Proceedings of the Seventeenth International Conference on
Civil, Structural and Environmental Engineering Computing
Edited by: P. Iványi, J. Kruis and B.H.V. Topping
Civil-Comp Conferences, Volume 6, Paper 3.2
Civil-Comp Press, Edinburgh, United Kingdom, 2023
doi: 10.4203/ccc.6.3.2

Numerical Prediction of Centrifuge Test for Liquefiable Sand Subjected to Strong Earthquake

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Abstract

Earthquake induced soil liquefaction lead to damage of underground structures. Consequently, accurate and reliable evaluation of liquefaction triggering and consequence is critical. Nevertheless, Numerical prediction of dynamic response for saturated sand subjected to strong earthquake remains challenging due to intensive nonlinearity. In this paper, the PDMY02 constitutive model was calibrated through laboratory element tests. The number of cycles to reach liquefaction were appropriately captured for Fujian intermediate sand. Subsequently, the calibrated model was used to numerically predict the seismic response of liquefiable loose and medium dense sand centrifuge tests in OpenSees. Overall, the dynamic properties of sand liquefaction were reasonably reflected by numerical blind prediction. After performing the scheduled centrifuge tests, the accuracy and limitation of numerical blind prediction can be evaluated.

Keywords: liquefaction, numerical prediction, constitutive model, centrifuge test, calibration, strong earthquake.

1 Introduction

Liquefaction induced earthquake damage occurred frequently in saturated soil. In recent years, liquefaction damage such as sand boil, water spray and ground settlement have been observed in the case of several major earthquakes worldwide, accompanied with uplift failure of underground structures in liquefiable ground [1,2,3]. Therefore, the dynamic properties of liquefiable sand subjected to earthquake have been studied through experimental and numerical methods for decades. In order to describe the seismic response of liquefiable ground, various dynamic constitutive models have been proposed for saturated sand [4,5,6,7]. However, reasonably reproducing the stress-strain response and excess pore water pressure accumulation for saturated sand subjected to strong earthquake with numerical simulation remains complicated due to intensive nonlinearity.

To evaluate the numerical prediction ability of different constitutive models for sand liquefaction and correlative effects, Liquefaction Experiments and Analysis Projects (LEAP) calibrated the liquefaction parameters of Ottawa sand based on soil laboratory element tests. Subsequently, 11 different constitutive models were selected to numerically predict the dynamic response of centrifuge shaking table tests for slight inclined saturated sand ground [8]. Nevertheless, the results indicate that none of the selected constitutive models can accurately predict the seismic response and excess pore water pressure accumulation and dissipation in centrifuge tests, particularly the soil deformation caused by liquefaction. The effectiveness and accuracy of numerical prediction depend on the calibration quality of input parameters. The same conclusions have been obtained from The H2020 European Project LiqueFACT, which aimed to assess and mitigate earthquake induced liquefaction potential across Europe [9,10].

It is obviously that numerical prediction based on calibrated constitutive model remains challenging. Furthermore, correlative research are principally focused on Ottawa sand, Hostun sand, and Ticino sand [8,9,11]. The identical constitutive model calibration and numerical simulation prediction framework has not yet been implemented for Fujian intermediate sand in China. The numerical prediction ability of dynamic constitutive models for different liquefiable sand still need further investigation.

In this paper, the PDMY02 constitutive model developed by Yang and Elgamal [4] was calibrated through laboratory element tests. The stress-strain response and the number of cycles to reach liquefaction were appropriately captured for Fujian intermediate sand. Subsequently, two dimensional numerical models were established for free field centrifuge tests in OpenSees [12]. The calibrated PDMY02 constitutive model aforementioned was used to numerically predict the seismic response of liquefiable loose and medium dense sand. Then, the numerical results were discussed in terms of acceleration response, excess pore water pressure, and ground settlement during strong earthquake induced liquefaction. After performing the scheduled centrifuge tests, the accuracy and limitation of numerical blind prediction can be reasonably evaluated.

