Physical Modelling in Geotechnics

Multi-dimensional modeling of liquefaction using I-soil model

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ABSTRACT: Design of infrastructure for resiliency in areas susceptible to seismic activities requires assessing the performance of individual infrastructure elements and the overall system performance during earthquakes in multi-dimensional (1D/2D/3D) space. This study evaluates the capabilities of a newly developed constitutive model, I-soil, in multi-dimensional space for seismic site response analysis with porewater pressure generation. I-soil model is a 3D hysteretic nonlinear soil plasticity model which is currently implemented in a solid-fluid fully coupled framework provided by LS-DYNA. This study retrieved accelerometer and porewater pressure transducer data from ten of the Liquefaction Experiments and Analysis Projects (LEAP) centrifuge experiments. CPT measurements and empirical correlations were adopted in soil properties interpretation while automating the model parameter calibration process using python scripts. The comparison between simulation results and measurement data indicated that the simulations can capture the Arias intensity and response spectra of horizontal acceleration time histories and the build-up of excess porewater pressure. The comparison also shows that 2D and 3D models can produce results closer to measurements than 1D models.

Keywords: centrifuge test, liquefaction, numerical simulation, constitutive model, solid-fluid coupling

1 INTRODUCTION

Design of infrastructure for resiliency in areas susceptible to seismic activities requires assessing the performance of individual infrastructure elements and the overall system performance during earthquakes in multi-dimensional (1D/2D/3D) space. The I-soil model developed by Numanoglu (2019) is a 3D nonlinear plasticity hysteretic soil constitutive model that can be used for multi-dimensional modelling of soil behaviour and soil-structure interaction problems. It has been used for simulating the response of medium dense to very dense sand under various engineering applications (Acar et al., 2019; Basarah et al., 2021; Numanoglu, 2019). This study is aimed to evaluate its numerical performance for multi-dimensional modelling of liquefiable soil.

2 I-SOIL MODEL IN LS-DYNA

I-soil model is a 3D nonlinear plasticity hysteretic soil constitutive model (Numanoglu, 2019) to study the settlement of sands under heavy structures during seismic loadings. The model uses (1) a piecewise linearized nonlinear framework (Chiang and Beck, 1994; Iwan, 1967) to capture the nonlinearity of sand response in a wide range of shear strain; (2) a generalized non-Masing hysteresis framework (Numanoglu et al., 2017) to model the hysteretic shear stress-strain behaviour under cyclic loading condition; (3) non-associated flow rule to calculate the shear induced plastic volumetric strains.

I-soil model was implemented in LS-DYNA platform (Numanoglu, 2019). It can be used with a solid-fluid fully coupled framework to model the porewater pressure response of soil under seismic loads.

3 LEAP-UCD-2017 CENTRIFUGE TESTS

Liquefaction Experiments and Analysis Projects (LEAP) is a sequence of research projects developed to produce high-quality experimental data to evaluate soil liquefaction modeling techniques (Kutter et al., 2020). LEAP-UCD-2017 synthesized twenty-four centrifuge tests performed in nine different facilities to model the lateral spreading of mildly sloping liquefiable soils. Fig. 1 shows the configuration and instrumentations at center for the centrifuge tests. A rigid container with a length of 20 m and a width of 4 m in prototype scale was used. Clean Ottawa F65 sand (D_{50}=0.2mm, C_u=1.47) was used to fill the container and form a mildly sloped (5°) surface with a height of 4m at the center. The sand is then saturated and covered with viscous fluid. The input motion is 20 seconds of 1Hz ramped sinewave with target peak acceleration of 0.2g. Ten of the twenty-four centrifuge tests were selected in this study, including KAIST1-2, RPI2-1, RPI3-1, UCD1-2, UCD2-1, UCD2-

2, UCD3-1, UCD3-2, ZJU2-1, and ZJU2-2.

