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Validating 1D Numerical Simulation of the Free Field Using Centrifuge Tests

A. Balachandra, C. Hayden & L. Wotherspoon
Department of Civil and Environmental Engineering, University of Auckland

C.R. McGann
Department of Civil and Natural Resources Engineering, University of Canterbury

ABSTRACT

The increasing shift towards performance based geotechnical earthquake engineering design requires an improved understanding of soil-structure interaction (SSI) for buildings on liquefiable deposits. While a number of authors have used centrifuge tests and numerical modelling to study this phenomena, a limited number of studies have been undertaken where numerical models have been validated against well-instrumented physical model tests or centrifuge tests. Therefore, this research focuses on validating numerical simulations developed using FLAC and the PM4Sand constitutive soil model and OpenSees and PDMY02 constitutive soil model against published centrifuge experiment data. By considering two numerical programs and constitutive soil models the research also aims to compare the relative performance of the two numerical simulations. This paper presents the validation of the simulated free field response against settlement, pore water pressure and accelerations measured in the centrifuge test, using a large array of instruments. This validation is an important step towards subsequent research involving SSI.

1 INTRODUCTION

Triggering of liquefaction due to earthquake shaking and its impact on land and built structures requires careful consideration in engineering design. The topic of liquefaction has been extensively studied and a number of liquefaction assessment procedures are currently available to engineers (Robertson & Wride, 1998; Moss et al., 2006; Idriss & Boulanger, 2008; Boulanger & Idriss, 2014). However, liquefaction-induced deformation of buildings is still largely estimated using simplified procedures that were developed to estimate post liquefaction, one dimensional consolidation settlement in the free field such as those proposed by Ishihara and Yoshimine (1992) and adopted by Zhang et al. (2002).

Liquefaction is a complex phenomenon, and simplified techniques cannot capture all the mechanisms that contribute to liquefaction-induced deformation of buildings (Bray & Dashti, 2014). Further insight into the response of buildings on liquefiable deposits can be obtained from centrifuge experiments or advanced numerical simulations. Centrifuge experiments provide a high level of control to define and assess geotechnical problems, where stress dependent response of soils is important, and can provide a well-constrained set of data for validation studies. However, due to the cost and time to construct and undertake a centrifuge test, they are often not practical for design engineers. Numerical models offer a more practical alternative for design engineers. However, validation of numerical models against well-defined datasets is essential to demonstrate their ability to capture physical mechanisms.

The primary focus of the research currently being undertaken by the authors is to validate numerical simulations of soil structure interaction (SSI) of buildings on liquefiable deposits against well-defined and well-constrained data collected from the T4.6-40 centrifuge experiment Hayden et al. (2014). The numerical models for this research are developed using FLAC and the PM4Sand constitutive soil model (Boulanger & Ziotopoulou, 2017) and OpenSees and the PDMY02 constitutive soil model (Yang et al., 2003). FLAC is an explicit finite difference program that is able to model structures supported on soil or rock that may undergo plastic flow when their yield limits are reached (Itasca Consulting Group Inc, 2016), while OpenSees is an open source finite element program for modelling geotechnical and structural systems under static and dynamic conditions (McKenna et al., 2000). This paper presents the first stage of this research and focuses on 1D free-field numerical simulations compared to measurements from the centrifuge experiment. This initial stage is important for subsequent validation of the SSI response of buildings on liquefiable deposits.

2 CONSEQUENCES OF LIQUEFACTION

Liquefaction typically occurs in loose saturated coarse grained soils due to the tendency for soil particles to contract under earthquake shaking, which can result in generation of excess pore pressure and a reduction in effective stress in the soil material, leading to a potential loss in strength and stiffness. The resulting liquefaction-induced total and differential settlement of buildings can be particularly damaging. Bray and Dashti (2014) note that liquefaction-induced settlement of structures is due to a combination of volumetric- and deviatoric mechanisms, which are not captured by simplified methods developed for the free field.

