Verification of PM4Sand in OpenSees

PEER Transportation Systems Research Program

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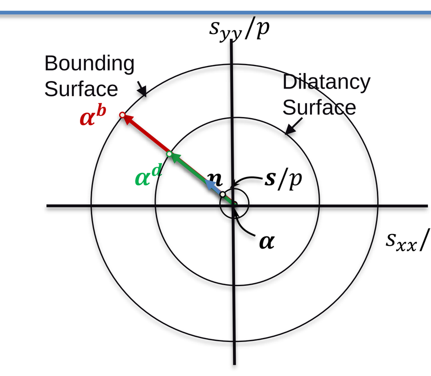
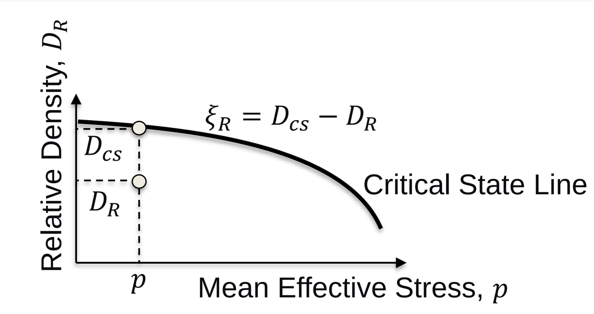
Introduction:

PM4Sand is a sand plasticity model for earthquake engineering applications proposed by Boulanger and Ziotopoulou (2017). This 2D plane-strain model follows the plasticity framework proposed by Dafalias and Manzari (2004) and is based on bounding surface plasticity and critical state concepts. The model has been calibrated at an element level to approximately simulate general trends observed in the field and empirical correlations commonly used in geotechnical earthquake engineering practice. By changing three primary input parameters, the user can achieve reasonable approximations of desired behavior including pore pressure generation and dissipation, limiting strains, and cyclic mobility. Using secondary parameters (18 in total and optional) the user can further fine-tune the response; although this is not necessary. Since its introduction, the PM4Sand model has drawn wide attention of geotechnical engineers and researchers due to its relatively easy calibration process and good agreement with field observations.

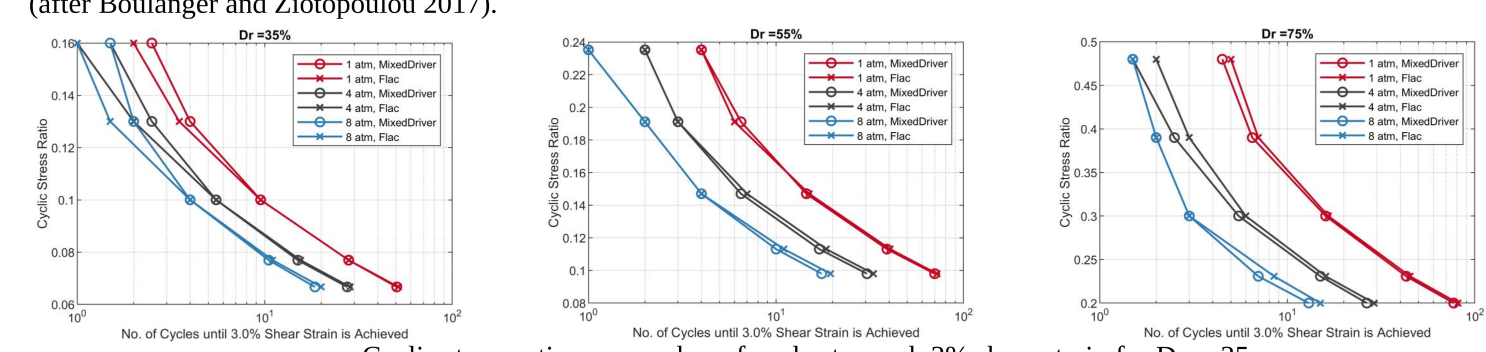
PM4Sand V3.1 is being implemented in OpenSees to produce comparable results to the model's current implementation in the commercial tool FLAC. In previous research, comparison of model responses at element level has shown a good match between FLAC and OpenSees. In current research, several 1D and 2D models are investigated to verify model's implementation in OpenSees against FLAC under complex loading conditions and boundary conditions. Another commercial tool PLAXIS is also included in this study. The simulations using FLAC and OpenSees are performed at University of Washington and simulations using PLAXIS are performed at PLAXIS, BV. Only selected cases from verification are shown to conserve space.



