Dynamic Behavior of Uniform Clean Sands: Evaluation of Predictive Capabilities in the Element- and the System-Level Scale

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ABSTRACT

This paper investigates and presents the numerical modeling and validation of the response of a uniform clean sand using monotonic and cyclic laboratory tests as well as a centrifuge model test comprised of a submerged slope. The dynamic response of the sand is modeled using a critical state compatible, stress ratio-based, bounding surface plasticity constitutive model (PM4Sand), implemented in the commercial finite-difference platform FLAC, and PM4Sand's performance is evaluated against a comprehensive testing program comprised of laboratory data and a well-instrumented centrifuge model test. Three different calibrations informed by the lab and centrifuge data are performed and the goodness of the predictions is discussed. Conclusions are drawn with regards to the performance of the simulations against the laboratory and centrifuge data, and recommendations about the calibration of the model are provided.

INTRODUCTION

Although earthquake-induced liquefaction essentially occurs at the grain level, its effects on civil infrastructure are studied at multiple scales and with many different tools. These include: case histories, bench-, reduced-, and full-scale experimental modeling (from direct simple shear and triaxial testing to centrifuge and shake table model testing), as well as constitutive and numerical modeling tools and platforms. Numerous liquefaction case histories and experimental investigations have significantly propelled knowledge in this field. The current understanding about liquefaction is predominantly based on observations of clean and uniform sands, yet well-graded coarse-grained soils encompass a broad range of soils that are often present in natural deposits near lakes and rivers, as well as in engineered fill materials in dams and levees. Recent research efforts suggest that disregarding the effect of gradation on soil liquefaction may lead to overestimations of the anticipated damage in system level analyses (Sturm 2019, Carey et al. 2021), and thus to conservative, cost-inefficient engineering designs. The same challenge extends to constitutive models used in nonlinear deformation analyses (NDAs) to evaluate the seismic performance of geosystems, which are also mostly based on theoretical frameworks and empirical observations of clean uniform sands, and as such do not accommodate the effect of gradation in their formulations.

Recent research has recognized the advantages of using NDAs towards estimating the seismic response of liquefiable soils. Amongst other factors, one of the key challenges in performing NDAs is the calibration of constitutive models capable of capturing the soil behaviors that are activated in a range of geosystems under seismic loading. Calibration procedures and modeling protocols have been developed to guide the selection of parameters for advanced constitutive models based on available data from in-situ tests and/or soil-specific laboratory tests.

The capabilities and limitations of predictive tools for liquefaction-related problems are typically evaluated within the framework of validation exercises wherein responses at the element- and the system-level of a boundary value problem are systematically evaluated. Past validation efforts pertaining to liquefiable systems (e.g., the international Liquefaction Experiments and Analyses Projects, LEAP, Kutter et al. 2020, Manzari et al. 2020) have contributed extensive experimental datasets and numerical simulations, and have established a baseline knowledge about current abilities to numerically predict liquefaction-related responses. Within LEAP, a prescribed submerged slope of Ottawa F65 sand subjected to shaking was modeled at numerous centrifuge facilities and numerically predicted using combinations of numerical tools. Lab data provided a calibration basis for the constitutive models. In LEAP, the numerical tools captured aspects of the behaviors but (i) the different levels of experimental conformity to the specifications clouded the conclusions, and (ii) the incomplete characterization of the lab or the centrifuge model tests did not provide a robust basis upon which conclusions could be drawn. Most importantly, it was shown that simultaneously capturing acceleration, pore pressure, and displacement responses was not trivial and indicated potential gaps even for the uniform sand tested at the time. These outcomes, although very useful, do not form a solid basis upon which complexities such as those introduced by the non-uniformity of a liquefiable coarse-grained soil can be studied.

The data from a comprehensive experimental and centrifuge testing program (Carey et al. 2021) performed at the Center for Geotechnical Modeling at UC Davis provide a unique opportunity to (1) holistically explore current capabilities in numerically capturing the response of uniform clean sands, (2) demonstrate the standard of practice for these materials, and (3) provide a basis for later expanding these models to more broadly graded soils. In this paper, the response of a well-characterized uniform sand is numerically investigated at the element level of DSS and TX tests and the system level of a well-instrumented and -characterized centrifuge model test comprised of a submerged slope of the same sand. The dynamic response of the sand is modeled using the constitutive model PM4Sand (Boulanger and Ziotopoulou, 2017), implemented in the commercial finite difference platform FLAC (Version 8.1, Itasca 2020). Three calibrations of PM4Sand targeting at observed behaviors in the lab and centrifuge are described, followed by a description of the numerical simulation performed for the prediction of the centrifuge model test, and a critical comparison between simulation and experimental results. Simulations are compared to selected experimental results to identify aspects of the experimental response the numerical simulation was able to reasonably capture. Conclusions are drawn with regards to the performance of the simulations against the laboratory and centrifuge data.

