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Physical Modeling and Response of Sand Deposits Subjected to Biaxial Base Excitation

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ABSTRACT

The effects of earthquake loading on site response are complex and three dimensional. A series of centrifuge tests were conducted to assess the 3D response and liquefaction of a level site deposit subjected to various biaxial (horizontal) base excitations. The deposit consisted of a dense Nevada sand layer and the tests were conducted at NEES@RPI centrifuge facility using a biaxial shaker and a 2D laminar box. Synthetic biaxial motions were used as base excitations. A dense array of accelerometers was used to monitor the deposit response. The recorded accelerations were used to directly evaluate the two components of the shear stress and strain vectors acting on the horizontal planes of the tested deposit.

Introduction

Accurate evaluation of soil response to earthquakes is important for the design and management of soil systems. Numerous experimental and numerical studies were conducted over the last four decades to analyze and quantify the response of soil deposits when subjected to base excitations. Most of these studies, and especially experimental ones, were conducted using uniaxial shaking. Few recent studies used biaxial shaking. For instance, Ng et al. (2003) were the first to publish results of centrifuge tests conducted using biaxial (horizontal) shaking. These tests were undertaken to study saturated embankments in Hong Kong. Su & Li (2006) used centrifuge testing (at Hong Kong university) to investigate the effects of multidirectional shaking on soil-pile interaction. Su & Li (2008) studied the effects of biaxial shaking on sand. They performed centrifuge tests using Toyoura sand and compared the results to numerical model predictions. There were also a number of numerical simulations studies that used multiaxial shaking. For example, Bielak et al. (1999) performed 2D numerical ground motion simulation for a small valley in Armenia to show the importance of biaxial excitations.

This article presents and discusses some results of a series of experiments of a level site deposit subjected to biaxial base excitations.

Centrifuge Tests

A number of centrifuge tests were conducted using the NEES@RPI (Network for Earthquake

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Engineering Simulation) centrifuge to assess the effects of bi-axial shaking on the response and liquefaction of saturated granular soil deposits.

Equipment and instrumentation

The tests were conducted using the NEES@RPI 2D shaker and 2D laminar box (Figure 1). The shaker was designed to conduct more realistic centrifuge simulations of earthquake excitations. Specifically, this shaker is capable of imparting two horizontal (orthogonal and independent) input accelerations to the base of centrifuge soil models. A 2D laminar container (Figure 1a) was used to minimize the boundary effects on the response of the tested deposits. This container is constructed from stacked 45 twelve-sided rings (made using a lightweight aluminum alloy). Each ring is 8.9 mm in height with a 594 mm inside diameter, and is separated from the rings above and below by 120 roller bearings, specifically designed to permit translation in the two horizontal directions with minimal frictional resistance. Relative displacements of up to 2.5 mm between rings a can be achieved. Thus, the container is capable of accommodating lateral displacements and (cyclic and permanent) shear deformations as large as 28 %. An adjustable restraint utilizing low-friction linear-rotary bearings is employed to maintain a downward force on the ring stack and ensure the container stability.

The tested models of a level site were equipped with a 3-elevation array of accelerometer and laser sensors having a 3D configuration (Figure 1b). Each elevation has seven accelerometers recording the soil motion in the two horizontal *x* and *y* directions, and a laser sensor measuring the lateral displacement of the laminate (at this elevation). Also, two vertical accelerometers were used to monitor any vertical motion that may generate in the soil by the biaxial excitation.

