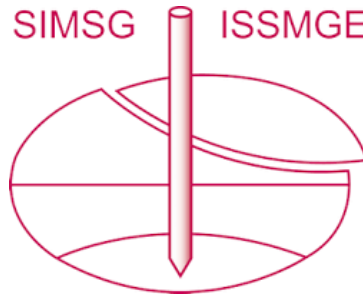


INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING



This paper was downloaded from the Online Library of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). The library is available here:

<https://www.issmge.org/publications/online-library>

This is an open-access database that archives thousands of papers published under the Auspices of the ISSMGE and maintained by the Innovation and Development Committee of ISSMGE.

The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Centrifuge tests on the liquefaction resistance of sand deposits in multiple seismic events

Essais par centrifugation sur la résistance à la liquéfaction des dépôts de sable lors de multiples événements sismiques

Bin Ye & Xiaoli Xie

Department of Geotechnical Engineering, Tongji University, China, yebin@tongji.edu.cn

ABSTRACT: Field observations in recent earthquakes demonstrated that previous seismic events affected the liquefaction resistance of sandy deposits significantly. However, seismic histories caused by several shakings with different seismic intensities have been rarely taken into account in assessing sand liquefaction resistance. In this paper, centrifuge shaking table tests were conducted to reveal the evolution characteristics of liquefaction resistance of a uniform saturated clean sand deposit in multiple shakings. The applied seismic sequence included 13 medium earthquakes (MEs) and 3 strong earthquakes (SEs) in a certain order (every four MEs was followed by one SE). The results demonstrate that the liquefaction resistance of sand deposit was affected by relative density, effective stress and seismic intensity of the previous shakings. The liquefaction resistance of the upper sand deposit decreased first and then increased under the former four MEs, while liquefaction resistance of the lower sand deposit increased gradually. The whole sand deposit showed a decreasing tendency in liquefaction resistance after being loaded with each SE, but the liquefaction resistance of the whole sand deposit increased again in the four MEs following each SE.

RÉSUMÉ : Des observations sur le terrain lors de récents tremblements de terre ont montré que les événements sismiques antérieurs avaient eu une incidence significative sur la résistance à la liquéfaction des dépôts sableux. Cependant, les histoires sismiques causées par plusieurs secousses avec des intensités sismiques différentes ont rarement été prises en compte dans l'évaluation de la résistance à la liquéfaction du sable. Dans cet article, des tests de table d'agitation de centrifugeuse ont été menés pour révéler les caractéristiques d'évolution de la résistance à la liquéfaction d'un dépôt de sable propre saturé uniforme dans de multiples secousses. La séquence sismique appliquée comprenait 13 tremblements de terre moyens (ME) et 3 séismes puissants (SE) dans un certain ordre (tous les quatre ME étaient suivis d'un SE). Les résultats démontrent que la résistance à la liquéfaction du dépôt de sable était affectée par la densité relative, la contrainte effective et l'intensité sismique des secousses précédentes. La résistance à la liquéfaction du dépôt de sable supérieur a d'abord diminué, puis a augmenté sous les quatre premiers ME, tandis que la résistance à la liquéfaction du dépôt de sable inférieur augmentait progressivement. L'ensemble du dépôt de sable a montré une tendance à la baisse de la résistance à la liquéfaction après avoir été chargé avec chaque SE, mais la résistance à la liquéfaction de l'ensemble du dépôt de sable a augmenté de nouveau dans les quatre ME suivant chaque SE.

KEYWORDS: Centrifuge modeling tests, seismic histories, liquefaction resistance, clean sand.

1 INTRODUCTION

Sand liquefaction, one of the most destructive geotechnical hazards, can induce failures of slopes, foundation settlement, damages of infrastructures, etc. Several field observations in recent earthquake cases demonstrated that the previous seismic histories have nonnegligible effects on the liquefaction resistances of sandy soils. In the 2011 Great East Japan earthquake, sand deposits in Kanto region was reliquified by the aftershocks and more severe damages was caused (Wakamatsu 2012; Yasuda et al. 2012; Towhata et al. 2014). Sand deposits were also found to be liquified more easily in the aftershocks of 2010-2011 Canterbury earthquake (Quigley et al. 2013). On the contrary, pervious earthquakes may also improve sand liquefaction resistance in the subsequent earthquakes due to densification effect. For example, the Wildlife Valley site which has been shaken with several medium shakings performed high sand liquefaction resistance during the 2011 El-Mayor Cucapah earthquake (El-Sekelly et al. 2017). Therefore, it's essential to correctly assess the sand liquefaction resistance of liquefiable deposits in multiple seismic events.