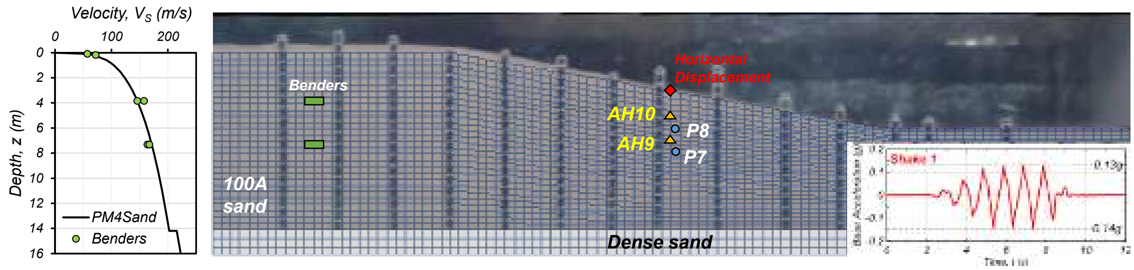

Figure 1. Input motion (Shake 1) and FLAC numerical grid used in the simulations overlaid on the centrifuge model test (prototype scale – approximate dimensions 70 m long x 16 m high in the side view shown here, and 17 m wide out of plane) in comparison to the shear wave velocity V_S profile.

SOIL AND EXPERIMENTAL PROGRAM

The considered soil is a sand sourced from a single marine deposit in Mauricetown, New Jersey, mechanically sieved to a uniform gradation and a mean grain size diameter of 0.18 mm. Henceforth, the sand will be referred to as "100A" sand (Sturm 2019). The physical properties of the tested 100A sand are: e_{min} = 0.579, e_{max} = 0.881, D_{50} = 0.18 mm, C_u = 1.68, G_s = 2.62 while the void ratio and dry density at the target D_R = 63% are 0.69 and 1549.6 kg/m^3 respectively. In addition, the hydraulic conductivity was measured using a falling head permeability test in the laboratory at the target D_R = 63%, with a measured value of 0.02 cm/s (Sawyer 2020).

The cyclic and dynamic behavior of the considered sand was investigated via an extensive laboratory and centrifuge model testing program. The laboratory investigation included monotonic triaxial tests and constant volume equivalent undrained cyclic DSS tests carried out on reconstituted samples of varying D_R's under two overburden stresses. In the centrifuge, a submerged embankment comprised of 100A sand was tested in a rigid container at 40g using the 9-m radius centrifuge (Fig. 1). The embankment was dry-pluviated to target D_R = 63%, overlying a dense sand layer (D_R > 90%) of the same material and then saturated under vacuum with a viscous pore fluid. A thin cap (0.5 cm) of coarse sand was added over the entire embankment to provide confinement for the surface accelerometers (not shown herein). The applicable average mean effective stress in the saturated model was 50 kPa. To track acceleration and porewater pressure responses during shaking, vertical arrays of sensors were placed throughout the model. Bender elements (Fig. 1) provided information regarding the shear wave velocities of the soil. GeoPIV and highspeed videos enabled the tracking of the horizontal displacements of the black vertical reference columns over the embankment depth. For sake of brevity, only the shallowest sensors of the mid-slope array will be shown in this paper (Fig. 1). The input container motion used to simulate earthquake shaking consisted of a sine wave with a frequency of 1 Hz (Fig. 1 insert and Carey et al. 2021, 2022a, b). Further details can be found in Carey et al. (2021, 2022a, b).