Schematic of bounding, dilatancy and yield surfaces (after Boulanger and Ziotopoulou 2017).



Bounding and dilatancy surfaces are related to critical state through relative state parameter index (ξ_R).

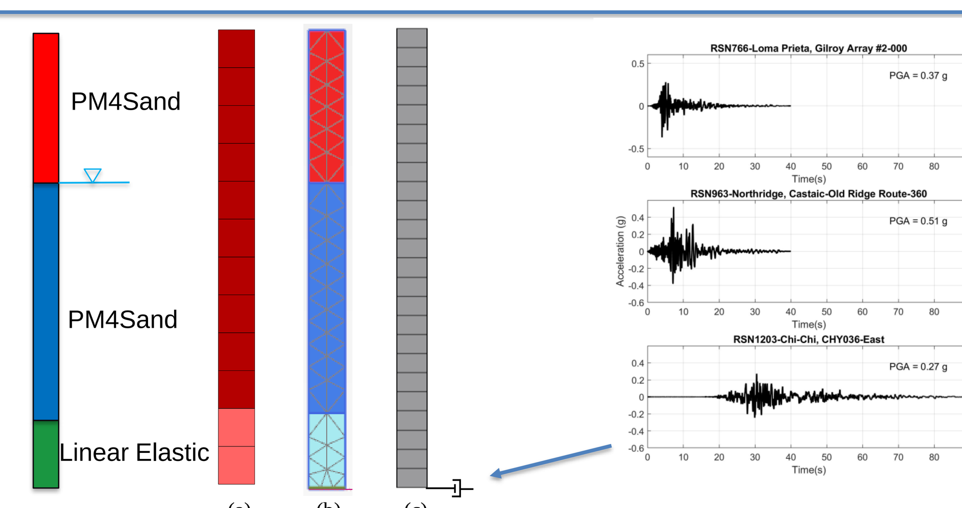


Cyclic stress ratios vs. number of cycles to reach 3% shear strain for D_R = 35, 55 and 75% with vertical consolidation stresses of 1, 4 and 8 atm. K_0 = 0.5

1D Soil Column Cases:

1D Level Ground Cases:

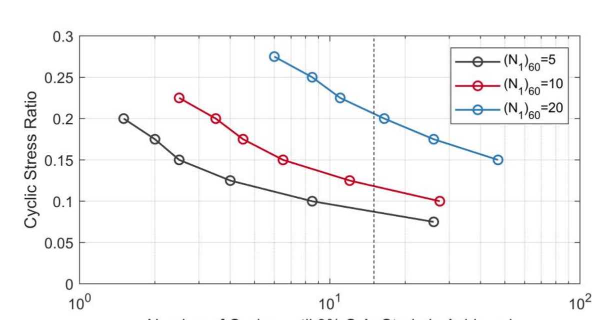
Three synthetic scenarios are considered: $(N_1)_{60}$ = 5, 10 and 20, respectively, to compare the response of PM4Sand model's implementation in OpenSees, FLAC, and PLAXIS. Two investigated profile configurations have the same 1 m linear elastic base and 2 m dry crust but two different thicknesses(3m and 6m) of the liquefiable layer. So total 6 profiles are investigated, e.g. N10T3 means $(N_1)_{60}$ = 10 for the 3 m thick liquefiable layer. In all the three programs, the same material input properties are used so are the analysis parameters like Rayleigh damping parameters. Although the modelers try to be as consistent as possible, there are some fundamental differences like FDM vs. FEM. Take model discretization as an example, (a) FLAC uses zones, (b) PLAXIS uses 15 nodes triangular elements, and (c) OpenSees uses stabilized single point 4-node quad elements (SSPquadUP) for dynamic analysis of fluid saturated porous media.



Schematic and meshes of 1D level ground model. Three outcrop motions with different characteristics are selected and applied using a dashpot to simulate a compliance base case.

Model Calibration:

Only PM4Sand model's primary input parameters are calibrated in this study and all secondary parameters are assigned default values. *Dr* is estimated using the relationship used by Idriss & Boulanger (2008). G_0 is computed using Andrus & Stokoe (2000). Then *hpo* is calibrated iteratively based on the liquefaction triggering correlation by Idriss & Boulanger (2008). Similar cyclic strength curves are obtained using OpenSees, FLAC, and PLAXIS.