Many element tests (Finn et al. 1970; Ishihara and Okada 1982; Wichtmann et al. 2005; Wahyudi et al. 2016; Toyota and Takada 2017; Iwai et al. 2020; Koseki et al. 2020) and physical model tests (Ha et al. 2011; Ecmis et al. 2015; El-Sekelly et al. 2016; Teparaksa and Koseki 2018; Ye et al. 2018a; Ye et al. 2018b; Padmanabhana and Shanmugamb 2020) has been conducted to reveal the liquefaction resistance of sand deposits with preloading histories. Centrifuge model tests have the

advantages of providing stress field of the real deposits and simulating the consolidation process of the whole sand deposits.

In practice, the earthquakes that hit the same place at different times normally have different seismic intensities. However, the liquefaction behaviors of sand deposits under multiple shaking events have been rarely reported. In this study, centrifuge shaking table tests were conducted on a saturated clean sand deposit to evaluate the evolution of sand liquefaction resistance under 16 shaking events. The seismic sequence includes two kinds of seismic motions which have different seismic intensities. Sand liquefaction resistance of the whole deposit was assessed based on the measured excess pore pressure during each shaking event. The effects of different seismic histories on the liquefaction resistance of sand deposits were analyzed and discussed.

2 EXPERIMENTAL SCHEME

2.1 Experimental conditions and tested soil

The dynamic centrifuge tests were conducted by TLJ-150 geotechnical centrifuge in Tongji University as shown in Fig. 1. The basic parameters of TLJ-150 centrifuge and the shaking table are listed in Table 1. The shaking table can produce sinusoidal or earthquake motions with 20 g peak amplitude in 50 g centrifugal field. A rigid model container with an internal dimension at 510 (in length) × 400 (in width) × 560 mm (in height) was used for preparing sand models, and a thin petrolatum layer was daubed uniformly on the inside of the model container to reduce the boundary friction between sand particles and the container walls.

Table 1 Basic parameters of TLJ-150 centrifuge and the shaking table.

Performance Index	Parameter
Effective rotation radius	3 m
Maximum capacity	150 g·ton
Maximum centrifugal acceleration	200 g
Maximum shaking acceleration	20 g*
Maximum shaking duration	4 s*
Frequency range of shaking motion	20~200 Hz

* Under 50 g centrifugal acceleration



Figure 1. The TLJ-150 geotechnical centrifuge and the shaking table.

Clean silica sand with sub-angular grains, produced in Anhui Province, China was used for preparing the specimens. The basic physical properties of the tested sand are listed in Table 2. The tested sand classified as poorly graded medium-fine sand and is prone to liquefaction under seismic motion.

Table 2. Basic properties of the Anhui sand.

Property	Value
d_{10} (mm)	0.25
d_{50} (mm)	0.50
Coefficient of curvature, C_c	1.38
Coefficient of uniformity, C_u	3.10
Specific gravity, G_s	2.65
Minimum void ratio, e_{min}	0.57
Maximum void ratio, e_{max}	1.09

If water is used as pore fluid of the centrifuge model, conflicts will exist between the kinematics and consolidation time scaling factors in dynamic centrifuge tests (Dewoolkar et al. 1999). The inconsistency of the two scaling factors results in significant differences of the sand liquefaction behaviors between the experimental model and the prototype ground. Methylcellulose solution (Adamidis and Madabhushi 2015) was widely used as the pore fluid to resolve the conflicts between kinematics and consolidation time factors through increasing the viscosity of the pore fluid (i.e., decreasing the permeability of the sand deposit). Methylcellulose solution with 25 cSt viscosity (0.6% concentration by weight) was used as the pore fluid in this study because the shaking table tests were conducted under 25 g centrifugal acceleration.