CONSTITUTIVE MODEL CALIBRATION

PM4Sand (Boulanger and Ziotopoulou 2017) is a critical state-compatible, stress ratio-controlled, bounding surface plasticity model that follows the framework presented by Dafalias & Manzari (2004), with modifications to improve the model's ability to approximate engineering relationships important to geotechnical earthquake engineering applications. The model is able to simulate the response of sand-like soils subjected to monotonic and cyclic loading. The model has three primary input parameters, 21 secondary parameters, the atmospheric pressure (P_a) which sets the units, and two flags. The model was developed such that it can be used given the three primary parameters, while all secondary parameters have been calibrated by the developers to reasonably approximate the range of behaviors exhibited by the broader body of data on clean sands. The secondary parameters can be modified to better capture observed behaviors when laboratory test or any other data are available. The PM4sand model is implemented for plane-strain applications as a user-defined dynamic link library (DLL) in FLAC (Itasca 2020).

The primary input parameters are the apparent relative density (D_R), the shear modulus coefficient (G_o), and the contraction rate parameter (h_{po}). D_R controls the dilatancy and stress-strain response of the soil, G_o controls the small-strain shear stiffness (G_{max}) and can be calibrated to match V_S measurements, and h_{po} controls the contractiveness and thus the cyclic strength of the soil, and can be iteratively calibrated to obtain a target cyclic strength (CRR) informed from experimental data or empirical correlations. Secondary parameters relevant to this work are: maximum e_{max} and minimum void ratios e_{min}; n^b which controls the position of the bounding surface, the peak effective friction angle, and the shear strain accumulation during cyclic mobility; and the Q and R parameters of Bolton's (1986) empirical relationship determining the position of the critical state line (CSL). Further details of the model formulation can be found in Ziotopoulou & Boulanger (2016), and Boulanger & Ziotopoulou (2017) and are omitted herein for brevity.

A total of three calibrations were performed for PM4Sand informed by both the lab and centrifuge data. The behaviors of interest herein are the cyclic strength and deformations of the liquefiable sand. Since the centrifuge model did not undergo flow deformations (Carey et al. 2021), the CSL is not reached and Q and R do not play a role other than setting the initial relative state of the soil. However, since TX data were available those secondary parameters were activated:

- Calibration 1 accounted for the cyclic strength and stress paths provided by the DSS tests and constrained the Critical State Line (CSL) through the TX monotonic data.
- Calibration 2 used the default location of the CSL and accounted only for the cyclic strength and stress paths provided by the DSS tests.

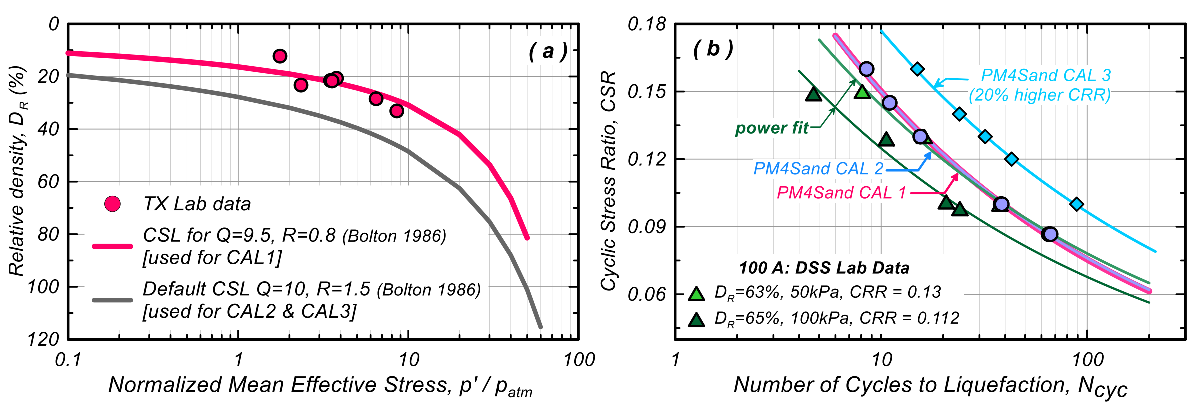

Figure 2. (a) Default and calibrated CSL versus TX data, and (b) CSR versus number of cycles to reach single amplitude shear strain of 3% for three calibrations compared to laboratory strength curves (100 kPa data shown for reference).

As will be seen later, Calibrations 1 and 2 yielded satisfactory acceleration and pore pressure results in the system-level analyses but overpredicted displacements. Informed by these results (Figure 5) as well as the uncertainties pertaining to DSS data (e.g., Budhu 1984) a third calibration was considered:

- Calibration 3 targeted a 20% higher cyclic strength for the liquefiable sand.