Cyclic stress ratios vs. number of cycles to reach 3% shear strain for $(N_1)_{60}$ = 5, 10 and 20, respectively.

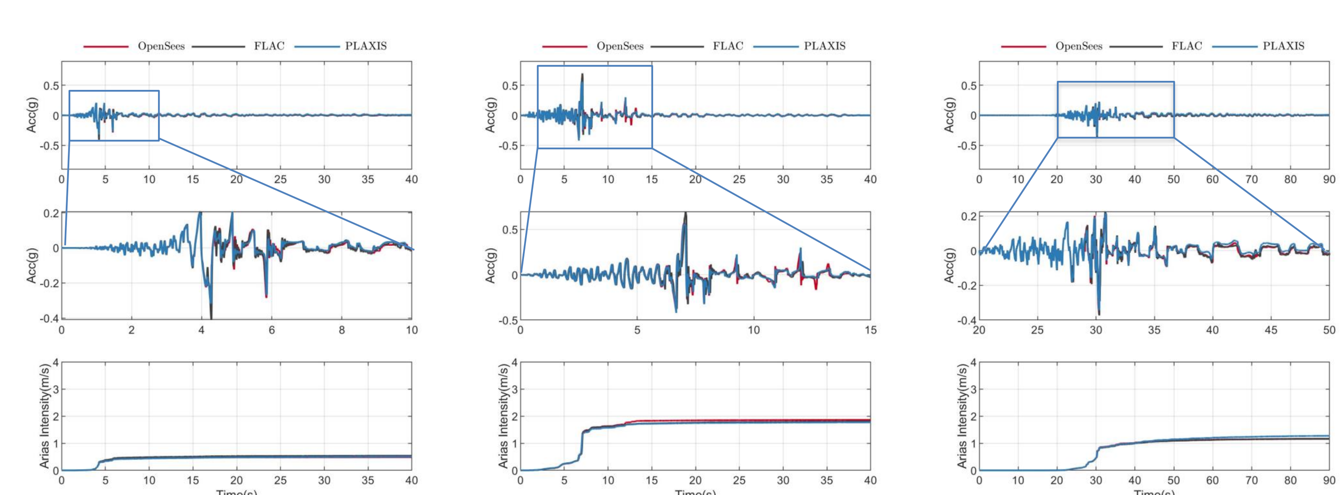
Input parameters

Scenario field condition			Model input parameters*		
$(N_1)_{60}$	Vs1 using Andrus & Stokoe (2000)	$CRR_{M=7.5}$ using Idriss & Boulanger (2008)	D_R	G_0	hpo
5	140.7	0.086	0.330	447	0.533
10	159.8	0.118	0.466	584	0.450
20	185.1	0.206	0.659	798	0.388

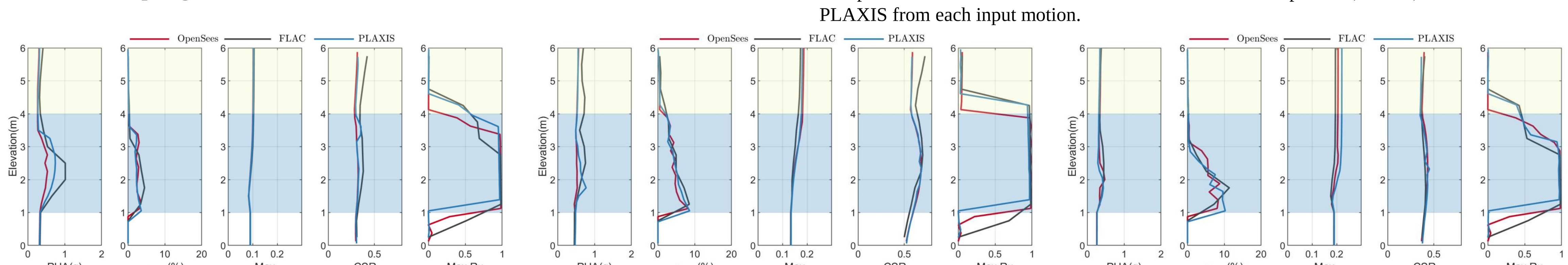
*All secondary parameters are assigned default values

Results:

The results from N10T3 case are shown here. All three programs generally produce very similar response with different levels of differences shown in stress-strain, acceleration and pore pressure responses. For example, FLAC tends to produce higher dilation pulses in liquefied layer. This is possibly due to a combination of different reasons, e.g., interpolation of data from integration points at different locations, numerical methods for integration, formulations for solid fluid coupling, etc..



