International Conference on Case Histories in Geotechnical Engineering

(2004) - Fifth International Conference on Case Histories in Geotechnical Engineering

17 Apr 2004, 10:30am - 12:30pm

# Shaking Table Tests on Effiency of New Type of Drains

Vlatko Sesov
*Institute of Earthquake Engineering and Engineering Seismology, Skopje, Macedonia*

Ikuo Towhata
*University of Tokyo, Tokyo, Japan*

Naoyuki Harada
*Technical Research Institute, The Zenitaka Corporation, Tokyo, Japan*

Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

# SHAKING TABLE TESTS ON EFFIENCY OF NEW TYPE OF DRAINS

**Vlatko SESOV**
Institute of Earthquake Engineering
and Engineering Seismology,
Skopje, Macedonia

**Ikuo TOWHATA**
University of Tokyo
Tokyo, Japan

**Naoyuki Harada**,
Technical Research Institute,
The Zenitaka Corporation
Tokyo, Japan

## ABSTRACT

One method to mitigate liquefaction-induced hazard is the use of a system of vertical drains to dissipate the excess pore water pressure generated by earthquake loading. Performance assessments for these systems require the estimation of vertical drain spacing such that a maximum threshold level of excess pore pressure ratio is not exceeded.
The objective of this research is to study efficiency of installing vertical drains on generation and dissipation of pore water pressure. For this purpose series of shaking table tests were performed using a laminar box, in Geotechnical Laboratory on Tokyo University. The ground model consists of two layers of saturated sand with relative densities of 80% and 40%. Two different types of vertical drains were investigated: prefabricated micro drain with diameter 22 mm and gravel drain with diameter of 30 mm.
Several shaking table tests were performed with different distribution pattern in order to achieved optimal spacing between vertical drains on dissipation of pore water pressure. The tests were carried out with harmonic loading at frequency of 10 Hz and varying the magnitude of input acceleration in wide range from 0.05 to 0.60 (g).
The results from above shaking table tests provided a detail view of efficiency of new type of vertical drains as one of the frequently used remedial measures against liquefaction.

## INTRODUCTION

The liquefaction phenomenon along with its accompanying manifestations represents a complex problem, which has been the subject of intensive investigations that have been going on for more than 30 years. The dynamic instabilities resulting from the liquefaction occurrence induce damage to underground structures and structures upon the surface.

For the last decades, we have witnessed the fact that liquefaction contributes to considerable increase of total damage due to earthquakes. In addition to direct damage caused by liquefaction, it also causes damages that do not primarily refer to structures but indirectly affect their functioning. The application of measures for improvement of soils against liquefaction has proved to considerably reduce the total losses due to earthquakes. One of the best documented examples supporting this statement is the Kobe earthquake of 1995 at Rokko and Port Island, where the soils that were treated by compacted sandy piles or by were compacted by vibration, showed considerable resistance to liquefaction, i.e., they did not liquefy despite the strong earthquake effect, while the non treated "natural" soil were characterized by a high liquefaction potential (Yasuda et al. 1996).

The intensive investigations of the dissipation method have contributed to wide application of the vertical drains. In the beginning, the most commonly used were the gravel drains, while prefabricated drains have lately been increasingly frequently applied. With this, there are initiated new fields of investigation of prefabricated drains for the purpose of their wider application and more optimal design. The main advantage of this type of drains in respect to the gravel ones is their fast and simple installation, faster dissipation of pore pressures, possibility of application on existing structures, installation in conditions of limited space for manipulation, possibility of additional intervention to prevent clogging of the drain, etc. Most of the investigations that have been performed within the frames of this project have been dedicated to experimental investigations of the efficiency of a new type of prefabricated drains.

## EXPERIMENTAL INVESTIGATIONS

Laboratory model tests on a shaking table using the laminar container in normal gravity field were performed. The laboratory tests were performed at the University of Tokyo, Civil Engineering Department in cooperation with Zenitaka Co. Tokyo. Model studies offer an opportunity to obtain special data such as pore pressure changes during shaking, large lateral flow of liquefied ground, amplification in ground at surface and at different elevations etc (Sasaki et al. 1992). One major problem in the model study is the size effect. There has to be some limit for the size of the container used in the laboratory, which creates the boundary effect, and size effect. Ground behaviour may be seriously affected due to this and it is more pronounced in earthquake geotechnical engineering, which involves large deformations. This problem can be reduced by using a laminar box. Laminar box is a large size shear box consisting of several horizontal layers, built such that the friction between the layers is minimum. Hence the layers move relative to one another in accordance with the deformation of the soil inside. It is rectangular in cross section with inside dimensions of 500 mm by 1000 mm in size and 1000 mm deep. Fig.1 a shows the overall view of the laminar box. The box was fixed at its base to the shaking table.