Figure 1: Difference in settlement between a pile-supported building, free field and building on shallow foundations (Ashford et al., 2011).

Volumetric mechanisms include settlement due to partial drainage during earthquake shaking, sedimentation or solidification of soil particles, post-liquefaction consolidation settlement and volumetric displacement due to soil ejecta, while deviatoric mechanisms include shear induced settlement due to partial bearing failure of the foundations and/or deformation due to SSI induced ratcheting of the structure (Bray and Dashti (2014). Figure 1 illustrates the results of these different mechanisms.

Liquefaction triggering can also alter the frequency content and amplitude of the ground motion and generally amplify long period ground motion content (typically periods of 0.4 s or greater) (Youd & Carter, 2005; Hartvigsen, 2007; Gingery, 2014). Youd and Carter (2005) note that the effect of liquefaction on the short period content appears to be dependent on the point at which liquefaction triggering occurs, with some evidence of de-amplification when liquefaction triggering occurs early during the earthquake shaking but not when triggering occurs later. Zeghal and Elgamal (1994) and Gingery (2014) observed high frequency acceleration spikes or significant amplification at very short periods (< 0.05 s), likely due to phase transformation behaviour as the soil cycled between contractive to dilative behaviour.

3 PREVIOUS STUDIES CONSIDERING SSI AND LIQUEFACTION

A number of validation studies of liquefaction, and to a lesser extent SSI response of buildings on liquefiable deposits, have been previously undertaken. Examples of past or ongoing studies include the Verification of Liquefaction Analyses by Centrifuge Studies (VELACS) (Arulanandan & Scott, 1993) and the Liquefaction Experiments and Analysis Project (LEAP), which is an ongoing international collaboration to validate numerical simulations of liquefaction response against centrifuge tests (Kutter et al., 2014).

This paper focuses on numerical modelling of one of the centrifuge tests that was undertaken as part of the Network for Earthquake Engineering Simulation Research (NEESR) Seismic Performance Assessment in Dense Urban Environments Project. Allmond et al. (2015) summarise nine centrifuge tests involving isolated and adjacent building models on liquefiable deposits that were undertaken as part of the project, including the test modelled in this paper. This database includes tests previously used in validation of OpenSees and PDMY02 (Karimi & Dashti, 2015) and FLAC and UBCSAND (Dashti & Bray, 2012). Key observations from these studies that are relevant to validation of 1D free-field numerical simulations include:

- Most of the volumetric settlement in the free field in the centrifuge tests occurred during strong shaking due to sedimentation and partial drainage, with the post-liquefaction, one dimensional consolidation settlement a relatively minor component of the total free field settlement measured. Both Karimi and Dashti (2015) and Dashti and Bray (2012) noted that the numerical simulations significantly underestimated settlements in the free field.
- Karimi and Dashti (2015) suggested that the underestimation of free field settlements may be due to increase in the hydraulic conductivity as the soil liquefies. The increase in hydraulic conductivity is difficult to assess and the hydraulic conductivity is typically modelled as a constant value in numerical simulations. They also suggested that the underestimation may be due to underestimation of the coefficient of volume compressibility in the PDMY02 constitutive soil model.
- Karimi and Dashti (2015) noted that the numerical simulations developed using OpenSees and PDMY02 approximated centrifuge acceleration and excess pore pressure response well at low levels of shaking.
- At higher levels of earthquake shaking, Karimi and Dashti (2015) note that the contractive-dilative response of the soils are captured in the initial loading cycles but the sharp dilative spikes are not captured over the remaining duration of the ground motion. They suggest this could be a result of PDMY02 model not updating the soil properties to account for shaking-induced densification.

4 1D NUMERICAL MODEL OVERVIEW

4.1 Centrifuge experiment

The T4.6-40 centrifuge experiment presented by Hayden et al. (2014), where the experiment number refers to the prototype scale thickness (4.6 m) and relative density (40%) of the liquefiable material, assessed the SSI response of isolated structures and structure-soil-structure interaction (SSSI) response of pairs of adjacent structures on liquefiable deposits. Figure 2 shows the layout of the T4.6-40 centrifuge experiment, with all dimensions presented in prototype scale. As the current paper focuses on the validation of the free field conditions using 1D numerical simulation, the simulated acceleration, pore pressure, and vertical settlement were compared against measurements obtained away from the structures.