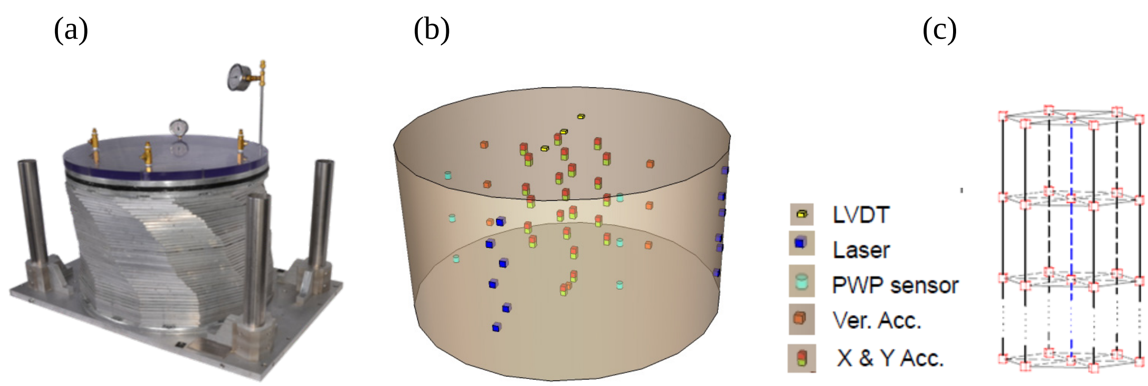

Figure 1: Testing equipment and instrumentation: (a) biaxial laminar container, (b) soil model and installed sensors, and (c) configuration of the central accelerometer array.

Testing procedure

The tested models of level site deposit consisted of a saturated Nevada 120 sand layer with a height of 28 cm representing a prototype depth of 7 m at 25g. The soil (Nevada 120) is clean uniform fine sand with a specific gravity of 2.65, grain size distribution characterized by D_{10}=0.09 mm, D_{50}=0.3 mm, and a uniformity coefficient of 2.07. The minimum and maximum void ratios are e_{min}=0.55 and e_{max}=0.751. The test discussed in this article employed a deposit with relative density of 75%, representing a dense sand deposit. The model was built using dry pluviation method, where the sand is placed in layers, typically 2 cm thick, using a pluviator. The pluviation process was interrupted at pre-defined elevations for the placement of the accelerometers. The container was placed thereafter on the shaker platform (centrifuge basket). Saturation took place on the shaker platform (to minimize disturbance to the deposit) and it is done under vacuum pressure using viscous fluid (25 times viscosity of the water). Thus, the tested model corresponds to a prototype with permeability comparable to that of natural Nevada sand. Figure 2 shows the saturated model ready for spinning. When the g-level reached 25g, the model was shaken with a series of biaxial base excitations.

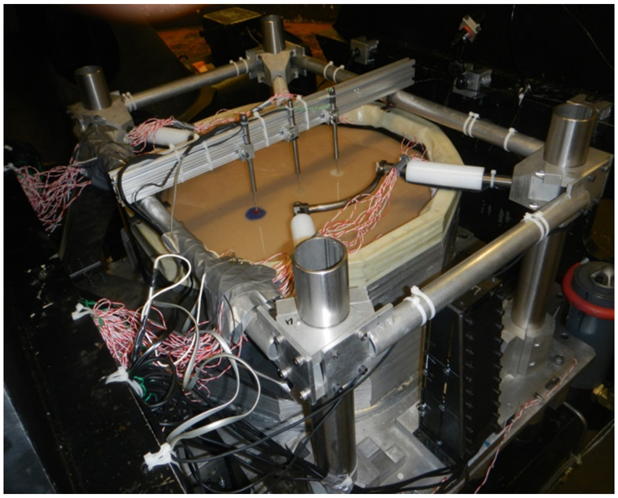

Figure 2: View of the laminar box with fully instrumented model.

