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EDUS PROJECT (EARTHQUAKE DAMAGE TO UNDERGROUND STRUCTURES)

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SUMMARY

Findings and the activities from the EDUS (earthquake damage to underground structures) project are highlighted in this paper. The project involves various types of unique experiments to clarify the seismic performance of buried structures such as pile foundations near and after the failure conditions. The major objectives of the EDUS project are to make fundamental studies on the seismic responses of soils and soil-pile and soil-pipe systems and to improve our understanding on their performance at extreme seismic events.

INTRODUCTION

A large number of pile foundations have been found damaged and failed during historically major earthquakes; e.g., damages and failures of piles in Niigata (Hamada and O’Rourke, 1992) and a number of pile foundations in Kobe due to the Hyogo-ken Nambu earthquake in 1995. The key causes of the damage and failures of the pile foundations in such earthquake were liquefaction and lateral ground movements due to liquefaction. However, pile foundations were also damaged due to the strong ground shaking caused by seismic activities. Therefore, there is a strong need for improved understanding of the dynamic behavior of and for better design methodologies for pile foundations.

This paper highlights our activities on an international joint research project titled EDUS (Earthquake Damage to Underground Structures). The ultimate objective of the EDUS project is to improve our understanding of the behavior and performance of pile foundations during destructive earthquakes. The project is organized and administered by WSU (Wayne State University) and NIED (National Research Institute for Earth Science and Disaster Prevention, Science and Technology Agency of Japan).

Table 1 summarizes our activities related to the EDUS project up to 1997. To accomplish the ultimate objective of the project, our activities include; 1) small-scale 1-g shaking-table tests, 2) large-scale 1-g shaking-table tests, 3) centrifuge tests, and 4) model pile-section tests. Results obtained from the variety of tests are used to improve our numerical prediction methods for seismic soil-pile interaction. We are particularly interested in the failure mechanisms of pile foundations. The test models that we designed for the EDUS project were made as simple as possible. Also, we adopted the same procedures and techniques to prepare and install the test models; we needed to achieve repeatability of test results and to make evaluation of numerical methods as simple and clear as possible.

LARGE-SCALE SHAKING-TABLE TESTS

One of the most significant components of the EDUS project is a series of large-scale shaking-table tests conducted at NIED in Tsukuba, Japan. The size of the shaking table is approximately 15 m by 15 m, and the payload is 500 tons. The maximum displacement and velocity amplitudes of the shaking system are 22 cm and 75 cm/sec. For this EDUS project, we designed and constructed a large-scale laminar shear box with a height of 6 m and plan dimensions of 11 by 3.5 m. Due to its huge size, we were able to employ models with small

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geometrical scaling factors on the order of, say, 1.0 to 1.5. Therefore, the phenomena observed in our large-scale tests should be reasonably representative quantitatively of what we observe in the field.

A typical shaking-table test model employed in the EDUS project is shown in Fig. 1, which involves a level sand layer and a pile foundation model. In some tests, of course, the model did not have a pile foundation model. The model pile foundation was installed into the laminar shear box before filling the shear box with the test sand. Efforts were made not to densify the sand around the piles to prepare the sand layer in a homogeneous condition as much as possible. The model piles were typically pinned at their tips, but their heads were in most cases nearly rigidly connected to their structural models.

The measurement system consisted basically of the strain gages attached to the piles and of accelerometers and pressure transducers in the sand layer and on the model piles, Fig. 1. The accelerometers and pressure transducers in the sand layer were secured onto a rolled plastic net, which was expected to follow essentially the movement of the sand layer during the test. Results from the large-scale shaking table tests will be highlighted below for two types of test conditions; tests with dry sand layer and tests with saturated sand layer.

Some Findings from Dry Sand Layer Cases Dry sand layers were subjected to shaking with a peak shaking-table acceleration in excess of 600 gals. With such high intensity shaking, the sand layer exhibited almost no amplification of shaking from its bottom to the top. The shear moduli of the sand layer were compiled and represented as a function of shear strain amplitudes. An example of such relations are shown in Fig. 2. These are generally consistent with those reported by previous works; e.g., Iwasaki et al (1978) and Ishibashi and Zhang (1993). The responses of the sand layer could be reproduced reasonably well using a nonlinear site response method such as SRANG (Kagawa, 1996), and numerical predictions by equivalent-linear methods were quite acceptable. It should be noted that the shapes of the stress-strain curves that these numerical methods use are in moist cases very much different from the ones estimated from test results.

