motions of increasing intensity, a D_r ~ 104% was computed. The shear wave velocities (V_s) measured by the bender elements agreed well with published correlations for Ottawa sand at D_r ~ 104% (e.g., Roberston 1995; Hardin and Drnevich 1972), as well as with a general correlation for Vs proposed by Menq (2003). Thus, we concluded that these relations could be used to estimate stiffness profiles for numerical modeling.

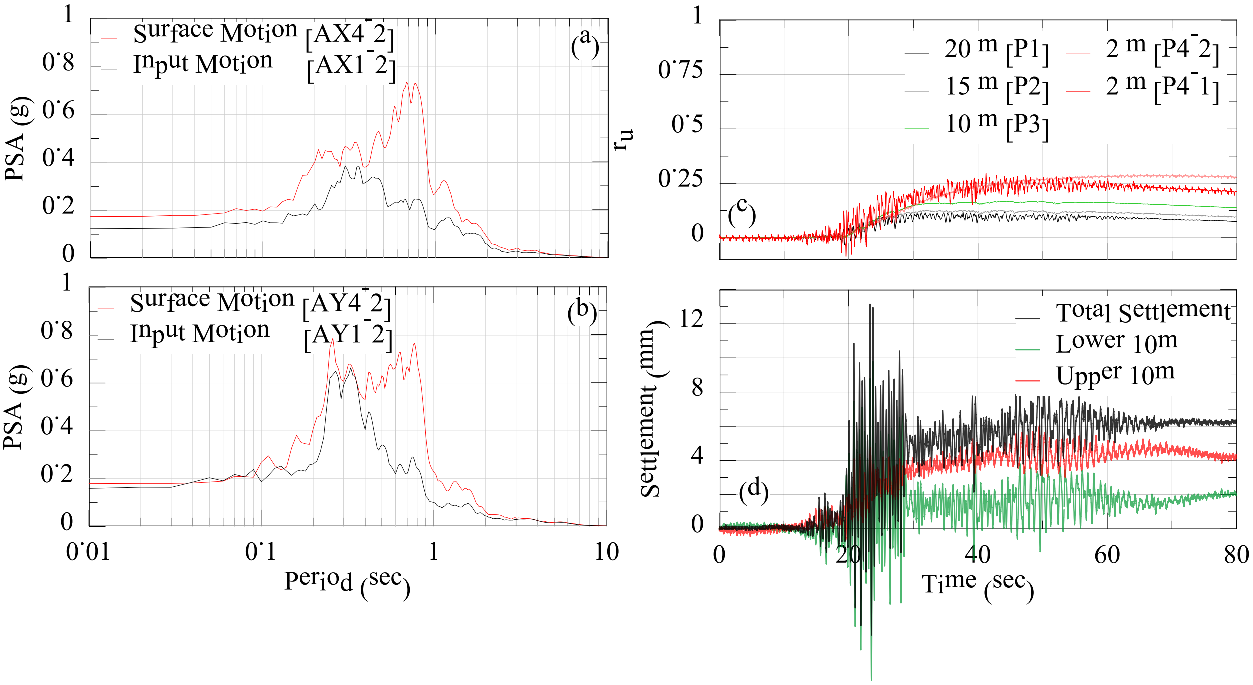


Figure 6. (a) X-direction input and surface response spectra; (b) y-direction input and surface response spectra; (c) porewater pressure ratio time histories; and (d) settlement time histories.

Numerical Modeling

The numerical modeling effort aims to calibrate existing constitutive models, and if required, to develop new models to better represent dense sand response to multidirectional cyclic loading. As a preliminary step, a 1D effective-stress, fully-coupled, shear-beam finite element (FE) model developed in the OpenSees FE analysis platform (Mazzoni et al. 2006) was used to model the soil profile. The model consisted of a 20.5-m thick soil column built using 3D Brick u-p and SSP Brick u-p elements (McGann et al. 2012) based on Biot's theory of porous media (Biot 1962). Pressure-dependent multi-yield surface plasticity (PDMY; Parra 1996; Yang 2000; Elgamal et al. 2002) and Dafalias and Manzari (DM; 2004) soil models were used. For the PDMY model, Darendeli (2001) modulus reduction curves were used with an implied soil strength correction (Hashash et al. 2010). In addition to hysteretic damping, viscous (Rayleigh) damping was employed to represent damping at small strains. Two-dimensional motions (taken from the centrifuge recordings at a depth of 20.5 m) were input at the base of the numerical soil column. Displacement compatibility was prescribed for model elements at the same elevation to represent a simple shear deformation pattern, and zero porewater pressure was prescribed at the ground surface to represent the water table. In addition to the FE analyses, 1D nonlinear, total-stress site response analyses were conducted using DEEPSOIL v5.1 (Hashash 2011). Again, Darendeli (2001) modulus reduction curves with an implied soil strength correction (Hashash et al. 2010) were used to define the soil material behavior. In addition to hysteretic damping, frequency independent viscous damping (Phillips and Hashash 2009) was used in the model.