2.2 Model preparation and experimental procedure

All the data in the subsequent figures was presented in prototype scale without specifications. Figure 2 depicts the schematic layout of the tested sand model. Two pieces of 4 cm thick sponge were set at the side walls of the model container to reduce the dynamic boundary effects. The seismic motions applied on the model were recorded by a piezoelectric accelerometer (A0) which was fixed at the bottom of the model container. Seven miniature pore pressure transducers (P1~P7) were embedded into the tested sand model to measure the excess pore pressure during shaking. Seven accelerometers (A1~A7) were utilized for measuring the horizontal acceleration response of the sand deposit. Two laser displacement transducers (LS2 and LS3) were instrumented to capture the vertical displacement of the ground surface.

A saturated deposit model with 30% initial relative density (D_r) was made by wet pluviation method which can simulate the natural sedimentary process of sand deposit (Ha et al. 2011; Ecemis et al. 2015; Jia et al. 2019; Wang et al. 2020). The height of the deposit model was 405 mm. Transducers were placed at the preferred positions as shown in Figure 2. Then the prepared deposit model was stood still for 24 hours under 1g condition to ensure that the tested model reached a stable state. Then the prepared model was installed firmly onto the platform of the shaking table. The centrifuge spun up gradually to 25 g centrifugal acceleration. Seismic motions were applied on the tested model after the static consolidation of the model at 25 g was completed (i.e., the pore pressure and the vertical displacement remained stable).

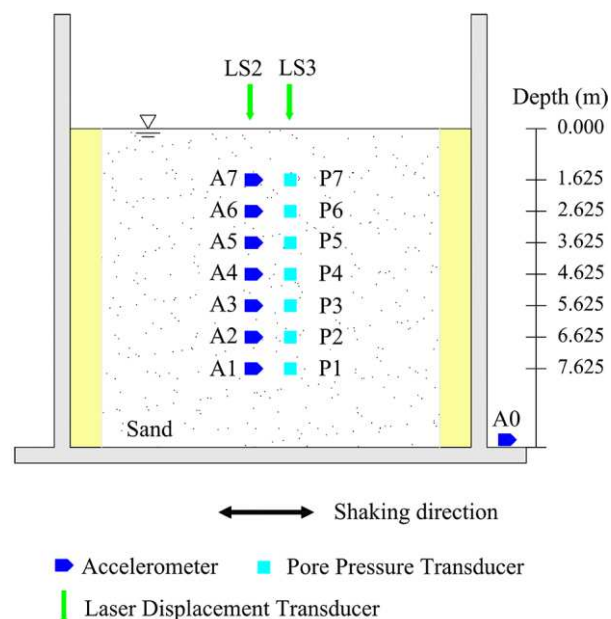


Figure 2. Schematic layout of the deposit model.

Two kinds of seismic motions called medium earthquake (ME) and strong earthquake (SE) were used in this study. Time histories of ME and SE are shown in Figures 3 (a) and (b), respectively. The predominant frequency and duration of these two motions were the same, i.e., 1Hz and 12s, respectively. The peak accelerations of ME (0.15 g) and SE (0.25 g) were different. The tested model was subjected to a predesigned seismic sequence. This loading sequence consisted of 16 shakings in a certain order (every four MEs was followed by one SE) as shown in Figure 3(c). Approximate 40 minutes was set between every two shaking events to ensure a completed dissipation of the generated excess pore pressure in the sand deposit.

Every shaking event was denoted by the type of the seismic motions plus its occurrence order in the whole shaking sequence.

For example, M1 represents the first shaking event and the base inputting motion is ME; and S5 represents the fifth shaking event and the base inputting motion is SE.