Figure 3 shows comparisons of strain-gage readings from three difference cases. All three cases had steel pipe piles. Case (a) involved no structural mass on top of the pile, and the model was excited by an earthquake time history recorded at the Port Island during the Kobe earthquake of 1995. Cases (b) and (c) had a steel mass as a structural model, and the shaking-table input was sinusoidal motion with a frequency of 3 Hz and acceleration levels of 400 and 600 gals. Figure 3 clearly shows that the kinematic interaction produces a pronounced peak in strain-gage reading in the lower half of the pile in Case (a), and that the kinematic and inertial interaction have comparable contributions to pile strain in Cases (b) and (c). These results suggest that the kinematic interaction can be very important to pile design, especially when the foundation soils will not degrade their stiffness during seismic shaking. Responses of the pile could be predicted reasonably well using a numerical method such as NONSPS (Kagawa, 1996), although the details of the p-y relations even for these relatively simple situations need to be improved.

Figure 4 shows a p-y relation, near the top of the pile, obtained from a sinusoidal shaking test with an acceleration amplitude of approximately 300 gals towards the end of the shaking. The soil-pile interaction is dominated by the inertial interaction, and the shape of the p-y curve may be similar to what we would expect for such situations. It should, however, be noted that the shapes of the p-y loops towards the final stage of shaking imply high viscous effects.

Some Findings from Saturated Sand Layer Cases When the sand layers were completely submerged and in loose conditions (i.e., relative density typically less than 40 %), the sand layers nearly liquefied during shaking. Sand boils were always observed during and after shaking. Figure 5 shows typical measurements of acceleration and pore-water pressures in the sand layer. As demonstrated by many researchers, due to pore-water pressure build-up, sand loses its stiffness and it transmits low frequency motion only. Also, even after complete liquefaction of the sand layer, motion is transmitted in loose sand due mainly to its dilatant behavior. We confirmed that the p-y relations for these cases also exhibited dilatant behavior of liquefied sand around the pile; soil reaction to the pile regains with increasing pile motion relative to the sand.

CENTRIFUGE TESTS

Centrifuge tests have been conducted to simulate the large-scale shaking-table test results. The major purposes of the centrifuge tests were to examine the degree of agreements between the large-scale and centrifuge test results and to improve our techniques for conducting centrifuge tests. So far, we performed two types of centrifuge tests: 1) tests to simulate the dynamic responses of dry sands, and 2) tests to simulate soil-pile interaction in saturated sand undergoing liquefaction.

Comparisons were made of the frequency response characteristics of dry sand layers obtained from the large-scale and centrifuge tests. The height of the sand layer was 5.0 m in the large-scale test, and the geometrical scaling factor of 15 was used in the centrifuge test. The unit weight of the test sand was approximately 1.6 gf/cm^3 in both tests. In the large-scale test, the acceleration amplitude was kept at 50 gals with the frequency of shaking slowly varied from 7 Hz to 1 Hz. The frequency response characteristics measured in these two types of tests agreed reasonably well. The most recent comparative tests on dry sand layers also show good agreements between the two types of tests, although some minor details of sand responses have been found somewhat different.

The centrifuge test model was used to simulate the soil-pile interaction in saturated sand undergoing liquefaction. The model pile foundation in the corresponding large-scale test consisted of four pre-stressed concrete piles with an outside diameter of 0.3 m, and inside diameter of 0.128 m, and a length of 6 m. The geometrical scaling in the centrifuge test was 15. The piles were pinned at their tips, but they were grouted into the structural mass at their heads. The spacing ratio (=center-to-center distance/diameter) of the piles was six to minimize pile-group interaction effects. The pre-stressed concrete piles supported a steel block with a weight of 22.2 tons to represent the inertial effects of typical mid-rise buildings with a number of stories of about 10.

Figure 6 shows profiles of pore-water pressures in the sand layers. Due to slight difference in excess pore-water pressure build-up and dissipation in the two types of tests, the sand layer in the centrifuge test was excited more severely than in the large-scale test especially in the early stage of shaking. Therefore, excess pore-water pressures developed more rapidly in the centrifuge test. Also, excess pore-water pressures dissipated quicker in the centrifuge test. This difference in pore-water pressure responses had a large impact on measured responses of sand and pile.