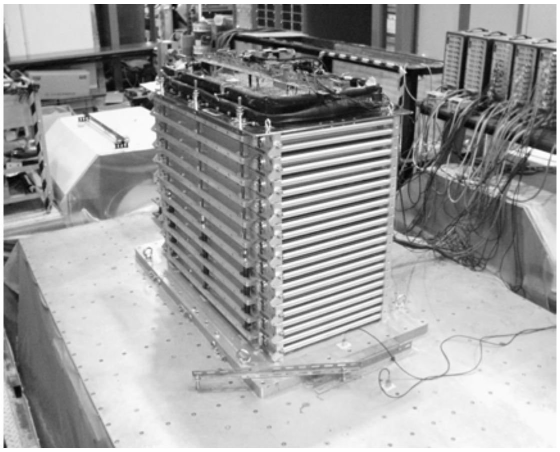

*Fig. 1. Laminar box at the University of Tokyo*

In the present research, a laminar box was used to study the efficiency of vertical drains on dissipation of pore water pressure as a remedial measure against liquefaction.

Law of similitude

A similitude was derived for the shaking table tests on saturated soil-structure-fluid model in 1g gravitational field. The main tool used for deriving the similitude were the basic equations, which govern the equilibrium and the mass balance of the soil skeleton, pore water and pile structures (Iai 1989). In deriving the basic equations , the following idealizations or approximations have been adopted: (1) soil skeleton is regarded as continuous medium, (2) deformation is regarded small so that the equilibrium equation after deformation is the same as that before the deformation, and (3) strain of the soil skeleton is regarded small so that the linear approximation of strain holds true. According to these assumptions the following scaling factors were adopted: the geometric scaling factor $\lambda=25$, the scaling factor for density of saturated soil $\lambda_\rho=1$ and the scaling factor for strain of saturated soil $\lambda_\varepsilon=\lambda^{0.5}$. Other scaling factors, which were determined from previously defined basic factors, are shown in Table 1.

Table 1. Scaling factors for model tests in case $\lambda=25$, $\lambda_\rho=1$ and $\lambda_\varepsilon=\lambda^{0.5}$

| Variable | Scaling factor (prototype/model) |
|---|---|
| size | 25 |
| acceleration | 1 |
| strain | 5 |
| time | 11.18 |
| frequency | 1/11.18 |
| stress | 25 |
| permeability* | 11.18 |

*Use special viscous liquid, solution with Cellulose

In order to determine the appropriate viscosity of mixture of Cellulose powder and water (CMC liquid), additional seepage tests were performed.

Ground models

Soil models that were subject of experimental shaking table investigations consisted of two layers of completely saturated IIDE sand of different relative densities (Dr = 80%, Dr = 40%) and a gravel layer on the model surface, Fig.2. At the same time, it is the basic soil model that, with minor modifications, was tested in almost all the experiments. The differences between the individual models refer, first of all, to the different disposition and the different types of vertical drains. A tested model, type of installed drains, their diameters and distribution pattern is summarized in Table 2.

Table 2. Tested models

| Model series | type of drain | number of drains | diameter D (mm) | spacing a (cm) |
|---|---|---|---|---|
| ADRA | micro drain | 6 | 22 | 10 |
| BDRA | no drain | - | - | - |
| CDRA | gravel drain | 6 | 30 | 10 |
| DDRA* | column | 6 | 22 | 10 |

*model with column pile but no drainage.

