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PORE PRESSURE GENERATION IN SATURATED SAND INDUCED BY ONE- AND TWO-DIMENSIONAL SHAKINGS

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ABSTRACT

The test data obtained from shaking table tests at the National Center for Research on Earthquake Engineering were processed and analyzed to study the effect of one- and two-dimensional shakings on soil liquefaction. The measured pore water pressures generated under one- and two-dimensional shakings at various locations within the sand specimens were compared. It was found that the ratios of the maximum excess pore water pressure generated in the sand specimens under two-dimensional shakings to that generated under one-dimensional shakings were always larger than 1.0 and the values were about the same at all different piezometer locations in the same shaking table test series. The ratio of the maximum pore pressure ratio, $(r_u)_{\max} = (\Delta u/\sigma_v')_{\max}$, under two-dimensional shakings to that under one-dimensional shakings is approximately 5.0, and 3.0 for Vietnam sand and Mailiao sand, respectively. Analyses based on these findings showed that the liquefaction resistance of sand under two-dimensional shakings is approximately 0.75 to 0.85 of that under one-dimensional shakings.

Key words: Pore pressure, liquefaction, shaking table test, multidirectional shaking, sand, earthquake.

1. INTRODUCTION

In the previous large earthquakes, *e.g.*, 1964 Japan Niigata Earthquake, 1995 Japan Kobe Earthquake, 1999 Taiwan Chi-Chi Earthquake, 2011 New Zealand Christchurch Earthquake, and 2011 East Japan Earthquake, extensive soil liquefaction occurred accompanied with ground settlement and lateral spreading. The soil liquefaction caused severe damage of structures, bridges, water front facilities, slope failures, and loss of properties and lives.

When saturated sand is subject to earthquake shakings or cyclic loadings, the sand grain structure tends to become more compact resulting in generation of excess pore water pressure and reduction of effective stresses. As the excess pore water pressure reaches the original effective overburden stress, the sand loses its grain contacts and behaves like a liquid without shear strength. The earthquake shakings applied on the in situ soil in the field are three-dimensional (3D) vibrations. Generally, the shakings on a horizontal plan induced by the upward shear wave propagation is the most concerned dynamic loadings in earthquake engineering. It should be noted that the two-dimensional (2D) shaking on a horizontal plan can be a multidirectional vibration. Current evaluation of soil responses and liquefaction subjected to earthquake shakings are mainly based on the results of field liquefaction cases and laboratory testing and analyses. The liquefaction potential evaluation methods according to the actual field liquefaction case histories included the effect of 2- or 3-dimensional shakings. On the other hand, most of the soil dynamic testing and liquefaction analyses consider only one-dimensional (1D) shaking condition. However, according to the general understanding, the liquefaction resistance of sand should be lower under 2D shakings than that under 1D shakings. The probable reasons are (1) the input energy in 1D shakings is lower than that in 2D shakings of the same vibration amplitude; (2) the sand particles have less constraint (more degrees of freedom) to move around (instead of riding over the other particles) under 2D shakings resulting in a higher tendency of soil contraction which in turn induces excess pore water pressures with less efforts.

Very few studies have been conducted on soil liquefaction under two- or three-dimensional shaking. Based on the pore water generation mechanism proposed by Martin *et al.* (1975) and the volume changes obtained in shaking table tests on dry sand by Pyke *et al.* (1974), Seed *et al.* (1978) obtained that the rate of pore water pressure generation under 2D shakings was approximately twice the generation rate under one-dimensional shakings. This finding became the basis of the reduction factor of 0.9 for considering the multidirectional shaking effect in estimating the field liquefaction resistances from the laboratory simple shear test results used in the present liquefaction potential evaluation methods (Seed 1979). Ishihara and Yamazaki (1980) and Ishihara and Nagase (1988) conducted laboratory multi-directional cyclic simple shear tests on sand, and found the liquefaction resistances of sand under multi-directional cyclic shakings were 70 ~ 90% and 82 ~ 86%, respectively, of those under one-directional shakings. Kammerer *et al.* (2002) also obtained the liquefaction resistance of sand under multi-directional cyclic simple shear loading conditions as low as 61% of that under one-directional loadings.