Comparisons of the profiles of bending moment in the piles indicated that the pile in the large-scale test vibrated at the second mode in the early stage of shaking and then at the first mode thereafter. However, the pile in the centrifuge test vibrated at the second mode from the beginning to the end of the test. Therefore, the pile moment in the centrifuge test was generally smaller than that in the large-scale test, except near the pile head.

The results highlighted above and the findings from our ongoing studies indicate that the results from these two types of tests give reasonable agreements and that advanced testing techniques may need to be developed to achieve closer agreements.

MODEL PILE-SECTION TESTS

A model pile-section testing device has been developed and used to augment data on static and dynamic interaction between the pile and its surrounding soil. More specifically, the device was to obtain detailed information about the soil reaction to pile as affected by the excess pore-water pressures developed in sand around the pile. The device consists of a pressure chamber, which houses a sand layer (plan dimensions of 93 cm by 125 cm with a thickness of 34 cm), and of a rigid hollow model pile (an outside diameter of 3.8 cm). The top of the model pile is rigidly connected to a driving system and is forced to move in one horizontal direction in a controlled manner. The pressure chamber was first filled with water and the test sand was then placed in the chamber at a relative density of approximately 37 %. The key information we measured consists of horizontal resistance to the model pile and changes in the pore-water pressures on the surface of the pile and in the sand. Some of the findings are highlighted below:

Backbone p-y Curves The backbone curves of the p-y relations obtained from a series of the model pile-section tests were compared with the static p-y curve predicted by the Reese and Cox method. The model pile-section tests were run at various values of loading rate, and their results vary considerably. Our results show that the slowest loading case involving a sinusoidal loading with a cyclic frequency of 0.0025 Hz gives the p-y curve that is consistent with the Reese and Cox prediction and that the faster loading cases give lower backbone p-y curves than slower loading cases. The pore-water pressure measurements indicate that the faster loading cases involve less time for excess pore-water pressure dissipation and lower p values.

These results demonstrate that the Reese and Cox method provides reasonable estimation of the p-y relation at relatively shallow depths and that the excess pore-water pressure build-up and dissipation in soils around a pile have controlling effects on p-y responses.

Cyclic p-y Curves The first-cycle p-y curves obtained from the model pile-section tests with cyclic frequencies of 0.0025, 0.25, and 0.5 Hz were compared. The comparisons revealed several interesting observations.

When the rate of loading is slow and excess pore-water pressures have sufficient time to dissipate, the backbone p-y curves tend to have "parabolic" shapes. This is no longer true when the rate of loading becomes faster and residual excess pore-water pressures tend to remain in sand around the pile. This was demonstrated in the p-y curves for frequencies of 0.25 and 0.5 Hz.

When the rate of loading is slow, the p-y curve is no longer symmetric with the initial p-y state. This is shown in the p-y curves for frequencies of 0.0025 and 0.25 Hz. Soil reaction to pile does not return to the initial neutral state. The sand around the pile is pushed into one direction with leaving some permanent distortion in sand. However, this offset of the origin of the p-y curve tends to be insignificant as the rate of loading becomes faster. Therefore, this offset is probably not so important in seismic soil-pile interaction where the rate of loading is around 0.5 to 2 Hz.

CONCLUDING COMMENTS

Some findings from our EDUS project have been presented in this paper. It was a major challenge to design, fund and fabricate the large-scale laminar shear box. Fortunately, the laminar shear box has encountered sufficient interest from various organizations and it has been utilized quite well since it was completed in the summer of 1995. Also, it was a challenge to develop techniques for preparing large-scale test samples in a consistent way. It was necessary for us to spend approximately three years to accomplish this using small-scale shaking-table models.

With the development of our capabilities of performing large-scale shaking-table tests, we hope that the modelling and testing techniques for centrifuge tests will make at a faster pace. The large-scale tests are always time-consuming and expensive, and they cannot be performed on a daily basis. On the other hand, centrifuge tests are by far less labor-intensive, and therefore they are economic.

The authors intend to present their findings from mainly their numerical analyses and developments in the next earliest opportunities. The authors express their sincere appreciation to those people who were involved in or who provided any forms of support to the EDUS project. Without their participation and help, this project could not have been realized.

