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EXPERIMENTAL INVESTIGATIONS ON DRAIN IMPROVEMENT METHOD - REDUCTION OF LIQUEFACTION POTENTIAL

Vlatko SESOV[1], Naoyuki HARADA[2], Ikuo TOWHATA[3] and Kosta TALAGANOV[4]

SUMMARY

The present study attempts to develop a new method for dissipation of excess pore water by installation of new type of prefabricated drains so called micro drains. The main advantages of this type of drain in respect to the traditionally used are 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. Investigations that have been performed within the frames of this project explored micro drains as mitigation measure against liquefaction. Series of shaking table tests were performed to investigate the efficiency of new type of drains. The results from these investigations confirm the high performance of micro drains as one of the most efficient measures against liquefaction.

INTRODUCTION

The occurrence of damage and loss of serviceability of structures due to soil liquefaction were evident during the strong earthquakes in past decades. Damages cause by earthquakes was very much increase when liquefaction took place. In addition to direct damage caused by liquefaction, it also causes damages that do not primarily refer to structures but indirectly affect their functions. This shows the importance of prevention of liquefaction of ground thereby to minimize damage. The mitigation of the consequences from liquefaction occurrence represents one of the primary goals of the investigations in earthquake geotechnical engineering. Improvements against liquefaction can be classified into: soil improvement that can prevent liquefaction and measures to be taken for the structures to prevent damage in case of subsoil liquefaction. The methods for improvement of soils against liquefaction are based either on the principles of improvement of the soil properties (increasing soil density, soil solidification, mechanical stabilization and soil drainage) or the principles of changing the stress and deformation state (increase of "confining" pressure, accelerating the dissipation of excess pore water pressure, etc.).

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[1] Associate Professor, IZIIS, Skopje, Macedonia. Email: vlatko@pluto.iziis.ukim.edu.mk
[2] Researcher, Zenitaka Corporation, Tokyo, Japan. Email: harada_naoyuki@zenitaka.co.jp
[3] Professor, University of Tokyo, Japan. Email: towhata@geot.t.u-tokyo.ac.jp
[4] Professor, IZIIS, Skopje, Macedonia. Email: kotal@pluto.iziis.ukim.edu.mk

Drain method as one of the mitigation measures against liquefaction have been widely used for more than twenty years in engineering practice. The investigations done by Booker and Seed (1977) have given considerable contribution particularly to the theoretical explanation of the method of dissipation of earthquake induced excess pore water pressure by using gravel drains. Afterwards, there have been intensive investigations on the dissipation method involving the use of gravel drains. Noteworthy among these are those performed by Sasaki & Taniguchi (1982) as well as Onoue, Mori & Takano (1987). It is characteristic that these investigations on the dissipation methods have been dominantly conducted by model experiments and in-situ experiments. The mentioned investigations explore in more detail the state of hydraulic conductivity not only in soil but in the drain itself taking into account well resistance of gravel drain. The intensive investigations of the dissipation method have contributed to wide application of the vertical drains. With this, there are initiated new fields of investigation of prefabricated drains for the purpose of their wider application. The main objective of this study is developing a new drain method to mitigate the seismic risk of liquefaction occurrence in loose sandy soils.

SHAKING TABLE TESTS

Equipment

Laboratory model tests on a shaking table using the laminar box in 1-G gravity field were performed. The laboratory tests were performed at the University of Tokyo, Civil Engineering Department in cooperation with Zenitaka Co. Tokyo. The laminar box used in the present study is rectangular in cross section with dimensions of 500 mm by 1000 mm in size and 1000 mm deep. This box consists of eleven horizontal rectangular rings, built so that the friction between the layers may be minimum. Fig. 1 shows the overall view of the laminar box.

