Stress-Density Model Validation: Free-Field Liquefaction Analysis Using OpenSees

Introduction

- Numerical liquefaction analyses require verified and validated constitutive models.
- Complexity of simulating liquefaction-induced phenomena, emphasises the need to enhance current models' performance and/or to develop new constitutive models.
- Stress-density [1,2] (S-D) is a constitutive model that has been recently verified and implemented in the finite element platform, OpenSees.
- This study, as the first effort to validate the stress-density model against centrifuge tests in OpenSees, encapsulates the 1D site response results.
- PM4Sand [3] is a widely used constitutive model that we also used in this study for comparison.

Method

- Results of two centrifuge tests [4,5] (~140 sensors, 55g in a 9 meters radius machine) are used for validation.
- Both tests have similar plans. The key variation is that the relative density of the liquefiable layer decreased from 50% in test T4.5-50 to 40% in test T4.6-40. Other changes are structural.
- Calibration of the model (Figure 1) intended to simulate the experimental liquefaction triggering curve for the (Nevada) sand, which comprises two important layers in the centrifuge tests.

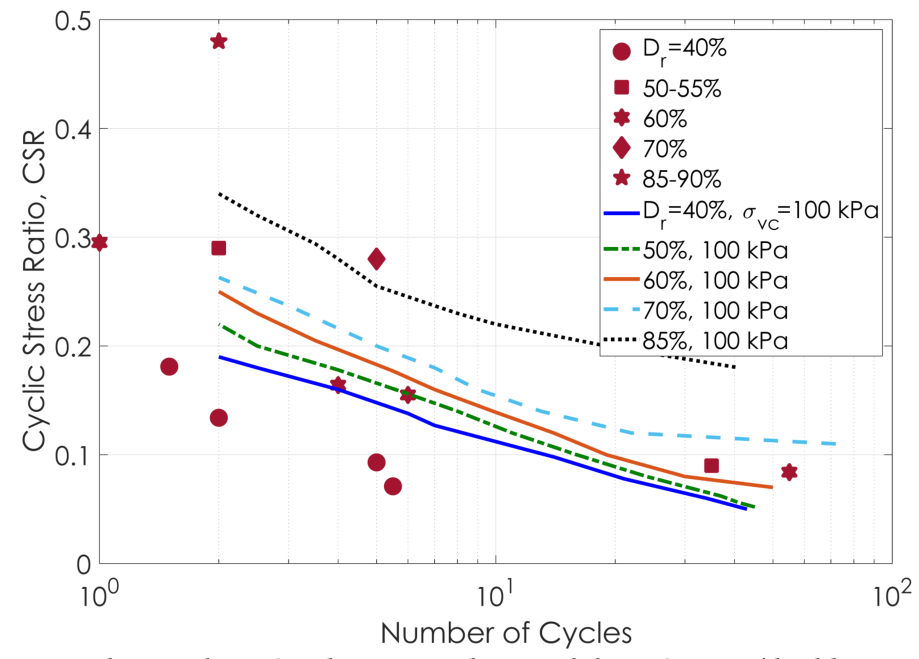

Figure 1: Relation between the number of cycles required to reach liquefaction (double-amplitude shear strain of 3%) and cyclic shear stress ratio (CSR) in numerical simulations (lines) and CSS experiments (markers) [6,7]

Modelling

- We performed one-dimensional effective stress analysis using OpenSees.
- Figure 2 (depicted in the *Results* section below) illustrates the schematic 1D model for the T4.6-40. The T4.5-50 profile is very similar to T4.6-40, which is not presented for brevity.
- Mesh sensitivity analysis showed that an element size around 0.2 m provides reliability up to 10 Hz. However, to match the sensor locations in the centrifuge tests we used 0.1x0.1 mesh.
- The input motions applied to the bottom of the numerical model are the recorded motions at the base of the centrifuge container. Their names are: large PRI, moderate PRI, moderate TCU and small PRI.
- Rayleigh damping of 2% was applied at natural frequency of 1.88 Hz and third modal frequency of soil deposit (9.39 Hz).