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Table 1 Overview of the EDUS Project (up to 1997)

Small-Scale Model Tests	1993~1998	
Small-Scale Shaking Table Tests	1994~1995	
Large-Scale Shaking Table Tests	1996	1997
Number of Tests :	11	10
Model Types :	Steel pipe piles PHC piles (prestressed) Pipe line models	Steel pipe piles RC piles
Sand Layers :	Level ground (moist sand) Level ground (saturated sand) Sloping ground (saturated sand)	Level ground of moist and saturated sand
Input Motions :	Sine waves Sweep tests Earthquake motionss (Kobe, Taft, and others) Step pulses	Random waves Rinkai Sine waves G0C waves Cyclic pile-head loading, etc.
Dynamic Centrifuge Tests	Steel pipe piles in moist and saturated sand.	RC piles in moist and saturated sand

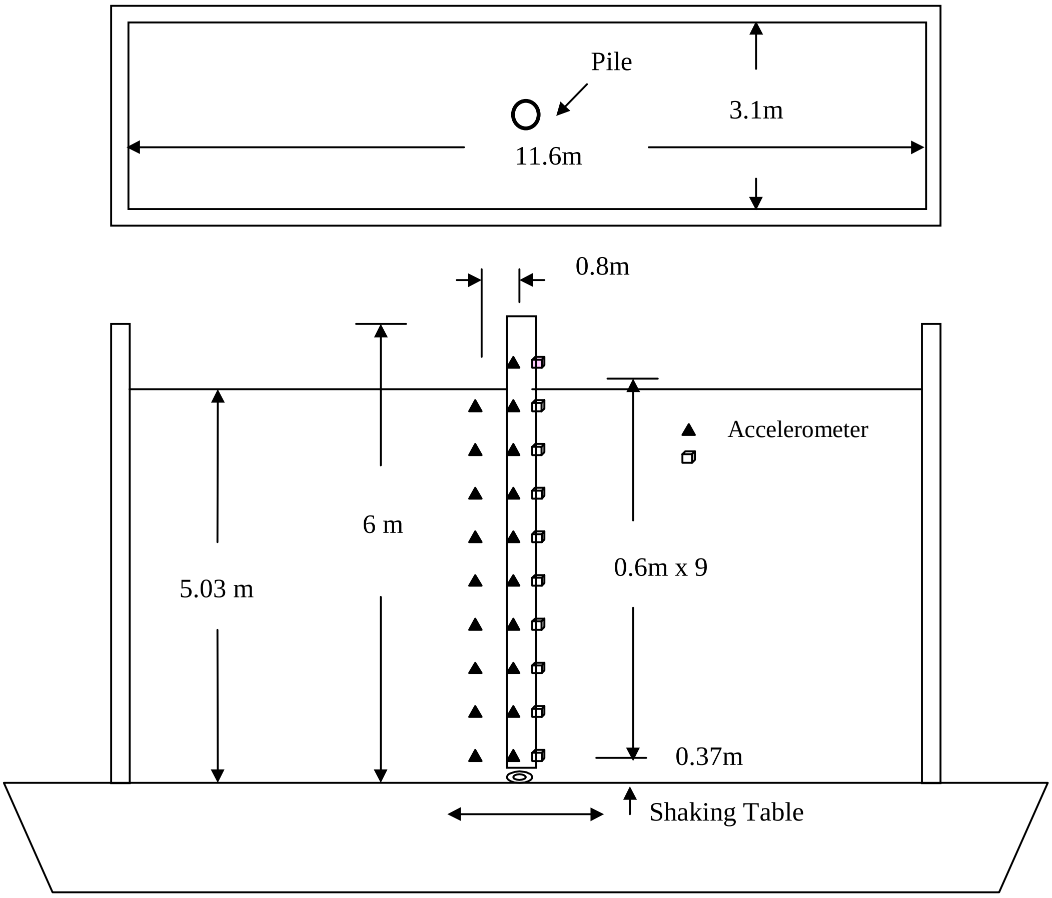


Fig. 1 Large-Scale Test Set-up

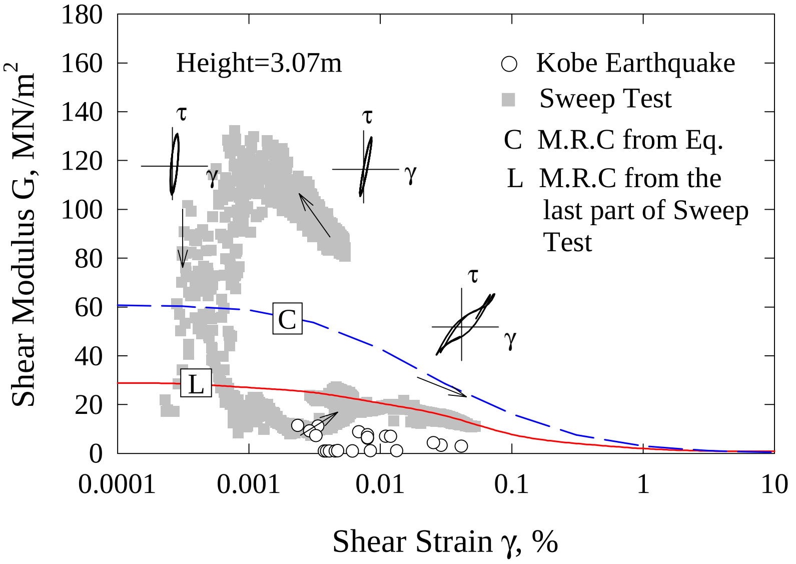
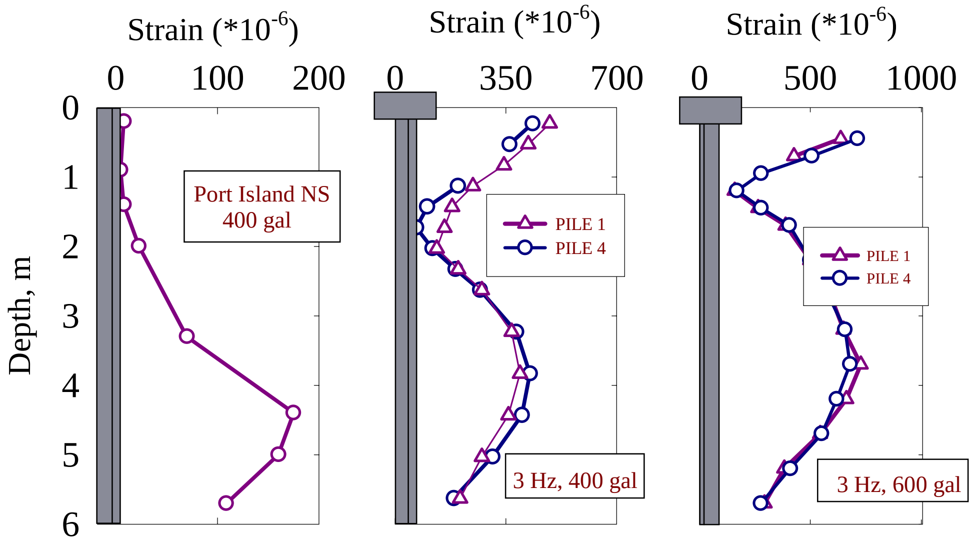