2 Centrifuge shaking table tests

A series of centrifuge shaking table tests are scheduled to be carried out using TK-C500 geotechnical centrifuge apparatus at Tianjin Research Institute for Water Transport Engineering to evaluate seismic response and soil-structure interaction in liquefiable soil. Centrifuge tests will be conducted in the following year.Two centrifuge tests with free field condition are selected for numerical blind prediction in this paper.

Fujian intermediate sand with particle size between 0.5mm and 1mm is selected for centrifuge tests. The model grounds are prepared by the air pluviation method inside a laminar container. The relative drop height is controlled to obtain loose and medium dense model grounds, with relative density of 30% and 50%, respectively. A layer of rubber film is wrapped on the inner wall of the laminar container to reduce boundary effect and prevent water leakage.

The geometric similarity ratio is set to 10, corresponding to a prototype site with a thickness of 5m. All the units elaborated in this paper are in prototype scale unless specified otherwise.The shaking table tests are conducted with a centrifugal acceleration of 10g. Silicone oil with a viscosity 10 times that of water is selected as the pore fluid to solve the contradiction between permeability time and dynamic time. The model grounds are slowly saturated under vacuum condition.

The model grounds are instrumented with accelerometers A0-A12, pore pressure transducers P1-P12, vertical displacement transducers D1-D3, lateral displacement transducers L1-L6, bending elements BE1-BE3 and compressing element CE1, as shown in Figure 1. Accelerations, pore water pressure, vertical settlement, lateral displacement, SV shear wave velocity and P compression wave velocity are measured in centrifuge tests.

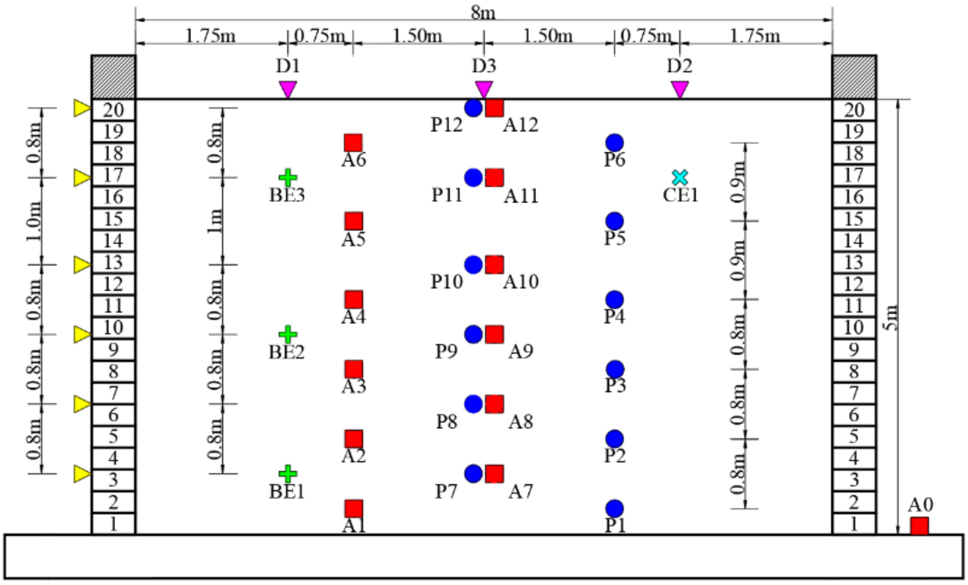


Figure 1: Centrifuge model scheme and instrumentation layout.

Under a centrifugal acceleration of 10g, the horizontal seismic input motion adopts the sinusoidal wave with frequency of 30Hz and cycle of 36, the peak acceleration is 4g, and the duration time is 1.2s. The amplitude of sinusoidal wave increases gradually in the three cycles before the peak, and decreases gradually in the three cycles after the peak. The seismic input motion is presented in Figure 2.