Accelerations and Stress-Strain Response

Acceleration time histories

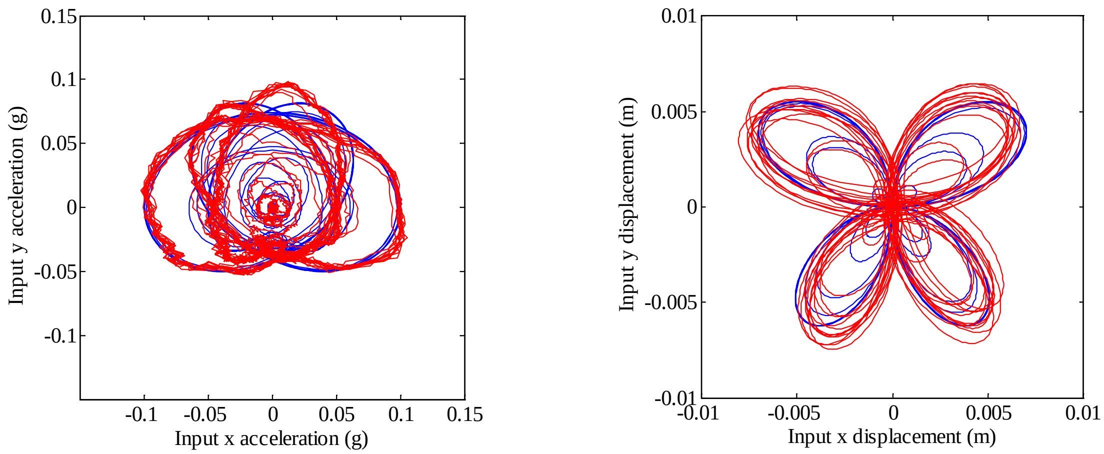

Figure 3: Input *x-y* base acceleration and trace of corresponding *x-y* displacements (blue line is signal sent to the shaker and red is the recorded signal).

The centrifuge soil model was subjected to a series of biaxial base excitations. The input consisted of synthetic motions with 1, 2, 3 Hz dominant frequencies and varying amplitude. Four specific input motions were obtained by varying the phase angle θ of the *y* and *x* accelerations ($\theta = \arctan(a_y/a_x)$). Figure 3 exhibits the accelerations of the test discussed herein, while Figure 4 shows only part of the corresponding phase angle time history (to ensure clarity). The variations of this angle show a pattern consistent with that of real earthquake records. The time histories of the input motion as well that of the accelerations recorded at 1m, 3 m and 7 m depths are presented in Figure 5.

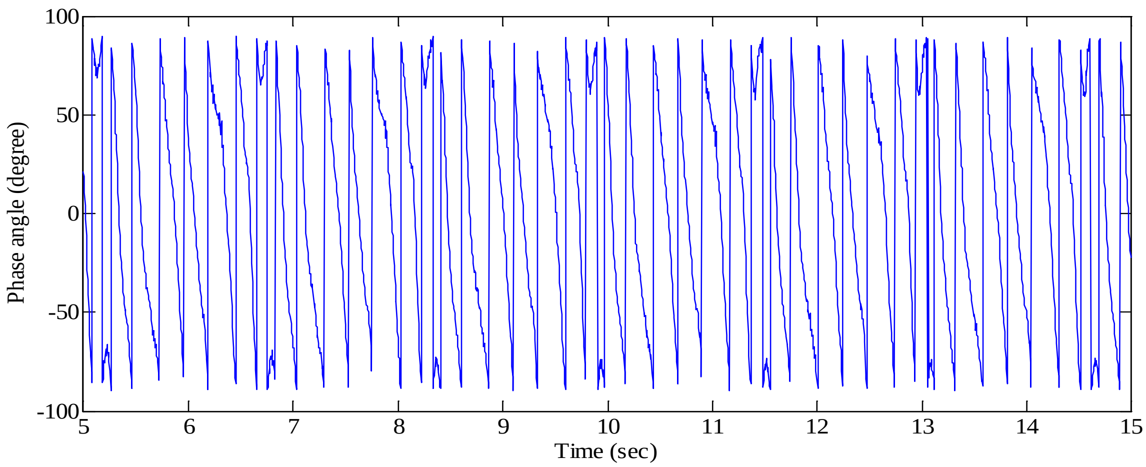

Figure 4: Phase angle of the *x-y* acceleration for the 5 s to 15 s time window.

