Chapter 29

LEAP-UCD-2017 Simulations at Tsinghua University

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Abstract Under the LEAP-UCD-2017 project framework, simulations of centrifuge shaking table tests on gently sloping ground are conducted in this study. A unified plasticity model for large post-liquefaction shear deformation of sand is used in the simulations. The model is able to provide a unified description of sand behaviour under different states from the pre- to post-liquefaction regimes. The model parameters are calibrated against undrained cyclic triaxial test results. Using the calibrated parameters, a series of Type-B simulations are performed to predict the results of nine centrifuge tests conducted at various facilities with different settings without previously knowing the test results. Using the same simulation setup, a sensitivity study is conducted to investigate the influence of soil density and input motion on the response of the slope.

29.1 Introduction

The LEAP (Liquefaction Experiments and Analysis Projects, Manzari et al. 2015) project is a collaborative effort to verify and validate numerical liquefaction models, following the influential work of the VELACS project (Arulanandan and Scott 1993–1994), the results of which are still often being used in validating numerical simulation methods for soil liquefaction.

Over the past two decades, significant developments in the constitutive modelling of soil liquefaction behaviour have taken place. The phenomenon and physics of soil liquefaction is better understood, and the state dependency of sand is better described. Hence, it is important and timely that such developments be validated against actual experimental data, aided with new developments in experimental technology.

This paper presents the simulations of geotechnical centrifuge tests on gently sloping ground under the LEAP-UCD-2017 project framework. A unified plasticity model for large post-liquefaction shear deformation of sand proposed by Wang et al.

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(2014) is used in the simulations of this study. The model is calibrated and used in Type-B simulations of centrifuge tests and sensitivity studies.

29.2 Constitutive Model

29.2.1 Model Formulation

The constitutive model used for the simulations of the centrifuge tests in LEAP-UCD-2017 is based on the unified plasticity model for large post-liquefaction shear deformation of sand developed by Wang et al. (2014) of Tsinghua University with modifications made to take better consideration of the influence of material state. This constitutive model has been validated against many laboratory element tests and has previously been applied to simulations of centrifuge tests (Chen et al. 2018; Wang et al. 2016; Wang 2016). This paper only presents a brief description of the specific modifications of the original model for the calibration and simulation of the cyclic triaxial data obtained for LEAP-UCD-2017 (El Ghoraiy et al. 2017, 2019). Readers should refer to Wang et al. (2014) for the full formulation of the original model.

The function $g(\theta)$ used for the description of the shape of the critical, maximum stress ratio and reversible dilatancy surfaces in the octahedral stress plane is modified based on Zhang's (1997) original proposition to be:

$$g(\theta) = \left(\frac{1}{1 + M_p(1 + \sin 3\theta - \cos^2 3\theta)/6 + (M_p - M_{p,o}) \cos^2 3\theta/M_{p,o}} \right)^{0.7} \quad (29.1)$$

In Eq. 29.1, M_p is the peak mobilized stress ratio at triaxial compression, ϕ_f is the corresponding friction angle, and $M_{p,o}$ is the peak mobilized stress ratio under torsional shear after isotropic consolidation. The original model does not have the exponent 0.7 in Eq. (29.1), which is introduced here specifically to better represent the difference in the p - q curves during the “butterfly orbit” between triaxial compression and extension observed in the reported triaxial tests. Compared with the triaxial test data, the original formulation overestimates the difference of peak mobilized stress ratio between triaxial compression and extension for Ottawa F65, and hence the exponent was introduced to reduce such a difference.