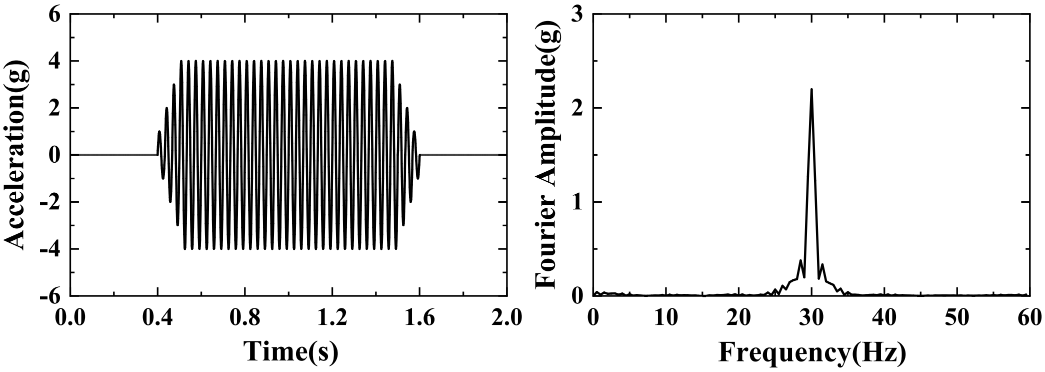


Figure 2: Acceleration time history and Fourier spectrum of the input motion.

3 Numerical models

3.1 Calibration of the constitutive model

Pressure-Dependent-Multi-Yield 02 constitutive model (PDMY02) is selected to simulate the response of the liquefiable Fujian intermediate sand [4].

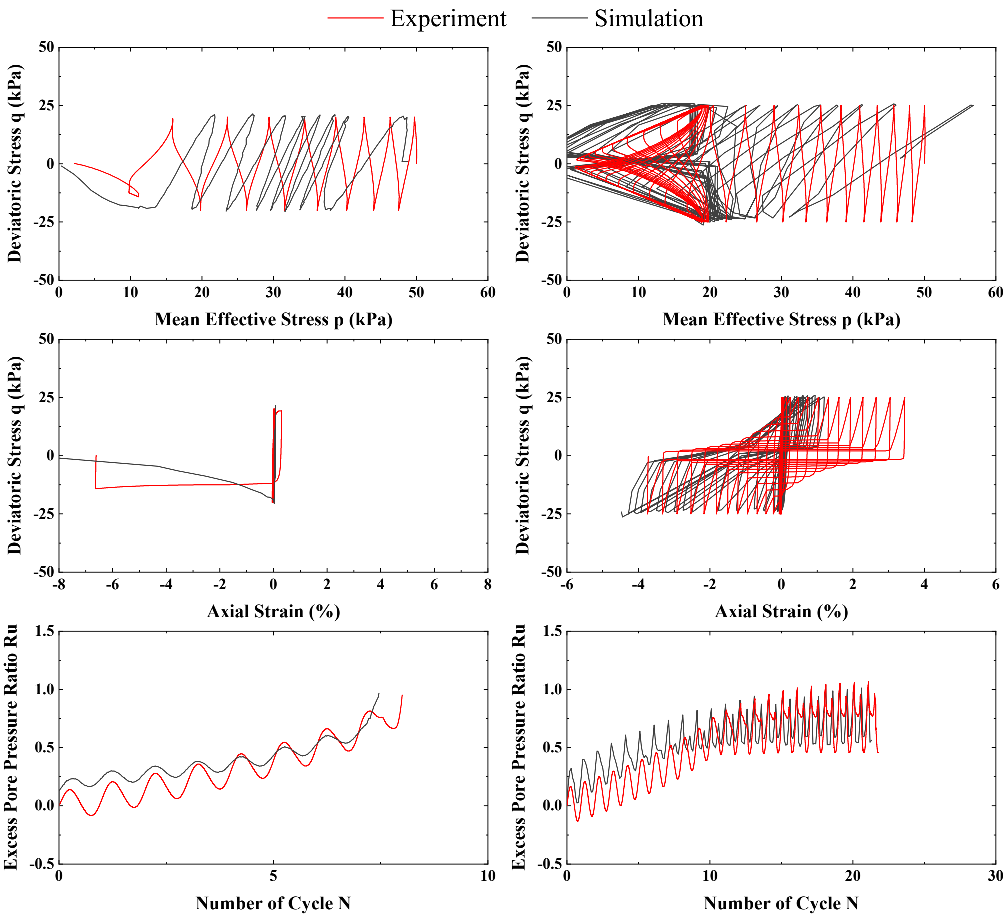
Calibration of the PDMY02 constitutive model is implemented in OpenSees [12]. 24 parameters need to be determined during calibration. 23 constitutive model parameters contained in PDMY02 and permeability coefficient for solid-fluid fully coupled element. Among these model input parameters, 16 basic physical and mechanical parameters can be obtained from indoor geotechnical test or invoked with default value in OpenSees. The other 8 parameters are related to contraction, dilation, and liquefaction damage which can be calibrated in cyclic triaxial (CTX) test.