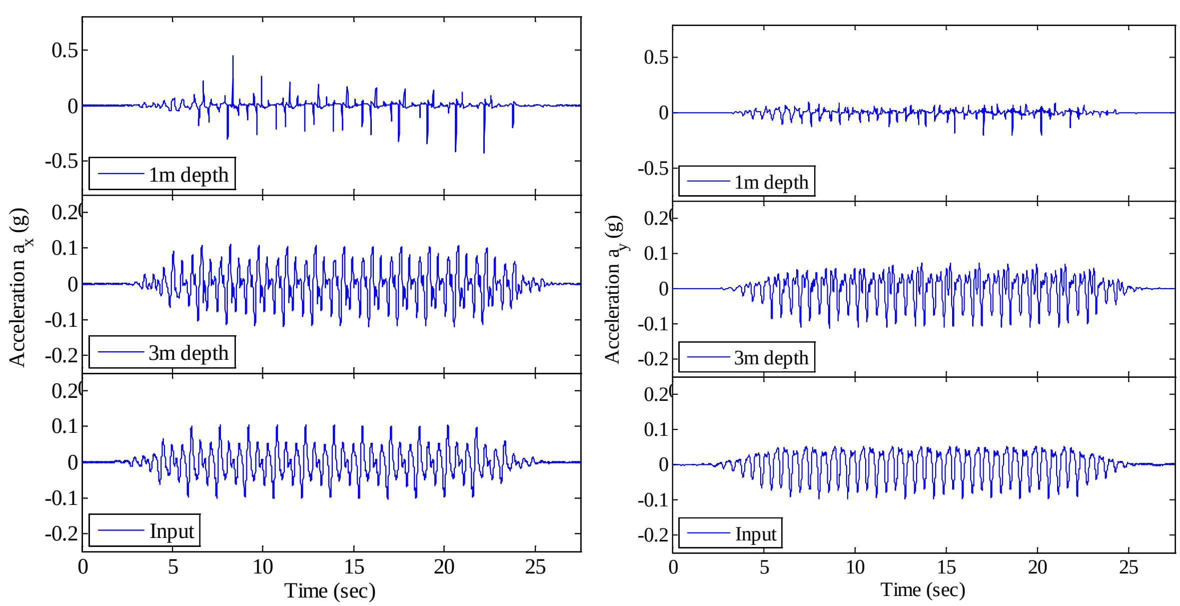

Figure 5: Acceleration in the *x* and *y* directions at various depths.

Stress-strain histories

The recorded accelerations were used to obtain the corresponding histories of the shear stress and strain vectors acting on horizontal planes. These stresses and strains were evaluated using the system identification technique that was developed by Zeghal, Elgamal and co-workers (Zeghal & Elgamal (1994), Zeghal et al. (1995)). This technique provides non-parametric estimates of shear stress-strain histories utilizing only accelerations records provided by vertical arrays of accelerometers. The technique is based on a two-dimensional shear beam idealization to describe the lateral displacement of a level deposit:

$$\frac{\partial \boldsymbol{\tau}}{\partial z} = \rho \ddot{\boldsymbol{u}} \text{ , with boundary condition } \boldsymbol{\tau}(0,t) = 0 \qquad (1)$$

where   is time, is depth, τ=[τ_xz (z,t)   τ_yz (z,t)]   is the horizontal shear stress vector (τ_xz (z,t) and τ_yz (z,t) are shear stresses in the x and y directions acting within the horizontal plane normal to the z vertical direction) and u ̈=[u ̈_(xz) (z,t)   u ̈_(yz) (z,t)]   is the absolute horizontal acceleration vector (u ̈_(xz) (z,t) and u ̈_(yz) (z,t) are accelerations in the x and y directions within the plane normal to z-axis).