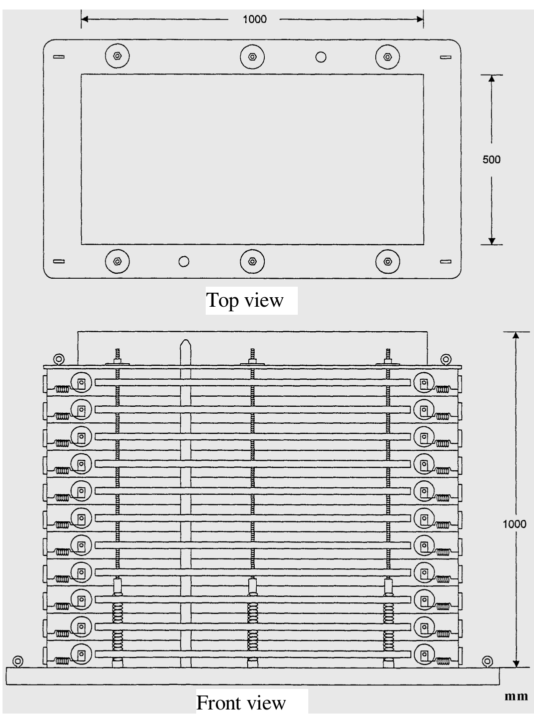

Fig.1. Layout of Laminar box

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.

Ground models

The basic ground model, Fig. 2 (model series BDRA) consists of two layers of saturated Silica sand (Iide), bottom layer with relative density of Dr=80%, upper layer sand with Dr=40% and on the top gravel layer 5 cm in thickness was made. The soil properties of ground model were the same in all tested models.

To investigate the efficiency of vertical drains as a measure against liquefaction basic ground model was improved by installation of 6 drains in upper layer with only 5 cm of their height being placed in the bottom layer. Spacing between drains was 10 cm. Two type of drains were installed: micro drains (model series ADRA) and gravel drains (model series CDRA) The setup of improved model with drains is presented in Fig.3. The locations of the pore water pressure transducers in improved models were installed in the vicinity of the drains to enable detail monitoring of the generation and dissipation of excess pore water pressure. The micro drains used in this study were manufactured by Zenitaka Corporation, Japan. Micro drain is made of steel screen hollow pipe with openings 0.1 mm. Model series are listed in Table 1.

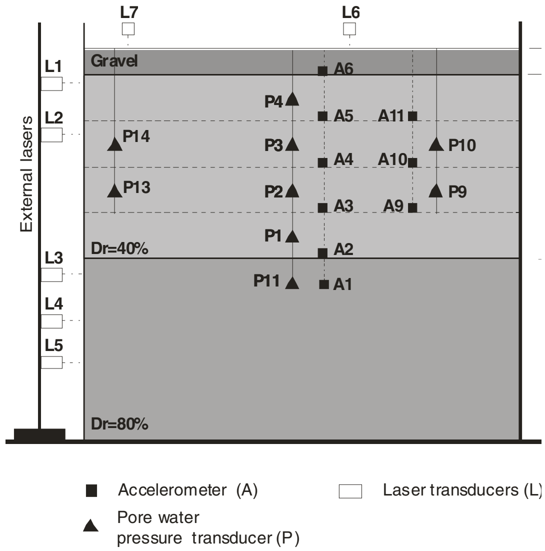

Fig.2 Basic ground model (BDRA)