According to the propositions made by Shamoto and Zhang (1997) and Zhang (1997), the dilatancy of sand is decomposed into a reversible and an irreversible component through which the dilatancy during load reversal and cyclic loading can be properly reflected. The generation rate, $D_{\text{re,gen}}$, of reversible dilatancy is:

$$D_{\text{re,gen}} = \sqrt{\frac{2}{3}} d_{\text{re},1} (\exp(1 + n_d \psi))^{-d_{\text{re},3}} (\mathbf{r}_d - \mathbf{r}) : \mathbf{n} \quad (29.2)$$

The state parameter ψ , proposed by Been and Jefferies (1985), is introduced to consider the dependency of sand behaviour on the current state. $d_{\text{re},1}$ and $d_{\text{re},3}$ are model parameters. $\mathbf{r}$ is the deviatoric stress ratio tensor, $\mathbf{r}_d$ is the projection of the current stress ratio on the reversible dilatancy surface, and $\mathbf{n}$ is a unit deviatoric tensor serving as the loading direction in deviatoric stress space in the model. The term $(\exp(1 + n_d \psi))^{-d_{\text{re},3}}$ in Eq. (29.2) is newly introduced compared with the original formulation here based on recent observations from undrained cyclic torsional tests on the increase of post-liquefaction shear strain as sand becomes looser.

The modified constitutive model has a total of 15 parameters, which can be calibrated using drained and undrained triaxial and torsional shear tests (El Ghoraihy et al. 2017, 2019).

29.2.2 Model Calibration

Undrained cyclic triaxial tests (El Ghoraihy et al. 2017, 2019) were presented to us for the calibration of the constitutive model prior to the simulations of the centrifuge tests. The four critical state parameters are hence directly obtained from Vasko (2015) without any alteration. The elastic modulus, plastic modulus, and dilatancy parameters are fitted based on three triaxial tests with various void ratios (0.585, 0.542, and 0.515) and CSRs (0.2, 0.28, and 0.6). Figure 29.1 shows the calibration

Fig. 29.1 Calibration of an undrained cyclic triaxial test on Ottawa F65 sand with void ratio of 0.585 and CSR of 0.2

Table 29.1 Model parameters obtained from calibration of the cyclic triaxial tests

Sand	G_o	κ	h	M	$d_{re, 1}$	$d_{re, 2}$	$d_{re,3}$	d_{ir}
Ottawa F65	300	0.008	3.0	1.45	0.3	60	3	3
Sand	α	$\gamma_{d, r}$	n^p	n^d	λ_c	e_0	ξ	
Ottawa F65	180	0.05	0.1	5.0	0.0112	0.78	0.715

Fig. 29.2 Simulation of an undrained cyclic triaxial test on Ottawa F65 sand with void ratio of 0.515 and CSR of 0.315

results of the undrained cyclic triaxial test on Ottawa F65 sand with void ratio of 0.585 and CSR of 0.2 (El Ghoraiby et al. 2017, 2019). The model parameters obtained from this calibration process are listed in Table 29.1. Simulations of the rest of the triaxial tests are then carried out without any further changes to the model parameters.

The simulation of a typical undrained cyclic triaxial test on Ottawa F65 sand with void ratio of 0.515 and CSR of 0.315 is plotted in Fig. 29.2. The calibration and simulation results of typical undrained cyclic triaxial tests highlights the model’s ability to capture the dilatancy of sand under cyclic loading and especially the accumulation of shear strain after the sample reaches initial liquefaction. With the introduction of state dependency, the model is able to provide a unified description of sand with different densities using the same set of parameters.

The results for liquefaction strength curves obtained from the simulations are plotted in Fig. 29.3 in comparison with the test results. The number of cycles until 2.5% single amplitude axial strain is achieved for each test is used to determine the liquefaction strength curves. In general, the strength curves are well represented by the numerical simulations though the discrepancy at low cyclic stress ratio is somewhat significant.

Fig. 29.3 Liquefaction strength curves for Ottawa F64 sand from the tests and simulations

29.3 Setup for Numerical Simulations of Centrifuge Tests

The simulations in this study are conducted using the open source finite element framework, OpenSees (McKenna and Fenves 2001). Solid-fluid coupled elements needed for the undrained and partially drained analysis of sand, which is essential for liquefaction analysis, are already incorporated into OpenSees (e.g. u-p elements by Yang et al. (2008)).

quadUP elements in the OpenSees framework is used for the dynamic analysis conducted. The element is a four-noded quadrilateral plane strain element that has two displacement degrees of freedom and one pore pressure degree of freedom at each node and follows the u-p formulation proposed by Zienkiewicz and Shiomi (1984).