Integrating the equation of motion and using the stress free surface boundary condition (Eq.1), the shear stress at any level z may be evaluated using:

$$\boldsymbol{\tau}(\mathrm{z},\mathrm{t}) = \int_0^z \rho \ddot{\boldsymbol{u}}\, dz \qquad (2)$$

Employing linear interpolation between downhole accelerations, the discrete counterpart of shear stress midway between levels z_{i-1} and z_i of the (i-1)$^{\mathrm{th}}$ and i^{th} accelerometers   may be expressed as:

$$\boldsymbol{\tau}_{i-\frac{1}{2}}(t) = \boldsymbol{\tau}_{i-1}(t) + \rho \frac{3\ddot{\boldsymbol{u}}_{i-1}+\ddot{\boldsymbol{u}}_i}{8}\, \Delta z_{i-1}, \quad i = 2,3, \ldots. \qquad (4)$$

In which subscript i refers to levelz_i, $\boldsymbol{\tau}_{i-\frac{1}{2}}$ is shear stress at level$(z_{i-1} + z_i)/2$, $\tau_i = \boldsymbol{\tau}(z_i, t)$, $\ddot{\boldsymbol{u}}_i = \ddot{\boldsymbol{u}}(z_i, t)$, and Δz_i is spacing interval. These stress estimates are second-order accurate. The corresponding shear strain vector is given by:

$$\boldsymbol{\gamma} = \frac{\partial \boldsymbol{u}}{\partial z} \qquad (5)$$

where $\boldsymbol{u}(z,t)$ is displacement vector and $\boldsymbol{\gamma} = \left[\boldsymbol{\gamma}_{xz}(z,t)\ \ \boldsymbol{\gamma}_{yz}(z,t)\right]$ is the shear strain vector. A second-order accurate shear-strain $\boldsymbol{\gamma}_{i-\frac{1}{2}}$ at levels $(z_{i-1} + z_i)/2$ may be expressed as (Zeghal et al 1995):

$$\boldsymbol{\gamma}_{i-\frac{1}{2}}(t) = \frac{\boldsymbol{u}_i - \boldsymbol{u}_{i-1}}{\Delta z_{i-1}}\ , \quad i = 2, 3, \ldots \ldots \qquad (6)$$

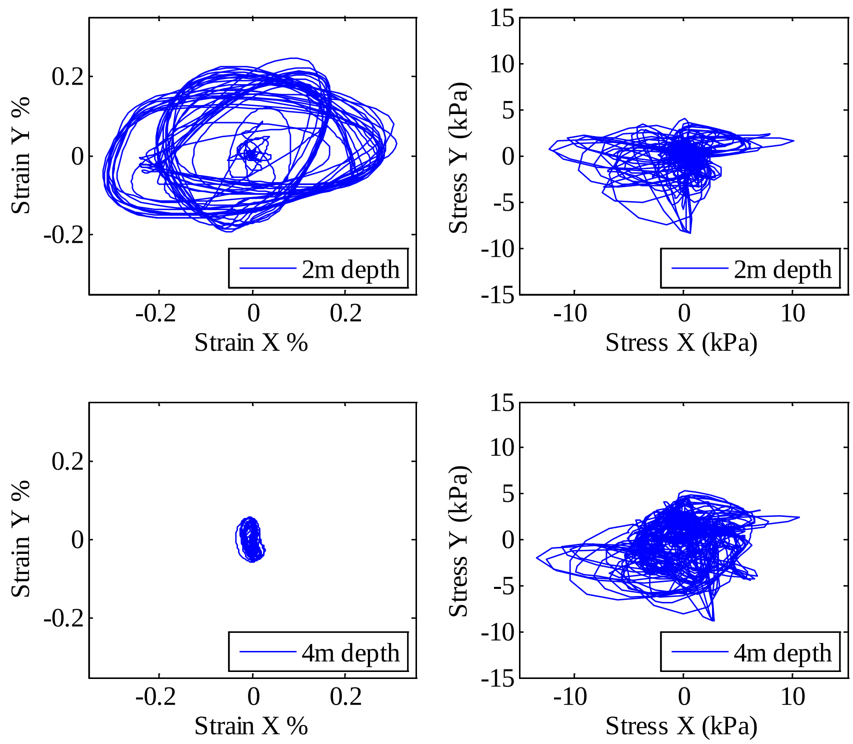

Figure 6: Stresses and strains in *x-y* plane (at selected depths).