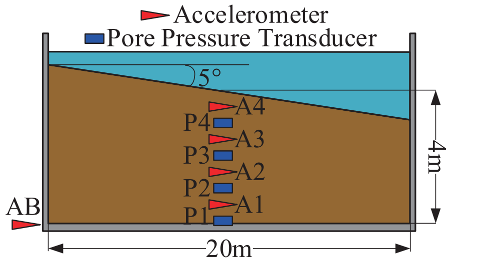

Fig. 1. LEAP-UCD-2017 model configurations and instrumentations

4 I-SOIL/LS-DYNA SIMULATIONS

4.1 Model calibration and development

The geometry and mesh for the multi-dimensional models in LS-DYNA are shown in Fig. 2. The fluid is modelled as an elastic material without shear strength. The soil is simulated with I-soil model.

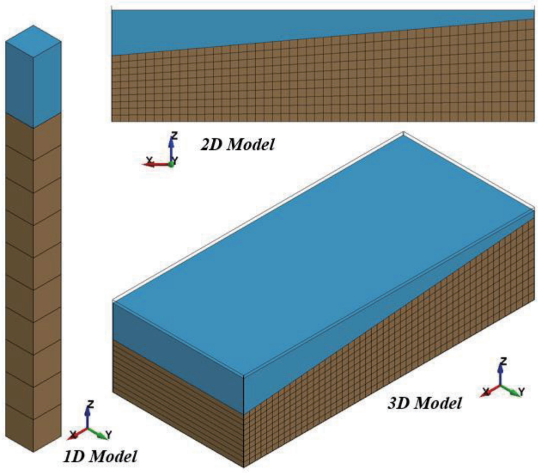

Fig. 2. 1/2/3D models in LS-DYNA

In-flight centrifuge miniature cone penetration test (CPT) profiles were used to interpret soil properties and generate model parameters. The measured CPT profiles with limited depth were extrapolated as shown in Fig. 3. CPT correlations in Kulhawy and Mayne (1990) was used, with an overburden stress correction procedure for in-flight centrifuge miniature CPT tests (Chen et al., 2021), to interpret the soil properties. Darendeli (2001) was adopted to generate normalized modulus reduction and damping curves. A general quadratic/hyperbolic strength-controlled constitutive model proposed by Groholski et al. (2016) was used to produce the stress-strain pairs for I-soil model. The MRDF Pressure-Dependent Hyperbolic model proposed by Phillips and Hashash (2009) was used to generate parameters for non-Masing type hysteretic damping.

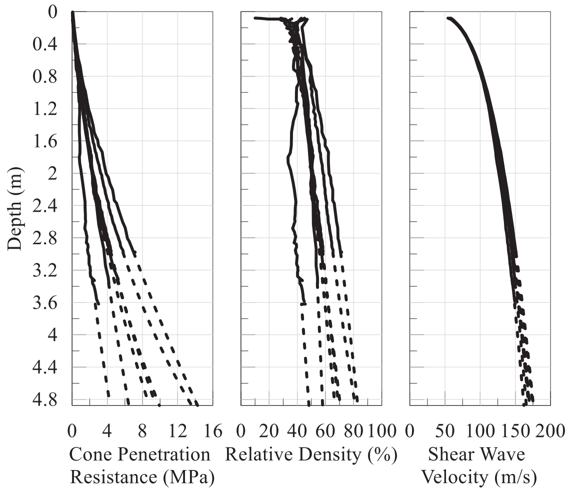

Fig. 3 Measured and extrapolated cone penetration test profiles with interpreted soil properties (CPT data source:Kutter et al., 2020)

4.2 Simulation results and comparison

The comparison between measured and simulated Arias intensity, as shown in Fig. 4, indicates that using I-soil in 2D/3D models can capture the intensity of the motion at different depths. The residuals of Arias intensity, as shown in Fig. 5, indicate that 1D model may overestimate the magnitude of the shaking.