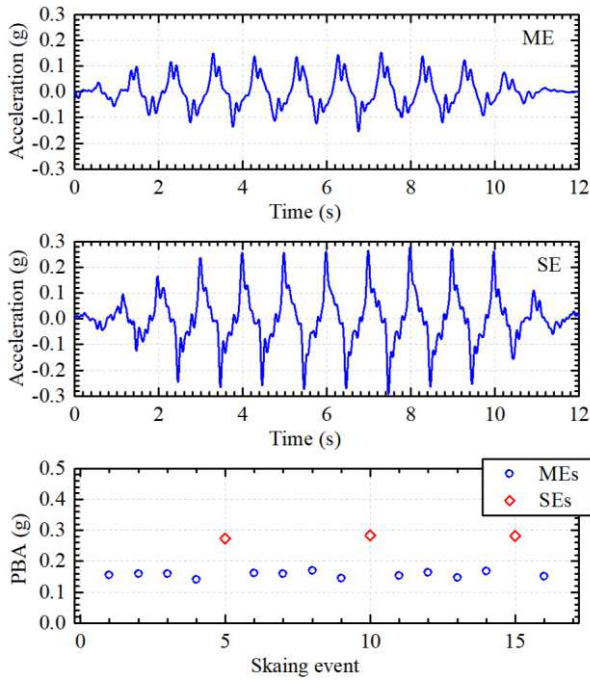


Figure 3. Input seismic motions: (a) Time history of ME, (b) Time history of SE and (c) Peak base acceleration of the 16 shaking events.

3 RESULTS AND ANALYSIS

Sand liquefaction resistance is an important property for comparing sand liquefaction behaviors in multiple shaking events. Here sand liquefaction resistance was evaluated by the excess pore pressure ratio (r_u) time histories. r_u is the ratio of excess pore pressure to the initial vertical stress (i.e., $r_u = \Delta u / \sigma_{v0}$). Sand liquefaction occurred when the excess pore pressure is equal to the initial vertical stress, i.e., $r_u = 1.0$. In liquefaction cases, the moment when $r_u = 1.0$ in deposits with higher liquefaction resistance is later than that in easily liquefied deposits. In non-liquefaction cases, the larger excess pore pressure is, the closer to 1.0 r_u is. Hence, sand liquefaction potential is higher with larger r_u .

Although the sand deposit was densified gradually with shaking events, sand liquefaction resistance did not increase accordingly. This intuitive experimental phenomenon was showed and analyzed as follows.

3.1 Evolution of the D_r of the sand deposit

Figure 4(a) displays the overall D_r of the sand deposit before each shaking event. D_r increased gradually from 35% before M1 to 67% before M16. Figure 4(b) describes the D_r increment in each shaking event. D_r increased the most after M1, and then increased less and less under repeated MEs. The D_r increment in SEs was a little more than that in the neighboring two MEs because SEs caused more intensive destruction on the sand deposit. D_r increment caused by SEs decreased gradually with the D_r of the whole sand deposit increasing,

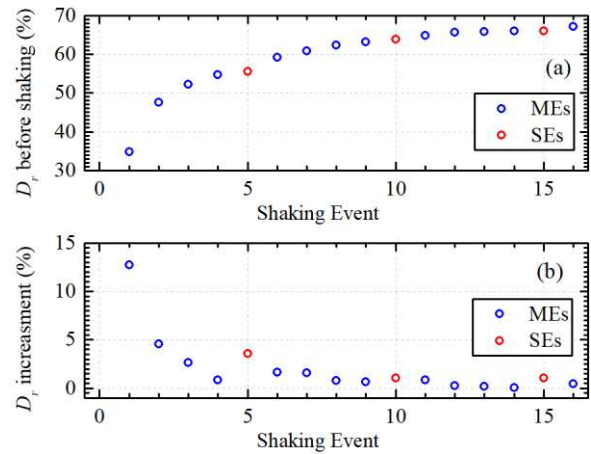


Figure 4. (a) D_r before each shaking event and (b) D_r increment.

