# Drained or partially drained - that is the question

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**ABSTRACT:** In physical model experiments on liquefaction, a boundary condition at the ground surface is in many cases drained because adding an impervious layer is too cumbersome. In reality, however, it is hardly seen that the ground water table is located at the ground surface. When focusing on damages caused by liquefaction, duration of liquefaction, which is greatly influenced by the drainage condition, is one of the key factors. This study experimentally demonstrates the difference on soil behaviour under drained and partially drained conditions. A loose saturated sandy soil whose height is about 95 cm was prepared in an acrylic cylindrical soil tank whose height and inner diameter are, respectively, 140 cm and 15 cm. Soil is liquefied by rotating the tank around its axis with sin wave with amplitude of +/-0.5 degrees and 50 Hz. Amount of surface settlement and transient behaviour of excess porewater pressure are observed and compared by varying the surface drainage condition. To control the surface drainage condition, an aluminium plate with side wall, a few millimetres smaller than the inner diameter of the cylinder, was placed on the surface to mimic a partially drained layer. Test results with the plate clearly show the influence of the partially drained layer as manifestation of large surface settlements associated with longer duration of liquefaction with large amount of sand ejecta. Significance of keeping the partially drained condition in physical model testing should be emphasized if a test is targeting to evaluate a scale of damage due to liquefaction.

## 1 INTRODUCTION

It is well understood that liquefaction occurs under undrained condition in an element scale, while, in real scale, it occurs under partially drained condition sometimes accompanied by a sand ejecta. In this paper, "partially drained condition" means "close to undrained condition." Flow liquefaction is clear evidence of partially drained condition in which high excess pore water pressure last for a long time (Yoshida and Finn, 2000).

In numerical analysis on liquefaction problem, it is quite easy to setup a model under either undrained or drained condition. In physical model tests, although the importance of having partially drained or undrained condition is obvious, it is tedious to setup a perfectly undrained boundary to the ground surface or in the ground. To realize this condition, low permeable material such as silt is often utilized to cover liquefiable layer, or dry sand is placed on top of liquefiable layer to form an unsaturated layer. In those cases, difficulty is that the depth of the ground water table is in strict sense uncontrollable due to capillary rise.

Ejection of sand from the ground, is widely acknowledged as a definitive indicator of liquefaction (e.g., Seed and Idriss, 1967, Bardet and Kapuskar, 1991, Wakamatsu, 2012, Ishihara, 2012, Yasuda et al., 2012). Also it is an indicator of the partially drained condition of the ground. Figure 1 schematically shows partially drained condition of liquefied ground with fissures and ejected sand. When the ground is partially drained with cracks, a layer of water may emerge under the impervious layer which may cause flow liquefaction if the ground is inclined.

During the 2010 and 2011 earthquakes in Canterbury, New Zealand, a substantial amount of naturally deposited liquefied soil was expelled along the Avon River (Cubrinovski and Green, 2010; Cubrinovski et al., 2012). The extent of soil ejecta was unexpected and led to the relocation of residents from the affected area. Similarly, in the 2011 off the Pacific Coast of Tohoku, Japan, earthquake, Urayasu in Chiba Prefecture experienced significant sand ejecta from reclaimed soil (Yasuda et al., 2012; Ishihara, 2012). The 2024 Noto Peninsula, Japan, earthquake caused severe liquefaction-induced lateral spreading in wide area, by which residential houses and pipelines were heavily damaged.

To simulate experimentally such a phenomenon, setting up the partially drained condition is inevitable. Although many experiments have been conducted under drained condition because of its simplicity, numerous studies have explored the mechanisms of sand boiling under partially drained condition, (e.g., Numata et al., 1999, Numata and Someya, 2004, Wibawa et al., 1990, Okawa, 1997, Kokusho, 1999, Yamaguchi et al., 2008a, 2008b, Yamaguchi et al., 2008, Ishikawa and Yasuda, 2012, Tobita, 2019),

By physical model testing, this study tries to demonstrate the effects of the surface drainage condition on the amounts of settlements during and after liquefaction.