Fig. 2 Shear Moduli of Dry Sand from Large-Scale Tests



(a) May 23, 1996 (b) May 28, 1997 (c) May 30, 1997

Pile Strain

Fig. 3 Pile Strain from Large-Scale Tests

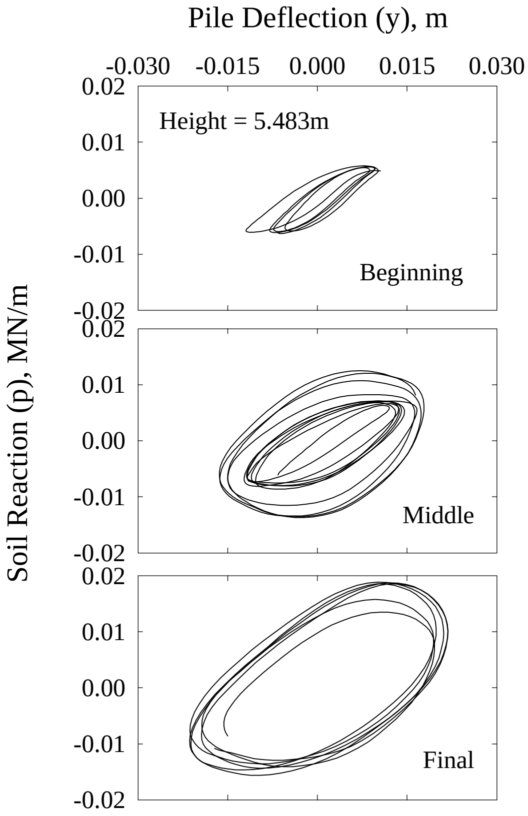


Fig. 4 p-y Responses
From Large-Scale
Tests

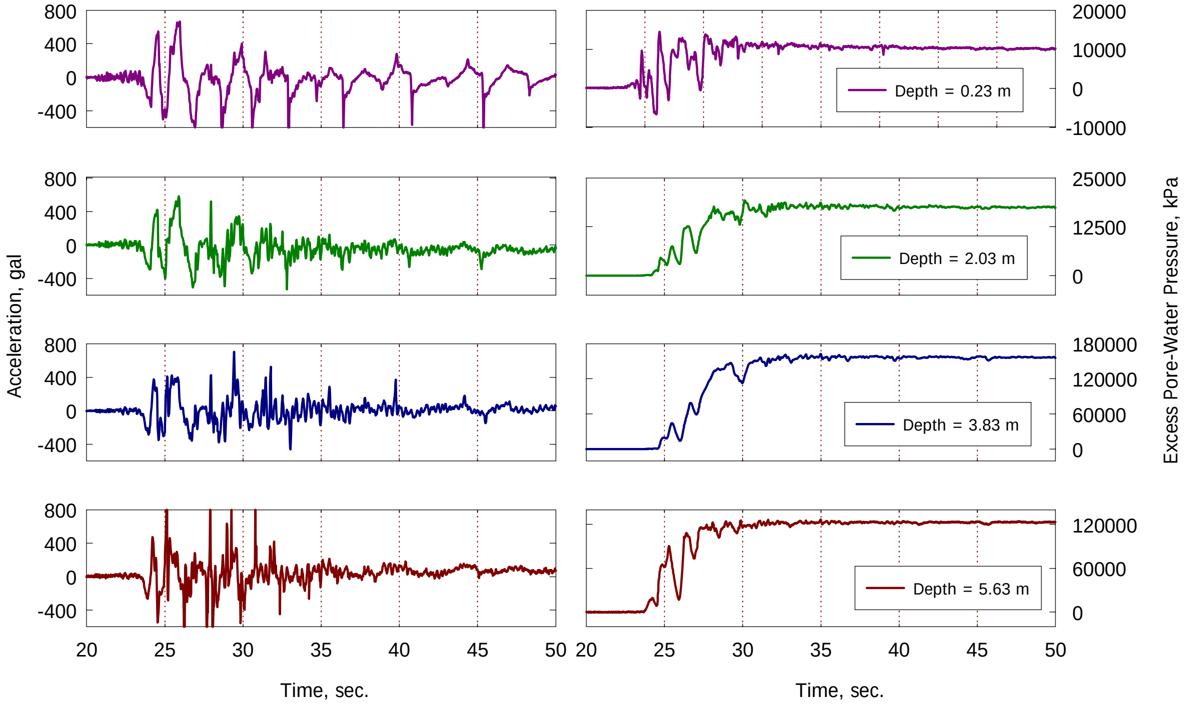


Fig. 5 Acceleration and Pore Pressure Responses of Sand Layer from Large-Scale Tests

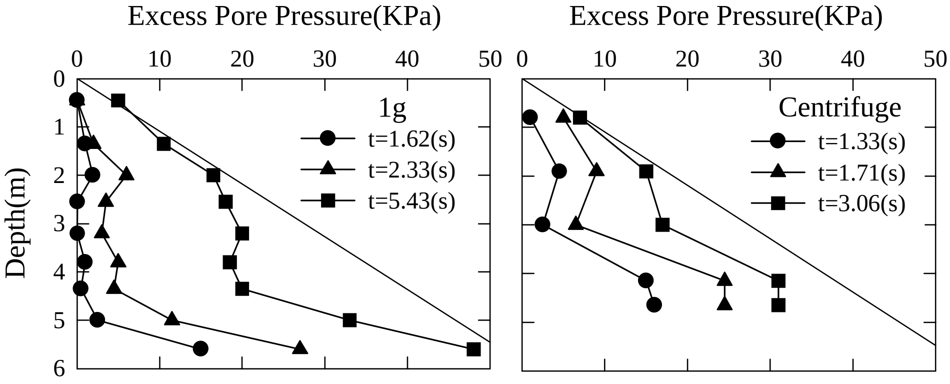


Fig. 6 Pore Pressure Responses of Sand Layer from Large-Scale and Centrifuge Tests