In all calibrations, D_R was taken as equal to the target air pluviation value of 63% which was verified through a pre-shaking cone penetration test (Carey et al. 2021). G_o was calibrated against the bender element V_S measurements at two depths underneath the upper bench of the model (profile shown in Fig. 1). The maximum and minimum void ratios were taken as equal to the values determined by Sturm (2019). The n^b secondary parameter was iteratively adjusted until a reasonable agreement was achieved between the rate of strain accumulation in the cyclic mobility regime in single element DSS simulations and in the laboratory data (D_R = 63% and vertical effective stress, σ'_{vo} = 50kPa). Strain accumulation in the cyclic mobility regime in PM4Sand can be controlled by select secondary parameters as explained by Boulanger and Ziotopoulou (2017) and shown by Tasiopoulou et al. (2019) and it is up to the analyst to decide through a sensitivity study which one achieves the best match while not compromising other aspects of the behavior.

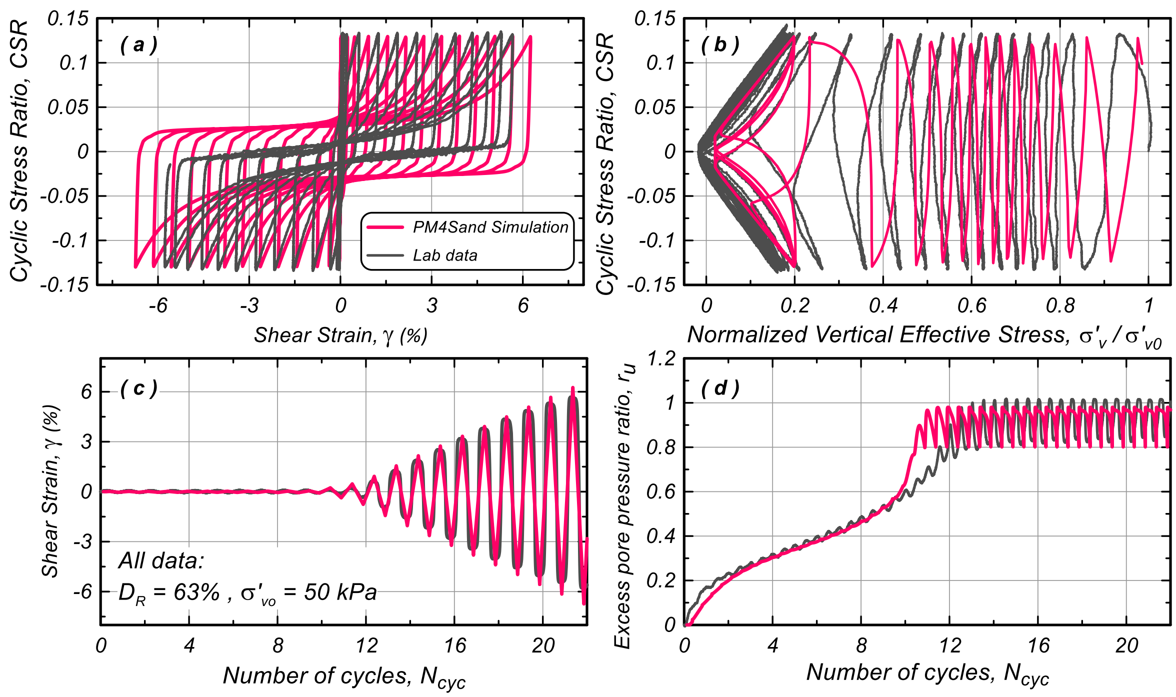

Figure 3. Calibration 1 simulations compared to the results of an undrained DSS test with an applied uniform CSR = 0.13 on a reconstituted sample of 100A sand with D_R = 63%.