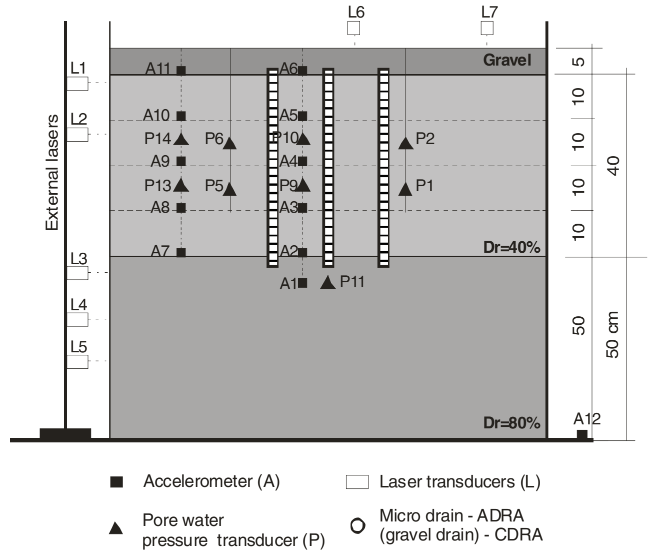

Fig.3 Model improved by drains

Table 1. Tested models

Model series	type of drain	number of drains	diameter D (mm)	Spacing (cm)
ADRA	micro drain	6	22	10
BDRA	no drain	-	-	-
CDRA	gravel drain	6	30	10

Silica sand whose index properties are listed in Table 2 was used in all the experiments.

Table 2. Index properties of Silica sand

Gs	2.616
D_{50} (mm)	0.15
e max	1.047
e min	0.584

Model preparation

Each model was constructed in the following procedure. 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 non liquefiable layer was made by dry deposition method. Later, cellulose liquid was introduced from the porous bottom of the box at very low pressure to minimize the damaging effect on the initially formed soil structure. The saturation period took a long time due high density of the layer and the high viscosity of the cellulose liquid. The second layer with 40% relative density representing liquefiable layer was made by the water sedimentation method. The cellulose liquid was first introduced into the box. As earlier, a predetermined amount of sand was weighed and poured in the laminar box. The level of cellulose liquid was raised to the next level carefully to maintain the water pressure as minimum as possible to eliminate the disturbance of the already formed ground. Drains both gravel and micro were installed in the upper layer of the model, with only 5 cm of their height being placed in the lower layer. The micro drains were installed prior to the preparation of the upper layer of the model. The gravel drains were installed as follows. Prior to the beginning of the preparation of the upper layer, plastic tubes (formworks) were placed and wrapped by a filter textile to prevent possible penetration of sandy grains into the gravel drain. Simultaneously with the preparation of the upper soil layer, the tube was filled with the previously determined amount of gravel. The plastic tube was then gradually taken out leaving behind the formed drain, i.e., the gravel wrapped with the filter textile. After the performed series of tests, their interior was checked to reveal that the penetration of sand into the drain was not significant.

Each model ground was excited in the longitudinal direction with harmonic sine waves. Shaking of models was performed at seven stages beginning with 50 gal, 100, 200, 300, 400, 500 & 600 gal 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.

TEST RESULTS

The generation and dissipation of excess pore pressure in saturated sandy layers were of a particular interest and they were observed during and after the termination of shaking. Figure 4 shows the time histories of excess pore pressure in vertical array of the model BDRA, at depths of 10, 20 and 30 cm in the central part of the container. The solid line represents the level of the initial effective stresses, σ_{v0}'. Intensity of shaking was 200 gal. 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 entire layer with Dr = 40% liquefied. Such a state of excess pore pressure was preserved during the shaking and even after shaking stopped.

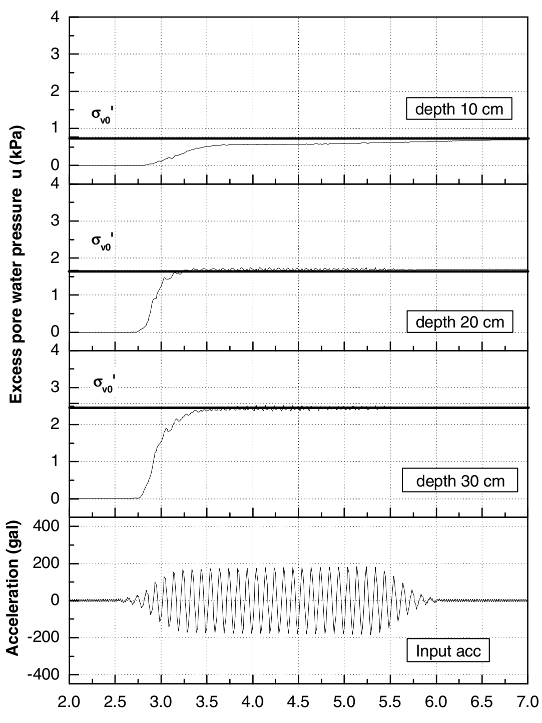

Fig.4. Time histories of *u* – BDRA model

Results of pore pressure dissipation, the time histories of excess pore pressure ratio r_u of the BDRA model are given in Fig. 5. 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.

