Mechanism of liquefaction-induced settlements with sand boiling

Tetsuo Tobita[1]

[1] Department of Civil, Environmental and Systems Engineering, Kansai University, 3-3-35, Yamate-cho, Suita, Osaka, 564-8680, Japan.

ABSTRACT

Mechanism of liquefaction-induced settlements associated with sand boiling is investigated with model testing. Loose saturated sand deposit is made in a transparent acrylic cylinder and torsional shaking is given to reproduce liquefaction. To mimic non-liquefiable layer on top of the liquefiable layer, an aluminum circular plate whose diameter is slightly smaller than the inner diameter of the cylinder is placed on the model ground surface. Boiled sand through the gap between the side wall of the cylinder and the plate was monitored from the side, and 4 excess pore water pressure transducers recorded transient variations of the water pressure, and 1 laser displacement sensor measured the settlement of the plate. The overburden load is varied by attaching an extra-mass along the rod connected with the aluminum plate. Major findings include; 1) The amount of settlements sharply increases when the boiled sands are piled up on the surface of the non-liquefiable layer. 2) The amount of settlement is largely influenced by the overburden loads when sand boiling is manifested. 3) Width of the gap through which boiled sand is passing has less influence on the amount of settlement.

Keywords: liquefaction, sand boiling, settlements, physical modeling

1 INTRODUCTION

Sand boiling or sands ejected from the ground has been recognized as a clear evidence of liquefaction occurrence (e.g., Seed and Idriss, 1967; Bardet and Kapuskar 1991, Wakamatsu, 2011; Ishihara, 2012; Yasuda et al., 2012). In 2010 and 2011 Canterbury, New Zealand, earthquake, huge amount of liquefied soil, which was naturally deposited, was ejected in the area along the Avon river (Cubrinovski and Green, 2010, Cubrinovski, et al., 2012). It had not been anticipated that such a huge amount of soil could be ejected. Then, it caused relocation of residents from the area. In the 2011 off the Pacific Coast of Tohoku, Japan, Earthquake, Urayasu, Chiba Pref., suffered similar sand ejecta of reclaimed soil (Yasuda et al., 2012; Ishihara, 2012).

The amount of ejected soil or the way of sand boiling may be inferring some basic and important information of the ground shaking and properties of the ground. However, it has been so far used merely as an evidence of liquefaction. Numata et al. (1999) conducted detailed study on the trench where liquefaction occurred and found that liquefied soils were sorted by their diameter or weight before ejecting from the ground. Numata and Someya (2004) accessed the effect of the sorting in model tests. Yamaguchi et al (2008) studied pattern of sand boiling and developed a method to evaluate the thickness of a liquefied layer. They reported that the porewater was trapped between liquefied and non-liquefiable layer. There are numbers of studies which investigated mechanism of sand boiling (e.g., Wibawa et al. 1990; Okawa, 1997; Yamaguchi et al., 2008ab; Ishikawa and Yasuda, 2012,). However, there are seldom researches which studied a relationship between the amount of settlements and sand boiling (e.g., Kawai et al. 2017). Through physical model testing, effect of overburden stress on the amount of settlements associated with sand boiling is investigated quantitatively.

2 MODEL TESTING FOR SAND BOILING

Mechanism of settlements associated with sand boiling was investigated through a series of the model testing. Loose saturated sand deposit was made in a transparent acrylic cylinder (Table 1 and Fig. 1). Toyoura sand (G_s=2.66, ρ_{dmax}=1.638 g/cm^3, ρ_{dmin}=1.329 g/cm^3) of 24.1 kg was poured into the cylinder. Then by boiling method the height of the surface of the model ground was adjusted at 950 mm from the bottom to obtain the relative density of Dr=40%.

Torsional shaking along the vertical center axis of the cylinder was given by an electrical motor to reproduce liquefaction, whose rotation angle was about +/- 0.5 degrees under 50 Hz. Duration of the input motion was about 2 seconds with which, as shown later, complete liquefaction was realized. Note that shear stress and strain thus induced might vary radially. However, it may be reasonable to assume that those effect may vanish after complete liquefaction.

To mimic the existence of a non-liquefiable layer on top of the liquefiable layer, an aluminum circular plate (called “loading plate” in Fig. 2) whose dimensions are given in Table 1, was placed on the surface of model ground. To make sand boiling through the gap between the side wall of the cylinder and the plate, a diameter of the plate (144 or 146 mm) was made slightly smaller than the inner diameter of the cylinder (150 mm). Through this gap (3 mm or 2 mm), liquefied sand could be ejected. The plate was equipped with a sidewall (Fig. 2) to catch the boiled sands. The elevation of the sidewall of the plate was varied (20 or 40 mm) to see the buoyancy effect of the plate on the settlement due to sand boiling. Overburden stress is given by attaching an extra-mass (100 or 250 g) along the rod connected with the plate whose self-weight is about 500 g. Inclination of the plate from horizontal surface was restricted by limiting the horizontal movement of the rod with a lid attached on top of the cylinder (Figs. 1 and 2).