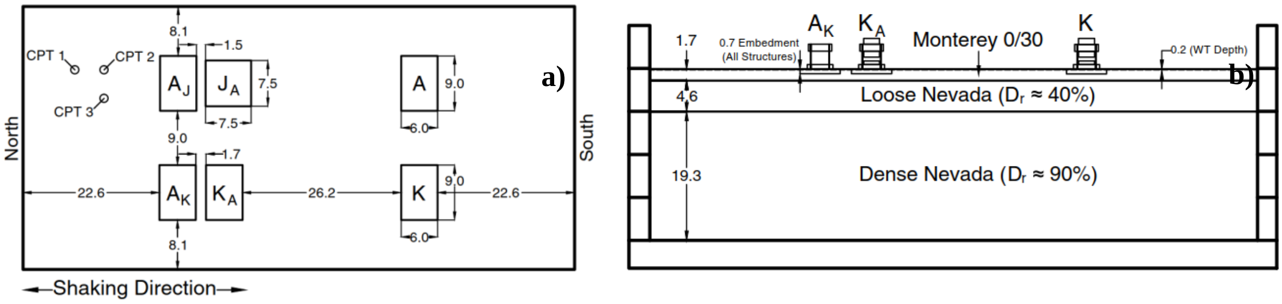

Figure 2: Layout of T4.6-40 centrifuge experiment showing prototype dimensions: a) Plan view of centrifuge test; b) Profile view of centrifuge test.

4.2 Ground motions

The four ground motions applied in the centrifuge were a small Port Island (PRISmall), moderate Port Island (PRIMod), large Port Island (PRILarge) and moderate TCU (TCUMod). The Port Island motions are shorter duration pulse-like motions modified and scaled from a ground motion recorded during the 1995 Mw 6.9 Kobe earthquake. TCUMod is a non-pulse motion with a longer significant duration (approximately 28 s, compared to about 8 s for the Port Island records) based on a modified and scaled version of the ground motion recorded at the TCU078 station during the 1999 Chi-Chi earthquake (Hayden et al., 2014). Figure 3 shows the acceleration response spectra for these four motions.

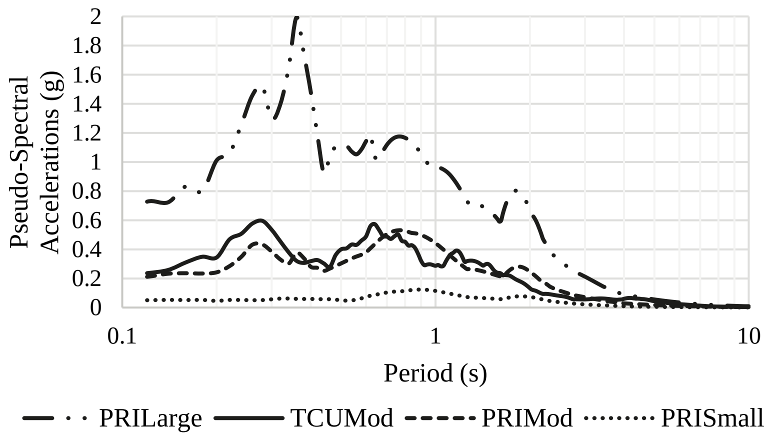

Figure 3: Response spectra for the ground motions considered for the 1D simulation.

4.3 Boundary conditions and mesh geometry

The boundary conditions adopted for the 1D numerical simulations were chosen to represent the likely boundary conditions in the centrifuge container. A rigid boundary has been assumed for the base of the numerical model to simulate the hard base of the centrifuge container. Along the model sides, a periodic boundary condition, suitable for a free-field model was achieved by tying together nodes at the same respective elevation so they undergo the same displacements. A uniform grid, consisting of a column of 0.1 m square zones, was adopted to simulate the soil profile from the centrifuge experiment.

