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LARGE SCALE BIAXIAL SHEAR BOX TESTS ON SHAKING TABLE

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SUMMARY

For the study of the behavior of saturated sand, especially liquefaction, under two-dimensional earthquake shaking, a physical model test using a large laminar shear box on the shaking table at the National Center for Research on Earthquake Engineering （NCREE） was developed. The shear box is composed of 15 layers of aluminum alloy frames with a specimen size of 1.88m×1.88m in plane and 1.52m in height. Each layer consists of an inner frame and an outer frame, which are allowed to move freely without torsion on the horizontal plane subjecting to a two-dimensional shear wave action induced by the shaking table. The sand specimen inside the shear box is prepared by the wet sedimentation method from a specially made pluviatior. Pore water pressures and accelerations within the soil, displacements, accelerations, and velocities of the frames at various depths were measured during tests under both one- and two-dimensional shaking. After each shaking test, the settlement of the sand inside the shear box was measured and evaluated. This paper compares the water pressure changes in the sand specimen under one- and two-dimensional shakings. It is found that the excess water pressures generated during a two-dimensional shaking are higher than those generated under one-dimensional shaking of the same magnitude. The sand at a shallower depth is more susceptible to liquefaction than the sand at a greater depth.

INTRODUCTION

In order to study the soil behavior, such as liquefaction and soil-structure interaction, large soil specimens have been placed on a shaking table that can reproduce the actual seismic ground shaking according to the earthquake recording under either 1 g or centrifugal conditions (e.g., De Alba [1], Hushmand [2], Taylor [3], Endo [4]). Thus, the soil behavior under the more realistic seismic loading conditions can be observed and analyzed. At present, most analyses of soil seismic behavior such as liquefaction are tested and modeled as a one-dimensional problem. The understanding of the soil behavior under two- and three-dimensional seismic loading conditions is very limited. (e.g., Pyke [5], Ishihara [6,7], Kramerer [8]). Up to present, no other large-scale physical model test under two-dimensional loading, either on 1g shaking table or in a centrifuge, was performed. A large-scale laminar biaxial shear box on the 5 m × 5 m shaking

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table at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan has thus been developed to test a large soil specimen under two-dimensional earthquake shaking for studies of liquefaction and soil-structure interaction in a level ground.

BIAXIAL LAMINAR SHEAR BOX

The biaxial laminar shear box developed at NCREE is composed of 15 layers of frames. Each layer consists of an inner frame with inside dimensions of 1880 mm × 1880 mm × 1520 mm and an outer frame of inside dimensions of 1940 mm × 2340 mm × 1520 mm. Both frames are made of a special aluminum alloy (specific gravity = 2.70) with a section dimension of 30 mm in thickness and 80 mm in height. The aluminum alloy is adopted for its sufficient strength and rigidity, and its lightweight to minimize the effect of the inertia of the frame on the soil movements. A 20-mm gap is provided between each frame to avoid rupture of the silicon rubber membrane. Surrounding these frames there are four rigid outside steel walls to support the frames. The setup of this device is shown in Figure 1 schematically.

As showed in Figure 1, there are sliding rails built on two opposite sides of the outer walls to provide a nearly frictionless movement of every outer frame in the X direction. Similarly, sliding rails are also provided on every layer of the outer frame that every layer of inner frame can move in the Y direction relative to the outer frame. With these fifteen layers of inner and outer frames, the soil at various depths can have multidirectional movements in the horizontal plane without torsion according to the wave actions induced by the shaking of the table.

In order to obtain a watertight shear box to contain the saturated soils, a 2-mm thick silicon rubber membrane was placed inside the box. The silicon rubber membrane was fixed at the top, bottom, and sixth inner frames of the shear box. Silicon sealant was applied at the seams to prevent leakage. Shear box was then tested on the shaking table with various input motions and the results showed that the performance of this biaxial laminar shear box was satisfactory.

Details of the design, manufacturing, and tests of the performance of the empty laminar shear box can be found in Ueng [9,10].