Results

- Figure 3 shows that S-D and PM4Sand models underrate the free-field settlement during the large PRI in the T4.6-40 approximately by a factor of 7.5 and 13 after 25 seconds, respectively. Constitutive models normally fail to capture free-field settlements caused by partial drainage.

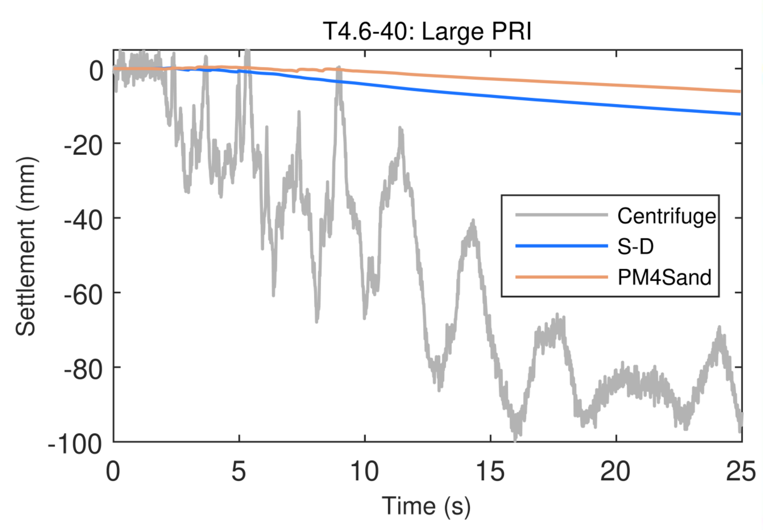

Figure 3: Free-field vertical settlement time history

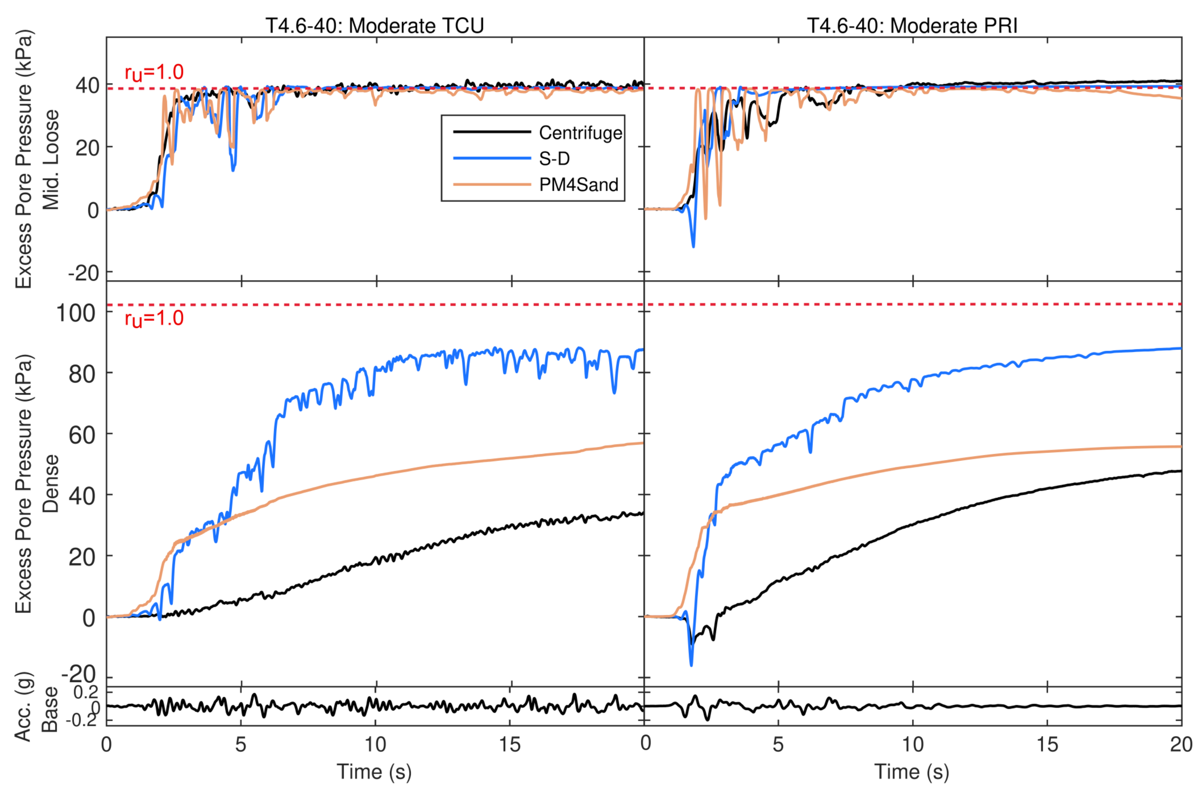

Figure 4: Pore water pressure time histories during moderate motions at dense and middle of loose layer in T4.6-40

- Centrifuge and simulations indicate liquefaction at the middle of the loose layer for both motions (Figure 4). At the dense layer the S-D model overpredicts the response by approaching the excess pore water pressure ratio (r_u) to 0.8, which denotes a near-liquefaction state.