There were uncertainties in these aforementioned results and their applications due to concerns about the saturation conditions of soil, specimen sizes and limitations of the testing equipment, such as loading and boundary conditions. In this study, shaking table tests on large saturated sand specimens within a biaxial laminar shear box were performed under 1D and 2D (multidirectional) shakings to better simulate the filed conditions, and the pore water pressure generation and liquefaction behavior under one- and two-dimensional shakings were compare to evaluate the effect of 1D and 2D shakings on liquefaction resistance of sand.

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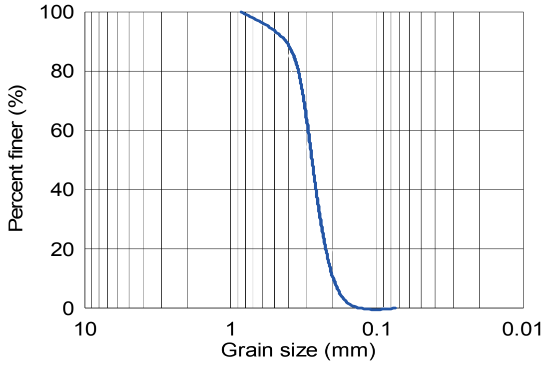
2. LARGE SHAKING TABLE TESTS

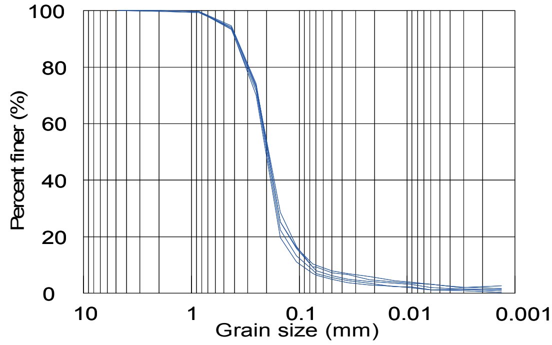
This study examines the results of nine series of shaking table tests (*A* to *I*) on Vietnam silica sand and two series of shaking table tests (*MA* and *MB*) on Mailiao sand conducted at the National Center for Research on Earthquake Engineering (NCREE). Details of the testing equipment, specimen preparation, instrumentation, testing procedures, and some of the test results in these shaking table tests were reported previously, *e.g.*, Ueng *et al*. (2006; 2008; 2010). Only brief descriptions of the shaking table tests relevant to the subject of this paper are given here.

Clean fine silica sand from Vietnam and Mailiao sand with 6 ~ 9% silt from the western coastal area of Taiwan were used in the shaking table tests. Figure 1 shows the grain size distribution curves of these sands. The sand specimens were placed in a biaxial laminar shear box developed at NCREE. The biaxial laminar shear box developed at NCREE, as shown schematically in Fig. 2, is composed of 15 layers of sliding frames. Each layer consists of two nested frames, an inner frame (1880 mm × 1880 mm) and an outer frame (1940 mm × 2340 mm). Both frames are made of a special aluminum alloy with 30 mm in thickness and 80 mm in height, except the uppermost layer that has a height of 100 mm. These 15 layers of frames are separately supported on the surrounding rigid steel walls with a gap of 20 mm between adjacent layers. A 2 mm thick silicone membrane was placed inside the box to provide a watertight shear box to contain the saturated sand. Thus, a sand specimen of 1880 mm × 1880 mm × 1520 mm can be placed inside the inner frames. Linear guideways consisting of sliding rails and bearing blocks are used to allow an almost frictionless horizontal movement without vertical motions. Each outer frame is supported by the sliding rails built on two opposite sides of the outer rigid walls. The bearing blocks on the outer frame allow its movement in the *X* direction with minimal friction. Similarly, sliding rails are also provided for each outer frame to support the inner frame of the same layer such that the inner frame can move in the *Y* direction with respect to the outer frame. With these 15 nested layers of inner and outer frames supported independently on the rigid walls, the soil at each depth can move in a 2D multidirectional fashion in the horizontal plane without torsion in response to the 2D vibrations exerted by the shaking table. The specimens of clean Vietnam sand and Mailiao sand with silt were prepared by the wet pluviation methods and staged wet sedimentation method, respectively, to obtain the desirable homogeneous specimen (Ueng *et al*. 2006, Ueng *et al*. 2008).