3.1 Sand Liquefaction resistance in M1~M4

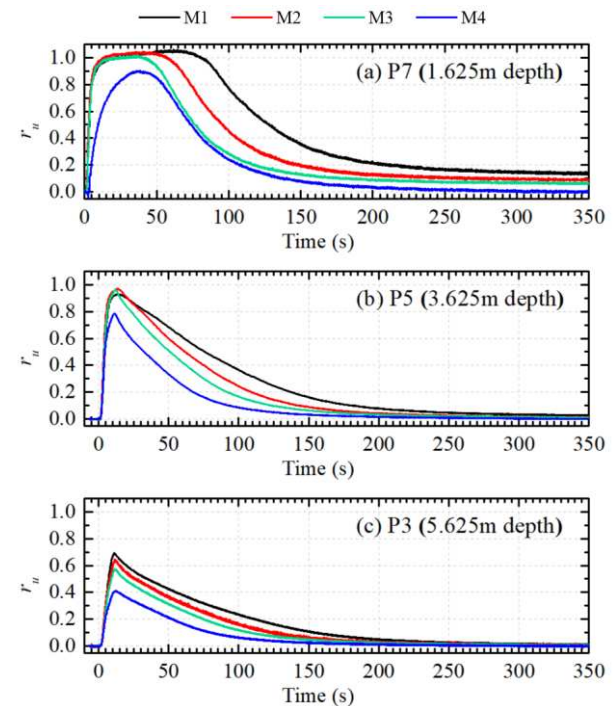


Figure 5. r_u time histories in M1~M4: (a) at 1.625 m depth, (b) at 3.625 m depth and (c) at 5.625 m depth.

Figure 5 shows the r_u time histories of the virgin sand deposit under four MEs. As shown in Figure 5(a), sand at the depth of 1.625 m (the upper deposit) was liquefied in M1~M3 and did not liquefy in M4. The moments of sand liquefaction were marked clearly in Figure 6. The liquefaction moment of the upper deposit in M2 was earlier than that in M1, indicating the liquefaction resistance of the upper deposit decreased after M1. Similarly, the liquefaction moment in M3 was later than that in M2, indicating the liquefaction resistance of the upper deposit increased after M2. As shown in Figures 5(b) and (c), sand at the depth of 3.625 m (the middle deposit) and sand at the depth of 5.625 m (the lower deposit) were not liquefied in the four shaking events. The peak value of r_u , i.e., $r_{u\max}$, at the middle deposit increased from M1 to M2 and then decreased from M2 to M4. The evolution of $r_{u\max}$ demonstrates that the liquefaction resistance of the middle deposit decreased after M1 and increased after M2. Although sand was densified dramatically after M1, the liquefaction resistance of the upper and middle deposit decreased in M2.

Conversely, the value of $r_{u\max}$ at the lower deposit decreased

gradually with shaking M1~M4 as in Figure 5(c), indicating the liquefaction resistance of the lower deposit increased gradually from M1 to M4. Therefore, sand liquefaction resistance of the whole deposit varied with sand depth. This might be caused by three reasons: (1) effective stress of the lower deposit was larger than that of the upper deposit; (2) sand fabric of the upper deposit changed more dramatically than that of the lower deposit since the excess pore pressure dissipated from the lower deposit to the upper deposit; and (3) the shallow sand might be loosened by the upward seepage effects of the pore fluid, decreasing D_r of the upper deposit.

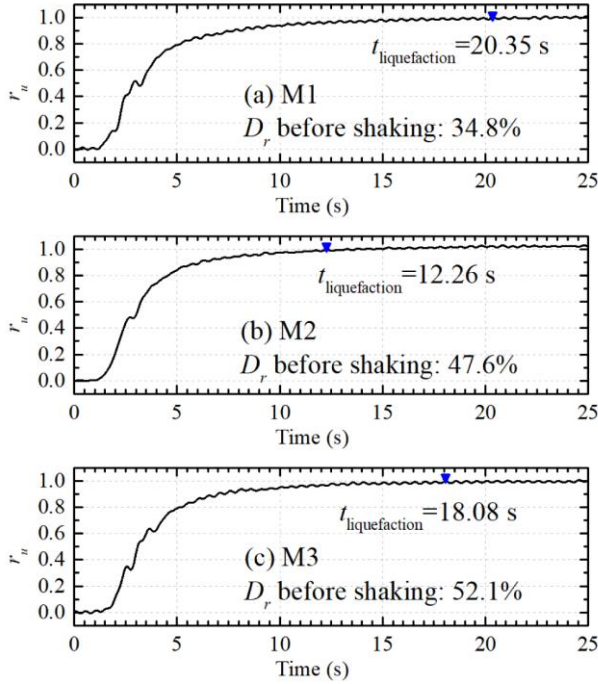


Figure 6. Enlarged r_u time histories (1.625 m depth) in the three consecutive liquefaction events: (a) M1, (b) M2 and (c) M3.