A series of drained and undrained monotonic and cyclic triaxial compression tests were conducted on Fujian intermediate sand. Basic physical and mechanical parameters for PDMY02 were obtained from drained and undrained monotonic triaxial compression tests at the Technical University of Munich. Liquefaction parameters for PDMY02 were calibrated in undrained cyclic triaxial tests at the Tongji University. Undrained cyclic triaxial tests were conducted on specimens with relative density of 30% and 50%. The specimens were isotropically consolidated under an effective confining pressure of 50kPa. The cyclic axial stress with amplitudes ranging from 10kPa to 20kPa and 20 kPa to 30kPa were applied to the loose and medium dense samples, corresponding to cyclic stress ratio (CSR) from 0.10 to 0.20 and 0.20 to 0.30, respectively. The loading frequency was 0.1Hz.

To calibrate the constitutive parameters for PDMY02, an eight-node hexahedral solid-fluid fully coupled SSPbrickUP element was used to simulate undrained cyclic triaxial test in OpenSees [13]. Parameters related to contraction, dilation, and liquefaction damage were set to match the numerical simulation with undrained cyclic triaxial test results. Liquefaction occur once excess pore pressure ratio (R_u) exceeded 0.99. The calibrated PDMY02 constitutive model appropriately captured the stress-strain response and the number of cycles to reach liquefaction (N) for Fujian intermediate sand. The comparison between experimental and numerical results of two representative undrained cyclic triaxial tests for loose and medium dense sand are illustrated in Figure 3. The relationship between the number of cycles to reach liquefaction (N) and the cyclic stress ratio (CSR) is shown in Figure 4. All the calibrated parameters for PDMY02 are presented in Table 1.

Parameter	Definition	CTX 30%	CTX 50%
ρ	Saturated soil mass density [ton/m^3]	1.916	1.944
G_r	Reference low-strain shear modulus [kPa]	1.23×10^5	1.40×10^5
B_r	Reference bulk modulus [kPa]	3.10×10^5	3.30×10^5
p_r	Reference mean effective confining pressure [kPa]	100	100
d	Pressure dependence coefficient [-]	0.5	0.5
$\gamma_{\max}$	Maximum octahedral shear strain [-]	0.1	0.1
φ	Friction angle [°]	31.3	32.7
φ_{PT}	Phase transformation angle [°]	23.3	27.7
e	Initial void ratio [-]	0.801	0.747
c_1	Constant of the rate of shear contraction [-]	0.048	0.020
c_2	Constant of dilation history on contraction [-]	3.0	3.0
c_3	Constant of overburden effect on contraction [-]	0.15	0.15
d_1	Constant of the rate of shear induced dilation [-]	0.0	0.15
d_2	Constant of stress history on dilation [-]	3.0	3.0
d_3	Constant of overburden effect on dilation [-]	0.20	0.25
l_1	parameter 1 to define permanent shear strain [-]	1.0	1.0
l_2	parameter 2 to define permanent shear strain [-]	0.0	0.0
cs_1	Parameter 1 to define the critical state line [-]	0.9	0.9
cs_2	Parameter 2 to define the critical state line [-]	0.02	0.02
cs_3	Parameter 3 to define the critical state line [-]	0.7	0.7
n	Number of yield surfaces [-]	20	20
p_a	Atmospheric pressure [kPa]	101	101
c	Numerical constant [kPa]	0.1	0.1
k	Permeability coefficient [m/s]	1.5×10^{-3}	1.5×10^{-3}

Table 1: Calibrated parameters for PDMY02.