1D and 2D input motions were imposed by the shaking table including sinusoidal accelerations with frequencies of 1, 2, 4, and 8Hz and amplitudes (A_{max}) from 0.03 to 0.15 g in *X*- and/or *Y*-directions. For 2D (multidirectional) shakings, there is a 90° phase difference between the input accelerations in *X* and *Y*-directions, *i.e.*, circular motions were applied in this study. Transducers for displacement and acceleration measurements were placed at various locations and depths on the outside rigid walls, the outer frames for *X*-direction motions, and the inner frames for *Y*-direction motions. Fifteen mini-piezometers and 7 mini-accelerometers were installed inside the shear box, as shown in Fig. 3, to measure the pore water pressures build-up and dissipation and the accelerations of soil at different locations and depths. Two settlement plates connected with LDTs were placed to observe the sand surface settlements during shakings.

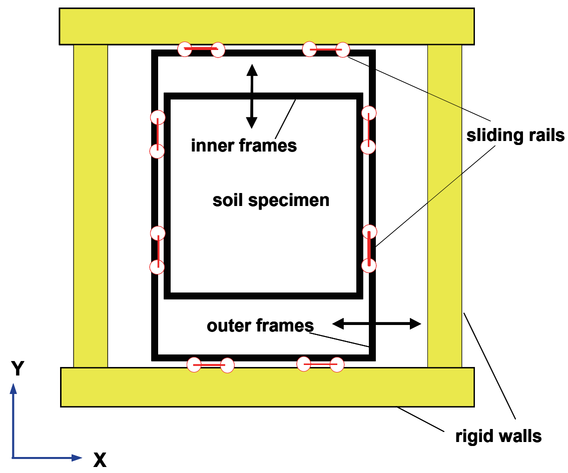


(a) Vietnam sand

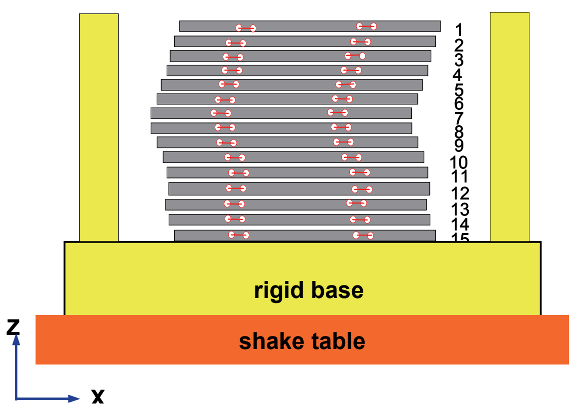


(b) Mailiao sand

Fig. 1 Grain size distributions of tested sands



(a) Plan view



(b) Side view

Fig. 2 Biaxial laminar shear box at NCREE (Ueng *et al.* 2006)

