*The paper was published in the proceedings of the 7th International Conference on Earthquake Geotechnical Engineering and was edited by Francesco Silvestri, Nicola Moraci and Susanna Antonielli. The conference was held in Rome, Italy, 17 – 20 June 2019.*

*Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions – Silvestri & Moraci (Eds)*
*© 2019 Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2*

# Effects of liquefaction-induced lateral spreading on a 3×3 pile group using 1g shake table and laminar shear box

S.M. Haeri, M. Rajabigol & S. Salaripour
*Sharif University of Technology, Tehran, Iran*

A. Kavand
*University of Tehran, Tehran, Iran*

H. Sayyaf, S. Afzalsoltani & A. Pakzad
*Sharif University of Technology, Tehran, Iran*

ABSTRACT: Liquefaction-induced lateral spreading has imposed severe damages to deep foundations of bridges and buildings. Despite several field and laboratory studies performed over the past decades, many aspects of soil-pile interaction have not been fully understood. Since there is no comprehensive approach to design piles against lateral spreading, further studies are needed. Physical modeling is an important and valuable method to investigate the seismic behavior of geotechnical structures; effect of liquefaction induced lateral spreading on piles is one of them. In this research, lateral spreading effect on a 3×3 pile group is evaluated implementing Sharif University of Technology shake table facilities. A laminar shear box with inner dimensions of 306 cm length, 172 cm width and 180 cm height, has been designed and constructed at SUT for this purpose. To build the model, similitude law for 1g tests is used. The model of soil layers consists of a 1 m thick liquefiable layer between two non-liquefiable layers. The piles and the soil at far field are fully instrumented to measure various parameters during and after shakings. The results including acceleration in various elevations of the soil, free field soil displacement and bending moment of some piles are presented and discussed. Also some results are compared with Haeri et al. (2013) test results that is conducted on a similar model using a rigid box to investigate the effects of boundary condition in physical modeling tests of similar geotechnical problems.

## 1 INTRODUCTION

Soil liquefaction-induced lateral spreading may cause severe damages to deep foundations of buildings and bridges. Several experimental, numerical and field studies have been performed to investigate the effects of lateral spreading on piles and to improve the current practice for design of piles against lateral spreading. Despite many studies in this respect, there is no general agreement about the amount and distribution of the forces and pressures applied on piles by lateral spreading; therefore, further researches are required. Physical modeling tests using shake table, as a powerful tool to investigate soil-pile interaction problems, have been conducted frequently by several researchers (e.g. Haeri et al., 2012 and 2013, Motamed et al., 2009, 2010 and 2013, He et al.2008 and Gao et al., 2011). Due to the numerous differences in the models, comparing or generalizing the results of these researches are often difficult or even erroneous. These differences includes soil characteristics, geometry including thickness of soil layers, existence of crust layer, container type (laminar or rigid), existence of pile cap and structure, etc. In this research, soil liquefaction-induced lateral spreading effects on a 3×3 pile group are investigated using shake table test and laminar shear box. Some of the test results are presented and discussed in this paper. In the following, some of the results are compared with the results reported by Haeri (2011) and Haeri et al. (2013). They conducted shake table test on a 3×3 pile group using rigid box. Comparing the results can enlighten the effects of the boundaries of physical models on the outcome of the experiments.

## 2 PHYSICAL MODEL

To study the effects of lateral spreading on a 3×3 pile group, the model was constructed and tested using shake table facilities of the Earthquake Engineering Research Center at Sharif University of Technology (SUT). SUT shake table is a 4 m× 4 m, 3DOFS facility, capable of taking models of up to 300 kN. The laminar shear box used in this research has outer dimensions of 4.2 m length, 2.4 m width and 2.0 m height and inner dimensions of 3.06 m length, 1.72 m width and 1.8 m height.