Low frequency components induce baseline drifts in the evaluated shear-strain histories and were filtered out together with minor amplitude high frequency components. A zero phase time domain FIR (finite duration impulse response) band-pass (0.5 Hz to 10.0 Hz) filter was employed. This filtering procedure doesn't introduce any phase shifts and the bandwidth was wide enough not to compromise the shear stress and strain properties. Representative shear stress-strain histories at different depths are depicted in Figures 6 and Figure 7.

Results and Discussion

The obtained stress-strain histories showed a complex bi-directional horizontal response as exhibited by Figures 6 and 7. For instance, the *x-y* strain paths and *x-y* stress paths (Figure 6) show that the soil strata experienced a multi-directional non-proportional (NP) loading. The associated stress-strain response was also marked by a coupled dilative response in the *x* and *y* directions, as shown in Figure 7. This figure explicitly shows a selected instance (shown with an "o" marker) where the dilative response at a large strain in the *x* direction led to a regain in stiffness not only in the *x* direction but also in the *y* direction even though the strain in this (*y*) direction was very small. This dilative coupling occurred repeatedly during several other instances. The coupled dilative response and non-proportional loading complicates the conventional counting technique of load cycles commonly used in liquefaction analyses (Green & Terri 2005). This is due to the fact that peaks and valleys of the stresses in the *x*, *y* directions $\tau_{xz}(z,t), \tau_{yz}(z,t)$ in general do not coincide so it is not fully clear how to count the cycles and also how to evaluate an equivalent stress condition to the biaxial one, Ishihara &

Yamazaki (1980). Also, the phase shift alters the stress loading paths from line-type paths to loop- type paths and the shape of the corresponding stress-strain loops differs from the common one-dimensional case Wichtmann et al. (2007) and Gutierrez et al. (1991). Furthermore, The NP loading leads to complex correlation linking the associated stresses and induced strains especially in the presence of a strong dilative response.