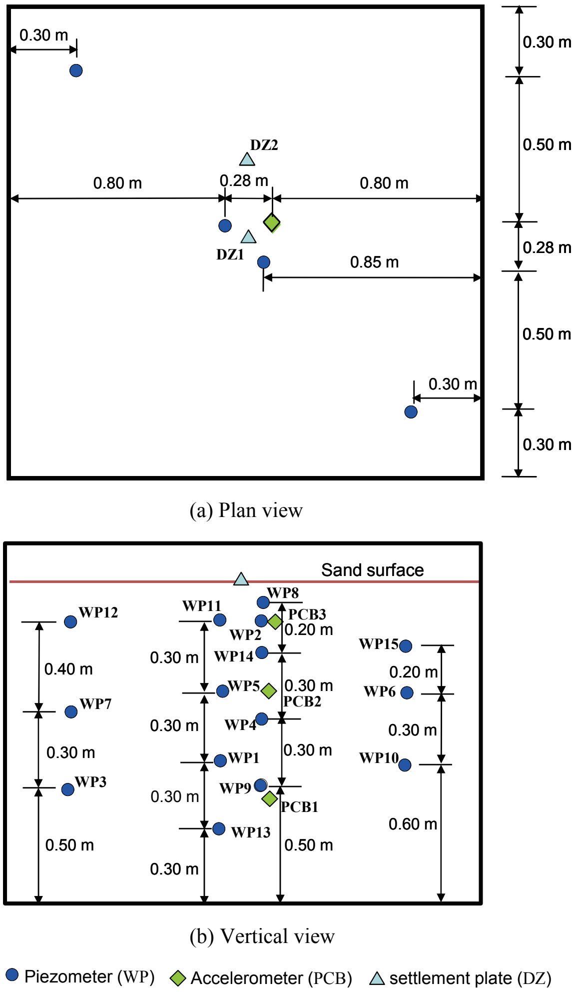


Fig. 3 Typical instrumentation inside the sand specimen

Figure 4 is a typical time history of excess pore pressure u_e measured by pressure transducers at various depths below the sand surface during a 1D shaking table test on Vietnam sand. It shows that in this shaking test, within the upper ≈ 637mm of the specimen, the pore pressures in the sand increased rapidly and the sand liquefied within 4 seconds after shaking started. Figure 5 shows the excess pore water pressure distribution along the depth of the specimen at various times during 1D and 2D shaking tests. It can be seen that 1D shaking induced less excess pore pressure and probably caused only a shallow liquefied layer, while, even with a higher density, the multidirectional 2D shaking caused higher pore pressure increases and a deeper liquefaction zone.

3. ANALYSES OF PORE PRESSURE GENERATIONS IN SHAKING TABLE TESTS

3.1 Selection of Test Data for Analyses and Comparisons

Among shaking table tests *A* to *I* on Vietnam sand and shaking table tests *MA* and *MB* on Mailiao sand conducted at NCREE, test results of 1D shaking tests were paired with that of the corresponding 2D shaking tests with approximately the same sand densities, and loading amplitudes, frequencies and durations. Thus, the pore pressure changes measured by each of the 15 pore pressure transducers installed inside the sand specimens during each pair of tests were compared to evaluate the effect of 1D and 2D shakings on the pore pressure generations. Figure 6 shows examples of comparisons of excess pore pressures generations by the same pore pressure transducer (WP13) in a pair of shaking tests for Vietnam sand and another pair of shaking tests for Mailiao sand under 1D and 2D shakings.

In a shaking table test, liquefaction mostly occurred down to a certain depth from the sand surface instead of the whole specimen. 2D shakings caused slightly, but insignificantly, greater depths of liquefaction than those induced by 1D shakings. The rate of excess pore pressure generations was generally higher under 2D shakings than that under 1D shakings. However, because the pore pressure increases were extremely rapid at the beginning of shaking, it is very difficulty to obtain sufficiently accurate rate of pore pressure generation from the test data. Therefore, the maximum excess pore pressures $(u_e)_{\max}$ measured by the pore pressure transducers were instead obtained for every pore pressure transducer. Since the water pressure transducers might move during shakings, the depth of the same transducer, or its measured hydrostatic pressure, could be different in two different shaking tests. Therefore, the pore pressure ratio $r_u = \Delta u/\sigma_v'$ was used to compare the excess pore pressure generations during