Figure 1 shows the schematic plan view and cross section of the model. As it can be seen, the model consisted of 4 soil layers: first layer was a thin layer of wet mixture of clay and bentonite as an impermeable layer to prevent water leakage as a second safe guard if the membrane breaks during or after the test. The 2$^{nd}$ layer from the bottom of the model to the top was a non-liquefiable sand layer with a relative density of about 80% and a slope of 7% in longitudinal direction. This layer was overlaid by a 1m thick liquefiable layer with a relative

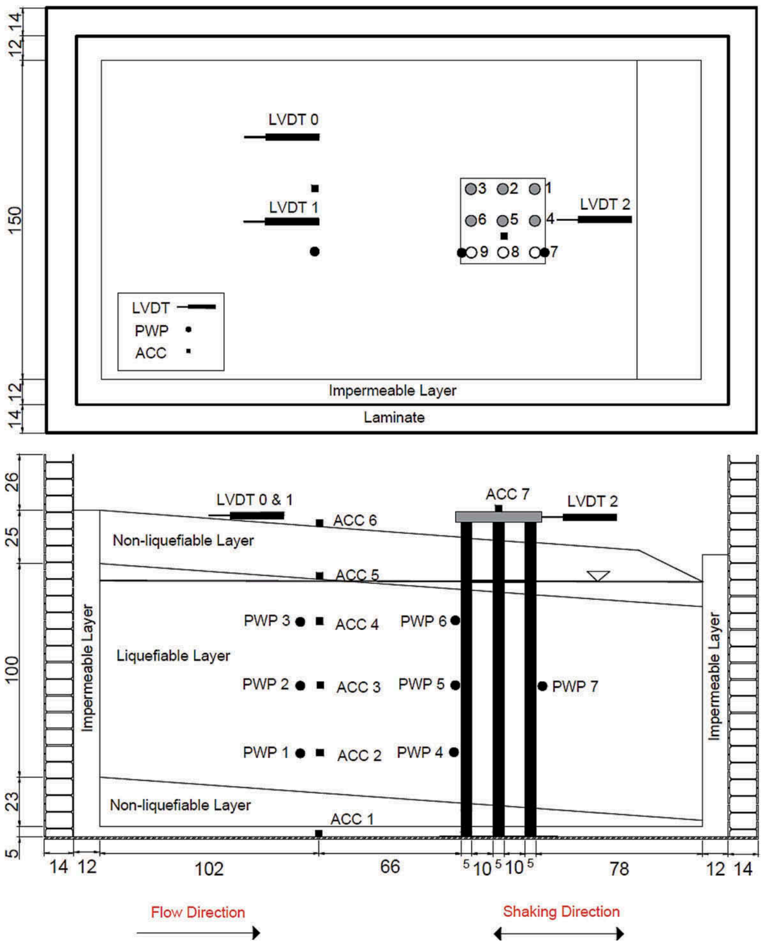


Figure 1. Schematic plan and section view of shake table model with the layout of transducers (units: cm)

Table 1. Properties of Firuzkuh silica sand no. 161

| Specific gravity | Mean grain size ($D_{50}$) (mm) | $D_{10}$ (mm) | Maximum void ratio ($e_{max}$) | Minimum void ratio ($e_{min}$) | Coefficient of uniformity ($C_u$) |
|---|---|---|---|---|---|
| 2.670 | 0.24 | 0.18 | 0.884 | 0.567 | 1.49 |

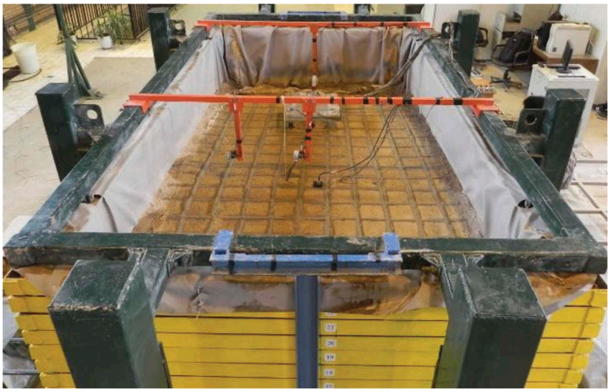

Figure 2. Top view of physical model in laminar box on shake table before shaking

density of about 10%. The liquefiable layer was constructed using water sedimentation technique. The upper layer was a non-liquefiable layer and was prepared by deposition of dry mixture of 88% sand and 12% clay. The sand used in physical model is standard Firuzkuh silica sand (no. 161) which is crushed sand with a uniform gradation that is widely used in Iran for geotechnical testing. A summary of the properties of Firuzkuh sand is outlined in Table 1.