Time histories of excess pore pressure ratio presented in Fig.5 show three characteristic zones. Zone (1) during shaking shows that excess pore pressure accumulated quickly in soil layers resulting in full liquefaction. In zone (2) after the end of shaking, still very high level of excess pore pressure ratio was maintained in ground model for long period of time. Dissipation started first at deeper layers but very slowly. In zone (3) after 5 min of shaking stopped, excess pore pressure ratio still didn’t dissipate completely. There is residual excess pore pressure ratio of 60% of initial effective vertical stresses and even more. The results pointed out that upper layer with relative density Dr=40% has high potential of liquefaction.

Shear stresses and shear strains were calculated from the acceleration time histories at two different time periods. Figure 6 shows two shear stress-strain (τ-γ) hysteretic loops at time: t_1=2.50-2.80 s and t_2=5.00-5.50 *s*. The shear stress-strain relationship at t_1 is characterized by a well-formed

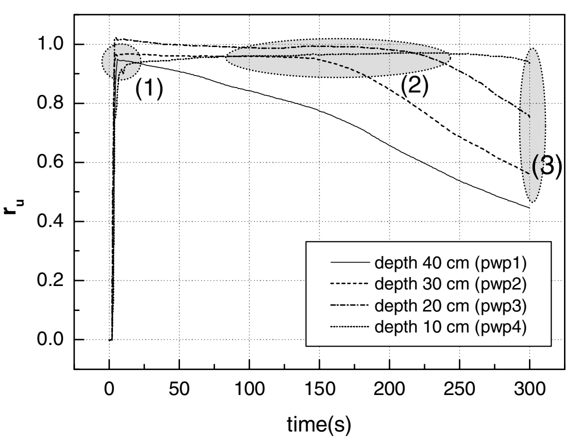

Fig.5. Dissipation of *u* – BDRA model

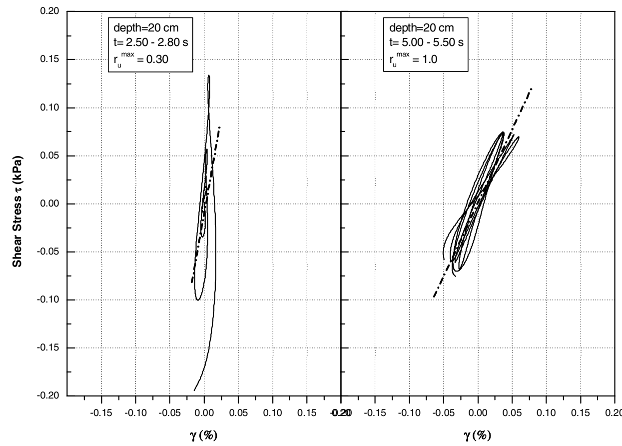

Fig.6. Shear stress-strain relationship - BDRA

hysteretic loop with an approximately vertical orientation showing that soil layer keep its rigidity. At time t_2, the τ-γ relationship is characterized by a hysteretic loop, which now, unlike the loop at time t_1, is inclined toward the horizontal axis. This means that degradation of layer stiffness takes place and soil layer lost its rigidity.

Basic ground model BDRA was improved by vertical drains. The drains were installed at an interval of 10 cm. Time histories of excess pore water pressure for the ADRA model under the excitation intensity of 200 gal are presented in Fig. 7. This diagram is composed of three graphs showing the time histories of the input excitation and the excess pore pressures at 1 and 3 cm distance from drains and depth 30 cm (transducers pwp1 and pwp3). The solid line represents the level of initial effective vertical stresses σ_{v0}'. Figure 8 shows the time histories of excess pore pressure ratio r_u for the entire duration of the experiment. Compared to the experiment on BDRA model with no drains (Fig.5) it is clear that micro drains accelerated the dissipation process and excess pore pressure ratio r_u dropped fast down.