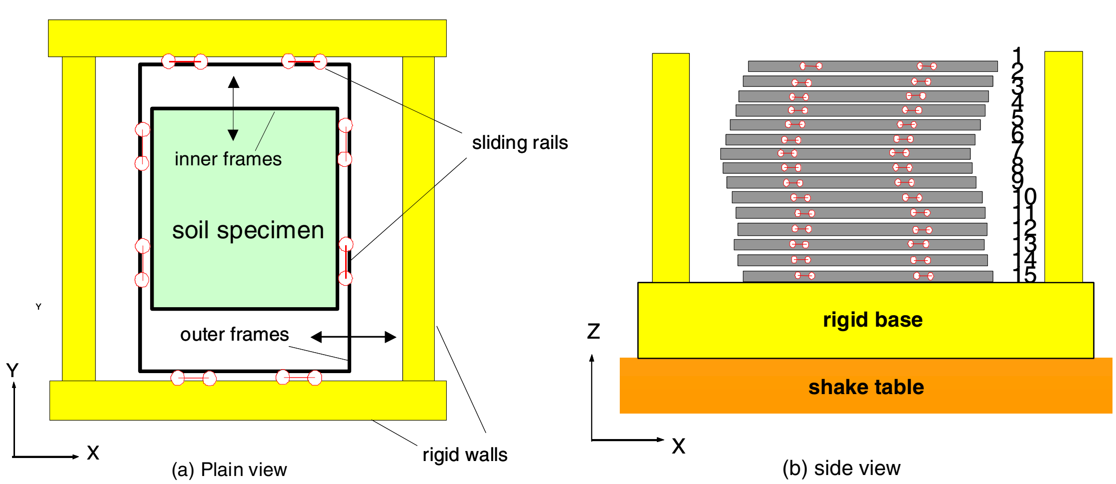


Figure 1: Schematic drawings of biaxial laminar shear box

SAMPLE PREPARATION

A commercially available clean silica fine sand from Vietnam was used in this study. The grain size distribution of the sand is shown in Figure 2. The basic properties are given in Table 1. The maximum and minimum index densities were tested according to ASTM D4253 Method 1B (wet method) and ASTM D4254 Method A.

A specially made pluviator as shown in Figure 3 was used for the preparation of the sand specimen inside the shear box by raining method. It was found that saturation of the specimen by introducing water into dry sand was very difficult and unreliable according to the small scale tests using a small container made of acrylic. Therefore, the wet sedimentation method was adopted for the sample preparation in this study. The sand was rained down into the shear box filled with water to a pre-calculated depth. The uniformity, density, and saturation of the specimen were checked with the cone penetration test (CPT) by a mini-cone of a diameter of 8.9 mm at various locations and P-wave velocity measurements across the specimen horizontally. The results indicated that the sand was well-saturated and the density of sand was uniform in a horizontal plane but increased slightly with depth.

Details of sample preparation for the large shear box were discussed in Ueng [11].

Table 1: Properties of Vietnam sand

Shape	Color	G_s	D_{50} (mm)	C_u	e_{max}	e_{min}	ρ_{max} (kg/cm^3)	ρ_{min} (kg/cm^3)
Sub-angular	White	2.65	0.29	1.72	0.912	0.610	1652	1385