4.4 Material model and parameters

Two nonlinear effective stress constitutive soil models, Pressure Dependent Multi-Yield 02 (PDMY02) as implemented in OpenSees and PM4Sand as implemented in FLAC, have been considered. PDMY02 is an elastoplastic soil constitutive model for simulating pressure-sensitive response of granular soil material and includes contractive and dilative response and generation of excess pore pressure under dynamic loading (Yang et al., 2003). PM4Sand follows the basic framework of the stress-ratio controlled, critical state compatible, bounding surface plasticity model of Dafalias and Manzari (2004) but modified to improve the simulation of the stress-strain behaviour that develops during liquefaction (Boulanger & Ziotopoulou, 2017).

The parameters for PM4Sand presented in Table 1 are based on Armstrong et al. (2012), and the parameters for PDMY02 presented in Table 2 are based on Karimi and Dashti (2015). The objective of these studies were to validate numerical simulations against centrifuge tests, which used the same sand as the T4.6-40 centrifuge experiment considered for this research. For PM4Sand the calibrated parameters presented by Armstrong et al. (2012) were adjusted for the relative densities that were used in the centrifuge experiment considered in this study using relationships published in Boulanger and Ziotopoulou (2017) and Armstrong et al. (2012). The default parameters that are suggested by the developers of the constitutive soil models were assumed for all other parameters not presented in Table 1 and Table 2. The use of previously calibrated parameters provides an advantage of avoiding potential bias (i.e. over calibration of parameters to fit a single centrifuge experiment). The following hydraulic conductivities were used in both software packages based on the values presented by Karimi and Dashti (2016), after adjusting for viscosity: Monterey sand 1.39×10^{-3} m/s, 'loose' Nevada sand 1.70×10^{-4} m/s, and "dense" Nevada sand 5.89×10^{-5} m/s.

Table 1: Soil parameters adopted for PM4Sand constitutive model

Parameter	**Loose Nevada Sand**	**Dense Nevada Sand**	**Monterey Sand**
Relative Density, Dr (%)	40%	90%	85%
Min and Max void ratio, e_{min} , e_{max}	0.485, 0.793	0.485, 0.793	0.54, 0.82
Shear Modulus Constant (G_0)	735	902	662
Contraction Rate Parameter (h_{p0})	0.056	0.0023	0.305

Table 2: Soil parameters adopted for PDMY02 constitutive model

Parameter	**Loose Nevada Sand**	**Dense Nevada Sand**	**Monterey Sand**
Relative Density (Dr %)	40%	90%	85%
Reference Shear Modulus (kPa)	46.2	101.9	133.3
Reference Bulk Modulus (kPa)	123.3	272.1	264
Friction and Phase Transformation Angle (deg.)	32, 30	40, 26.5	42, 32
Void ratio, e	0.73	0.58	0.56

5 RESULTS AND DISCUSSION

Figures 4 and 5 present the comparison of simulated and measured ground surface motions for the moderate Port Island and TCU motions and small and large Port Island motions, respectively. The response is presented in the form of simulated (using PM4Sand and PDMY02) and measured 5% damped acceleration response spectra within the liquefiable layer. Note that the centrifuge test had two arrays of free-field accelerometers, so there are two experimental lines in the figures and they provide a sense of spatial uncertainty in the experimental results.

As shown in Figure 5, simulated and measured accelerations agree well at low levels of earthquake shaking (i.e. PRISmall) where low levels of non-linear soil behaviour is expected. At moderate levels of shaking (i.e. PRIMod and TCUMod), the simulated long period (> 0.4 s) components in the liquefiable layer compare well with the measured accelerations. However, the high frequency acceleration spikes due to phase transformation behaviour are not captured by the PDMY02 simulations, which is consistent with the results of Karimi and Dashti (2015). The PM4Sand simulations capture the high frequency acceleration spikes well, but the magnitude of the accelerations are generally greater than the measured values.