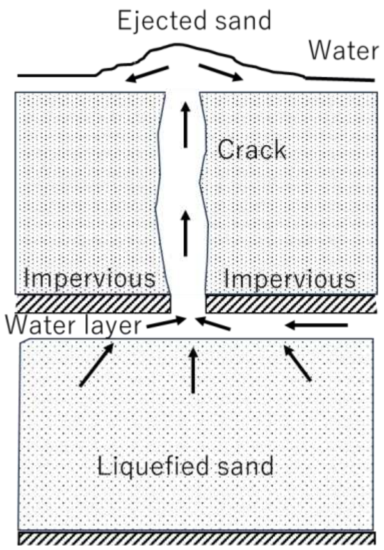



*Figure 1. Schematic view of the cross section of the ground under liquefaction with a fissure and sand ejecta.*

## 2 MODEL FOR PARTIALLY DRAINED CONDITION

Effects of partially drained conditions were examined through a series of model tests (Tobita, 2019). A loose, saturated sand deposit was created in a transparent acrylic cylinder with a height of 1400 mm and an inner diameter of 150 mm as shown in Figure 2. Dimensions of equipment and model ground is listed in Table 1. The cylindrical shape was chosen because it lacks corners that could negatively affect the uniformity of sand boiling.

To simulate a non-liquefiable layer over the liquefiable sand, an aluminium circular plate (Figure 3) was placed on the model ground surface. The plate's diameter (144 or 146 mm) was slightly smaller than the cylinder's inner diameter (150 mm), creating a 3 mm or 2 mm gap for partial drainage, allowing excess pore water pressure to escape with liquefied sand. The plate included a sidewall (Figure 3) to catch the ejected sands (Figure 4). The sidewall height was varied (20 or 40 mm) to study the buoyancy effect on settlement due to the wight of ejected sand. Overburden stress was simulated by adding extra weight (100 or 250 g) along a rod connected to the plate (e.g., 100 g in Figure 3), whose self-weight was approximately 500 g. The inclination of the plate is limited by restricting horizontal movement of the rod with a lid on top of the cylinder (Figures 2 and 3).

Toyoura sand (specific gravity: $G_s$=2.66, max. and min. dry density: $\rho_{dmax}$=1.638 g/cm³, $\rho_{dmin}$=1.329 g/cm³) weighing 24.1 kg was placed in the normal water in the cylinder. Then, using the boiling method, the model ground surface was adjusted to a height of 950 mm from the bottom, achieving a relative density of Dr=40% (Figure 5).

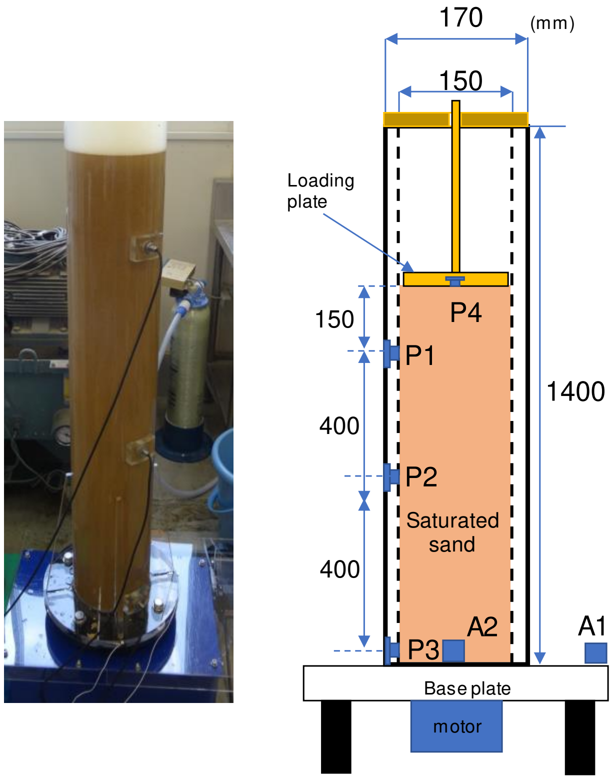



*Figure 2. A view of the acrylic cylindrical container and its dimension and sensor location.*