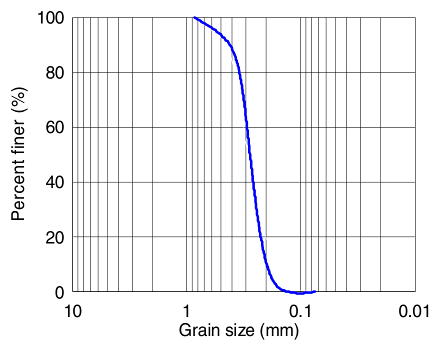


Figure 2: Grain size distribution of Vietnam sand

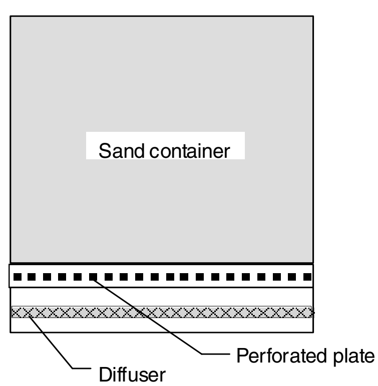
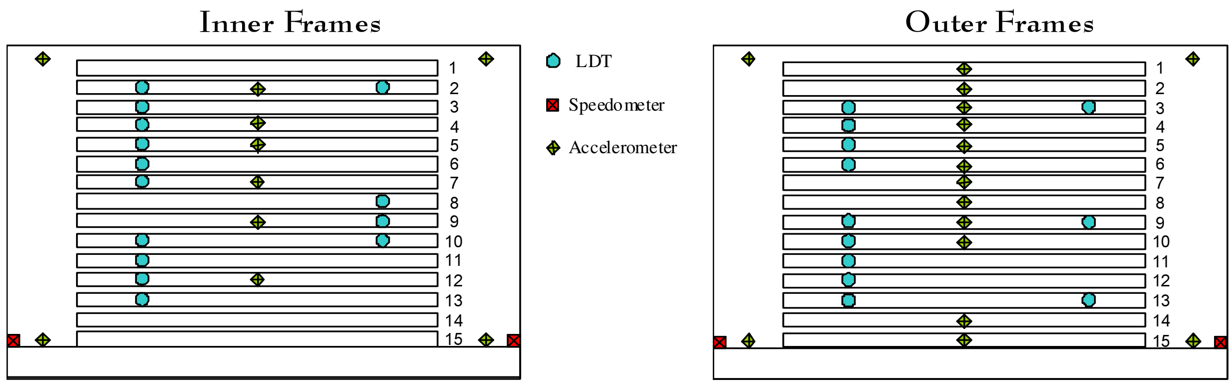


Figure 3: Schematic drawings of the pluviator

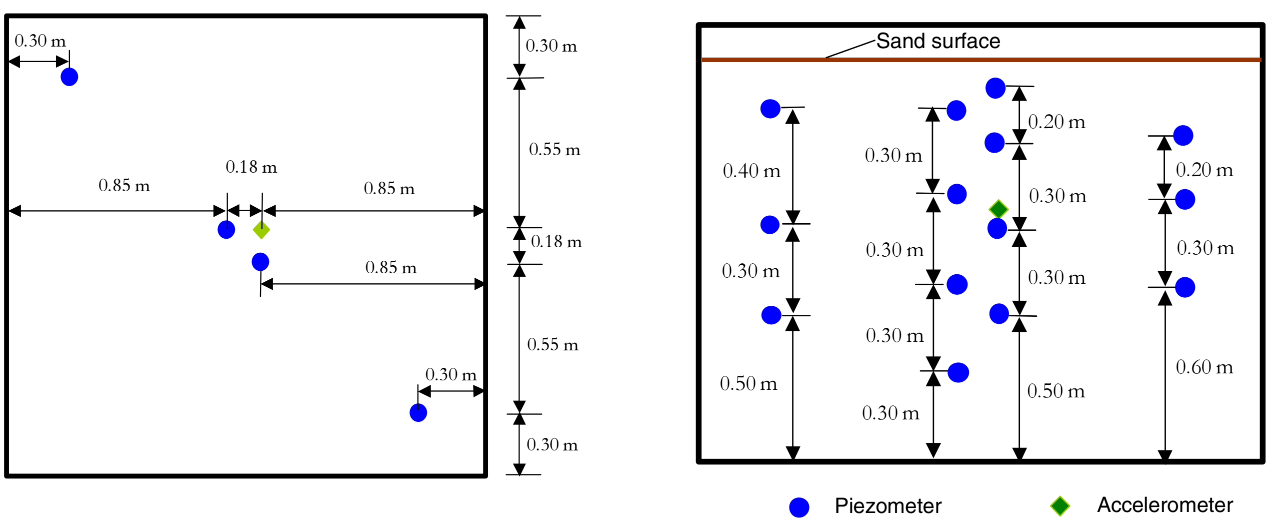
INSTRUMENTATION

Transducers for displacements, velocities, and accelerations were placed at various locations and depths on the inner frames, the outer frames, and the outside walls. Figure 4 shows the layout of the instrumentation on the shear box. In addition, mini-piezometers and mini-accelerometers are installed inside the box for pore water pressure and acceleration measurements at different locations and depths, as shown in Figure 5, before placing the sand into the shear box. They are positioned with thin fishing wires during sample preparation. The wires were cut prior to the shaking tests to prevent disturbance on the behavior of the specimen under the shaking tests.