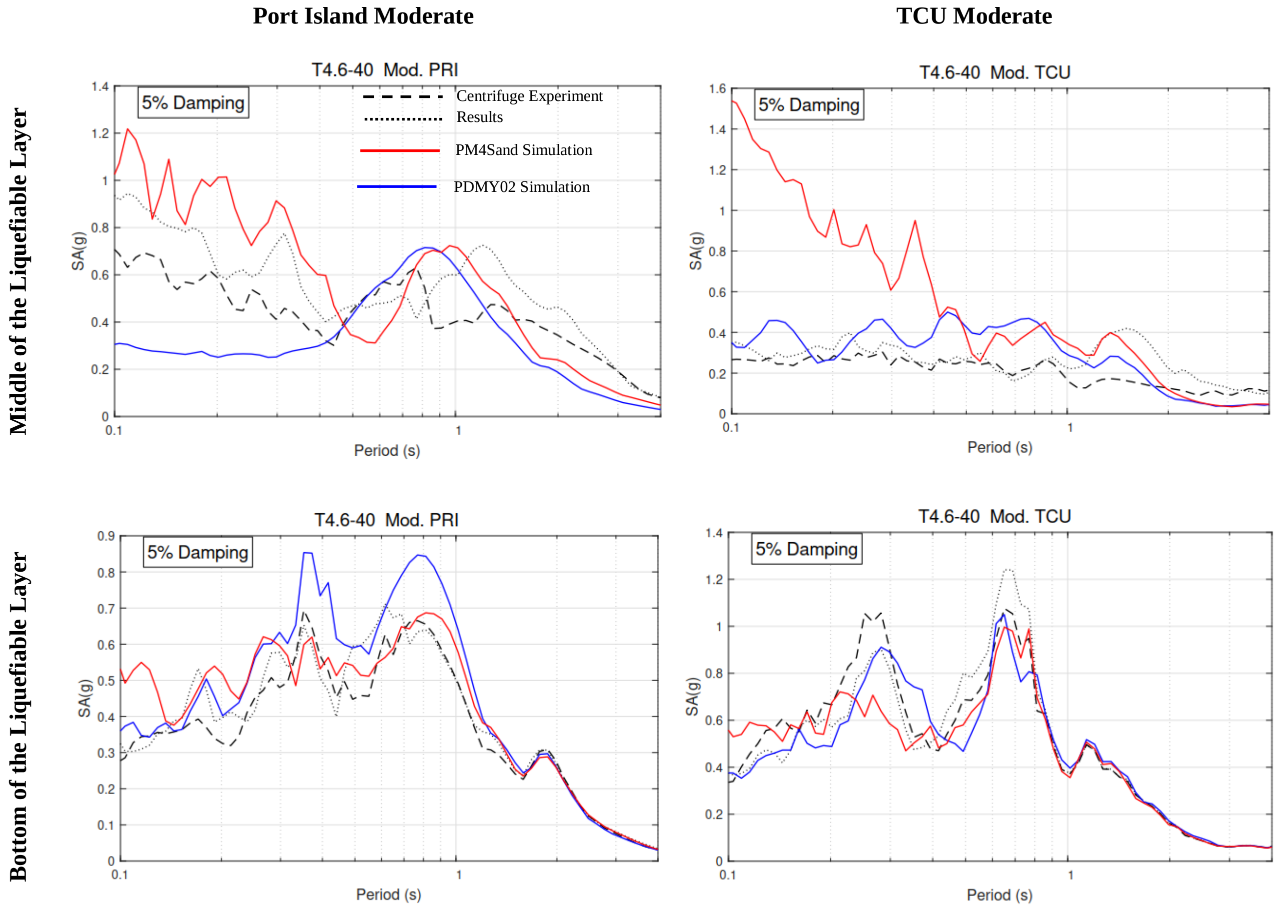

Figure 4: Simulated vs. measured acceleration response for PRIMod and TCUMod ground motions.