The similitude law proposed by Iai (1989) were used to calculate mechanical and geometrical properties of the piles in model scale. For this purpose, the geometrical scale was selected as $\lambda$=8 (prototype/model). Therefore, the piles used in model had 150 cm length, 5 cm outer diameter and 0.15 cm thickness. All model piles were made of aluminum pipes (T6061 alloy).

Different types of transducers were installed in the model (e.g. displacement, acceleration, pore water pressure). Besides, six piles -specified by numbers 1 to 6 shown in Figure 1- were instrumented with required strain gauges. Pair strain gauges were installed on 7 sections of mentioned piles to measure pure bending moment during the test. Figure 2 shows top view of constructed model before loading. The loading was a 36 sinusoidal cycles with frequency of 3 Hz and applied parallel to the ground slope. The loading included 3 cycles at the beginning and 3 cycles at the end of the shaking. Therefore 30 sinusoidal cycles with acceleration amplitude of 0.3g and 36 cycles in total was applied to the model.

## 3 TEST RESULTS

In this experiment, 7 accelerometers were installed in the free field (at an appropriate distance from piles and boundaries). Time histories of acceleration recorded by these accelerometers during the test are presented in Figure 3. At the early stages of shaking, the amplitude of acceleration records in liquefiable layer decreased due to soil liquefaction. Significant effects of soil liquefaction on the accelerometer (ACC2) located at the lower end of the liquefiable layer along with upper accelerometers can be seen obviously. The amplification of acceleration can be seen in ACC2 at the time duration before triggering of liquefaction.

Time history of surface displacement recorded by two displacement transducers are shown in Figure 4. These two displacement transducers (LVDT0 and LVDT1) were installed in the upstream side of the model. LVDT1 was located in the longitudinal middle line of the model