Ground model was made by two different methods, namely Dry Deposition and Water Sedimentation depending on the desired density. The dense layer Dr=80%, representing an unliquefiable layer was made by dry deposition method. Since the layer had to be highly densified, dry sand was initially prepared in layers of 10 cm. After placing a required amount of dry sand inside the test box, it was tamped to achieve the desired density. Later, CMC liquid was allowed from the porous bottom of the box at very low pressure to have minimum damaging effect on the initially formed soil structure. The saturation period was taking more than ten hours because of the high density of the layer and the high viscosity of the CMC liquid. The second layer with 40% relative density representing liquefiable layer was made by the water sedimentation method. The CMC liquid was first allowed into the box. As earlier, predetermined amount of sand was weighed and poured in the laminar box. The water level was raised to the next level with care being taken to maintain the water pressure as minimum as possible to eliminate the disturbance of the already formed ground. Later, the extra water on the surface was removed and the level of ground surface from the top of the box was measured at different points along the edge and in the middle for the purpose of evaluation of the initial void ratio. The surface of such constructed ground was covered by impermeable PVC sheet. Then gravel was poured above this sheet with thickness of 3-5 cm. Vertical drains were installed in the second liquefiable layer.

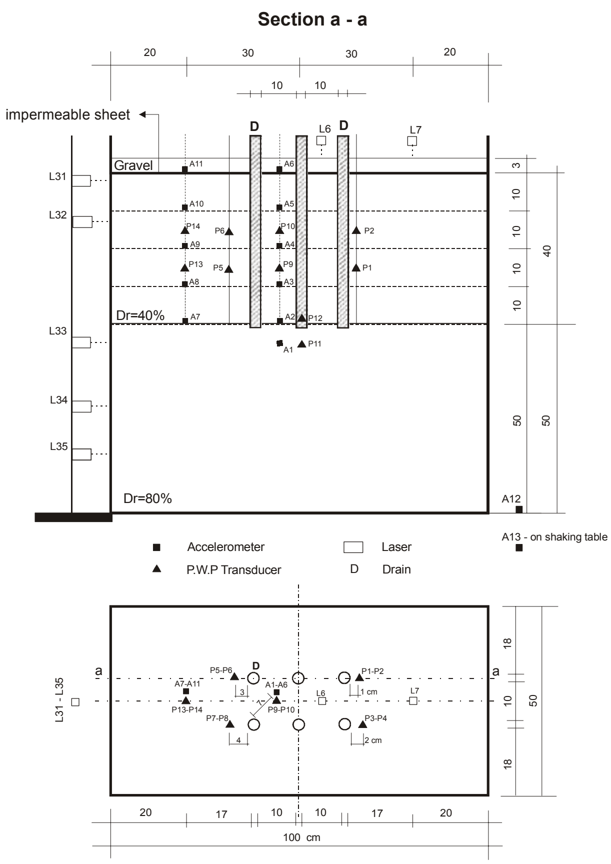


*Fig. 2. Model layout and location of transducers*

Instrumentation

Several kinds of transducers were used to measure the desired parameters during shaking, namely, accelerometers, pore water pressure transducers and laser-devices for measuring of horizontal displacement and settlement. Accelerometers and P.W.P. transducers were embedded in the ground, at 10 cm spacing. Special attention was paid to assure stability for the accelerometers during strong shaking. For this purpose, the transducers were placed on acrylic mounts 50 mm square in cross section and 25 mm deep. Larger base area increased the stability of transducers and it helped also in representing the behavior of the larger mass of soil. Transducers were placed during the process of ground making. Laser-devices, which measured horizontal displacement, were attached to the steel column fixed on the shaking table at an appropriate distance from the laminar box. Lasers, which measured settlement, were attached on the steel rods to the top of the laminar box. Fig.2 shows the typical layout of the transducers used in the models.

Excitation

Each model ground was excited in the longitudinal direction with harmonic sine waves, fig. 3. Shaking of models was performed at seven stages beginning with 0.05 g, 0.10, 0.20, 0.30, 0.40, 0.50 & 0.60 g at frequency of 10 Hz and duration of 3 sec. Each stage of shaking was followed by a stationary period to allow for dissipation of the developed excess pore water pressure. The recording time for all time histories was 300 sec., which was necessary for obtaining enough data for analyzing the dissipation history of porewater pressure.