In Calibration 1, the secondary Q and R parameters of the empirical CSL were calibrated on the basis of results of monotonic TX tests performed on air pluviated samples of 100A under isotropically consolidated drained conditions (Fig. 2a). Kamai and Boulanger (2013) also presented a lab-specific calibration of the Q and R parameters. Calibration 2 did not consider the TX data and kept the default PM4Sand Q and R values. The original default and the newly calibrated critical state line informed by the TX data are plotted in Fig. 2a alongside with the experimental data. In all cases, h_{po} was calibrated via single-element undrained cyclic stress-controlled DSS simulations until a satisfactory match was achieved for the targeted cyclic strength (Fig. 2b). Figure 2b illustrates the Cyclic Stress Ratio (CSR) versus number of cycles curves for a triggering criterion of 3% single amplitude shear strain for all Calibrations and demonstrates that Calibrations 1 and 2 are essentially identical proving the consistency of the approach depending on the data considered. Figure 3 compares experimental data and single-element simulations for Calibration 1 for a selected DSS test (CSR = 0.13). The results are presented in terms of stress-strain loops (Fig. 3a), stress paths (Fig. 3b), shear strain evolution (Fig. 3c), and excess pore water pressure generation (Fig. 3d). Table 1 summarizes all PM4Sand input model parameters that were assigned values other than their default during the calibration. Default values for the remaining parameters are provided by Boulanger and Ziotopoulou (2017). These sets of parameters were used to model the dynamic soil behavior of 100A sand in the centrifuge model test simulation, without any further adjustment.

Table 1. PM4Sand input model parameters for 100A sand and the three calibrations.

	PM4Sand Inputs	Calibration 1	Calibration 2	Calibration 3
Primary	D_R	63%		
	G_o	863		
	h_{po}	0.012	0.045	0.12
Secondary	e_{max}	0.881 *(default 0.8)*		
	e_{min}	0.579 *(default 0.5)*		
	n^b	0.25 *(default 0.5)*		
	Q	9.5	10 *(def)*	10 *(def)*
	R	0.8	1.5 *(def)*	1.5 *(def)*
Cyclic Strength	$CRR_{PM4Sand}$ **(3% at 15 cycles)**	0.133 (Fig. 2b)	0.133 (Fig. 2b)	0.16 *(20% up from Cal 1 & 2)*

SYSTEM-LEVEL NUMERICAL SIMULATION

The geometry of the analysis domain was based on the prototype dimensions (Fig. 1). The numerical mesh consists of 100 zones along the width and 31 zones along the height, yielding 101 gridpoints in the x- and 32 gridpoints in the y-direction (Fig. 1). Due to its limited thickness, the coarse sand cap was not accounted for in the numerical model and was substituted by its equivalent mechanical pressure. The 2 m-thick dense sand at the base was modeled with an elastic model, with its stiffness estimated according to the Hardin & Black (1968) relationship calibrated for the 100A sand V_S measurements (Fig. 1). Hysteretic damping was also considered to account for the energy dissipation of the dense base layer under cyclic loading and the sigmoidal sig4 model (Itasca, 2020) was assigned, with its parameters defined from the predicted Darendeli (2001) normalized shear modulus curve for a confining stress of 100 kPa. The mechanical boundary conditions in the simulations replicated the boundary conditions imposed by the rigid container used in the centrifuge model tests, without explicitly simulating the rigid box that surrounded the soil (Ziotopoulou 2018). The elevation of the free water surface was 17.60 m (prototype scale) from the base. Flow of water was allowed across the top surface of the model and restricted across the container boundaries. The experiments were submerged, so pore pressures and saturation were fixed at the top nodes, and pressure was applied to simulate the weight of the fluid. The values of the surface pressure from the water (both the external pressure and boundary pore pressure) were updated during the simulation to account for any settlement of the soil surface.