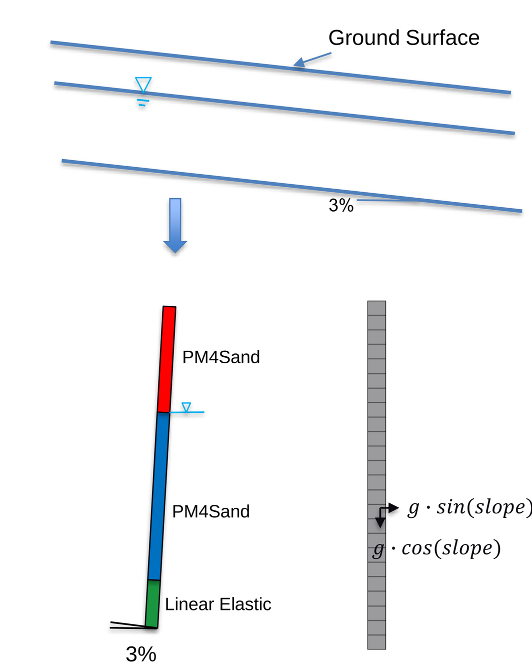
Comparison of acceleration time histories at surface from OpenSees, FLAC, and PLAXIS from each input motion.



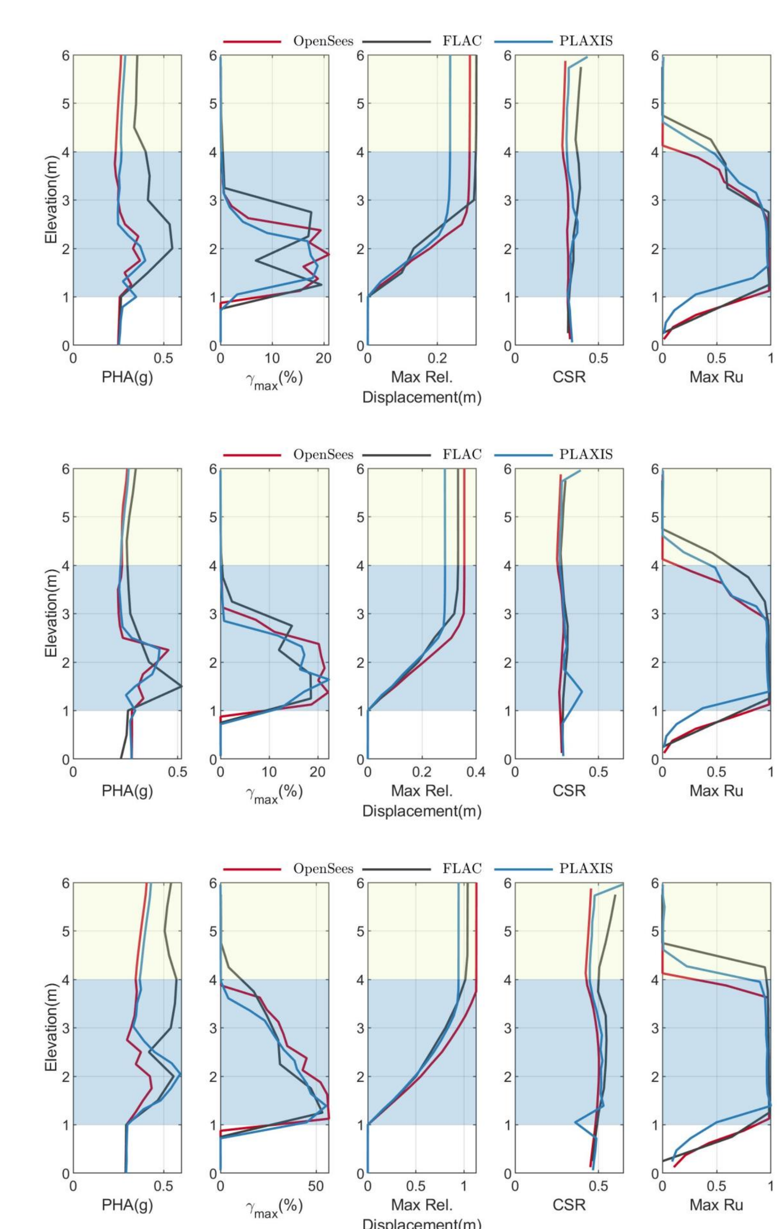
Comparison of profiles of PHA, maximum displacement, max shear strain, CSR and maximum pore pressure ratio from OpenSees, FLAC, and PLAXIS with each input motion.