Figure 7 compares recorded and computed accelerations for the moderate ground motion (same motion shown in Figure 6) in terms of the x- and y-direction response spectra at a depth of 2 m. In general, the computed and recorded spectra are in reasonable agreement, although the computed spectra overestimate the recorded spectra in the 0.3 to 0.6 s period range. To quantify the differences between the computed (numerical modeling) and measured (centrifuge test) response, residuals were calculated for the response spectra (in log-log space) for each input motion in both the x- and y-directions as:

$$\text{Residual } S_a = \log\left(S_{a,\text{recorded}} / S_{a,\text{computed}}\right) \tag{1}$$

where S_a is the spectral acceleration. Therefore, positive residuals indicate that the computed S_a was less than the measured value, and negative residuals indicate that the computed S_a was greater than the measured values. Figure 7(b) presents the residuals calculated for the 1D DEEPSOIL, DM finite element, and PDMY finite element models at a depth of 2 m. The residuals generally are less than ±0.25 for periods up to 10 seconds.

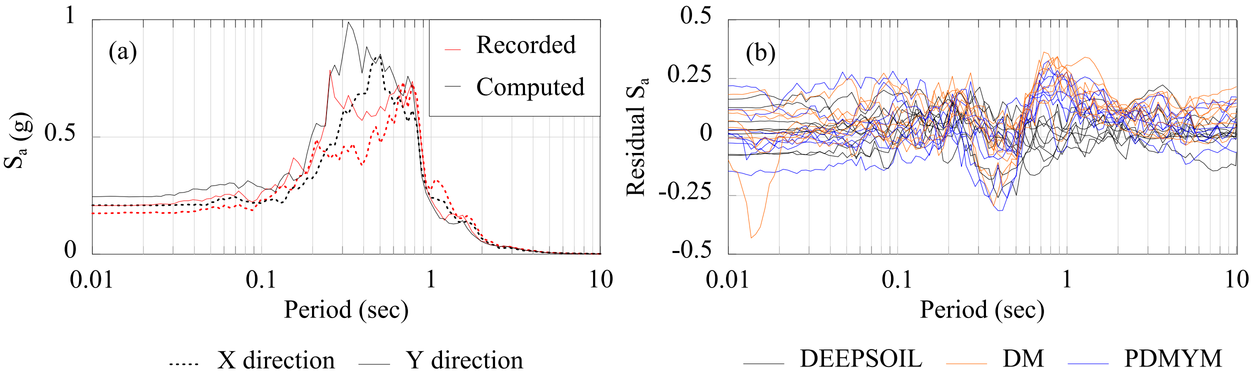


Figure 7. (a) Sample spectral accelerations at depth of 2 m for moderate input motion; and (b) residual spectral accelerations computed at 2 m depth using different material models.

Conclusions

The paper presented an overview of a unique experimental and numerical modeling program that will study the effect of multidirectional loading on volumetric strains of a range of dense, compacted sand gradations. The experimental testing program includes multidirectional cyclic direct simple shear tests performed using a newly-constructed device at Illinois (I-mcDSS) and a set of dynamic centrifuge tests. The numerical modeling program will focus on validating existing models and, if necessary, developing new constitutive models to better describe dense sand response to multidirectional cyclic loading. Preliminary results of I-mcDSS and centrifuge tests conducted on a dense Ottawa sand (clean, uniform gradation) illustrate volumetric behavior to multidirectional cyclic loading under undrained and partially drained conditions. The results show non-uniform ground motion amplification, non-uniform porewater pressure generation, and non-uniform volumetric strains with depth. Preliminary results from the numerical modeling program illustrate that 1D computational models provide reasonable agreement (in terms of spectral response) with ground motions measured in the centrifuge test.

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