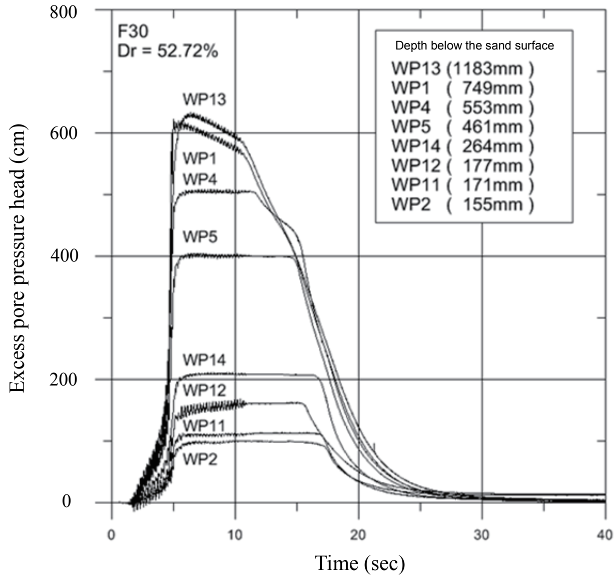
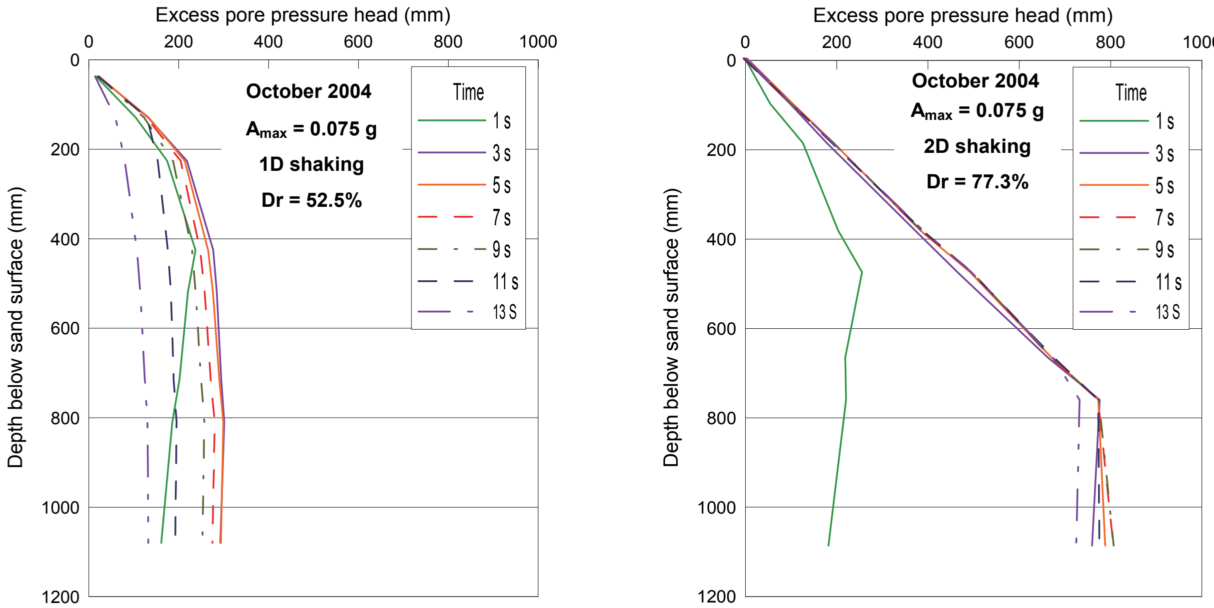


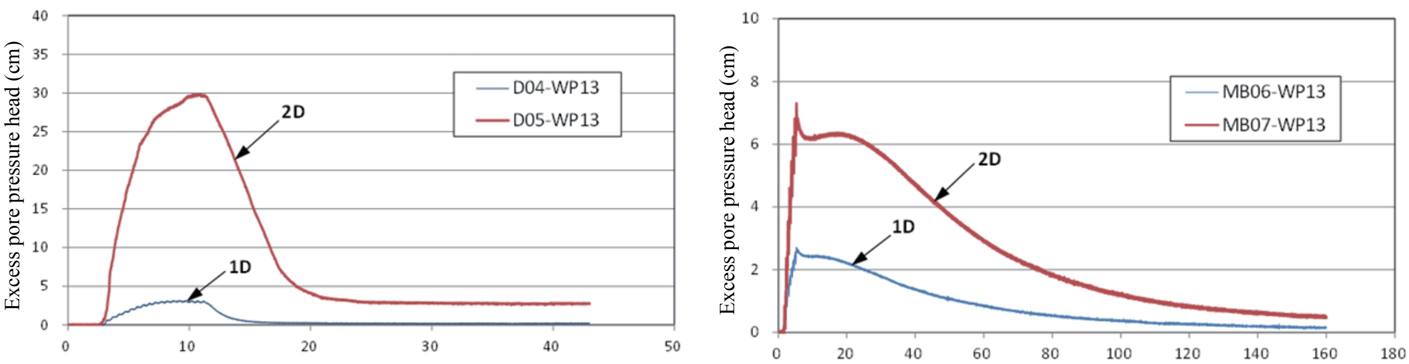
Fig. 4 Pore water changes at various depths during a 1D shaking test, October 2004



(a) 1-D shaking

(b) 2-D shaking

Fig. 5 Excess pore water pressure distributions versus depth during shaking tests