(a)

(b)

Figure 3: Comparison between experimental and numerical results of CTX: (a) Loose sand with CSR=0.20; (b) Medium dense sand with CSR=0.25.

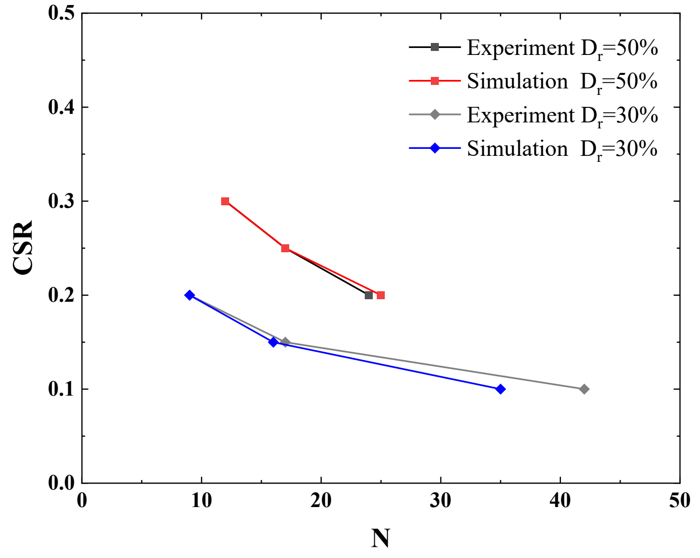


Figure 4: Relationship between *N* and CRR

3.2 Numerical models of centrifuge tests

Numerical models for free field centrifuge tests with plane strain condition were established at prototype scale in OpenSees. A 4-node quadrilateral solid-fluid fully coupled quadUP element for dynamic plane strain analysis was used to simulate free field centrifuge tests of loose and medium dense Fujian intermediate sand. Model grounds were assigned with the calibrated PDMY02 constitutive model.

The boundary conditions of the model grounds were fixed on the bottom without drainage and free drainage on the top. Nodes located on both sides of the model grounds were constrained to equal degrees of freedom in all directions to simulate the lateral equi-displacement boundary conditions of laminar container in the centrifuge tests. The model mesh size was set to 0.1m.

36 horizontal sinusoidal wave cycles with a frequency of 3Hz and a peak amplitude of 0.4g were input on the bottom of the model grounds. The energy dissipation of saturated sand was reflected by Rayleigh damping composed of mass and stiffness in proportion with 2% damping ratio.