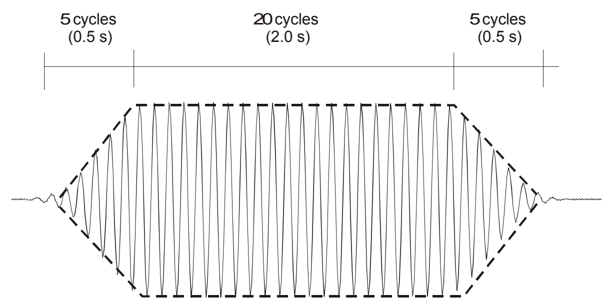


*Fig. 3. Input excitation*

RESULTS FROM THE TESTS

Model with no drains

The generation and the dissipation of excess pore pressure were of a particular interest and it was observed during and after the termination of the shaking. Figure 4 shows the time histories of $r_u$ along height of the model BDRA, at depths of 10, 20 and 30 cm in the central part of the container. The time axis was scaled to t=2-7 s for the purpose of presenting, in more detail, the effect of excitation upon the generation of excess pore pressure. The solid line represents the level of initial effective stresses.

It can be observed that, during the first several excitation cycles there was an intensive accumulation of excess pore pressure in the model layers. The values of pore pressure show that the state of excess pore pressure is close to the state of initial effective stresses and initial liquefaction for the entire layer with Dr = 40%. Such a state of excess pore pressure was preserved during the shaking and even after shaking stops.

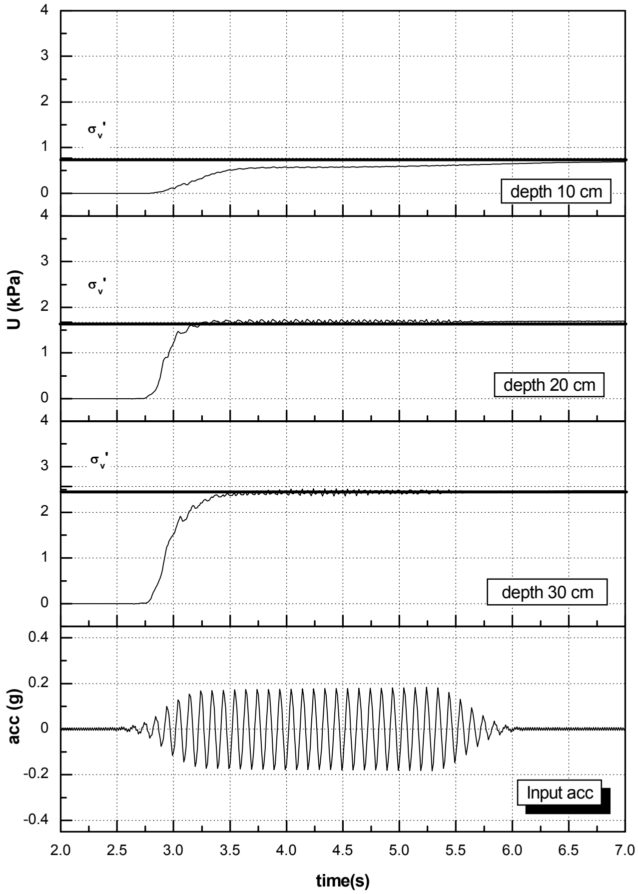


*Fig. 4. Generation of pore pressure – model with no drains*

To better present the pore pressure dissipation in Fig. 5, the time histories of U and $r_u$ along the height of the BDRA model are given, however in this case, the time axis was scaled to $t_{max}$ = 300 s, i.e., throughout the entire duration of recording of the experiment. Figure 5 shows that dissipation takes place after a certain time period from termination of excitation and the reaching of the maximum values of excess pore pressure. The development of dissipation is relatively slow which is also proved by the fact that even after 300 s from the termination of the excitation, the excess pore pressure ratio $r_u$ does not reach the zero value, i.e., there is still high residual non-dissipated excess pore pressure.