(a) Vietnam sand

(b) Mailiao sand

Fig. 6 Comparisons of excess pore pressure changes (in terms of water height) under 1D and 2D shakings

1D and 2D shakings in this study. In the liquefied zone, $(u_e)_{max}$ would always equal the effective overburden pressure σ_v', *i.e.*, $r_u = 1.0$, during both 1D and 2D shakings. That is, no comparison can be made for pore pressures generation inside the liquefied or nearly liquefied zones. Thus, only the data obtained prior to liquefaction or in the non-liquefied zones were used for comparison in this study. As a result, a total of 19 pairs of shaking tests for Vietnam sand (Table 1) and 17 pairs of shaking tests for Mailiao sand (Table 2) were selected from the results of shaking table tests performed at NCREE. It is noted that a few pairs of tests with noticeable higher relative densities under 2D shakings were used because of scarceness of test data under these test conditions. However, the comparison results showed the same consistent trend with that of other pairs of data.

Table 1 Pairs of 1D versus 2D shaking table tests of Vietnam sand specimens for comparisons

Pair	Shaking test	*X*-direction		*Y*-direction		Duration (sec)	Liquefaction depth (cm)	D_r (%)	$\frac{((r_u)_{max})_{2D}}{((r_u)_{max})_{1D}}$
		Freq. (Hz)	A_{max} (g)	Freq. (Hz)	A_{max} (g)				
1	A01			2	0.04	8		16.79	4.57
	A03	2	0.02	2	0.04	8		34.29	
5	C03	2	0.03			10		23.55	2.88
	C05	2	0.03	2	0.03	10		29.30	
7	C18	2	0.02			10		60.95	1.53
	C20	2	0.03	2	0.03	10		60.95	
8	C19	2	0.05			10		60.95	1.40
	C21	2	0.05	2	0.05	10		61.44	
9	D02			2	0.03	10		7.05	3.21
	D03	2	0.03	2	0.03	10		7.11	
10	D04			2	0.05	10		7.87	10.28
	D05	2	0.05	2	0.05	10	29.59	8.54	
13	E07			2	0.05	20		15.50	2.87
	E13	2	0.05	2	0.06	20		22.24	
19	F01			2	0.03	10		20.37	3.90
	F03	2	0.04	2	0.02	10		21.15	
20	F05			2	0.05	10		21.61	10.74
	F16	2	0.05	2	0.05	10	23.24	25.65	
21	F09			1	0.05	10		22.87	15.13
	F17	1	0.06	1	0.05	10	42.72	27.88	
22	F13			4	0.05	10		23.62	3.00
	F18a	4	0.07	4	0.06	10	51.49	33.16	
23	F22			2	0.08	10	22.63	40.21	2.70
	F33	2	0.08	2	0.08	10	94.50	63.12	
29	F46			4	0.10	10		88.66	8.34
	F53	4	0.13	4	0.10	10	26.56	97.15	
30	H01			2	0.03	10		33.22	10.59
	H02	2	0.04	2	0.03	10	22.19	33.46	
33	I11			2	0.03	11		26.59	5.29
	I13	2	0.04	2	0.03	11		26.98	
34	I12			4	0.03	6.5		26.78	2.50
	I16	4	0.04	4	0.03	6.5		27.52	
36	I19			4	0.04	6.5		28.00	11.29
	I22	4	0.06	4	0.05	6.5	9.95	35.81	
37	I25			2	0.02	11		56.66	1.81
	I27	2	0.03	2	0.03	11		56.83	
40	I30			4	0.05	6.5		57.38	6.91
	I32	4	0.06	4	0.05	6.5	13.49	60.46	
Ave.									5.73

Table 2 Pairs of 1D versus 2D shaking table tests of Mailiao sand specimens for comparisons