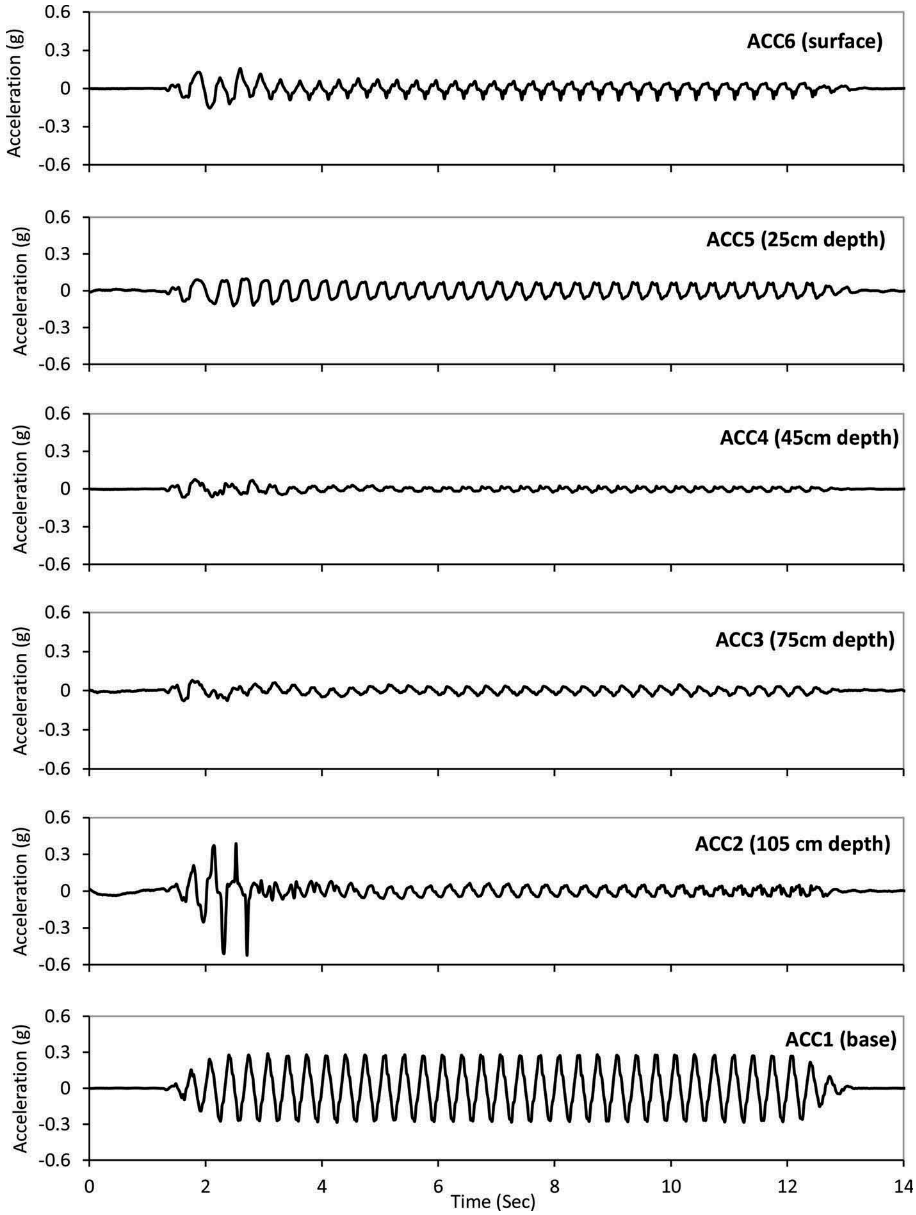


Figure 3. Time histories of accelerations recorded during the test

well upstream of the piles cap, hence the measured data by LVDT1 might slightly be affected by the presence of the piles in downstream. LVDT0 was located in the left upstream side of the model for which no physical barrier was present. This is the reason behind the slight difference between two records of displacements shown in Figure 4. Measured data by LVDT0 illustrates that the max surface displacement recorded is 43 mm, while the residual surface displacement is about 32 mm.

Measured bending moment profile among piles 1 and 3 at different times are demonstrated in Figure 5. Max bending moments in piles occurred at the base of liquefied layer. Figure 6 shows time histories of bending moments of piles 1 and 3 at the base of liquefied layer. Pile3 located in front of the group (upslope) experienced slightly more bending moment than of pile1 (downslope). Also monotonic component of bending moment of pile3 is about 25% greater than that of pile1. This is due to greater kinematic force applied to the front piles of the group by greater soil displacement in the upstream. This results are in good agreement with Haeri et al. (2012) results. They conducted shake table test to investigate lateral spreading effects on pile group (without pile cap) in a sloping ground. Also the results are in line with what reported by Haeri et al. (2013) for a shake table test on a pile group of 3×3 subjected to lateral spreading induced by liquefaction.

Haeri et al. (2011, 2013) conducted shake table test to investigate lateral spreading effects on a 3×3 pile group. The rigid container (box) used in that research had inner dimensions of 3.5 m length, 1m width and 1.5 m height. There are many similar features between present