The configuration of the mesh is illustrated in Fig. 29.4, which consists of 1280 elements and 1377 nodes. The simulations are conducted in the prototype scale. The bottom boundary of the model is constrained in both x and y directions and is undrained. The lateral boundaries are undrained and constrained in the x direction. The model container itself is not explicitly simulated. Constant pore pressure is applied on the surface of the model. Since the water table is not reported for the centrifuge tests, we assume that the water table is level with the top of the slope to guarantee that the model is fully submersed. The curvature of the centrifuge model ground surface to compensate for the non-parallel nature of the centrifugal force is not considered in the simulations.

The Krylov Newton solution algorithm along with a ProfileSPD approach is used to solve the system of equations (OpenSees manual). Hilber-Hughes-Taylor (HHT) time integration scheme is used. The boundary conditions are enforced using the

Fig. 29.4 Finite element mesh for LEAP-UCD-2017 simulations

Table 29.2 Initial void ratio and density of each centrifuge test provided for the LEAP-UCD-2017 simulations

Test	e_{in}	ρ
CU-2	0.650268	1.999838
Ehime-2	0.59971	2.031437
KAIST-1	0.557724	2.059238
KAIST-2	0.66405	1.991557
KyU-3	0.618815	2.019264
NCU-3	0.604116	2.028604
UCD-1	0.591592	2.036698
UCD-3	0.598311	2.03234
ZJU-2	0.650062	1.999962

penalty method with the penalty number of 10^{12} . For the test of convergence, a norm of the displacement increment test is used with a 10^{-3} tolerance and maximum number of iterations of 50.

The constitutive model described in the previous section is implemented in OpenSees as described by Wang et al. (2014). The model parameters used are as listed in Table 29.1, which are kept constant during the entire simulation process. The same constant permeability of 1.4×10^{-4} m/s is used for all the analyses in this study. The initial void ratio and density used for each test are listed in Table 29.2.

The input motions for the Type-B simulations follow the exact motions provided to us from the centrifuge tests, including both horizontal and vertical motions. The input motions used for the NCU-3 and UCD-3 centrifuge test simulations are plotted in Fig. 29.5 as typical examples. For the sensitivity analysis, the motions designated for LEAP-UCD-2017 are used. Prior to the seismic event simulations, each simulation involves a gravity step to obtain the initial state of stresses in the model under centrifugal acceleration. The initial pore pressure, and the vertical effective, horizontal, and shear stress after spin-up and before shaking in a typical simulation are illustrated in Figs. 29.6, 29.7, 29.8, and 29.9. Note that due to the constant pore pressure boundary condition soil surface, the pore pressure contour in Fig. 29.6 is horizontally layered.

Fig. 29.5 Examples of input motions used in the Type-B simulations **(a)** NCU-3; **(b)** UCD-3

Fig. 29.6 Initial pore water pressure (kPa) in a typical simulation

Fig. 29.7 Initial vertical effective stress (kPa) in a typical simulation

Fig. 29.8 Initial horizontal effective stress (kPa) in a typical simulation

Fig. 29.9 Initial shear stress σ_{xy} (kPa) in a typical simulation

29.4 Type-B Simulation Results

29.4.1 Typical Results

This section exhibits the results of a typical dynamic analysis on the NCU-3 centrifuge test. Figure 29.10 shows the simulated and experimentally measured horizontal accelerations at the locations of accelerometers AH1-AH4. At greater depths (AH1), the numerical and experimentally obtained accelerations match well. However, the Type-B simulations do not capture the spikes in the recorded acceleration time histories. The spikes are most likely caused by the sudden increase in soil stiffness as the soil leaves liquefaction during shear due to dilatancy. This suggests that the parameters used in these simulations likely underestimates the reversible dilatancy component. As for the pore pressure time histories in Fig. 29.11, the simulation results tend to over-predict the time needed for excess pore pressure to dissipate, which could be due to the increase in permeability after liquefaction. The final horizontal and vertical displacement contours of the model are plotted in Figs. 29.12 and 29.13. The contour plots are drawn with the deformed mesh, with deformation amplified by 4 times. The maximum horizontal displacement in the simulation appears slightly downslope of the center and reaches 0.398 m, which is greater than the maximum horizontal displacement measured in test NCU-3 of 0.349, and is also greater than the average horizontal displacement of the two centermost markers at 0.279 m.