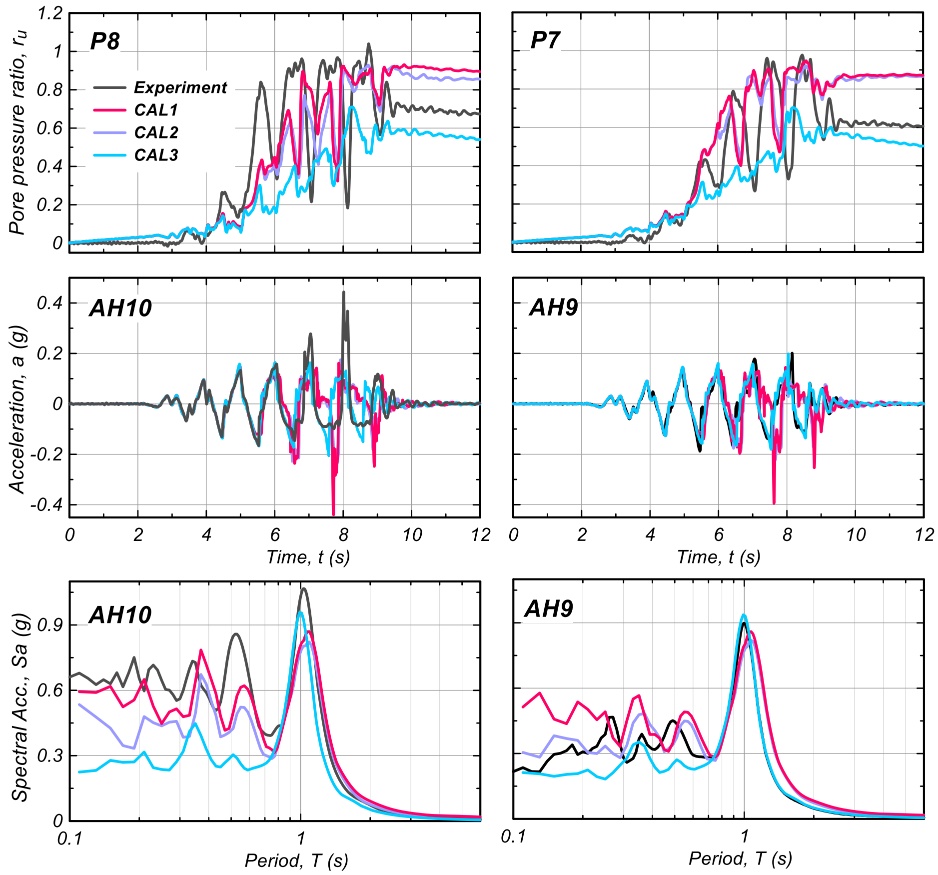

Figure 4. Comparison of experimentally measured and numerically simulated responses for all three calibrations. Results presented at select locations (Fig. 1) in terms of pore pressure ratio and acceleration time histories as well as acceleration response spectra (5% damping).

The input motion was applied as a horizontal acceleration time history to the base and sides of the model. The first shake of the applied sequence during the centrifuge experiment (Carey at al. 2021), with a PGA of 0.144 g, is considered herein (Fig. 1). The time step for the simulation was set to 5e-6 s, smaller than the default of the explicit forward marching software, to ensure that the numerical front is always preceding the physical one. All simulations were conducted with large deformations enabled, which allowed the mesh nodes to update their coordinates during dynamic shaking, and the geometry progressively to change. Rayleigh damping was set to 0.5% at a center frequency of 1 Hz (frequency of input motion) to account for small strain damping which is not captured by the constitutive model.

Results of the simulations are compared in Fig. 4 in terms of time histories of excess pore pressure ratio, horizontal accelerations and acceleration response spectra. Calibrations 1 and 2 were, as expected, almost identical in the system level and they closely matched the observed responses in terms of excess pore pressures and accelerations. In terms of acceleration response spectra, the predominant period of the deposit was captured well at the examined locations, while the discrepancies in the low period range of AH10 are due to a strong dilation spike around 8 sec not captured by the simulation. In terms of excess pore pressure ratios, at both instrument locations P7 and P8, the results are quite satisfactory with a slight overall underestimation in Calibration 3, which is expected based on its 20% higher strength.

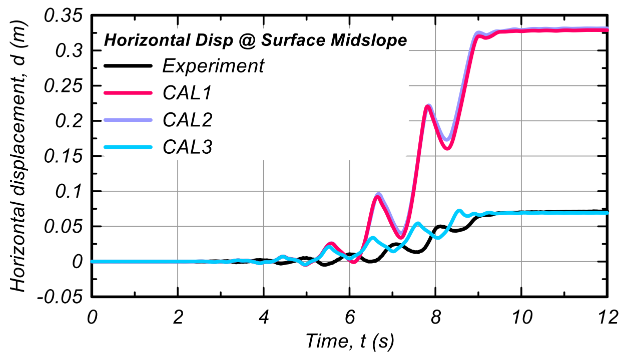

Figure 5. Comparison of horizontal displacement measured at the surface of the embankment slope with numerical simulations for the three calibrations.