*Table 1. Dimensions of testing equipment.*

| | 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 |

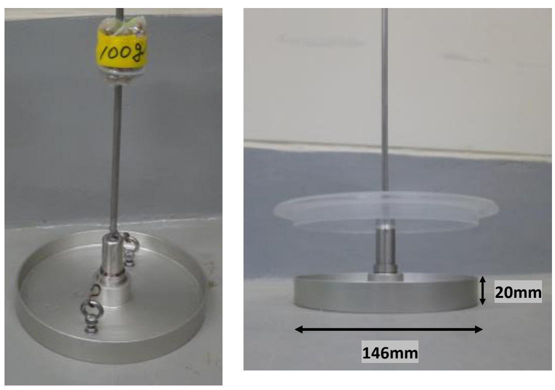



*Figure 3. An aluminium plate with 100 g of additional weight and a lid to cover the cylinder top.*


*Figure 4. Accumulation of ejected sand on the aluminium plate during settlement*

An electric motor was used to induce torsional shaking along the cylinder's vertical centre axis, simulating liquefaction, with a rotation angle of about ±0.5 degrees at 50 Hz. The shaking lasted approximately 2 seconds, which was sufficient to achieve complete liquefaction. Time histories of the excess pore water pressure ratio of both drained and partially drained condition shown in Figure 6 demonstrates that the entire sand deposit is liquefied, as all measured excess pore water pressures (P1, P2, and P3) reach an excess pore pressure ratio $r_u$=1. While shear stress and strain induced by this method may vary radially, it is reasonable to assume these effects diminish after complete liquefaction.

Two accelerometers (A1 and A2 in Figure 2) were attached to the base plate to measure radial and tangential input accelerations. Three pore pressure transducers (P1 to P3) were installed on the cylinder's side wall at 400 mm intervals (Figure 2). Another pore pressure transducer (P4) was attached to the aluminium plate to measure excess pore water pressure trapped under the plate as water film (Kokusho, 1999). A laser displacement transducer was used to measure the plate's settlement, and video recordings from the side of the cylinder visually documented the settlement process.

Figure 7 outlines the identification of each test case using a specific case ID. For example, the case “PT20-146-WL20.250” uses a plate with a 20 mm sidewall height, a 146 mm diameter, and an added mass of 250 g.

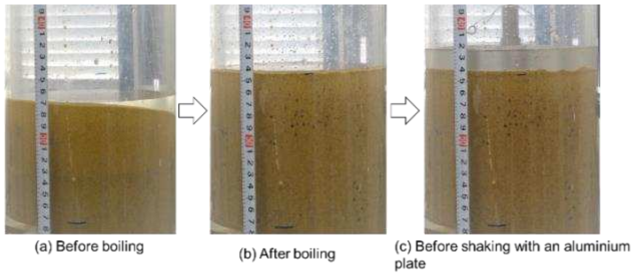



*Figure 5. Preparation steps of the model ground: (a) sand is pluviated in the water, (b) water is given from the bottom of the cylindrical container to cause boiling of the ground and adjust the depth of the model ground, and (c) the aluminium plated is placed on top of the ground surface.*

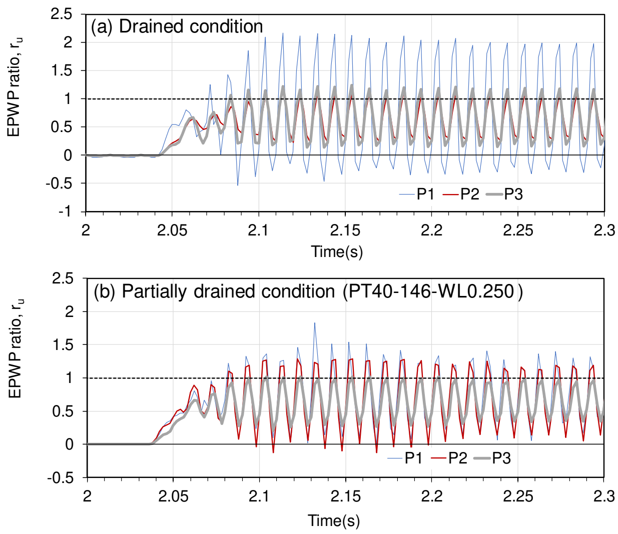



*Figure 6. Time histories of the excess pore water pressure ratio: (a) without loading plate, (b) with loading plate; PT20-146-WL20.250.*