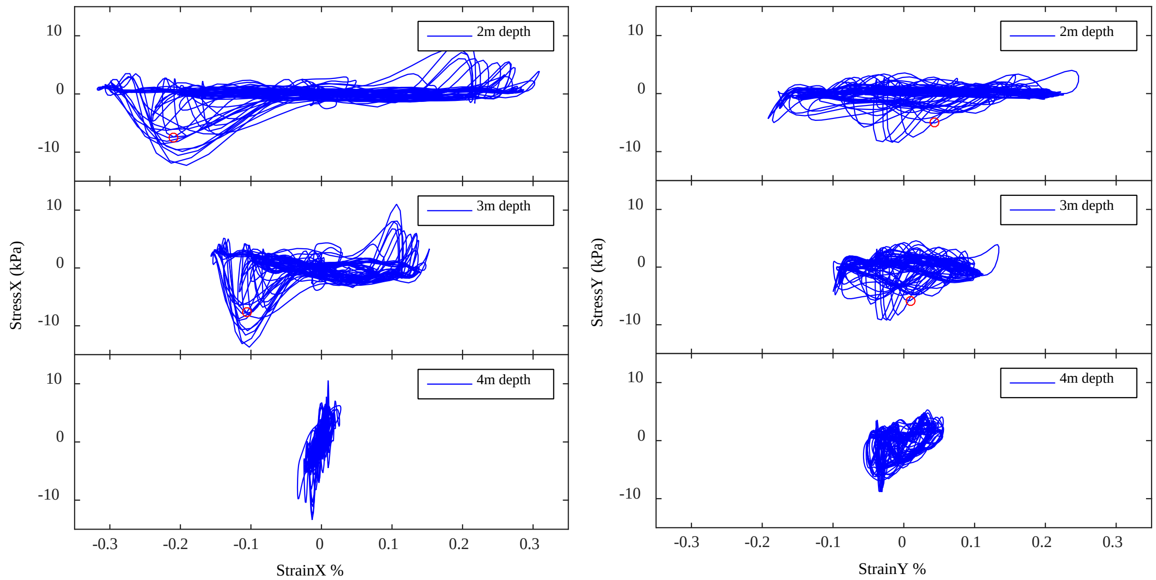

Figure 7: Stress-strain loops at depths of 2, 4 and 6 m respectively (the red circle corresponds to instance of large dilations in the *x* direction leading to a regain in stiffness in the *y* direction even though the strains were very small in this y direction).

Conclusions

This paper presented the outcome of a series of centrifuge tests conducted to assess the effects of a bi-axial shaking on the response of level ground deposits. The recorded accelerations were used to evaluate the two components of the shear stress and strain vectors acting on the horizontal planes of the tested deposits. These stresses and strain showed a complex response pattern associated with coupling of the soil response in the two horizontal (*x* and *y*) direction during phases of large strains and associated dilative response. The observed accelerations and shear stress and strain histories showed a non-proportional response that necessitate modifications to the conventional counting technique of load cycles commonly used in liquefaction analyses.

Acknowledgments

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References

Bielak, J., Xu, J. and Ghattas, O. "Earthquake ground motion and structural response in alluvial valleys" *J. Geotechnical & Geoenv. Engrg.,Vol*. 1999; 125 : 413-423.

El-Shafee, O., Spari, M., Abdoun, T., and Zeghal, M. “Analysis of the response of a centrifuge model of a level site subjected to biaxial base excitation”. *Geotechnical Special Publication, n 234 GSP*, 2014; p 1081-1090.

Green, R. A., and Terri, G. A. “The number of equivalent cycles concept for liquefaction evaluations—Revisited.” *Journal of Geotechnical and Geoenvironmental Engineering* ASCE; 2005; **131**(4): 477-488.

Gutierrez, M., Ishihara, K., and Towhata, I. “Flow theory for sand during rotation of principal stress direction.” Soils Found., 1991; **31**(4): 121–132.

Ishihara K. and Yamazaki F. “Cyclic simple shear tests on saturated sand in multi-directional loading”. *Soils and Foundations*, 1980; **20**(1):45-59.

Ng, C.W.W., Li, X.S., Van Laak, P.A. and Hou, D.Y.J. "Centrifuge modeling of loose fill embankment subjected to uni-axial and bi-axial earthquakes” *J. Soil Dynamics & Earthquake Engrg.*, 2003; **24**: 305-318.

Su, D. and Li, X.S. "Centrifuge modeling of pile foundation under multi-directional earthquake loading” *Physical Modelling in Geotechnics-6th ICPMG*, 2006; **1**: 1049-1055.

Su, D. and Li, X.S. "Impact of multidirectional shaking on liquefaction potential of level sand deposits” *Geotechnique*, **58** (4): 259-267. 2008

Su, D. "Resistance of short, stiff piles to multidirectional lateral loadings” *J. Geotechnical Testing*, 2012; **35** (2): 1-17.

Zeghal M, A. W. Elgamal, H. T. Tang, and J. C. Stepp. “Lotung downhole array. II: evaluation of soil nonlinear properties,” *Journal of Geotechnical Engineering*, 1995; **121**(4): 363–378.

Zeghal, M., and Elgamal, A.-W. “Analysis of site liquefaction using earthquake records,” *Journal of Geotechnical Engineering*, ASCE, 1994; **120**(6):996-1017.

Wichtmann T., Niemunis A., and Triantafyllidis T. “ On the influence of the polarization and the shape of the strain loop on strain accumulation in sand under high-cyclic loading.” *Soil Dynamics and Earthquake Engineering*, 2007; **27**(1):14-28.