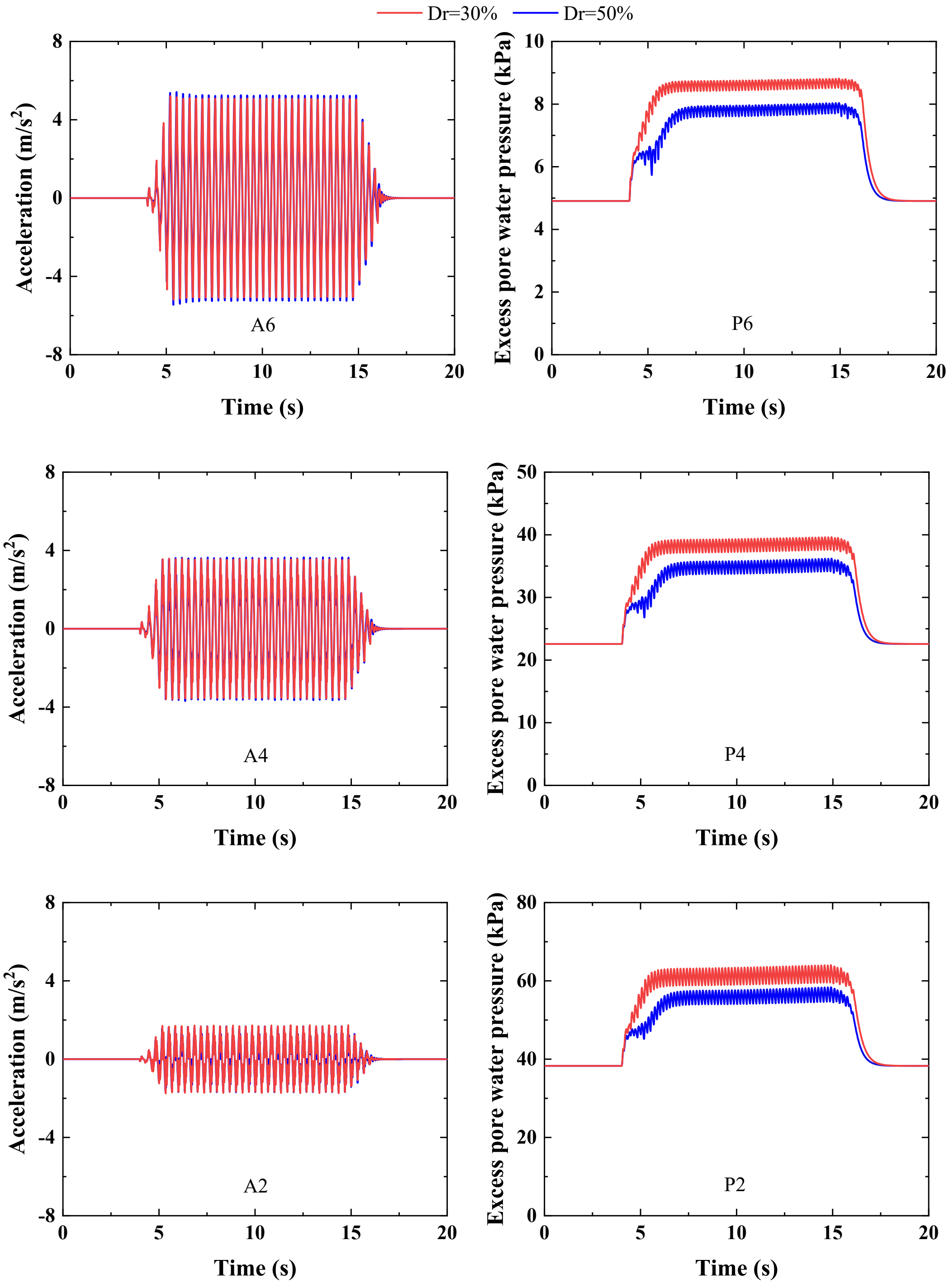
4 Results of numerical prediction

The numerical simulation is conducted in two stages. In the first stage, the geostatic stress analysis is carried out. In the second stage, the dynamic analysis is performed with seismic excitation.

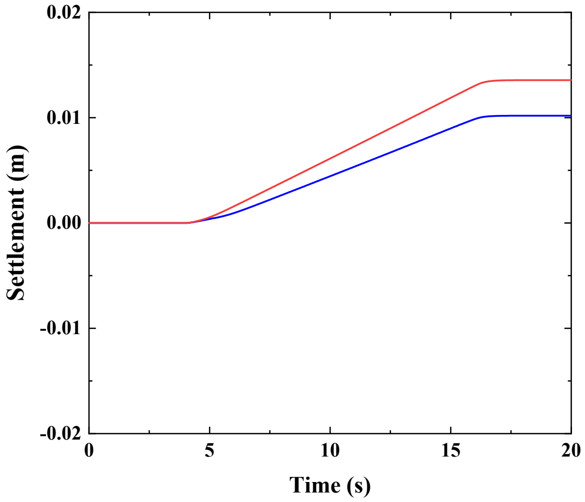
The numerical prediction results of the centrifuge shaking table tests are presented in Figure 5. Including acceleration response, excess pore water pressure, and ground settlement. As shown in Figure 5a, a slight amplification effect from bottom to top of the ground occur in the acceleration response. The model ground transforms from solid phase to liquid phase due to liquefaction, reducing transmission of shear wave and suppressing the amplification effect of acceleration response. As presented in Figure 5b, the excess pore water pressure continuously accumulates with the input of seismic excitation and dissipates once shaking ends. The excess pore water pressure in loose sand tends to stabilize after 1 second of shaking, indicating that liquefaction has been triggered at this time. While medium dense sand takes 2 seconds. Loose sand liquefies faster than medium dense sand. Excess pore pressure ratio (R_u) contour for centrifuge tests at the maximum moment is presented in Figure 6. Compared with medium dense sand, loose sand is more prone to deeper liquefaction. The numerical results of acceleration response and excess pore water pressure are relatively reasonable.