The comparison of the horizontal displacement time histories for the midslope is shown in Fig. 5, while the results in terms of horizontal displacement contours are illustrated in Fig. 6. Calibrations 1 and 2 overpredicted displacements by a factor of 3. This could be due to various factors either implying the underestimation of cyclic strength in the lab or its increase under the operating conditions of a geosystem: (i) nonuniformities in DSS tests (Budhu 1984) may be compromising their ability to simultaneously and reliably capture pore pressure generation, triggering, and post-triggering strain accumulation, (ii) deformations in the centrifuge can be dominated by boundary effects (e.g., arching), and (iii) the actual cyclic strength of the sand could have been higher due to sloping ground effects (e.g., Boulanger 2003). Calibration 3 was then specifically developed to address this uncertainty, and predicted the displacement time history and the displacement contour pattern very successfully.

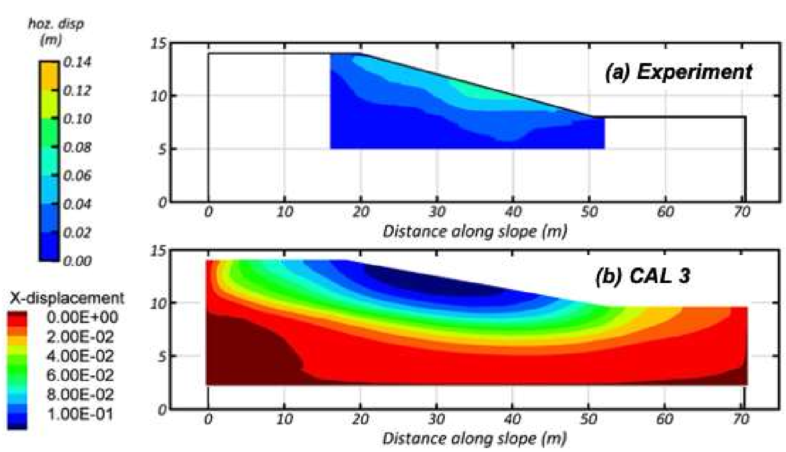

Figure 6. Contours of the (a) experimentally measured versus (b) numerically predicted horizontal displacements for Calibration 3 at the end of the shaking (all units in meters).

SUMMARY AND CONCLUSIONS

This paper presented numerical simulation results from single element and system level analyses of a uniform sand. The analyses were performed using the constitutive model PM4Sand and the numerical platform FLAC. The boundary value problem examined was a well-instrumented centrifuge model test of a submerged embankment of the same uniform sand. PM4Sand was calibrated against the results from monotonic TX and cyclic undrained DSS laboratory tests (cyclic strength curves and stress paths) on the sand. The calibration of primary and secondary (as deemed appropriate based on the availability of data) input model parameters was presented for two scenarios of considering the TX data or not for constraining the CSL line. A third calibration was informed by the system level performance of the first two calibrations. The numerical model setup was described followed by results in terms of accelerations, excess pore pressures, and horizontal displacements. The two calibrations honoring lab data only were found identical and their results at the system level provided a good match for accelerations and pore pressures but overpredicted displacements. The closer examination of factors contributing to this response informed a “forensic” Calibration 3 that aimed at reconciling both lab and centrifuge data. Overall, the results suggest that the combination of: (1) the numerical tools used (FLAC with PM4Sand), (2) the availability of high-quality laboratory data that can serve as a calibration basis constraining multiple aspects of the soil’s behavior, and (3) the availability of high-quality system level (centrifuge) experimental data that confidently describe the system’s response, can yield reliable predictions and can be leveraged for future investigations of more complex geosystems.

For the case examined herein, the TX data were found useful in constraining the CSL and combined with the high-quality DSS data, they provided an additional degree of confidence in constraining the 100A soil’s response at the element level. Ultimately, since this was not a flow liquefaction problem, the DSS data alone would have sufficed as was shown by Calibrations 1 and 2. Initial system level analyses that overestimated displacements hinted at possible sources of uncertainty that could be the individual or combined effects of: boundary conditions (e.g., interface between container walls and soil), the use of one calibration for the whole embankment instead of differentiating between zones with different overburden stresses, the calibration for level ground conditions as opposed to the mildly sloping ground conditions operating under the embankment, as well as the overall sensitivity of predicted deformation to constitutive model input parameters. Calibration 3 had the best overall performance and thus proved that more holistic (lab and large-scale) investigations are needed in order to develop a robust basis for the study of more complex systems. Future efforts will (a) investigate the sources of discrepancies in the acceleration, pore pressure, and displacement predictions, and (b) further refine the ability to calibrate constitutive models against the lab data or empirical relationships that are only available in practice.

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