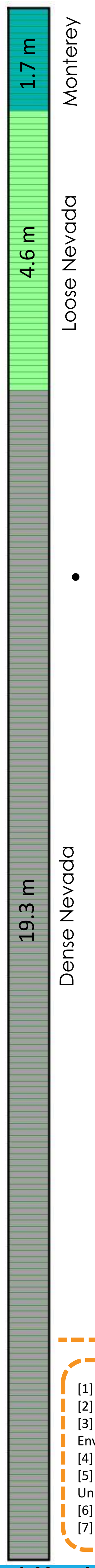

Figure 2: 1D free-field model schematic

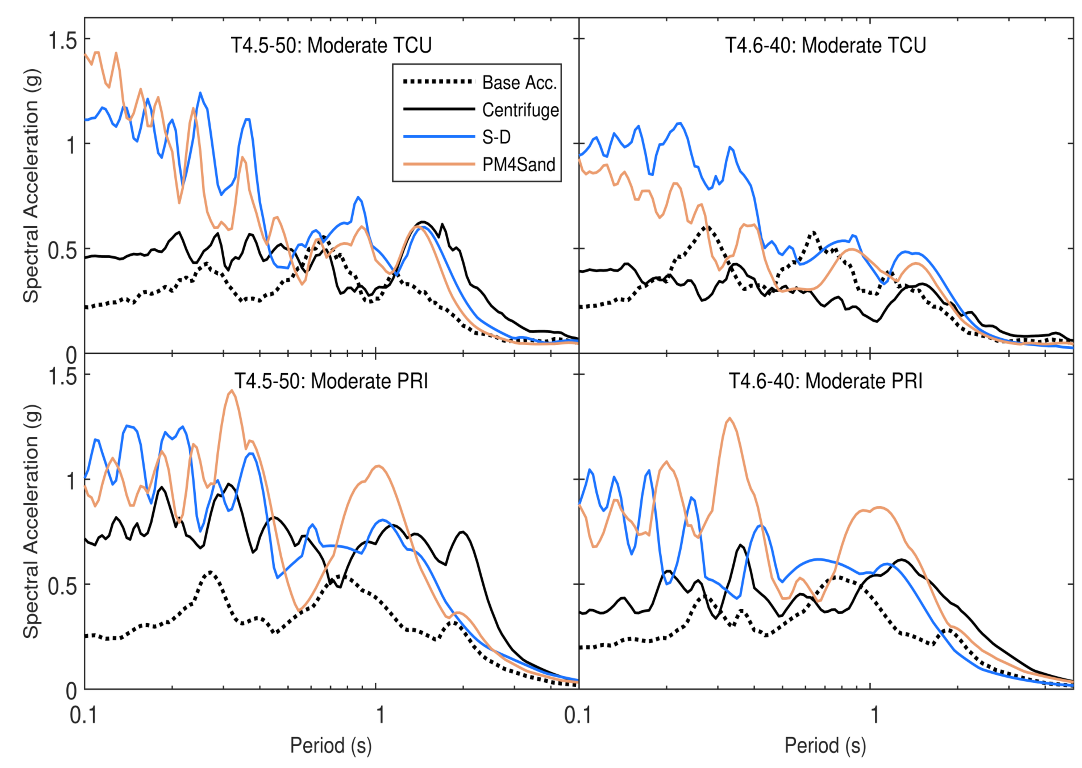

Figure 5: Response spectra (5% damped) at surface during the Moderate PRI and Moderate TCU motions in T4.5-50 and T4.6-40

- Figure 5 shows that during the moderate PRI event, the S-D model is in a reasonable agreement with the centrifuge for periods between 0.25 to 1.5 seconds.
- During the moderate TCU motion, the S-D model mostly overestimates the response except for periods longer than 2 seconds.
- Overestimation of response in high-frequency parts can be attributed to overestimation of dilation spikes by both models.