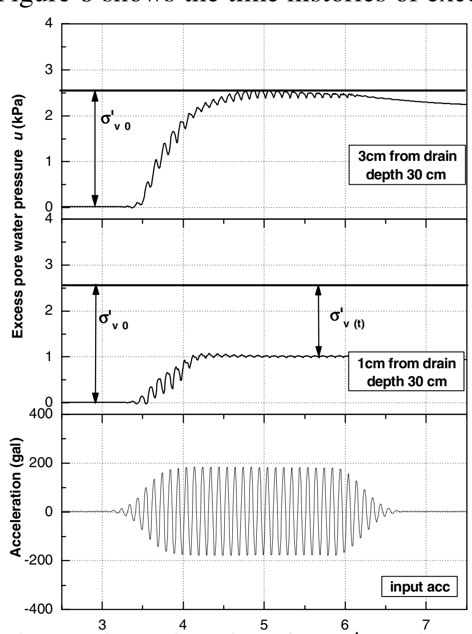

Fig.7. Time histories of *u* – ADRA model

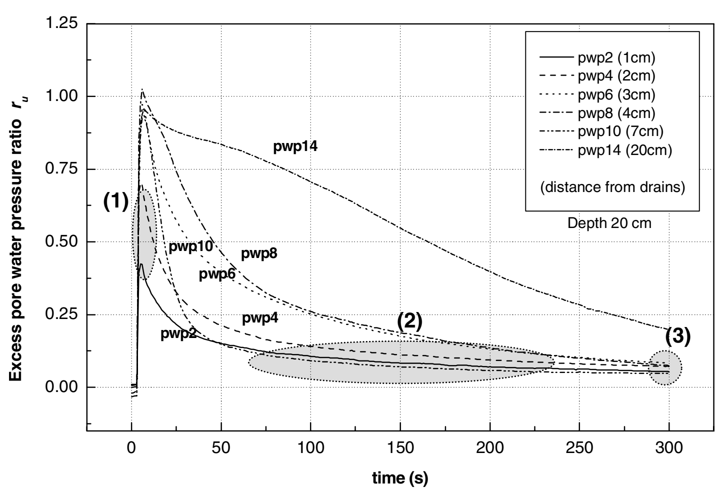

Fig.8. Dissipation of r_u – ADRA model

In Fig. 8 are presented three characteristic zones similar to Fig.5. Zone (1) during shaking shows no big accumulation of excess pore pressure. In zone (2) after the end of shaking, dissipation took place , decreasing the excess pore pressure ratio very quickly. Zone (3) after 5 min of shaking stopped, excess pore pressure ratio dissipates completely and returns to initial values.

DISCUSSION

The installation of the vertical drains led to the modification of the state of excess pore pressure in loose saturated sandy soils. This modification mainly refers to decrease of the level of maximum pore pressure resulting in avoidance of liquefaction. The relationship between the maximum excess pore water pressure ratio r_u and excitation intensity are given in Fig.9 & Fig.10 for different distance from drains. These figures show that improved model with micro drains presents considerable decrease of r_u at lower distances from the drains of 1 - 2 cm, whereas, with the increase in distance and excitation intensity, excess pore pressure ratio r_u approaches the corresponding values for the non treated soil model.