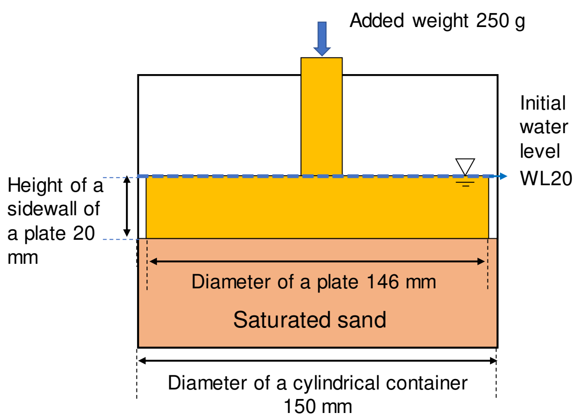



*Figure 7. Example of the case ID of PT20-146-WL20.250.*

## 3 DRAINED AND PARTIALLY DRAINED BEHAVIOUR

By varying above mentioned parameters on testing, total 70 tests were conducted (Tobita, 2019, Yoshimura, 2018). Here, to investigate the effects of drained and partially drained conditions on settlement behaviour, a few cases are selected: One is for drained condition (PT0-0-WL0.0), and the other is for partially drained condition (PT40-146-WL10.250).

Figure 8 compares time histories of the excess pore water pressure of (a) drained and (b) partially drained condition. In both cases, duration of shaking is about 2 s. Then for the drained case pore water pressure dissipation of P2 is started at 20.2 s as indicated by the solid arrow, while that of the partially drained condition 30.3 s about 10 s delayed. For P1, dissipation is started at 48.1 s in the drained condition while in the partially drained condition 60 s about 12 s delayed. For P3, in both cases, as it is expected, dissipation begins immediately after shaking. For the drained case, excess pore water pressure is completely dissipated at about 55 s, while for the partially drained case, it may take more than 70 s.

Time history of the settlement of the aluminium plate for the case of the partially drained case corresponding to Figure 8(b) is plotted in Figure 9. For the drained case (Figure 8(a)), the continuous measurement of the settlement with instrument was not done but final value was measured by a ruler and plotted with an open circle in Figure 9. For partially drained case, settlement starts simultaneously with liquefaction. Then, after a brief interval from shaking, liquefied sand starts to rise in the gap with minor settlement of the plate. The settlement of the plate is accelerated with the ejected sand flown into the plate until about 55 s, which gives an additional mass to the plate. Then, the speed of settlement (slope of the curve) becomes almost constant about 30 mm/s. For the partially drained case, the final amount of the settlement is about 90 mm. For the drained case, it is about 30 mm. This large difference on settlement is caused by elongated duration of liquefaction and sand ejection through the gap between the side wall of the aluminium plate and the container.

Next, significance of the partially drained condition on liquefied sand behaviour is illustrated in Figure 10. As a trial, continuous shaking under the same amplitude and frequency as above was given to the container of the drained condition until no more settlements being observed (Figure 10(a)). It took 3 min. and 30 s to reach the settlement of about 10 cm. The relative density after the shaking was Dr=93.7%. By observation, it was speculated that if the shaking is stopped the settlement might also be stopped. Thus, the settlement/contraction is driven by the shear due to shaking, i.e., negative dilatancy. On the other hand, in the partially drained condition in Figure 10(b), total settlement of about 15 cm was achieved with the duration of shaking only 2 s. Although the relative density after shaking is unknown, the ground beneath the plate was softer than that of the drained case. In the partially drained case, the ground is less densified than that of the drained case. This is indicating the mechanism of re-liquefaction occurred along the Avon River in 2010 and 2011 earthquakes in Christchurch (Cubrinovski and Green, 2010; Cubrinovski et al., 2012), and 2011 Tohoku, Japan earthquake (Wakamatsu, 2012).