(a)Inner frames (b)Outer frames

Figure 4: Instrumentation layout on the shear box



(a) Plane view (b) Vertical view

Figure 5: Instrumentation layout inside the shear box

SHAKING TABLE TESTS

A series of shaking tests have been conducted on the sand specimen in the biaxial laminar shear box on the shaking table at NCREE on four separate dates, i.e., August 2002, January 2003, April 2003 and November 2003. Various one- and two-dimensional input motions were imposed by the shaking table. The input motions included sinusoidal (2 Hz and 4 Hz) accelerations, with amplitudes from 0.03g to 0.15g in X and/or Y directions. In the two-dimensional shaking, there is a 90° phase difference between the input acceleration in X and Y directions, i.e., a circular or ellipse motion was applied. The acceleration, full and reduced amplitudes, recorded at Yuan-Lin and She-Tou seismograph stations in Chi-Chi Earthquake were also imposed in X and Y directions. For example, Table 2 shows the test sequence in the April 2003 shaking table tests.

Table 2: Shaking table tests, Apr. 2003

Input Motions	X (N-S)		Y (E-W)		Duration (s)
	Freq. (Hz)	A_{max} (g)	Freq. (Hz)	A_{max} (g)	
Case1 (1-D)			2	0.03	10
Case2 (1-D)			2	0.05	10
Case3 (1-D)	2	0.03			10
Case4 (1-D)	2	0.05			10
Case5 (2-D)	2	0.03	2	0.03	10
Case6 (2-D)	2	0.05	2	0.05	10
Case7 (2-D)	2	0.05	4	0.05	10
Case8 (2-D)	2	0.05	2	0.075	10
Case9 (1-D)	Chi-Chi Earthquake, She-Tou (E-W),25%				
Case10(1-D)	Chi-Chi Earthquake, She-Tou (N-S), 25%				
Case11(2-D)	Chi-Chi Earthquake, She-Tou, 25% (PGA=0.20g)				
Case12(1-D)			2	0.05	10
Case13(1-D)			2	0.05	10
Case14(1-D)			2	0.05	10
Case15(1-D)			2	0.03	10
Case16(1-D)			2	0.03	10
Case17(1-D)			2	0.05	10
Case18(1-D)	2	0.03			10
Case19(1-D)	2	0.05			10
Case20(2-D)	2	0.03	2	0.03	10
Case21(2-D)	2	0.05	2	0.05	10
Case22(2-D)	2	0.05	4	0.05	10
Case23(2-D)	2	0.05	2	0.075	10
Case24(1-D)	Chi-Chi Earthquake, She-Tou (E-W)				
Case25(1-D)	Chi-Chi Earthquake, She-Tou (N-S)				
Case26(2-D)	Chi-Chi Earthquake, She-Tou, PGA=0.20g				

TEST RESULTS

Sand surface settlement and density changes

The sand surface settled, i.e., the density of sand increased during each shaking and the amounts of settlement increased with the intensity of shaking as expected especially when there was liquefaction of the specimen. Table 3 shows the settlement and the average dry density after each shaking test calculated according to the height of the sand specimen in the April 2003 shaking table tests. The test results showed that significant settlement occurred only when there is liquefaction of the soil. The settlement of the sand specimen after liquefaction tended to be larger for the specimen of lower relative density. Soil samples were taken using short thin-walled tubes at different locations and depths after the completion of the shaking table tests. The densities of these samples were obtained as shown in Figure 6. The results depict a somewhat lower dry density of the soil obtained in the thin-walled tubes than that calculated according to the height of the sand surface. It is also found that the density of the sand in the shear box increases slightly with depth.

Pore water pressure changes

Pore water pressure changes measured at different depths in the sand specimen under one- and two-dimensional sinusoidal shaking of the same amplitude in the shaking table tests are compared. The depths referred in the following discussion are the initial positions of piezometers before shaking table tests. The depths changed due to the movements of the transducers during shaking. Therefore, these depths are approximate and they are used for reference of the comparisons. For the same amplitude of shaking, two-dimensional shaking tests were conducted after one-dimensional tests. Therefore, the sand is generally denser in two-dimensional tests than that in one-dimensional tests in the comparisons.

Figure 7 shows the comparisons of water pressure changes at depths of 242 mm, 659 mm and 1053 mm below the sand surface under one- and two-dimensional sinusoidal shakings with an input amplitude (A_{max}) of 0.05g in the January 2003 shaking test. It can be seen that the water pressure increments under a two-dimensional shaking were higher than that during a one-dimensional shaking, even though the density of sand was higher (Dr ≈ 38%) during two-dimension shaking than that during one-dimensional shaking (Dr ≈ 11%).