3.2 Sand Liquefaction resistance affected by SEs

Figures 7 and 8 show the r_u time histories in all SEs and the MEs before and after the corresponding SEs. Figure 7 displays the r_u time histories of the upper deposit while Figure 8 describes the r_u time histories of the lower deposit. As shown in Figure 7(a), the upper sand did not liquefy in M4. However, the upper deposit reliquefied in M6 despite of a higher D_r after being liquefied by S5. As shown in Figures 7(b) and (c), the values of $r_{u\max}$ in the MEs after SEs were higher than those in the MEs before SEs. These phenomena demonstrate that the values of $r_{u\max}$ decreased in the MEs after the sand deposit was previously shaken by SE once.

The negative effects of the previous SEs on sand liquefaction resistance were also found in the lower deposit as shown in Figure 8. Though the $r_{u\max}$ of the lower deposit was relatively small in S10 and S15, the $r_{u\max}$ in the MEs after the SEs was still higher than that in the MEs before the SEs. Therefore, sand liquefaction resistance of the whole liquefiable deposit decreased after the sand deposit was previously shaken by more intensive seismic events, due to disruptions from the strong shakings on sand particles structures regardless of high or low excess pore pressure caused by the strong shaking events.

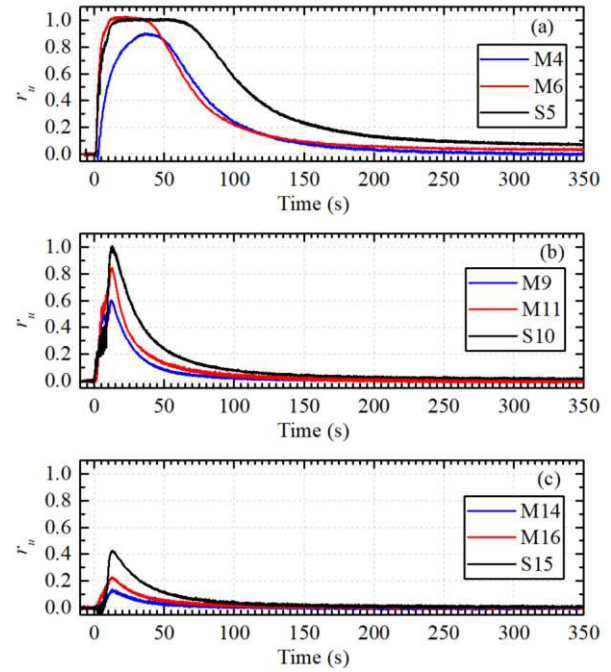


Figure 7. r_u time histories at 1.625 m depth: (a) MEs before and after S5, (b) MEs before and after S10 and (c) MEs before and after S15.

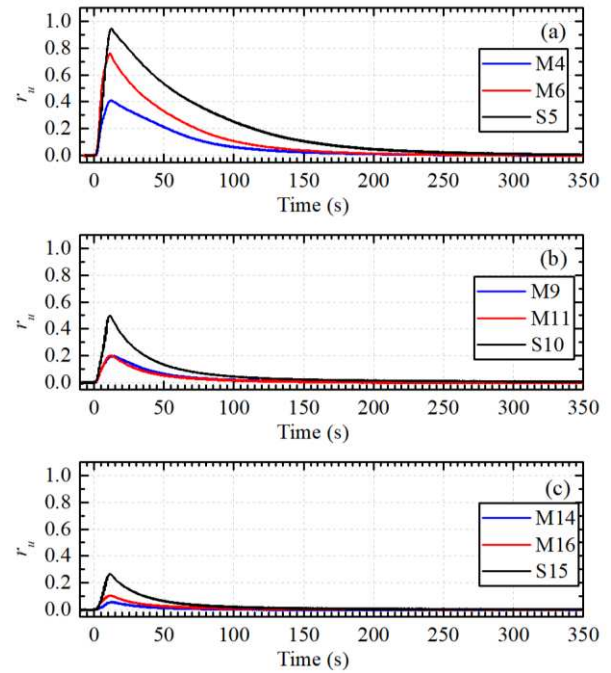


Figure 8. r_u time histories at 5.625 m depth: (a) MEs before and after S5, (b) MEs before and after S10 and (c) MEs before and after S15.