Fig. 29.10 Simulated and test horizontal acceleration at the locations of accelerometers AH1-AH4 for the NCU-3 centrifuge test

Fig. 29.11 Simulated and test excess pore pressure at the locations of pore pressure transducers P1-P4 for the NCU-3 centrifuge test

Fig. 29.12 Final horizontal displacement contour (deformation of the model is amplified by 4 times, unit: m)

Fig. 29.13 Final vertical displacement contour (deformation of the model is amplified by 4 times, unit: m)

29.4.2 Overall Comparison Between Simulation and Test Results

The simulated maximum horizontal displacement in all nine centrifuge tests used for the Type-B predictions are presented and compared with the measured maximum horizontal displacement and average horizontal displacement of the two centermost markers in Table 29.3. If the test results are used in a non-biased comparison with the

Table 29.3 Simulated maximum horizontal displacement compared with the measured horizontal displacement in all nine centrifuge tests used for the Type-B predictions

Test No	Test ID	D_r	Motion	PGA_{eff} (g)	Average horizontal displacement of center 2 markers in test (m)	Maximum horizontal displacement in test (m)	Maximum horizontal displacement in simulation (m)
1	CU-2	0.463	1	0.195	0.490	0.520	0.462
2	Ehime-2	0.638	1	0.158	0.100	0.160	0.418
3	KAIST-1	0.782	2	0.168	0.004	0.009	0.312
4	KAIST-2	0.416	2	0.166	0.007	0.205	0.456
5	KyU-3	0.572	2	0.133	0.200	0.266	0.406
6	NCU-3	0.622	1	0.176	0.279	0.349	0.398
7	UCD-1	0.666	1	0.149	−0.002	0.079	0.343
8	UCD-3	0.642	1	0.183	0.160	0.306	0.372
9	ZJU-2	0.464	1	0.148	0.263	0.315	0.415

simulation results, the displacements predicted in the Type-B simulations in this study generally overestimate lateral deformation of the soil slope.

However, it should be pointed out that the inconsistencies in the centrifuge test results may in fact hinder such comparisons. Take tests NCU-3 and UCD-3 as two examples. The sand in the UCD-3 test is slightly denser than that in the NCU-3 test, while the peak input acceleration of UCD-3 is slightly greater than that in the NCU-3 test. Intuitively, the horizontal displacement in these two tests should be similar in terms of both value and distribution. The measured results in Fig. 29.14 contradicts such understandings. The measured horizontal displacement in test UCD-3 is significantly smaller than that in the NCU-3 test. The measured maximum horizontal displacement in the UCD-3 test of 0.306 m is only an anomaly compared with the results of the other markers in the same test; the displacement of the markers are generally less than half of those in the NCU-3 test. The average horizontal displacement of the two centermost markers is 0.349 m in the NCU-3 test, while being only 0.160 m in the UCD-3 test. Such drastic discrepancies in the deformation of the slopes of two experiments with very similar settings is very hard to explain and is certainly not possible to be simulated by the same procedure using the same parameters. The simulation results show that the Type-B prediction of maximum horizontal displacement for the two tests are 0.398 m and 0.372 m, respectively. In a non-biased comparison, one can say that the displacement in the UCD-3 test is significantly “overestimated” though such an overestimation is mostly due to the variation in test results rather than being due to deficiencies in the numerical simulations.