In the April 2003 shaking test, the comparisons of water pressure changes between one- and two-dimensional shakings of A_{max} = 0.05g are given in Figures 8 and 9, respectively. For the lower sand densities (Dr = 14%-30%), Figure 9 shows that there is about the same amount of water pressure increase under one- and two-dimensional shakings with a higher sand density in two-dimensional shaking. It implies the same tendency of higher water pressure generation in two-dimensional shaking. Figure 9 indicates that, for the denser sand (Dr ≈ 60%), very small water pressure was generated under both one- and two-dimensional 0.05g sinusoidal shakings and no significant increases of density of sand were induced by such shakings. The results also showed that two-dimensional shaking caused higher water pressure increases at various depths of the specimen.

According to the measurements of water pressure changes at different depths in the sand specimen as shown above, it is found that the sand at a shallower depth is more susceptible to liquefaction than that at a greater depth. In many cases, the shallower soil liquefied without liquefaction of the deeper soil. The excess pore water pressure tends to dissipate faster for the deeper soil than for the shallower soil.

Comparison of soil responses and frame movements

Acceleration within the soil and that of the frame at the same depth under one-dimensional sinusoidal shaking are compared. In the January 2003 shaking tests, the acceleration time histories within the soil and those of the inner frame at the same depth and pore water pressure changes near the accelerometer within the soil during one-dimensional shaking of the A_{max} = 0.05g and A_{max} = 0.075g are given in Figures 10 and 11, respectively. Figure 10 indicated that the induced acceleration within the soil and that of the inner frame is identical. Figure 11 showed that the induced acceleration within the soil and that of the frame under one-dimensional shaking was almost the same before liquefaction, whereas the acceleration within the soil decreased after liquefaction, but that of the frame became irregular with spikes. Such behavior can be explained by the sudden loss of stiffness of the soil. The results also showed that soil responses and frame movements at the same depth are almost the same before liquefaction. Therefore, we can analyze the induced motions at different depths during the shaking tests for the study of ground motion responses under one- and two-dimensional shaking before liquefaction.

Table 3: Settlements and densities after each case of shaking, Apr. 2003

	Sand surface (m)	Dry density (kg/m^3)	Void ratio	Dr		Sand surface (m)	Dry density (kg/m^3)	Void ratio	Dr
Preparation	1.447	1418	0.869	14.13%	Case 14	1.347	1527	0.735	58.43%
Case 1	1.447	1418	0.869	14.26%	Case 15	1.347	1527	0.735	58.43%
Case 2	1.429	1437	0.844	22.33%	Case 16	1.347	1527	0.735	58.46%
Case 3	1.425	1440	0.840	23.69%	Case 17	1.347	1527	0.735	58.54%
Case 4	1.416	1450	0.827	27.89%	Case 18	1.347	1527	0.735	58.54%
Case 5	1.414	1452	0.825	28.81%	Case 19	1.347	1527	0.735	58.54%
Case 6	1.397	1471	0.802	36.40%	Case 20	1.346	1529	0.734	59.02%
Case 7	1.387	1482	0.789	40.80%	Case 21	1.346	1529	0.733	59.07%
Case 8	1.373	1498	0.770	47.08%	Case 22	1.346	1529	0.733	59.27%
Case 9	1.370	1501	0.765	48.53%	Case 23	1.340	1535	0.726	61.58%
Case 10	1.350	1524	0.739	57.26%	Case 24	1.311	1571	0.687	74.48%
Case 11	1.349	1525	0.737	57.82%	Case 25	1.293	1594	0.662	82.66%
Case 12	1.348	1526	0.737	58.04%	Case 26	1.268	1627	0.629	93.76%
Case 13	1.348	1527	0.736	58.35%					