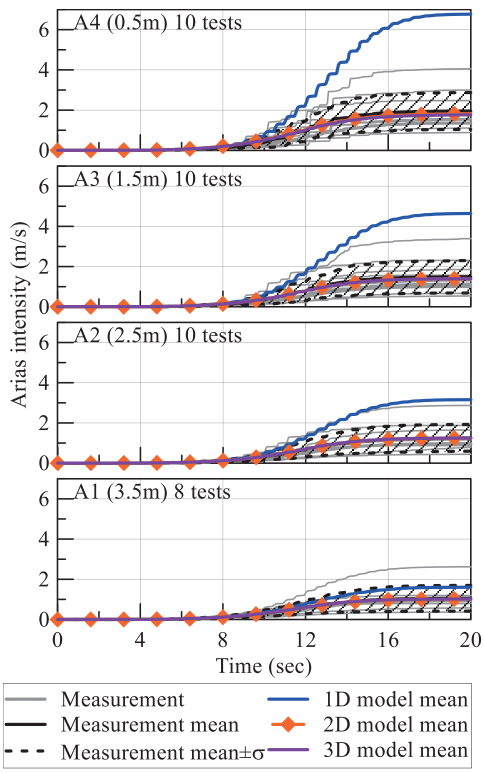

Fig. 4. Measured and simulated Arias intensity for horizontal acceleration time histories at central array

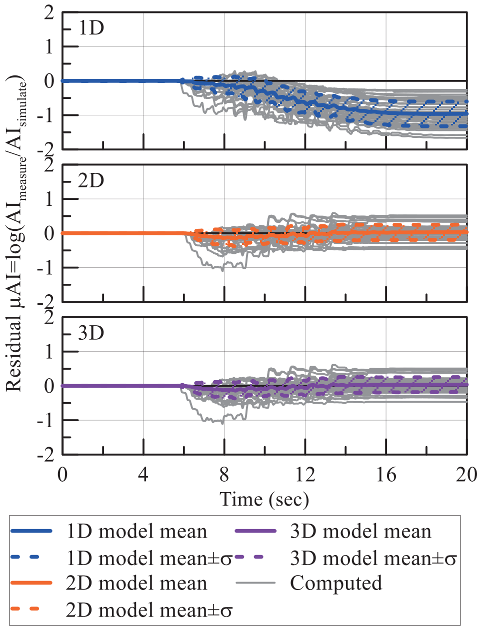

Fig. 5. Simulation residuals of Arias intensity for horizontal acceleration time histories at central array

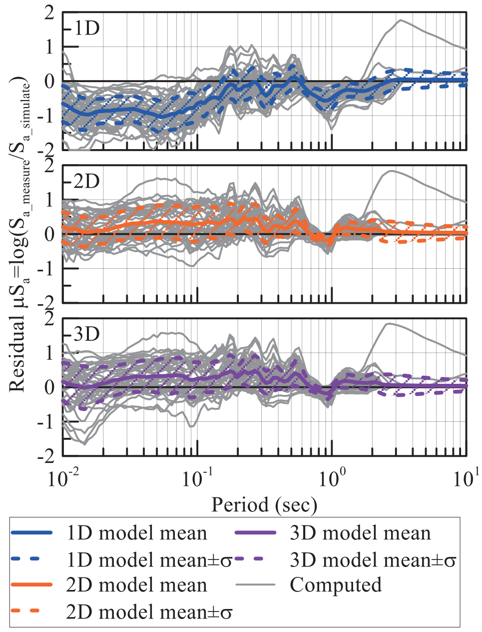

Fig. 7. Simulation residuals of response spectrum for horizontal acceleration time histories at central array

The comparison between measured and simulated response spectrum, as shown in Fig. 6, shows that using I-soil in 2D/3D models can capture the response spectrum better than 1D simulations where the response spectrum is generally overestimated at high frequencies. The residuals of response spectrum, Fig. 7, indicate that 2D/3D simulations show better agreement with the measurements, compared to 1D simulations.