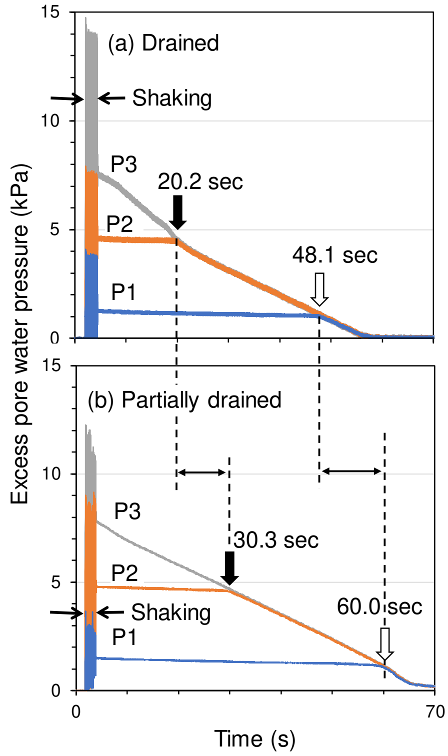



*Figure 8. Time histories of excess pore water pressure: (a) Drained condition, (b) Partially drained condition.*

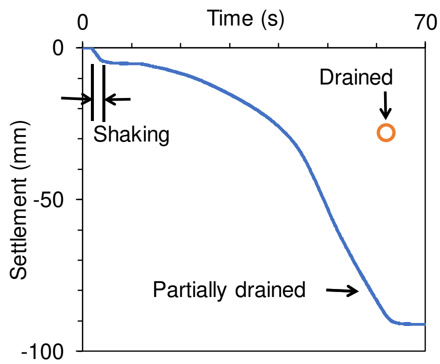
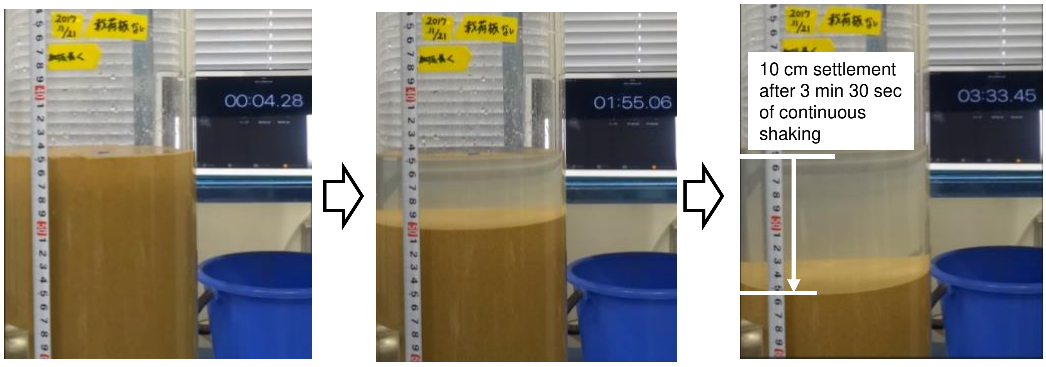
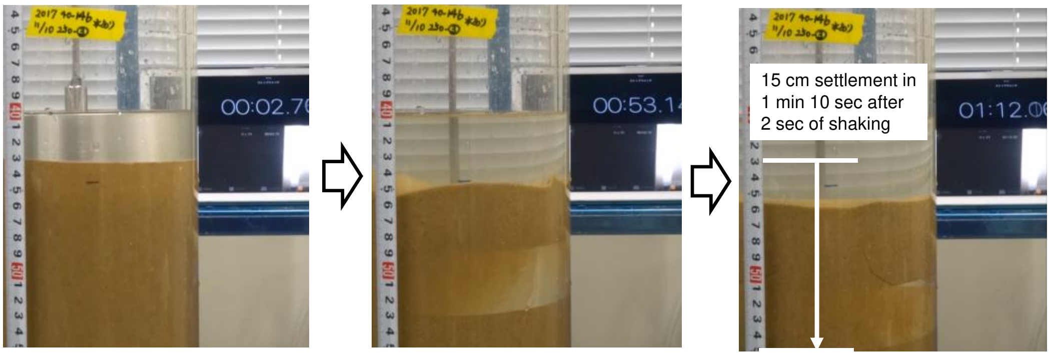