Pair	Shaking test	*X*-direction		*Y*-direction		Duration (sec)	Liquefaction depth (cm)	D_r (%)	$\frac{((r_u)_{max})_{2D}}{((r_u)_{max})_{1D}}$
		Freq. (Hz)	A_{max} (g)	Freq. (Hz)	A_{max} (g)				
1	MA01			1	0.03	10		46.90	5.07
	MA02	1	0.03	1	0.03	10		47.19	
2	MA03			2	0.03	10		48.79	1.45
	MA04	2	0.03	2	0.03	10		49.18	
3	MA05			4	0.03	10		49.46	7.05
	MA07	4	0.03	4	0.03	10	66.95	49.64	
5	MA10			1	0.05	10		55.42	3.24
	MA11	1	0.05	1	0.05	10	10.13	57.46	
7	MA14			1	0.075	10		59.64	7.46
	MA15	1	0.075	1	0.075	10	92.69	60.06	
13	MB01			2	0.03	10		52.36	1.85
	MB03	2	0.03	2	0.03	10		52.35	
14	MB04			1	0.05	5		52.38	5.96
	MB05	1	0.05	1	0.05	5		52.46	
15	MB06			2	0.05	5		52.73	2.84
	MB07	2	0.05	2	0.05	5	15.13	53.03	
16	MB08			4	0.05	5	14.62	54.28	1.63
	MB09	4	0.05	4	0.05	5	24.17	55.38	
17	MB10			8	0.05	5	54.06	55.65	1.57
	MB11	8	0.05	8	0.05	5	63.38	57.31	
18	MB12			1	0.05	10		58.57	1.58
	MB13	1	0.05	1	0.05	10		59.10	
19	MB14			2	0.05	10		59.33	4.81
	MB15	2	0.05	2	0.05	10	12.6	59.19	
20	MB16			2	0.075	10	22.24	60.06	2.12
	MB17	2	0.075	2	0.075	10	31.78	61.20	
21	MB18			2	0.075	20	31.14	62.75	2.24
	MB19	2	0.075	2	0.075	20	50.64	63.95	
23	MB22			4	0.075	10	26.95	68.43	2.44
	MB23	4	0.075	4	0.075	10	25.56	69.03	
27	MB32			2	0.1	30	69.11	79.87	1.72
	MB33	2	0.1	2	0.1	30	121.78	81.29	
28	MB38			2	0.03	10		84.57	1.49
	MB39	2	0.03	2	0.03	10		84.34	
Ave.									3.21

3.2 Results of Comparisons of Pore Pressure Generations

The test results showed that, prior to liquefaction, the pore pressure generations under 2D shakings were always higher than those under 1D shakings in the same comparing pair of shaking tests and the ratio of the excess pore pressure induced by 2D shakings to that induced by 1D shaking measured at various pressure transducers at different locations was about the same throughout the sand specimen. Comparisons of $(r_u)_{max}$ in a pair of shaking tests on Vietnam sand and another pair of shaking tests on Mailiao sand are given in Figs. 7 and 8, respectively. In these figures, the $(r_u)_{max}$ measured by a pore pressure transducer under 2D shaking (vertical axis) was plotted against that measured by the same transducer under 1D shaking (horizontal axis). It can be seen that, in the same pair of shaking tests, the points of relationship of 2D versus 1D shakings are approximately on a straight line passing through the origin. That is, the ratio of $(r_u)_{max}$ induced by 2D shakings to that induced by 1D shakings measured at every pore pressure transduce in the sand specimen was approximately the same, *i.e.*, equal to the slope of the correlation line for each pair of shaking tests as shown in Figs. 7 and 8. The

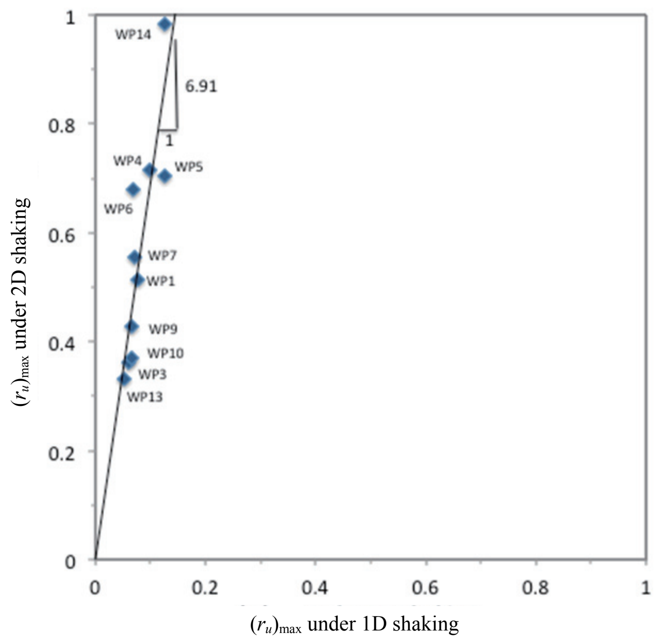


Fig. 7 **Comparison of $((r_u)_{max})_{2D}$ versus $((r_u)_{max})_{1D}$ for Vietnam sand test Pair No. 19**