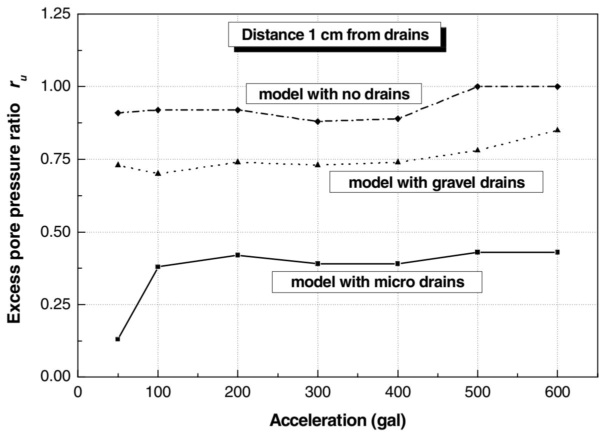

Fig.9. Max r_u at 1 cm from drains

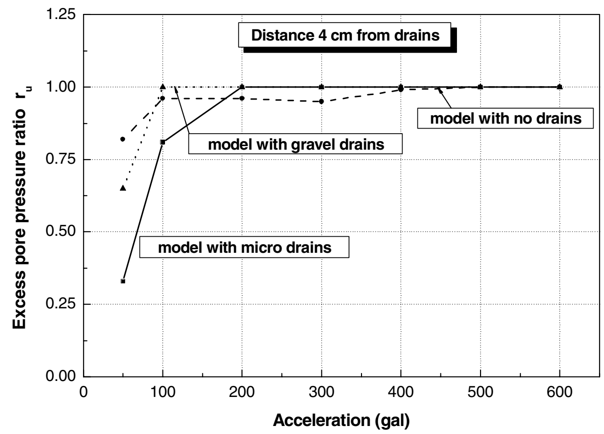

Fig.10. Max r_u at 4 cm from drains

Another important issue on which micro drains have significant effects is elongating the necessary time to liquefaction. Results presented in Fig.11 show that drains significantly increase the time (cycles) to liquefaction occurrence. This tendency decrease on higher intensity of shaking. Another important issue on which drains have significant effects is elongating the necessary time to liquefaction. Results presented in Fig.11 show that drains significantly increase the time (cycles) to liquefaction occurrence. This tendency decrease on higher intensity of shaking. Generation rate of excess pore pressure in model with and without drains were analyzed and presented in Fig. 12. As it is shown in this graph drains decreased the maximum generation rate and also shifted the time the time when maximum generation rate took place

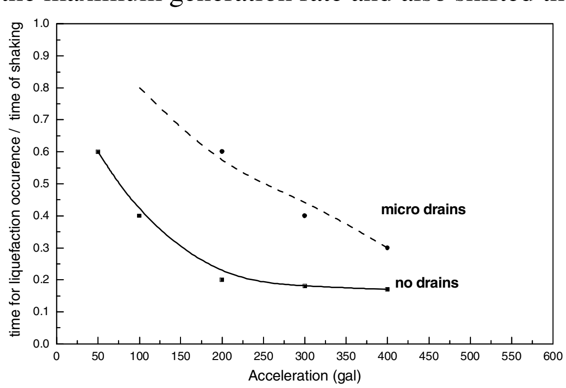

Fig.11. Necessary time for liquefaction

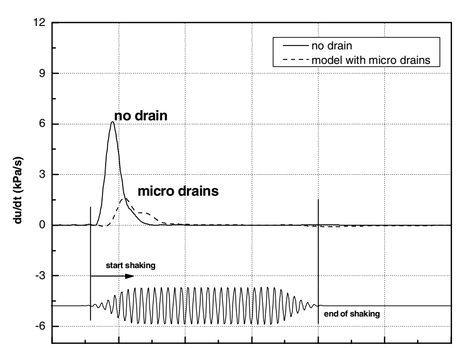

Fig.12. Time history of generation rate of u

CONCLUSIONS

Based on the results from the experiments and analyses performed within the frames of this study, the following conclusions can be made:

- Presented micro drains considerable decrease the excess pore water pressure ratio generated by earthquake shaking in potentially liquefiable soils.
- Installed micro drains decreased the maximum generation rate of excess pore water pressure.
- Micro drains also have a positive role upon the shortening of the time period for complete dissipation.
- Proposed new drain method proved to be more efficient that traditionally one.
- The effect of the installed drains upon the stress and strain states could not be observed with the experiments done on improved soil models.

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