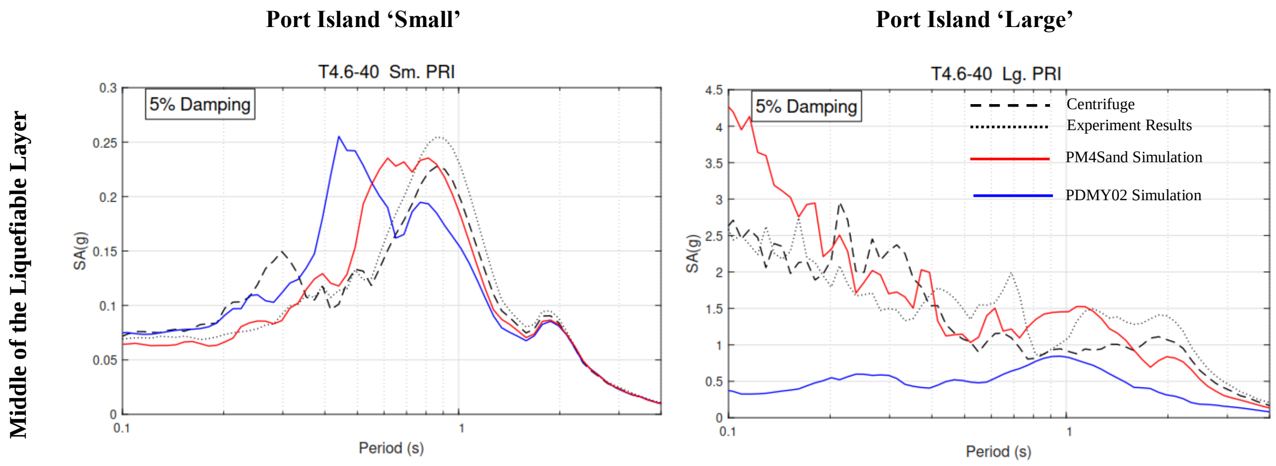

Figure 5: Simulated vs. measured acceleration response for PRISmall and PRILarge ground motions.

The results from the centrifuge experiment also appear to show a different response at short periods when excited by pulse-like and non-pulse ground motions, with high amplification of short period content observed under pulse-like motions and a more damped response observed under the longer duration, non-pulse ground motion. This distinction is not captured well by the numerical models considered in this study, with simulations developed using PM4Sand showing a better match with experimental results for PRIMod ground motion while the simulations developed using PDMY02 showing a better match for the TCUMod ground motion.

For large levels of earthquake shaking (i.e. PRILarge), the PDMY02 simulations significantly underestimate the acceleration as it travels through the liquefiable layer, whereas the PM4Sand simulations agree well with the centrifuge experiment results with the exception of simulated accelerations at frequencies greater than 5 Hz, which are significantly greater than the measured experimental results. The PDMY02 simulations under PRILarge earthquake shaking capture the response during the initial loading cycles well but following this there is a sudden and significant reduction in the shear modulus and increase in material damping resulting in the overdamped response observed above. While there was some improvement in the simulation when different combination of soil parameters were considered, the PDMY02 response at the PRILarge earthquake shaking generally provided poorer results compared to PM4Sand in this study.

Figure 6 presents comparison of simulated and measured free field vertical settlement at the ground surface. Generally, vertical settlement were significantly underestimated in the numerical simulations, which is consistent with observations made by others in recent validation studies. The exception to this is the TCUMod ground motion, where relatively small free field settlements were measured in the experiment resulting in a better comparison with the simulated results. Overall, the numerical simulations considered in this study were generally not able to capture the significant volumetric settlements that occurred during earthquake shaking.