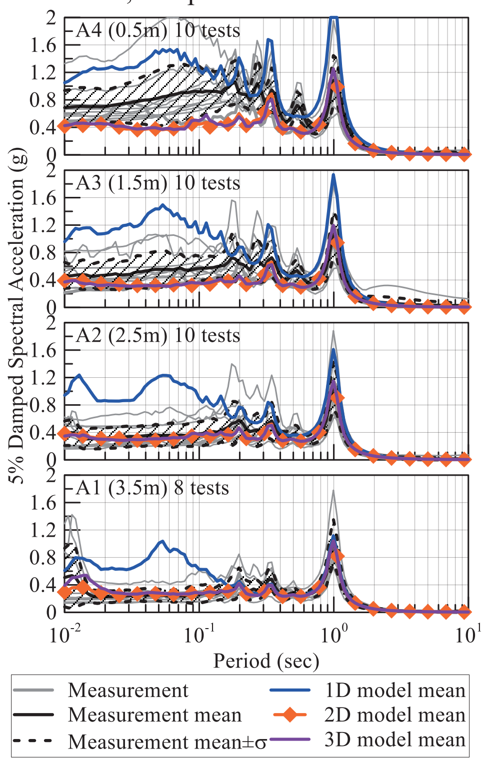

Fig. 6. Measured and simulated response spectrum for horizontal acceleration time histories at central array

The comparison between measured and simulated porewater pressure ratio, as shown in Fig. 8, indicate that the simulations can capture the trend of excess porewater pressure generation. Two and three-dimensional models may underestimate the maximum porewater pressure ratio but performs better in terms of dilation tendency compared to the 1D models where large negative porewater pressure build up is observed.

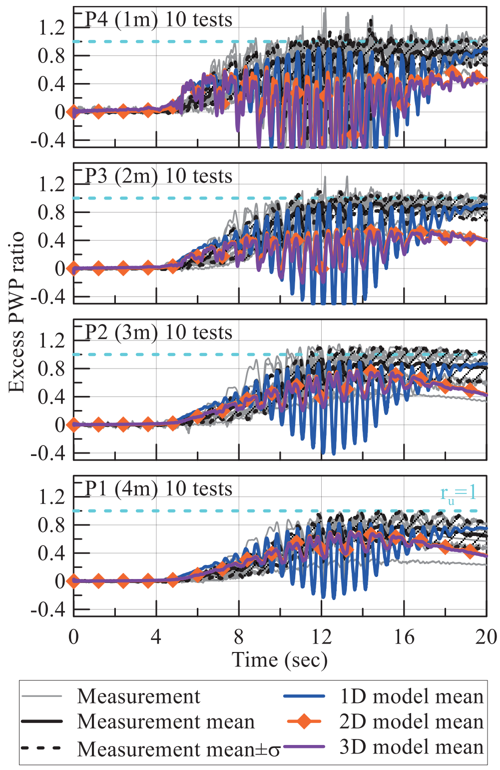

Fig. 8 Measured and simulated excess porewater pressure ratio at central array

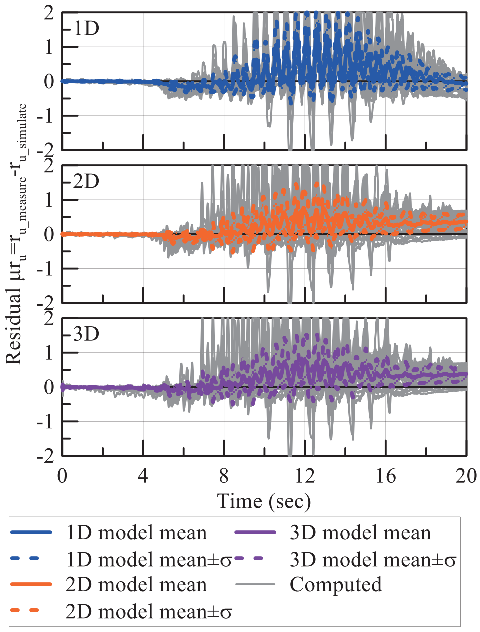

Fig. 9 Simulation residuals of excess porewater pressure ratio at central array

The residuals of porewater pressure ratio, Fig. 9, indicate that 2D/3D models show less dilation spikes, and their results compare better to measurements than 1D models.

5 CONCLUSIONS

This study simulated the LEAP centrifuge tests for soil liquefaction with mildly sloping surface using I-soil model on LS-DYNA platform. The results indicate that simulations can reasonably estimate the Arias intensity, response spectra of horizontal acceleration time histories and the build-up of excess porewater pressure. The comparison also shows that 2D and 3D models lead to better agreement to measurements than 1D model, as they better represent the boundary conditions of the boundary value problem (i.e., explicitly modeling the centrifuge boundaries).

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