1D Sloping Ground Cases:

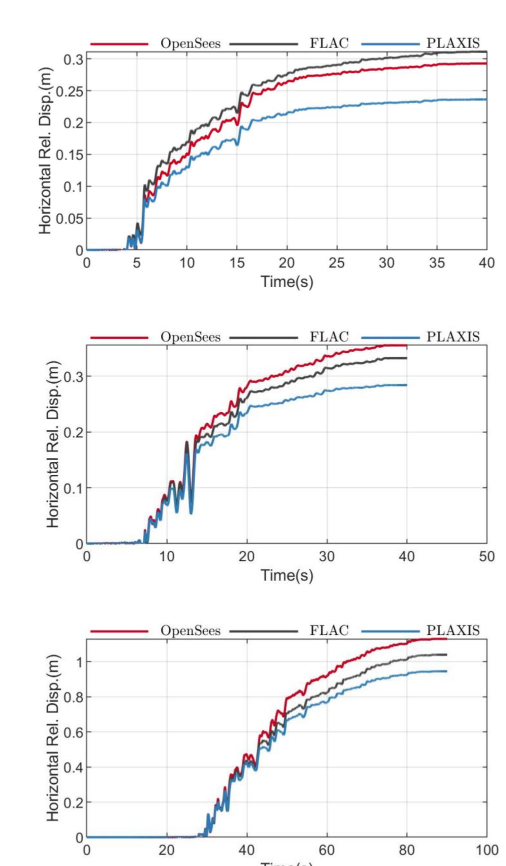
The level ground case is slightly modified to simulate an infinite slope case to verify material's response of analysis for liquefaction induced lateral spreading. The direction of gravitational acceleration is modified to account for the constant slope. Those three previous selected motions are scaled to different PGAs, i.e., 0.1g, 0.2g, and 0.3g to study sensitivity of results to shake intensity. Comparing to the level ground case, a relatively larger degree of discrepancy is observed in the obtained results. PLAXIS tends to predict smaller magnitude of lateral displacements comparing to FLAC, while OpenSees tends to predict larger magnitude. However the overall responses are consistent among all three programs.



Schematic of 1D sloping ground model. The slope is applied by changing the direction of gravitational acceleration. Hence a constant slope is modeled.



Comparison of profiles of PHA, maximum displacement, max shear strain, CSR and maximum pore pressure ratio from OpenSees, FLAC, and PLAXIS with each input motion.



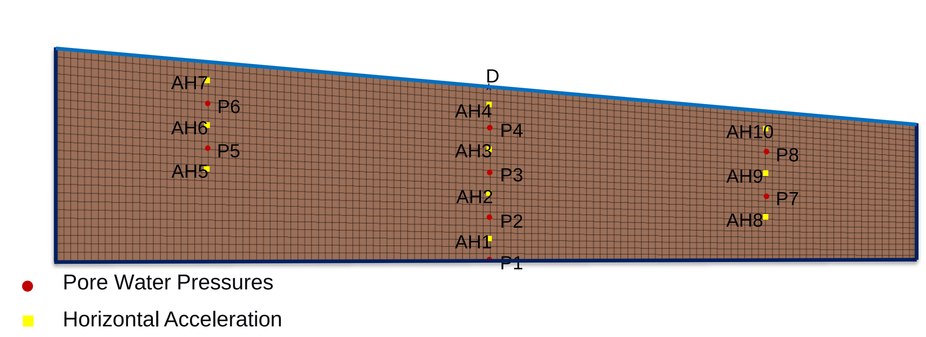
Comparison of horizontal displacement at surface from OpenSees, FLAC, and PLAXIS with each input motion.

2D Sloping Ground Cases:

Taking advantage of author's previous experience with LEAP (Liquefaction Experiments and Analysis Projects), the 1D sloping ground case is further extended to the 2D prototype model defined in LEAP to compare model's response of a more complex case in OpenSees and PLAXIS. Material and analysis input parameters are adopted from the LEAP project. So are the input motions.