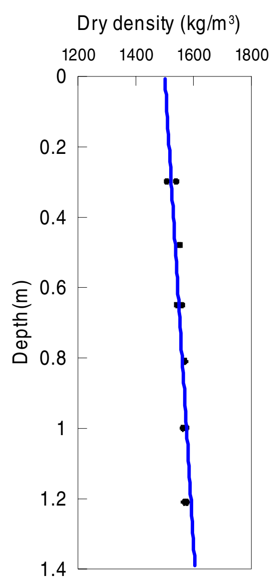
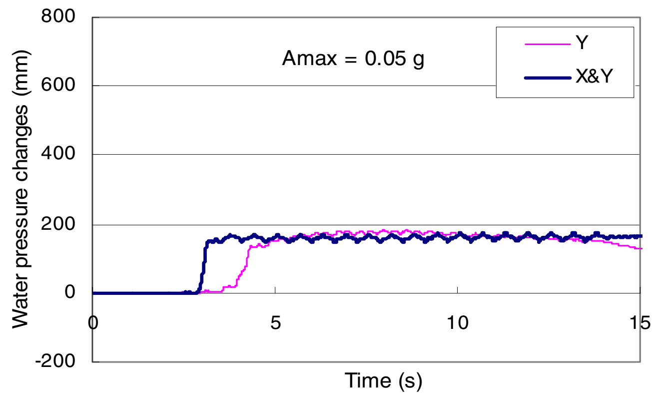
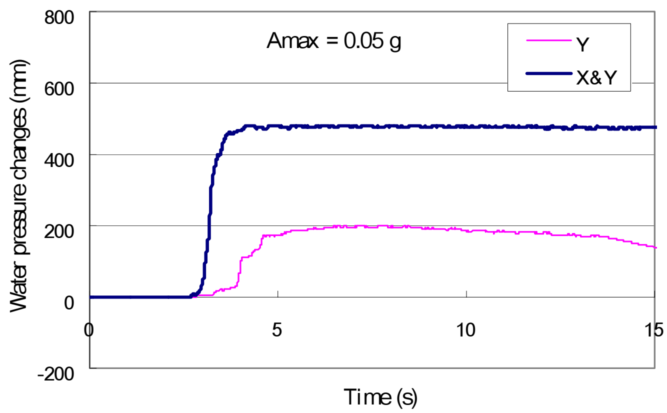


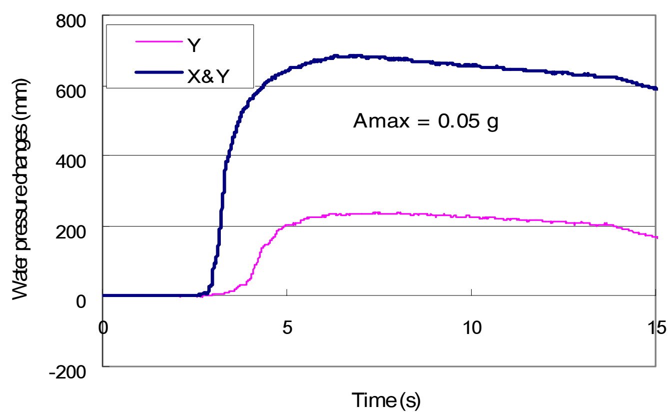
Fig. 6: Dry densities after shaking test, Apr. 2003