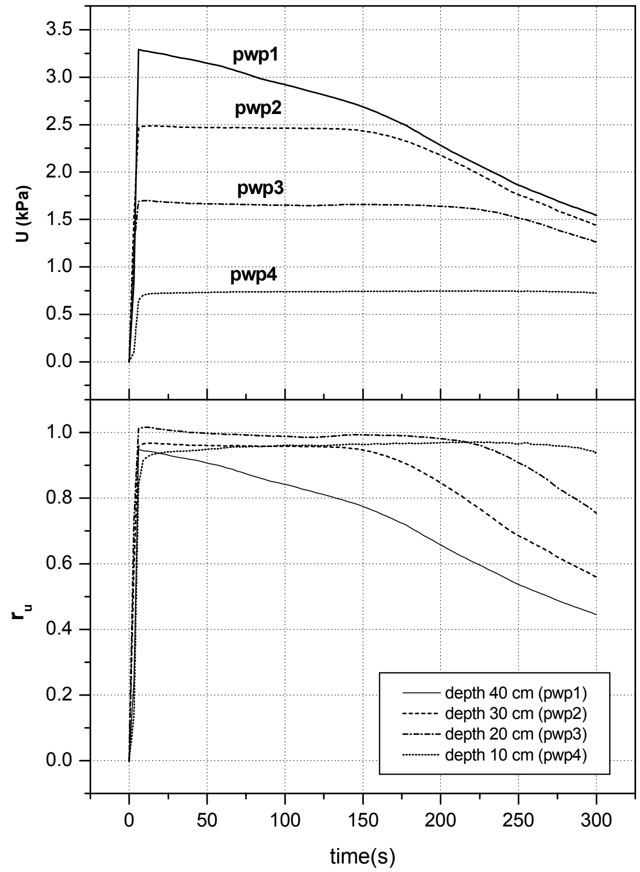


*Fig. 5. Dissipation of pore pressure – model with no drains*

<u>Model with drains</u>

This soil model is identical to the main model BDRA with no drains in respect to the preparation of the layers, the relative densities and the boundary conditions, the different being in the installation of a set of 6 drains in each of the ADRA model. The drains were placed at a distance of 10 cm, in that way, original soil models were obtained. The locations of the pwp transducers were selected such that they enabled detailed monitoring of the generation and the dissipation of the pore pressure in the vicinity of the drains Fig.2, or more precisely, at distances 1, 2, 3 and 4 cm (transducers- pwp1 to pwp8), then in the central part between the sets of drains (transducers pwp 9 and pwp 10) and at greater distance from drains (transducers pwp13 and 14). Presented further shall be the results from the experiments on the model with the micro-drains.

The results on the time traces of excess pore pressure for the ADRA model under excitation intensity of 0.2 g are presented in Fig. 6. The plot is composed of three graphs showing the time histories of the input excitation and the excess pore pressures at 1 cm distance from drains, transducers pwp1 and pwp2. The solid line represents the level of initial effective normal stresses σ'.

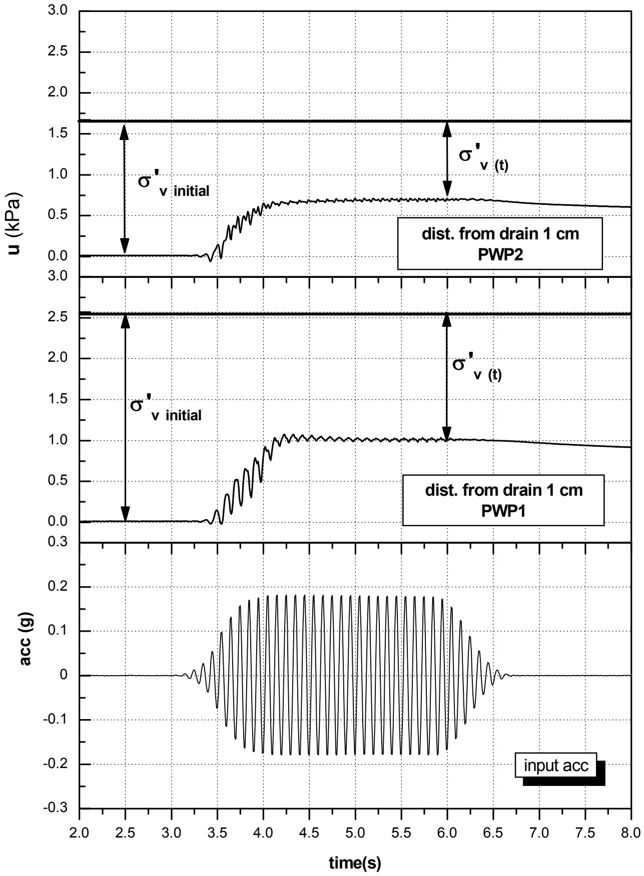


*Fig. 6. Generation of pore pressure – model with micro-drains*

From the presented diagrams, it can be noticed that, the excess pore pressure does not reach the level of initial effective normal stresses σ', actually the level is less that 50 % of $\sigma'_{init}$. The shape of the time histories of excess pore pressure shows that there is no big accumulation of excess pore pressure. The difference in respect to the same such time histories obtained for the BDRA model with no drains (see Fig.4) becomes immediately evident.