The model is calibrated based on lab tests performed for Ottawa F65 sand. *Dr* is chosen to be 0.65 and G_0 is calibrated iteratively to match the initial stress-strain behavior of lab tests. Then *hpo* is calibrated iteratively to match the CRR curve obtained from lab tests. Some secondary parameters are also modified.

Results from the case that simulates the centrifuge test performed at Cambridge University are shown here.

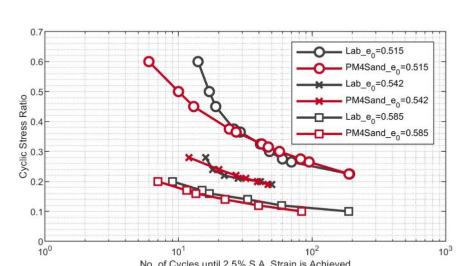


Finite Element mesh and location of recorded pore water pressures (P) and accelerations(AH).

Input parameters

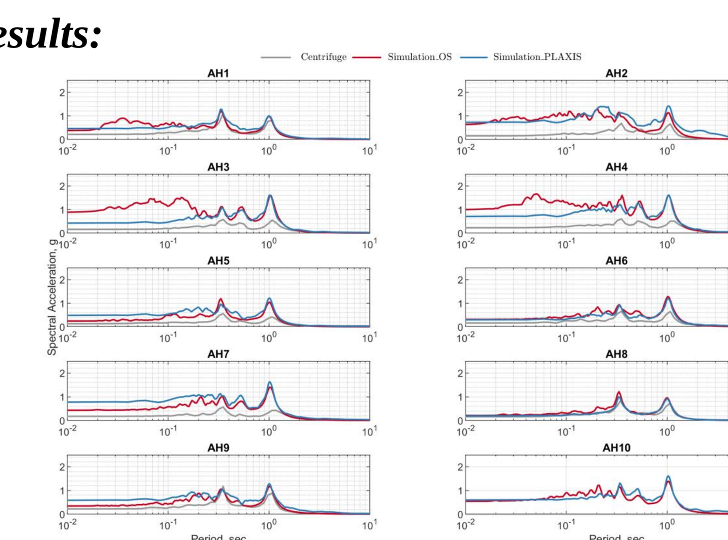
Primary Parameters	D_R	0.65
	G_0	350.0
	h_{p0}	0.07
Secondary Parameters	e_{min}	0.4915
	e_{max}	Varies
	ϕ_{cv}	35.6
	c_z	200.0
	υ	0.15

* All the other secondary input parameters are kept as default values

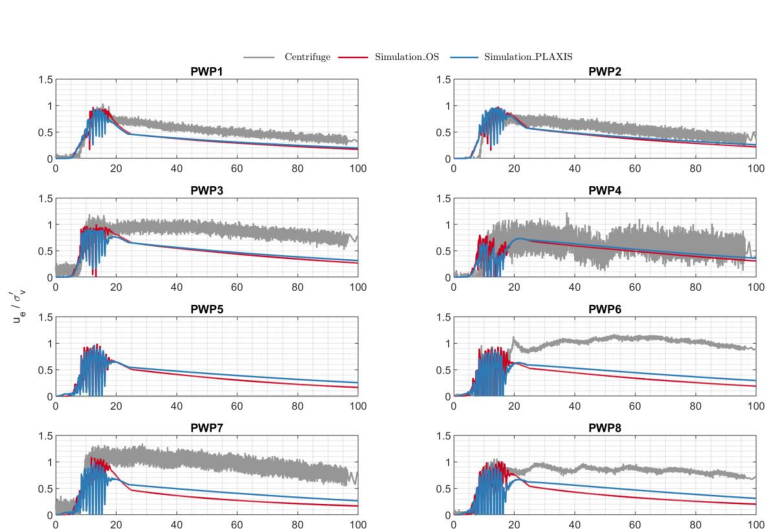


Element level calibration: Comparison of number of cycles required to reach 2.5% single amplitude shear strain in simulations and laboratory tests.

Results:



Comparison of acceleration response spectra (5% damping) between OpenSees and PLAXIS.



Comparison of pore pressure time histories between OpenSees and PLAXIS.

Acknowledgement:

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References:

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