The ground settlement continuously increases with the input of seismic excitation, as shown in Figure 5c. Larger settlement occur in loose sand compared with medium dense sand. However, the ground settlement in the numerical prediction results seem to be underestimated due to underestimation of volumetric compressibility in PDMY02. The same situation is observed by Ramirez [14]. It is unreliable to artificially reducing the hydraulic conductivity without fundamental improvement. The adjustment of numerical simulation remains to be verified in centrifuge tests.

Overall, the dynamic properties of sand liquefaction are reasonably reflected by numerical blind prediction. The suppression trend of amplification effect in acceleration response and the accumulation and dissipation of excess pore water pressure have been captured.The accuracy and limitation of numerical blind prediction can be evaluated in further centrifuge tests.

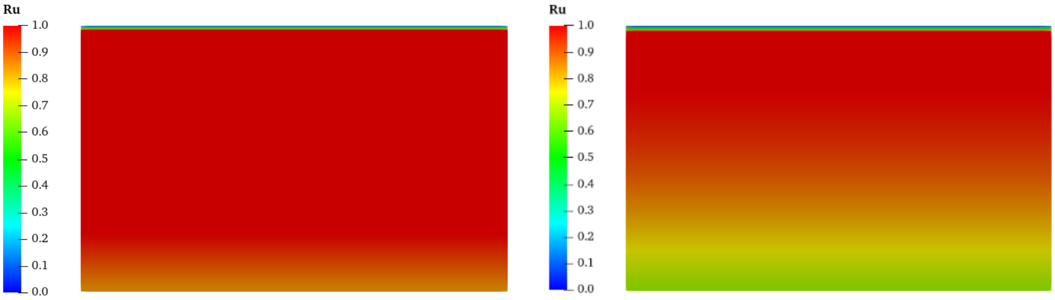


(a) (b)



(c)

Figure 5: Numerical prediction time history of centrifuge tests:
(a) Acceleration; (b) Excess pore water pressure; (c) Ground settlement.



(a) (b)

Figure 6: Excess pore pressure ratio (R_u) contour for centrifuge tests:
(a) Loose sand with D_r=30%; (b) Medium dense sand with D_r=50%.

5 Conclusions

The PDMY02 constitutive model is selected to numerically predict the seismic response of liquefiable loose and medium dense Fujian intermediate sand in centrifuge tests. The PDMY02 is calibrated to capture the stress-strain response and the number of cycles to reach liquefaction. Then, the numerical results are discussed in terms of acceleration response, excess pore water pressure and ground settlement during strong earthquake induced liquefaction. The numerical results of acceleration response and excess pore water pressure are relatively reasonable, while the ground settlement may be underestimated. The dynamic properties of sand liquefaction are reasonably reflected by numerical blind prediction. After performing the scheduled centrifuge tests, the accuracy and limitation of numerical blind prediction can be evaluated.

Acknowledgements

The authors acknowledge support from the National Natural Science Foundation of China (5201101237). The authors also acknowledge the scholars of Zentrum

Geotechnik in Technical University of Munich and Department of Geotechnical Engineering College of Civil Engineering in Tongji University.

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