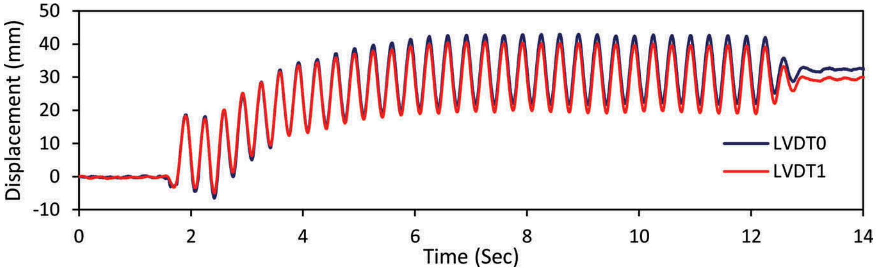


Figure 4. Time histories of surface soil displacement

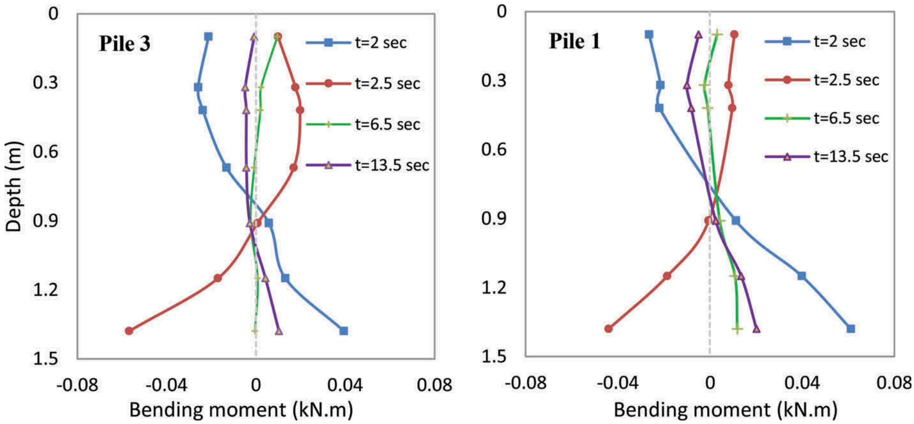


Figure 5. Profile of measured bending moment of pile1 (downslope) and of pile3 (upslope)

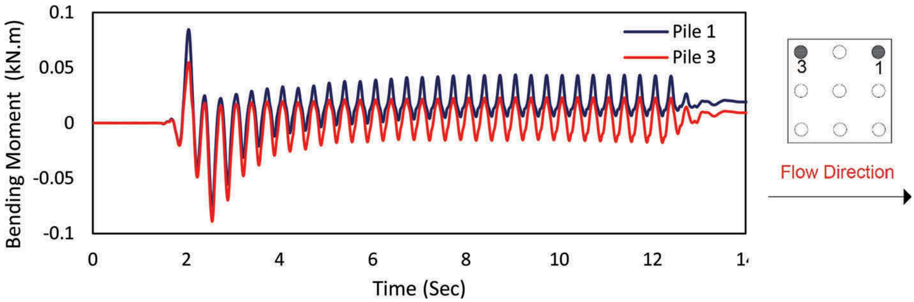


Figure 6. Time history of measured bending moment of piles 1 and 3 at the base of liquefiable layer

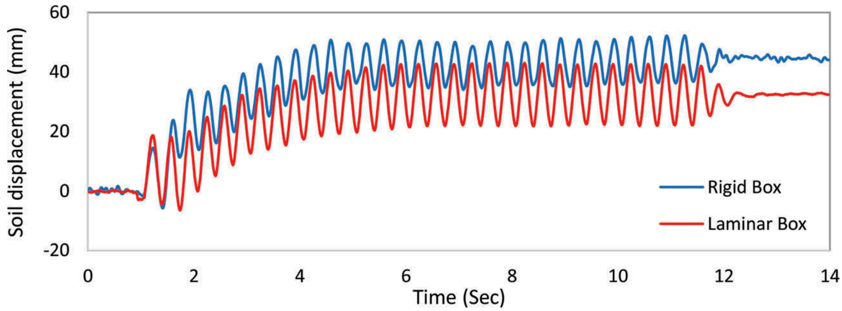


Figure 7. Time history of surface displacement of the soil in model tests using laminar and rigid boxes

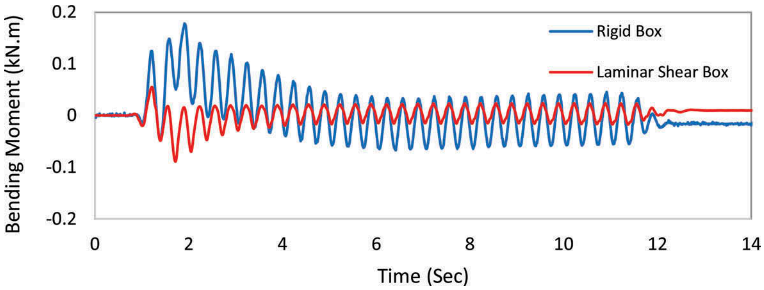


Figure 8. Time history of measured bending moments of shake table tests using laminar and rigid box

research and Haeri et al. (2011, 2013) In fact the characteristics of these two physical models are identical except for the type and dimensions of the containers used for these two tests. One is rigid and slightly longer and the other is laminar and slightly wider. Therefore any difference between the results obtained from these two researches can be attributed to the boundary effects on model response.