Two accelerometers on the base plate were attached in either the radial or tangential directions. Three pore pressure transducers were installed on the side wall of the cylinder with 400 mm intervals (Fig. 1). Another pore pressure transducer was installed at the bottom of the plate to measure excess pore water pressure just beneath the plate where squeezed pore water from the liquefied and then consolidated ground may be trapped. One laser displacement transducer is installed to measure the settlement of the plate (Fig. 1). Also, to visually monitor the process of settlements with sand boiling, video image was recorded from the side of the cylinder.

Table 1. Dimensions of testing equipment and model sand deposit.

	Parameter	Unit	Value
Acrylic cylinder	Inner diameter	mm	150
	Length	mm	1,400
	Depth of the sand deposit	mm	950
Aluninum plate	Diameter	mm	144 / 146
	Elevation of sidewall	mm	20 / 40
	Self weight	gf	500
	Added weight	gf	0 / 100 / 250

Figure 3 explains how each test case can be identified by the given case ID. For example, as shown in Fig. 3, the case "PT20-146-WL20.250" uses the plate whose sidewall height is 20 mm, diameter is 146 mm, the ground water level is 20mm from the surface of the sand, and added mass is 250 g.

Time histories of the excess pore water pressure ratio of with/without the loading plate (Fig. 4) clearly show that whole sand deposit is liquefied, i.e., all the excess pore water pressures measured by P1, P2 and P3 reach r_u=1.

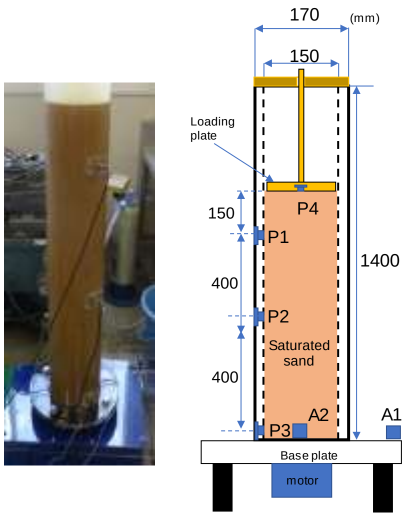

Fig. 1. Schematics of an acrylic cylindrical container for sand boiling test.

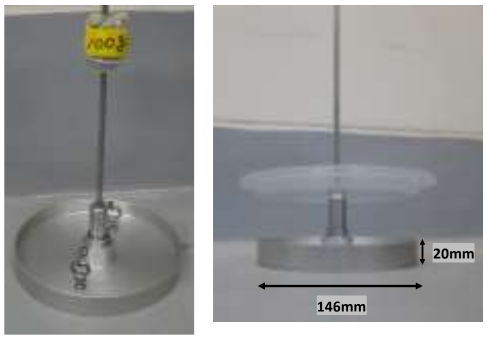

Fig. 2. View of an aluminum plate with 100 gf of additional weight and a lid to cover the cylinder.

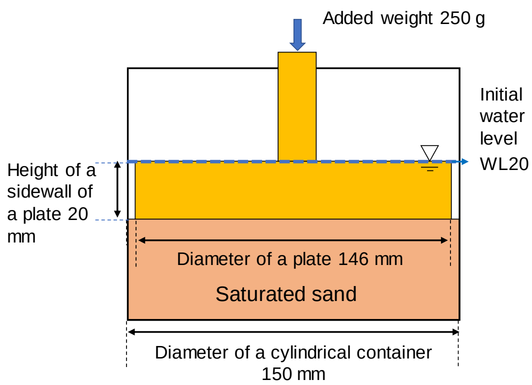

Fig. 3. Example of the case ID of PT20-146-WL20.250.