*Figure 9. Time history of the settlement of the aluminium plate for the case of partially drained condition. Measured settlement for drained condition by a ruler is plotted with an open circle.*




(a) Drained condtion




(b) Partially drained condition

*Figure 10. Comparison of the settlement behaviour between (a) Drained condition with 3 min 30 sec of continuous shaking and (b) Partially drained condition after 2 sec of shaking. In the partially drained condtion (b), liquefied sands are ejected through the gap, while in the drained condition (a), the ground surface is continuously settled without sand ejection*

## 4 CONCLUSIONS

A series of dynamic model testing to study the influence of drained and partially drained conditions under liquefaction was conducted. The model ground was constructed in an acrylic cylindrical container of the inner diameter of 150 mm. Loosely saturated model ground (Dr=40%) with Toyoura sand was made by the boiling method. To mimic the partially drained condition, an aluminium plate whose diameter was slightly smaller than the inner diameter of the container was utilized and placed on top of the liquefiable ground. Shaking in the torsional direction along the central axis of the container was given with +/- 0.5 deg. and 50Hz. Excess pore water pressure was dissipated through the gap of the side wall of the plate with sand ejection.

Significance of keeping the partially drained condition or close to the undrained condition in physical model testing should be emphasized if a test is targeting to evaluate a scale of damage due to liquefaction. In this study, the settlement of 15 cm was achieved with only 2 s of shaking under the partially drained condition, while, under the drained condition, about 10 cm of the settlement was achieved with continuous shaking of 3 min and 30 s.

Development of a physical and flexible method to simulate the partially drained condition is needed for more reasonable assessment of damage due to liquefaction.

## 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*, 43(4): 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. https://doi.org/10.1016/0267-7261(86)90024-2
Kokusho, T. (1999). Formation of water film in liquefied sand and its effect on lateral spread, *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, 125(10): 817-826. https://doi.org/10.1061/(ASCE)1090-0241(1999)125:10(81
Liu, L. (1992). *Centrifuge earthquake modelling of liquefaction and its effects on shallow foundations*. Ph. D thesis, Rensselaer Polytechnic Institute, Troy, NY.
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, 93(3): 83-108. https://doi.org/10.1061/JSFEAQ.0000981
Tobita, T. (2019). Factors affecting liquefaction-induced settlements with sand boiling, In *Earthquake Geotechnical Engineering for Protection and Development of Environment and Constructions* Silvestri & Moraci (Eds), pp. 5290-5296. Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-0-367-14328-2,
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. Japan Society for Natural Disaster Science*, 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). https://doi.org/10.2208/jscejc.64.79
Yamaguchi, A., Yoshida, N. and Tobita, Y. (2008b). Experimental study about reliquefaction mechanism, *Journal of Japan Association for Earthquake Engineering*, 8(2): 46-62 (in Japanese). https://doi.org/10.5610/jaee.8.3_46
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. https://doi.org/10.1016/j.sandf.2012.11.004
Yoshida, N. and Finn, W.D.L. (2000). Simulation of liquefaction beneath an impermeable surface layer, Soil Dynamics and Earthquake Engineering, 19(5): 333-338. https://doi.org/10.1016/S0267-7261(00)00018-X
Yoshimura, Y. (2017). Experimental study on the estimation of settlement due to liquefaction. Graduation thesis, Kansai University, Osaka, Japan (in Japanese).