- Figure 6 shows that during the large event, dilation spikes emerge in experiment and simulations. The overestimated pore water pressure in the dense layer that reflected from the single-element response of the S-D model support the large dilation spikes observed even in the middle of dense layer.

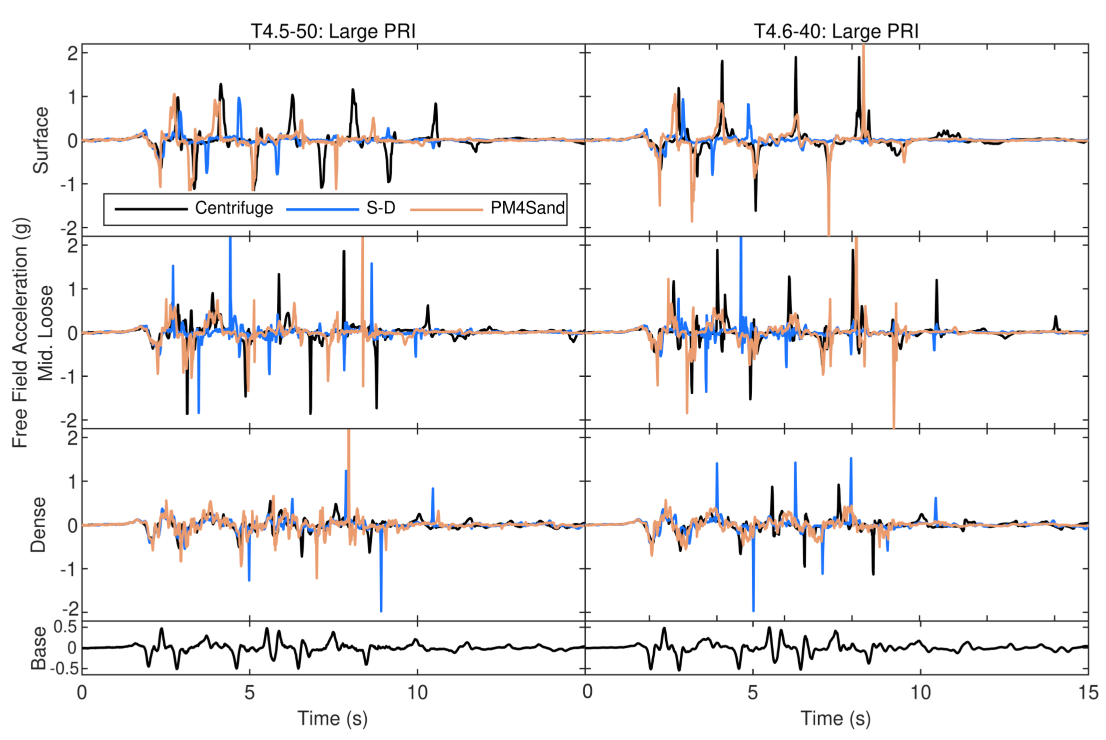

Figure 6: Experimental acceleration time histories against numerical simulations with S-D and PM4Sand models during the Large PRI motion in T4.5-50 and T4.6-40

Conclusion

- The S-D model can reasonably predict the soil behaviour—acceleration, pore water pressure generation— in free-field site response analyses
- Looking at all events, the S-D model predicts the pore water pressure build-up pattern well in the liquefiable layer, while overpredicting that in the dense layer.
- The next step, which will follow the current study, is the validation of 2D models with structures that could lay the groundwork for using the S-D model in a wider area.

Acknowledgement

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QuakeCoRE
NZ Centre for Earthquake Resilience
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