Figure 7 shows the time histories of excess pore pressure ratio $r_u$ for the entire duration of the experiment. The dissipation curve for different distances from the drains can clearly be observed. Compared to the experiment on model with no drains under same intensity of shaking, it is obvious that micro-drains accelerate the dissipation process and value of $r_u$ drops relatively fast down to the initial values. The dissipation curve for different distances from the drains can clearly be observed.

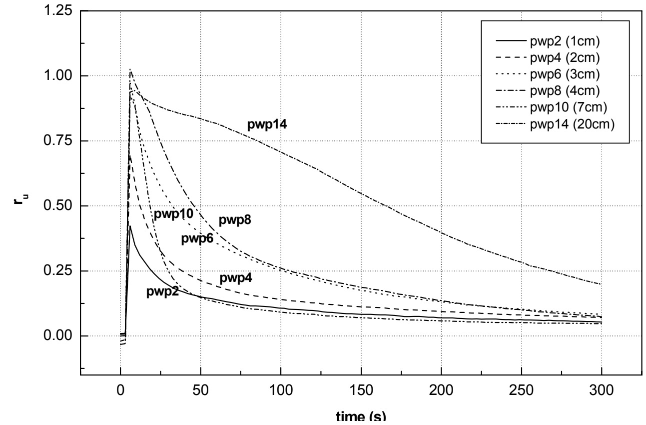


*Fig. 7. Dissipation of pore pressure – model with micro-drains*

## EFFICIENCY OF DRAINS

The installation of the vertical drains led to the modification of the state of excess pore pressure. This modification mainly refers to decrease of the level of maximum pore pressure resulting in avoidance of liquefaction occurrence. The maximum values of $r_u$ depending on distance from the drains and the excitation intensity are given in Fig.8a, Fig.8b and Fig.8a. Compared to the model with no drains, there is a considerable reduce of $r_u$ at lower distances from the drains of 1 - 2 cm, whereas, with the increase in distance and excitation intensity, the $r_u$ values approach the corresponding values for the nontreated soil model.