Time history of soil displacement (free field) of these two researches are shown in Figure 7. The maximum soil displacement in the tests by laminar box and rigid box were 43 and 52 mm, respectively. It seems that the greater wave reflection from the boundary walls of rigid box resulted in larger lateral displacement relative to that of laminar shear box. In fact, laminar shear box minimizes the lateral stiffness of the container in order to ensure the soil domination in response of soil-box system and hence the wave reflection effects on soil-pile system reduced significantly.

Time history of measured bending moment at base of the liquefied layer of two piles in models using laminar shear box and rigid box are presented in Figure 8. Both piles were located at the same position in group (pile3 of the present research was selected). At the beginning of the loading, there is some consistency between the bending moment values of the two tests, however the difference between bending moments for two different tests as the tests proceed is a very clear indication of the effects of wave reflection on pile response in rigid box as compared to that of the laminar box.

## 4 CONCLUSIONS

Shake table test on a physical model was conducted to investigate the effects of lateral spreading induced by liquefaction on a 3×3 pile group using a laminar shear box. The results indicate that the maximum bending moment occurred at the base of the liquefied layer. The role of pile location in the group was investigated and the results showed that the pile located in front (upslope) of the group experienced larger bending moment than that of the pile located in downslope. Some results obtained during this research are compared with a similar research using rigid box. Bending moment values at the base of the liquefied layer and surface displacement of the two shake table tests have been compared. It was found that boundary condition has significant effects on the response of soil-pile system to liquefaction induced lateral spreading. Model with rigid box experienced greater soil displacement and bending moments due to greater wave reflections from the rigid boundaries.

## ACKNOWLEDGMENTS

This study was conducted as part of the research contract no. Geo-93-016 between Sharif University of Technology (SUT) and Construction and Development of Transportation Infrastructures Company, Ministry of Roads & Urban Development of Iran. The experiment was conducted at Shake Table Facilities of Civil Engineering Department, Sharif University of Technology.

## REFERENCES

Gao. X., Ling. X., Tang. L., Xu. P. 2011. Soil–pile-bridge structure interaction in liquefying ground using shake table testing, *journal of soil dynamics and earthquake engineering*, 31: 1009-1017.

Haeri. S.M. 2011. Investigating soil liquefaction-induced lateral spreading effects on stability of deep foundations of harbors, *research report prepared for Transportation Research Institute*, Ministry of Road and Urban Development of Iran, research contract no. 88B8T1P110, (in Persian).

Haeri, S.M., Kavand, A., Rahmani, I., Torabi, H. 2012. Response of a group of piles to liquefaction-induced lateral spreading by large scale shake table testing, *Soil Dynamics and Earthquake Engineering*, 38: 25-45.

Haeri, S.M., Kavand, A., Asefzadeh, A., Rahmani, I. 2013. Large scale 1-g shake table model test on the response of a stiff pile group to liquefaction induced lateral spreading, *Proceedings of the 18$^{th}$ International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, France.

He. L., Elgamal. A., Hamada. M., Meneses. J. 2008. Shadowing and group effects for piles during earthquake-induced lateral spreading, *Proceedings of the 14$^{th}$ World Conference on Earthquake Engineering*, Beijing, China.

Iai. S. 1989. Similitude for shaking table tests on soil–structure–fluid model in 1g gravitational field, *Soils and Foundations*, 29(1): 105-118.

Motamed. R., Towhata. I. 2010. Shaking Table Model Tests on Pile Groups behind Quay Walls Subjected to Lateral Spreading., *Journal of Geotechnical and Geoenvironmental Engineering*, 136(3): 477-489.

Motamed. R., Towhata. I., Honda. T., Tabata. K., Abe. A. 2013. Pile group response to liquefaction-induced lateral spreading: e-defense large shake table test, *Soil Dynamics and Earthquake Engineering*, 51: 35-46.

Motamed. R., Towhata. I., Honda. T., Yasuda. S., Tabata. K, Nakazawa. H. 2009. Behaviour of pile group behind a sheet pile quay wall subjected to liquefaction-induced large ground deformation observed in shaking test in e-defense project, *Soils and Foundations*, 29(3): 459-475.