Fig. 29.14 Comparison of simulated and measured horizontal displacement for NCU-3 and UCD-3 tests. The measured test results are presented in Birdseye views of the surface markers. The simulation results are presented in side view contours (m)

29.5 Sensitivity Study

Using the same material parameters and model geometry setup, a sensitivity analysis is carried out in this study to analyze the influence of soil density, input motion intensity, high frequency component of the input motion on the displacement, and liquefaction of the sloping ground. The soil density and input motion information are listed in Table 29.4. Three different relative densities, including 50%, 65%, and 75%, are adopted in this study. The same input motion with the PGA scaled up or down is used for simulations NS-1 to NS-5; another motion with greater high frequency component is used for simulations NS-6 and NS-7.

The simulation results show that at high relative density, i.e. 65–75%, the relative density significantly influences the soil displacement; this is due to the fact that as the sand becomes denser, the soil becomes more difficult to reach liquefaction, which is evident from the duration of liquefaction after the end of shaking. For the same reason, the influence of input motion PGA is significant at low PGA levels. For example, the soil displacement in NS-5 is only around half of that in NS-1.

The high frequency component of the input motion is shown to have little influence on the liquefaction and displacement of the soil. The high frequency component of the input motion in NS-6 is significantly greater than that in NS-1, and the 1 Hz component is slightly smaller. The resulting displacement of NS-6 is slightly smaller than that of NS-1, suggesting that the 1 Hz component plays a much more significant role on the soil response than the high frequency component.

Table 29.4 Information and results of the sensitivity study

Simulation #	NS-1	NS-2	NS-3	NS-4	NS-5	NS-6	NS-7
Dry density (kg/m ³)	1651	1608	1683	1651	1651	1651	1651
Soil	Ottawa F65	Ottawa F65	Ottawa F65	Ottawa F65	Ottawa F65	Ottawa F65	Ottawa F65
D_r (assuming $\rho_{\max} = 1765$ & $\rho_{\min} = 1476$ kg/m ³)	65%	50%	75%	65%	65%	65%	65%
PGA (g)	0.150	0.150	0.150	0.250	0.110	0.14	0.20
PGA of 1 Hz component (g)	0.135	0.135	0.135	0.270	0.099	0.11	0.16
PGA of the high frequency component (g)	0.021	0.021	0.021	0.035	0.015	0.08	0.11
Simulation result: X-displacement at middle point on the specimen surface (m)	0.365	0.384	0.283	0.425	0.184	0.328	0.398
Simulation result: Duration of liquefaction at P4 after end of shaking (s)	72	68	55	74	36	65	74

29.6 Conclusion

This study describes the simulations conducted at Tsinghua University for LEAP-UCD-2017. The calibration of the constitutive model, Type-B simulation of nine centrifuge tests, and sensitivity studies are presented in this study.

A unified plasticity model for large post-liquefaction shear deformation of sand is used in the simulations of this study; the model is able to provide a unified description of sand behaviour under different states from the pre- to post-liquefaction regimes. The constitutive model is calibrated against undrained cyclic triaxial tests with various void ratios and CSRs with the results highlighting the models' advantage in capturing the accumulation of shear strain during cyclic loading after initial liquefaction. In general, the strength curves of the tests are well represented by the numerical simulation results though the discrepancy at low cyclic stress ratio is somewhat significant.

Applying the model parameters obtained from the calibration process, the open source finite element framework, OpenSees, is used to conduct Type-B simulations of nine centrifuge tests with different soil densities and input motions. The simulation results show that the deformation of the model slopes of some tests are well predicted while there are significant differences between simulation and test slope displacement for a few other tests. This is to some extent due to the discrepancies between the tests conducted at various facilities. The dilatancy spikes observed in the

tests are not captured in the simulations, possibly due to a relatively small dilatancy parameter used. Another notable difference between simulation and test is that the post-shaking dissipation of excess pore pressure in the simulations takes much longer, possibly due to the increase in permeability after liquefaction in actual tests.

Sensitivity studies on the influence of soil density, input motion intensity, high frequency component of the input motion on the displacement, and liquefaction of the sloping ground were carried out. As expected, the relative density and input motion intensity are found to be influential factors. The high frequency component of the input motion is shown to have little influence on the liquefaction and displacement of the soil.

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