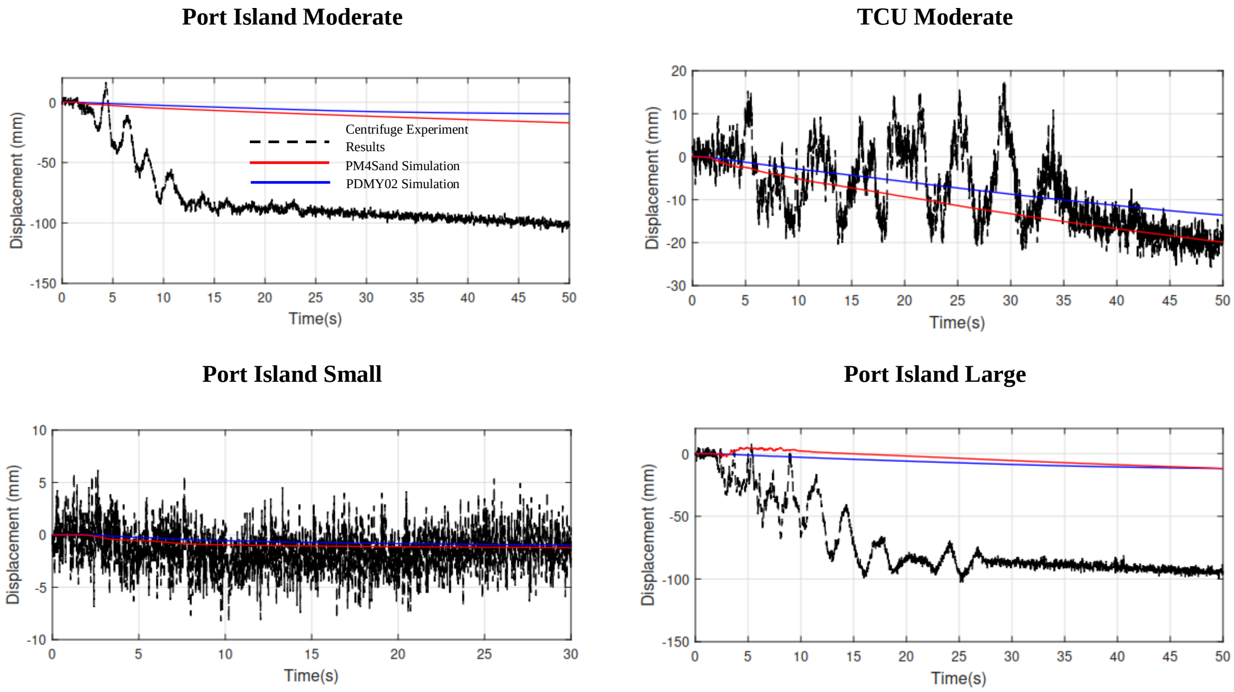

Figure 6: Comparison of simulated vertical settlement at the surface against centrifuge experiment results