(a) 242 mm below sand surface

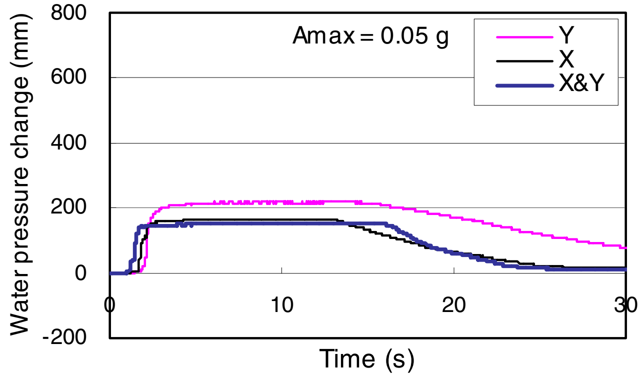


(b) 659 mm below sand surface

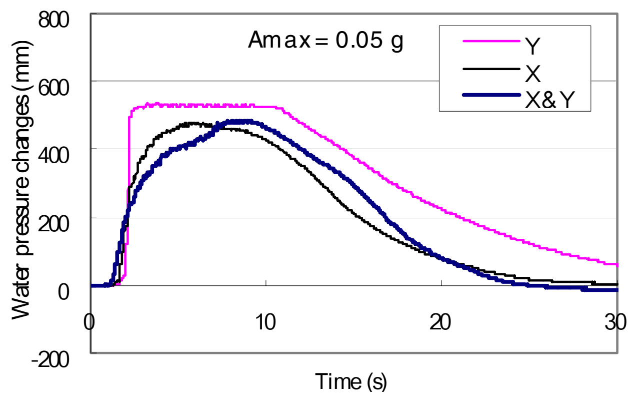


(c) 1053 mm below sand surface

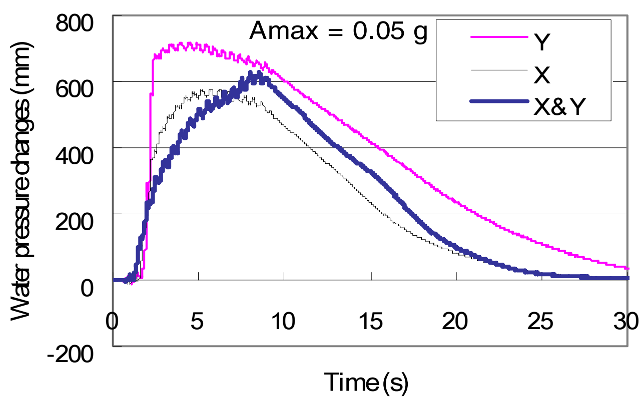
Figure 7: Water pressure changes, Jan. 2003



(a) 317 mm below sand surface

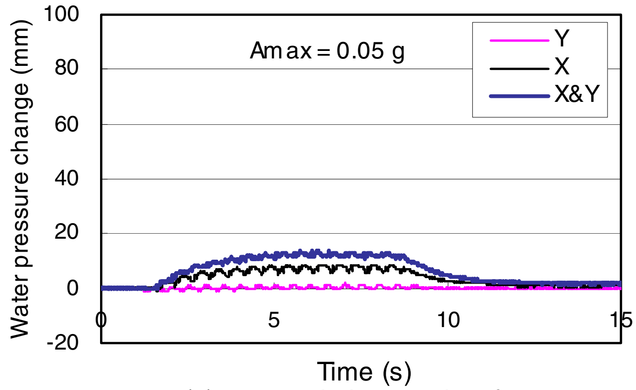


(b) 700 mm below sand surface

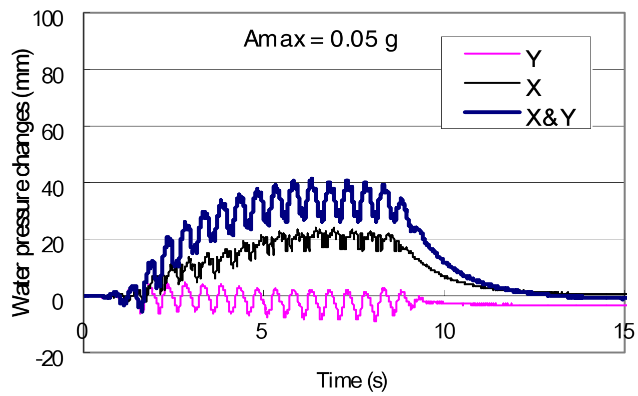


(c) 947 mm below sand surface

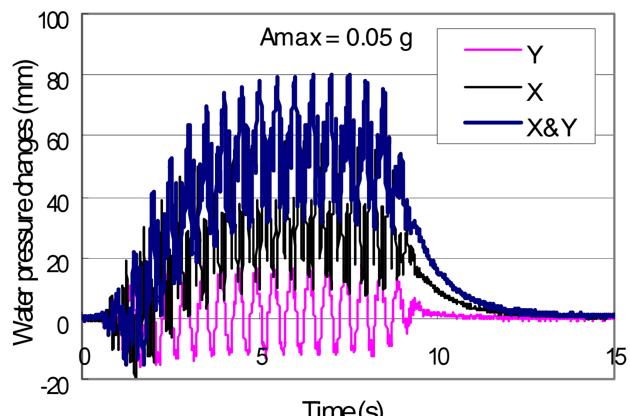
Figure 8: Water pressure changes, Dr = 14-30%, Apr. 2003