3.3 Sand Liquefaction resistance affected by MEs after SEs

Figure 9 shows the r_u time histories of the whole sand deposit in M6 ~ M9. As shown in Figure 9(a), the upper deposit liquefied in M6 but did not reliquefy in M7, while the sand reliquefied three times in M1~M3, indicating sand reliquefaction resistance was influenced by the D_r of the whole deposit. The value of $r_{u\max}$ at the three measured positions decreased gradually from M6 to M9. Sand liquefaction resistance of the whole deposit increased gradually. As mentioned in section 3.2, the seismic histories of S5 reduced sand liquefaction resistance. As indicated by Figure 9, MEs after S5 restored and strengthened sand liquefaction

resistance of the deposit.

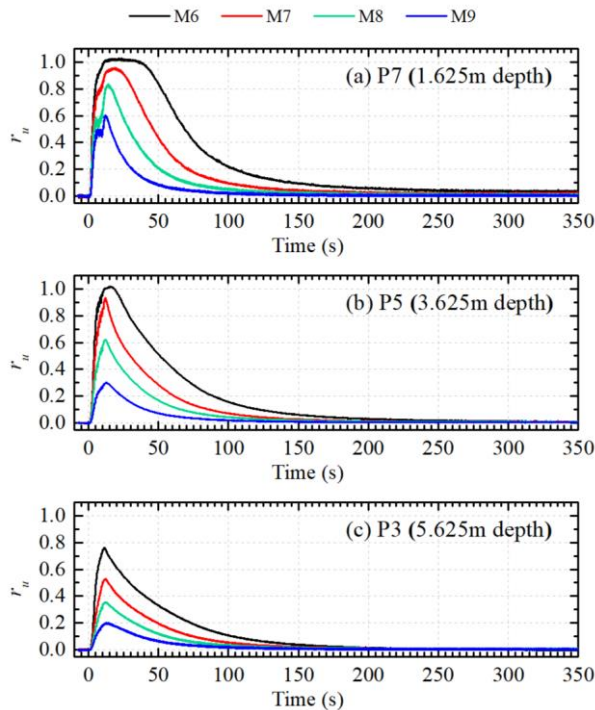


Figure 9. r_u time histories in M6~M9: (a) at 1.625 m depth, (b) at 3.625 m depth and (c) at 5.625 m depth.

4 CONCLUSIONS

A centrifuge model was shaken by a series of 16 seismic events in a designed order to investigate the effects of seismic histories on the liquefaction resistance of clean sand deposits. Based on the test results, conclusions are summarized as follows.

- Liquefaction resistance of the virgin deposit under repeated shaking events was variable with deposit depths. The upper deposit relquefied several times and sand liquefaction resistance decreased after the first shaking, whereas the deep sand did not liquefy and showed increasing liquefaction resistance.
- The whole sand deposit showed lower liquefaction resistance after suffering strong seismic events. Sand liquefaction resistance of the deposits in strong shaking events increased gradually with sand densification.
- The liquefaction resistance of the whole sand deposit which was ever shaken intensively increased gradually under consecutive moderate shakings though the sand relative density just increased slightly.

5 ACKNOWLEDGEMENTS

This study was supported by the National Natural Science Foundation of China [No. 41977225].

6 REFERENCES

Adamidis O. and Madabhushi G.S.P. 2015. Use of viscous pore fluids in dynamic centrifuge modelling. *International Journal of Physical Modelling in Geotechnics* 15 (3), 141-149.

Dewoolkar M.M., Ko H.-Y. and Pak R.Y.S. 1999. Centrifuge modelling of models of seismic effects on saturated earth structures. *Géotechnique* 49 (2), 247-266.

Ecemis N., Demirci H.E. and Karaman M. 2015. Influence of consolidation properties on the cyclic re-liquefaction potential of sands. *Bulletin of Earthquake Engineering* 13 (6), 1655-1673.

El-Sekelly W., Dobry R., Abdoun T. and Steidl J.H. 2016. Centrifuge modeling of the effect of preshaking on the liquefaction resistance of silty sand deposits. *Journal of Geotechnical and Geoenvironmental Engineering* 142 (6), 04016012.

El-Sekelly W., Dobry R., Abdoun T. and Steidl J.H. 2017. Two case histories demonstrating the effect of past earthquakes on liquefaction resistance of silty sand. *Journal of Geotechnical and Geoenvironmental Engineering* 143 (6), 04017009.