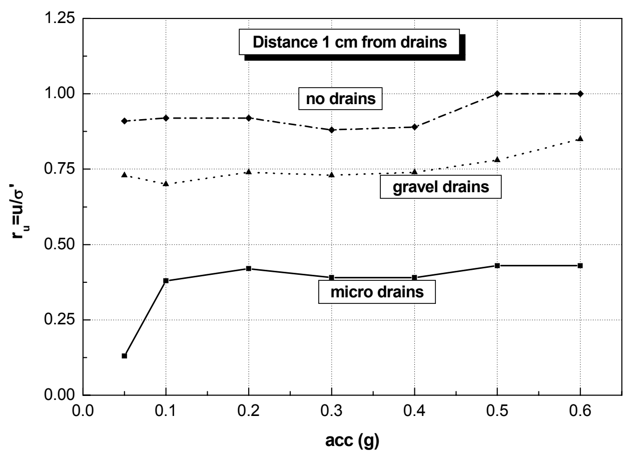


*Fig. 8a. Max. excess pore pressure ratio $r_u$ distance 1 cm from drains*

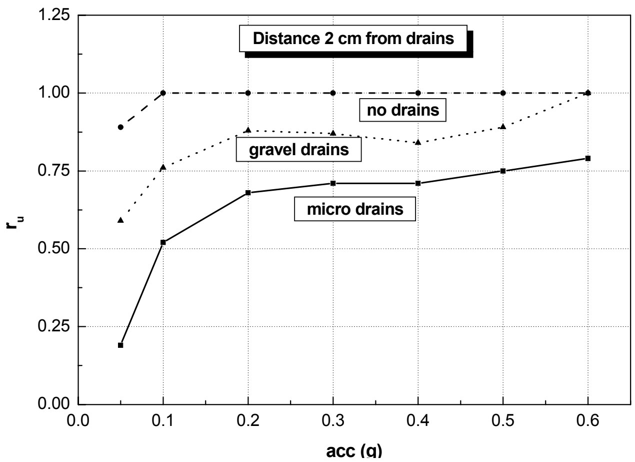


*Fig. 8b. Max. excess pore pressure ratio $r_u$ distance 2 cm from drains*

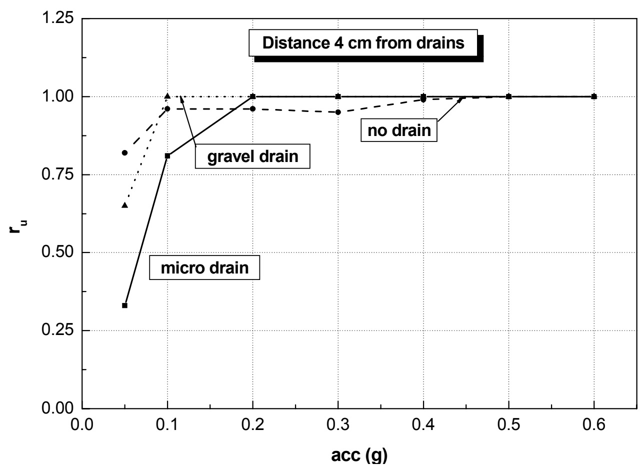


*Fig. 8c. Max. excess pore pressure ratio $r_u$ distance 4 cm from drains*

Based on the results of the experiments, the following can be observed. The micro-drains - for distances of 1 cm from the drain, provide excess pore pressure ration $r_u$ level within the allowable limits ($r_u < 0.5$) under the excitation intensity of up to 0.6 g. For distances of 2 cm, they provide this level only under excitation of up to 0.2 g. For distances exceeding 3 cm and excitation intensities exceeding 0.1 g, the micro drains do not provide $r_u$ level that will be below the maximum allowable one.

The gravel drains - for distances of 1 cm from the drain, provide $r_u$ level that is close to the limits of the adopted maximum of $r_u = 0.5$, whereas for distances exceeding 1 cm and intensity of shaking higher than 0.05 g they do not provide the adopted allowable level of $r_u$.

## CONCLUSIONS

The dissipation method as one of the methods for mitigation against liquefaction is the main subject of investigation in this research study. The dissipation method is applied on a two-layered soil deposit by installation of two types of drains: prefabricated drains, the so-called micro drains and gravel drains. The soil model (the non-treated one) is characterized by a high liquefaction potential which particularly refers to the upper layer with Dr=40%. The results show that liquefaction occurs in the layer with Dr = 40% under harmonic excitation intensity of 0.05g, whereas the layer completely liquefies under intensity of 0.1 g. The state of excess pore pressure represented via excess pore pressure ratio $r_u = u(t)/\sigma'_{init}$ represents the main criterion for the evaluation of the efficiency of the installed drains. The shaking table tests show that micro drains proved to be more efficient that the gravel ones. The micro drains preserve the $r_u$ at the level of 0.6 for distance of 2cm from the drains under maximum excitation intensity of 0.2 g. For distances of less than 2 cm, the micro drains completely control the $r_u$ level also under higher excitation intensities. The gravel piles retain the $r_u$ level to the value of 0.6 (0.70) only at distances of 1 cm. In addition to the effect upon the coefficient of excess pore pressure $r_u$, the drains also have a positive role upon the shortening of the time period for complete dissipation. The applied approach of model experiments on a shaking table provides good opportunities for investigation of the dissipation method. In that direction, the application of the laminar container in the construction of the models enables more realistic simulation of the soil conditions and good simulation of generation and dissipation of excess pore pressure.

## ACKNOWLEDGMENT

Shaking table tests at the University of Tokyo were carried out in collaboration with Zenitaka Co. The investigation is a part of Ph.D. thesis work of the first author and it was supported by research grant from University of Tokyo and Japanese Government. The support is gratefully acknowledged.

## REFERENCES

Iai Susumu [1989]. Similitude for Shake Table Tests on Soil-Structure-Fluid Model in 1g Gravitational Field, Soils and Foundations Vol.29. No.1.: pp.105-118

Sasaki, Y. Towhata, I. Ken-ichi, T. Kazuhiko, Y. Hideo, M. Yukio, T. & Shoichi, S. [1992]. Mechanism of Permanent Displacement of Ground Caused by Seismic Liquefaction, Soils and Foundations Vol.23. No.3.: pp.79-96

Yasuda, S. Ishihara, K. Harada, K. & Shinkawa, N. [1996] Effect of soil improvement on ground subsidence due to liquefaction, Special issue of Soils and Foundations Jan.1996 : pp.99-107