(a) 317 mm below sand surface

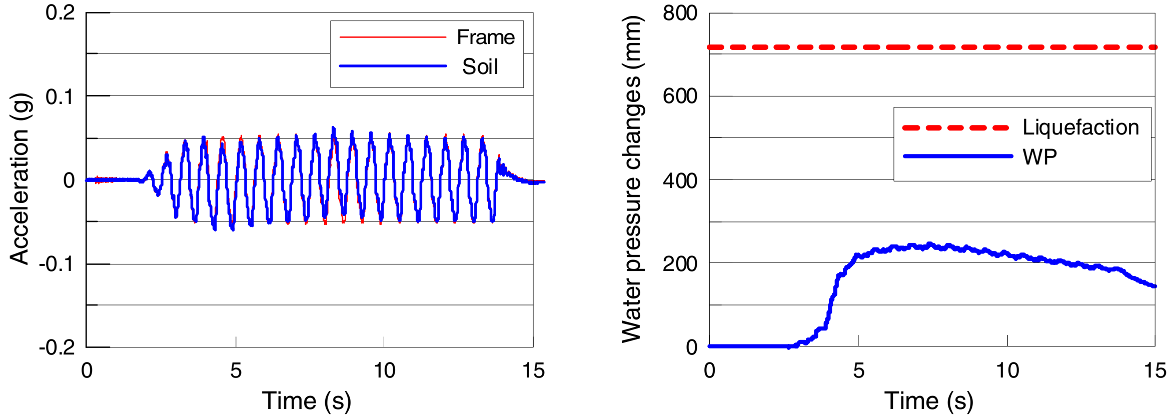


(b) 700 mm below sand surface



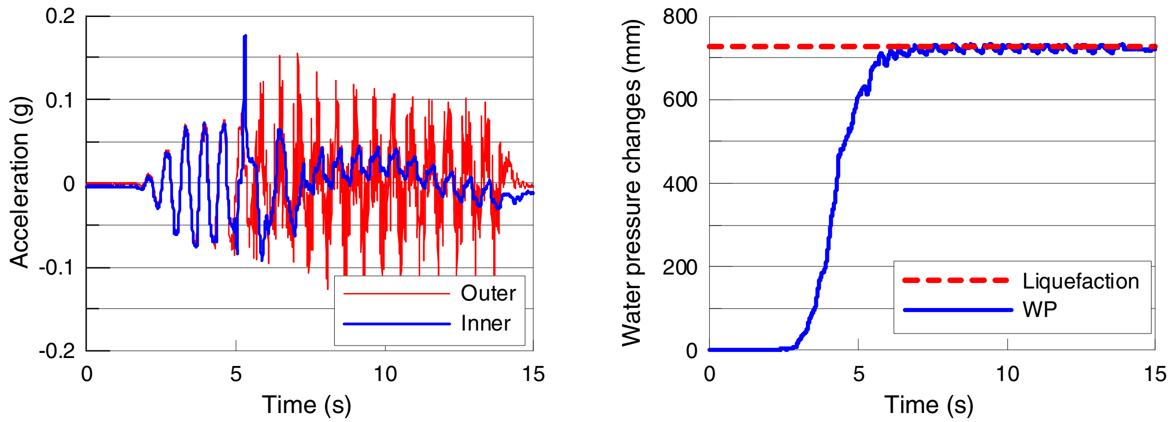
(c) 947 mm below sand surface

Figure 9: Water pressure changes, Dr = 60%, Apr. 2003



(a) Acceleration time history (b) Water pressure changes

Figure 10: 1-D shaking of A_{max} = 0.05g, Jan. 2003



(a) Acceleration time history (b) Water pressure changes

Figure 11: 1-D shaking of A_{max} = 0.075g, Jan. 2003

CONCLUSIONS

A large laminar shear box with a specimen size of 1880 mm × 1880 mm × 1520 mm was developed and manufactured at NCREE. A series of one- and two-dimensional shaking table tests were performed on saturated Vietnam sand in the shear box to study the water pressure changes and liquefaction in the specimen. The settlement of the sand specimen after liquefaction tended to be larger for the specimen of lower relative density. The test results showed that the pore water pressures generation during a two-dimensional shaking were higher than those under the one-dimensional shaking of the same acceleration magnitude. The sand at a shallower depth is more susceptible to liquefaction with a slower excess pore water pressure dissipation than that at a greater depth.

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