Finn W.D., Bransby P.L. and Pickering D.J. 1970. Effect of strain history on liquefaction of sand. *Journal of the Soil Mechanics and Foundations Division* 96 (6), 1917-1934.

Ha I.-S., Olson S.M., Seo M.-W. and Kim M.-M. 2011. Evaluation of relquefaction resistance using shaking table tests. *Soil Dynamics and Earthquake Engineering* 31 (4), 682-691.

Ishihara K. and Okada S. 1982. Effects of large preshearing on cyclic behavior of sand. *Soils and Foundations* 22 (3), 109-125.

Iwai H., Ni X., Ye B., Nishimura N. and Zhang F. 2020. A new evaluation index for relquefaction resistance of Toyoura sand. *Soil Dynamics and Earthquake Engineering* 136, 106206.

Jia M., Zhao T., Xie X., Chen X. and Zhou J. 2019. A novel experimental system for studying the sand liquefaction characteristics from macroscopic and microscopic points of view. *Bulletin of Engineering Geology and the Environment*.

Koseki J., Yokoyama D. and Morimoto T. 2020. Cyclic Bi-Axial Tests on Assembly of Metal Rods Under Constant-Volume Condition to Study Re-Liquefaction Behavior. *Transportation Infrastructure Geotechnology* 7 (3), 478-495.

Padmanabhana G. and Shanmugamb G.K. 2020. Reliquefaction Assessment Studies on Saturated Sand Deposits under Repeated Acceleration Loading Using 1-g Shaking Table Experiments. *Journal of earthquake engineering*.

Quigley M.C., Bastin S. and Bradley B.A. 2013. Recurrent liquefaction in Christchurch, New Zealand, during the Canterbury earthquake sequence. *Geology* 41 (4), 419-422.

Teparaksa J. and Koseki J. 2018. Effect of past history on liquefaction resistance of level ground in shaking table test. *Géotechnique Letters* 8 (4), 256-261.

Towhata I., Maruyama S., Kasuda K., Koseki J., Wakamatsu K., Kiku H., Kiyota T., Yasuda S., Taguchi Y., Aoyama S. and Hayashida T. 2014. Liquefaction in the Kanto region during the 2011 off the pacific coast of Tohoku earthquake. *Soils and Foundations* 54 (4), 859-873.

Toyota H. and Takada S. 2017. Variation of Liquefaction Strength Induced by Monotonic and Cyclic Loading Histories. *Journal of Geotechnical and Geoenvironmental Engineering* 143 (4), 04016120.

Wahyudi S., Koseki J., Sato T. and Chiaro G. 2016. Multiple-liquefaction behavior of sand in cyclic simple stacked-ring shear tests. *International Journal of Geomechanics* 16 (5), C4015001.

Wakamatsu K. (2012) Recurrence of Liquefaction at the Same Site Induced by the 2011 Great East Japan Earthquake Compared with Previous Earthquakes. Paper presented at the The 15th world conference on earthquake engineering, Lisbon, Portugal.

Wang J., Salam S. and Xiao M. 2020. Evaluation of the effects of shaking history on liquefaction and cone penetration resistance using shake table tests. *Soil Dynamics and Earthquake Engineering* 131 (4), 106025.

Wichtmann T., Niemunis A., Triantafyllidis T. and Poblete M. 2005. Correlation of cyclic preloading with the liquefaction resistance. *Soil Dynamics and Earthquake Engineering* 25 (12), 923-932.

Yasuda S., Harada K., Ishikawa K. and Kanemaru Y. 2012. Characteristics of liquefaction in Tokyo Bay area by the 2011 Great East Japan Earthquake. *Soils and Foundations* 52 (5), 793-810.

Ye B., Hu H., Bao X. and Lu P. 2018a. Reliquefaction behavior of sand and its mesoscopic mechanism. *Soil Dynamics and Earthquake Engineering* 114, 12-21.

Ye B., Zhang L., Wang H., Zhang X., Lu P. and Ren F. 2018b. Centrifuge model testing on relquefaction characteristics of sand. *Bulletin of Earthquake Engineering* 17 (1), 141-157.