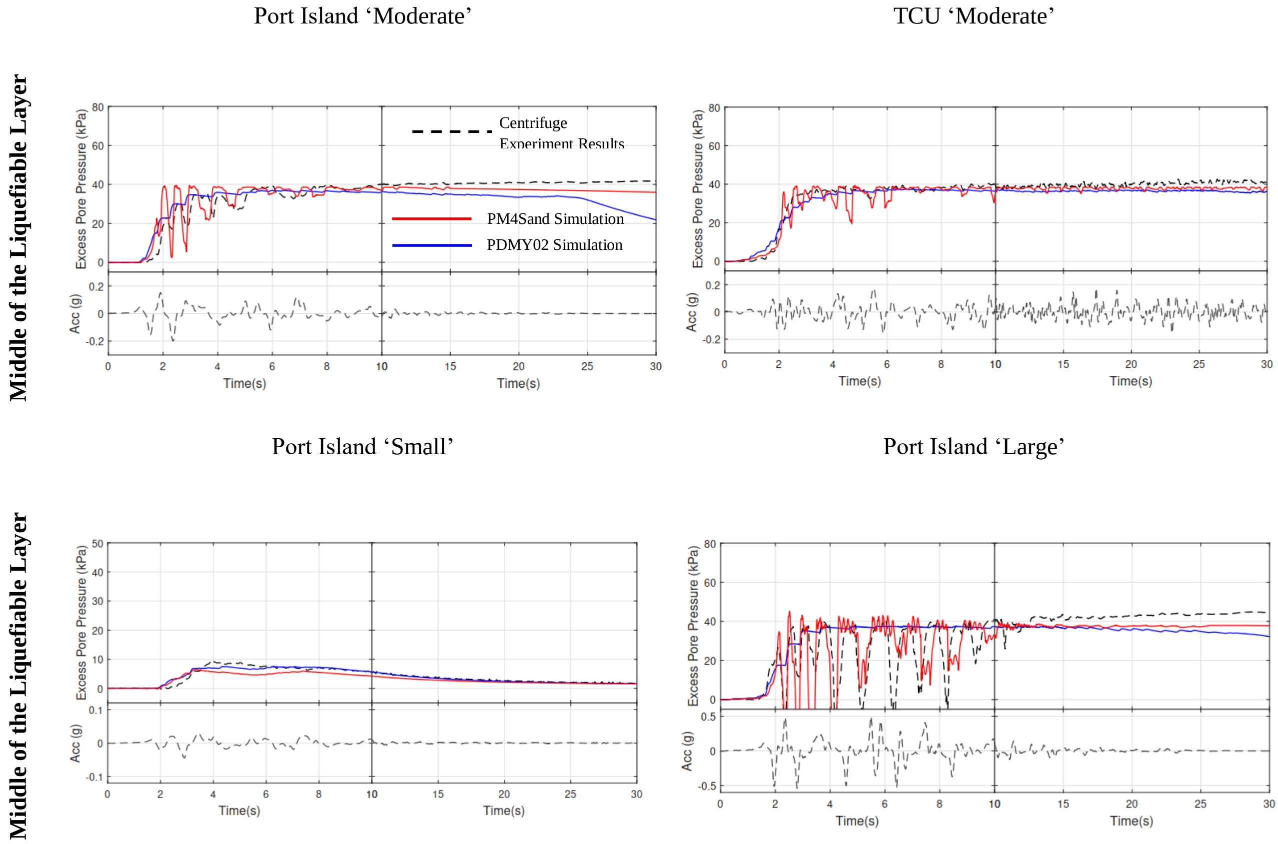

Figure 7: Comparison of simulated excess pore pressure response in the middle of the liquefiable layer with measurements from the centrifuge experiment.

Figure 7 compares the simulated and measured excess pore pressure at the middle of the liquefiable layer. The input ground motions applied at the base of the model are provided for reference. The simulated rate of pore pressure generation agrees well with the centrifuge results. The PM4Sand simulations show sharp spikes that likely reflect a dilative soil response and the consequent decrease in pore pressure and increase in effective stress. These sharp dilative spikes are noted for all motions considered, while the PDMY02 models generally did not capture this response. Sharp dilative spikes are evident in the centrifuge measurements for the Port Island ground motions but are not evident for the non-pulse moderate TCU ground motion. Again this highlights some of the difficulty in capturing the effects of ground motion properties using the numerical models considered in this study.

6 CONCLUSIONS

This paper presents the validation of 1D free field numerical simulations against a previous centrifuge experiment. The numerical simulations were undertaken using PM4Sand as implemented in FLAC and PDMY02 as implemented in OpenSees. The simulated and measured pore pressure and acceleration response generally agreed well, particularly at lower levels of earthquake shaking. Differences between the two numerical simulations were noted when simulating pulse-like and non-pulse ground motions and at higher levels of earthquake shaking, where the PM4Sand simulations performed better for pulse-like motions, and PDMY02 performed better for non-pulse motions. Both numerical tools under-predicted free field vertical settlements, which is generally consistent with observations in other recent validation studies.

The validation of free field conditions was an important step before proceeding with the subsequent study that is currently being undertaken to validate the SSI response of buildings on liquefiable deposits.

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