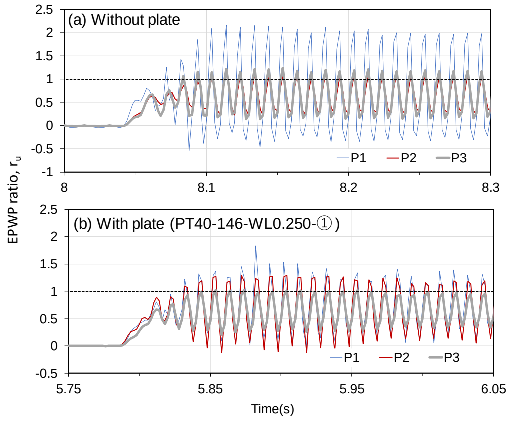

Fig. 4. Time histories of the excess pore water pressure ratio: (a) without a loading plate, (b) with the loading plate; PT20-146-WL20.250.

3 TEST RESULTS

By varying above mentioned parameters on testing, total 70 tests were conducted. Figure 5 depicts an example of sand boiling and settlements of the plate for the case of PT20-146-WL20.250. After a brief interval from the shaking, sand started to rise in the gap with minor settlement of the plate (Fig. 5b). The settlement of the plate was accelerated with the ejected sand flown into the plate, which gave an additional mass to the plate (Fig. 5c).

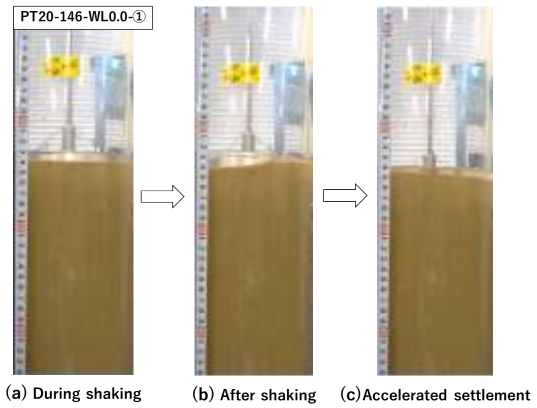

Fig. 5. Transition of boiled sand and the loading plate: PT20-146-WL20.250.

Figure 6 shows time histories of the settlement of the plate for the cases of various overburden loads (500, 600, and 750 g). In Fig. 6, the case with no plate (PT0-0-WL0.0) is plotted as a solid marker for which continuous measurement of settlement was not made. The largest settlement of about 130 mm is observed for the case of the heaviest case (initial total overburden mass: 750 g), which is more than 4 times of settlement than that of the case of without a plate. Figure 6 indicates that the amount of residual settlement is in proportion to the initial overburden loads.

Also, in Fig. 6, the speed of settlement increases after a brief interval from the shaking. That timing is indicated by up-pointing arrows in Fig. 6. From the video images, they correspond to the timing when the ejected sand flew into the plate. That is, heavier the overburden mass is, faster the sand boiling occurs. Fig. 6 also indicates that the rate of settlement after sand boiling (slope of the curves after the arrows in Fig. 6) is slightly larger for the cases of a larger overburden mass. Hence, the ground settlements are largely influenced by the overburden loads due to a non-liquefiable layer when the sand boiling is manifested.

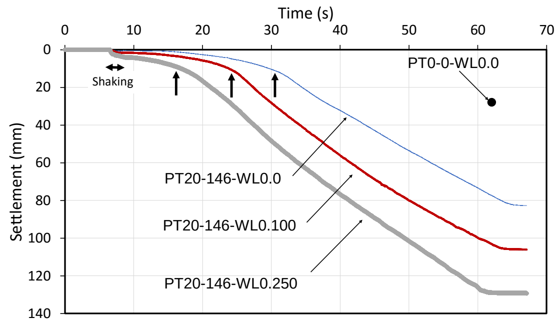

Fig. 6. Time histories of ground settlements with no plate (0 N/m^2) (PT0-0-WL0), with the plate of 500 g (301 N/m^2) only, with the plate and additional weight of 100 g (361 N/m^2) and with the plate and additional weight of 250 g (452 N/m^2).

Figure 7 shows variation of residual settlements versus the initial overburden mass for the use of the plates of different diameters and sidewall elevation. Here, in Fig. 7, the initial water depth is undistinguishing. As expected, the residual settlement increases with the total initial overburden mass. Compared the settlements of PT20-146 with those of PT20-144, average settlements of the plate are nearly identical. When the elevation of the sidewall is larger, PT40-146, the settlement is reduced about 30% on average from the cases of PT20-146. This might be due to a larger buoyancy of the plate which reduced the overburden loads. Also, the high sidewall might hinder inflow of the boiled sands in the plate.

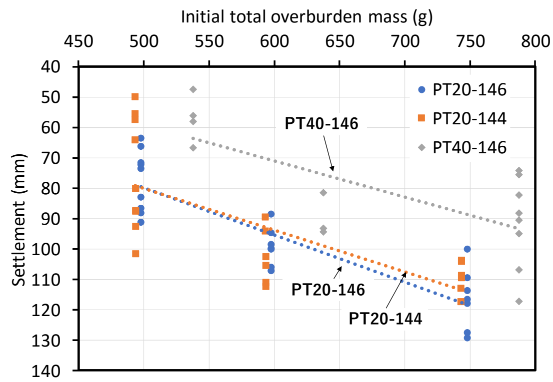

Fig. 7. Initial overburden mass versus settlement of the plate.

4 CONCLUSIONS

A series of dynamic model testing to study the influence of overburden loads on the amount of settlements due to the boiled sand of liquefied soil was conducted. The model ground was constructed in an acrylic cylinder of the inner diameter of 150 mm. Loosely saturated model ground (Dr=40%) with Toyoura sand was made by the boiling method. Sand boiling was replicated from the gap between the side wall of the cylinder and the plate placed on top of the model ground surface to mimic non-liquefiable layer. Dynamic motion was given in the torsional direction along the center axis of the cylinder with +/- 0.5 deg. of 50Hz. Major findings are;

1. The amount of settlements sharply increases when the boiled sands are piled up on the surface of the non-liquefiable layer.
2. The amount of settlement is largely influenced by the overburden loads when sand boiling is manifested.
3. Width of the gap through which boiled sand is passing has less influence on the amount of settlement.

Fundamental data to predict the amount of settlement due to sand boiling was obtained through the small-scale model testing. Next step may be to construct analytical procedure for predicting the amount of boiled sand and associated settlements.

.

ACKNOWLEDGEMENTS

The author acknowledges Mr. Yuya Yoshimura for conducting a series of experiments as part of his graduation thesis.

REFERENCES

Bardet, J. P. and Kapuskar, M. (1991). The liquefaction sand boils in the San Francisco Marina district during the 1989 Loma Prieta Earthquake, International Conferences on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, 1687-1691.

Cubrinovski, M. and Green, R. A. (2010). Geotechnical reconnaissance of the 2010 Darfield (Canterbury) earthquake, Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 43, No. 4, December 2010, pp. 243-320.

Cubrinovski, M., Henderson, D. and Bradly, B. (2012). Liquefaction impacts in residential areas in the 2010–2011 Christchurch Earthquakes, Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake, 811-824.

Ishihara, K. (2012). Liquefaction in Tokyo Bay and Kanto Region in the 2011 Great East Japan Earthquake, Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake, 63-81.

Ishikawa, K. and Yasuda, S. (2012). Study of sand boiling characteristics along Tokyo bay during the 2011 Tohoku-Pacific Ocean earthquake, 15WCEE, No. 1651.

Iwasaki, T. (1985). Soil liquefaction studies in Japan: state-of-the-art, Soil Dynamics and Earthquake Engineering, 5(1), 2-68.

Kawai, T., Kim, J., Kazama, M. and Yoshii, T. (2017). An experimental study of sand boiling in relation to shearing characteristics of liquefied soil, Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, 1537-1540.

Numata, A. and Someya, N. (2004). Simplified model experiment of sand dike due to liquefaction, 39th Japan National Conference on Geotechnical Engineering, D-07.

Numata, A., Mori, S., Tohno, I. and Endo, K. (1999). A study on sand dikes and sand boils caused by liquefaction, Journal of JSCE, 638(III-49), 311-324 (in Japanese).

Ohkawa, H. (1997). Consideration on the mechanism of liquefaction, Journal of JSCE, 568(III-39), 13-20.

Seed, H. B. and Idriss, I. M. (1967). Analysis of soil liquefaction: Niigata earthquake, Journal of the Soil Mechanics and Foundations Division, ASCE, 1967, Vol. 93, Issue 3, Pg. 83-108.

Wakamatsu, K. (2012). Recurrent liquefaction induced by the 2011 Great East Japan Earthquake compared with the 1987 earthquake. Proceedings of the International Symposium on Engineering Lessons learned from the 2011 Great East Japan Earthquake, Tokyo, 675-686.

Wibawa, B., Ohta, H. and Okuma, T. (1990). An experimental study of sand boiling due to liquefaction, J. JSNDS, 9-3, 42-59.

Yamaguchi, A., Yoshida, N. and Tobita, Y. (2008a). Estimation of thickness of liquefied layer from sand boiling pattern, Journal of JSCE, 64(1), 79-89 (in Japanese).

Yamaguchi, A., Yoshida, N. and Tobita, Y. (2008b). Experimental study about reliquefaction mechanism, The Japan Association for Earthquake Engineering (JAEE) Journal, 8(2), 46-62 (in Japanese).

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.