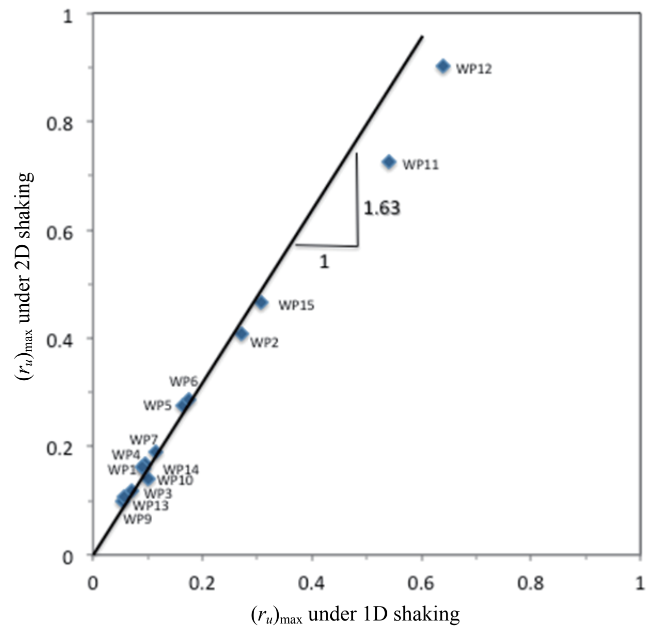


Fig. 8 **Comparison of $((r_u)_{max})_{2D}$ versus $((r_u)_{max})_{1D}$ for Mailiao sand test Pair No. 9**

values of $((r_u)_{max})_{2D}/((r_u)_{max})_{1D}$ for the comparison pairs are also shown in Tables 1 and 2. For Vietnam sand, the values of $((r_u)_{max})_{2D}/((r_u)_{max})_{1D}$ range approximately from 1.5 to 15.0. For Mailiao sand, they are between 1.4 and 7.5, mostly under 5.0.

Figures 9 and 10 are plots of results of $((r_u)_{max})_{2D}$ versus $((r_u)_{max})_{1D}$ at the locations of the piezometers of all the comparison pairs for Vietnam sand and Mailiao sand, respectively. Even though the data are somewhat scattering, after eliminating the extreme values, 5.0 and 3.0 can be considered as the reasonable average values of ratios of pore pressures generated by 2D shakings to that induced by 1D shakings of the same amplitude, frequency, and duration for Vietnam sand and Mailiao sand, respectively.

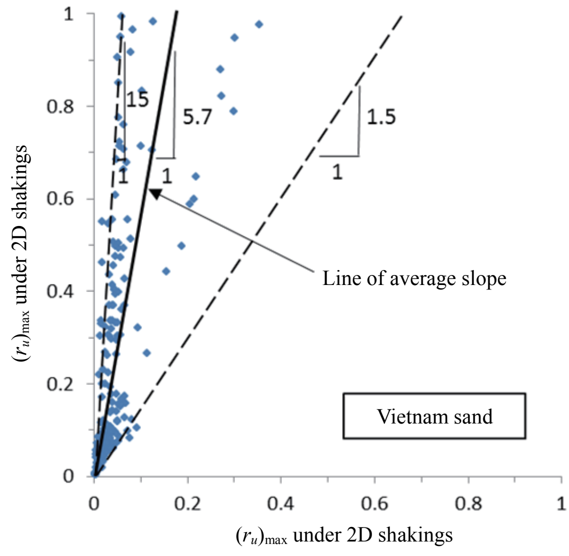


Fig. 9 **Correlation of $((r_u)_{max})_{2D}$ versus $((r_u)_{max})_{1D}$ for Vietnam sand**

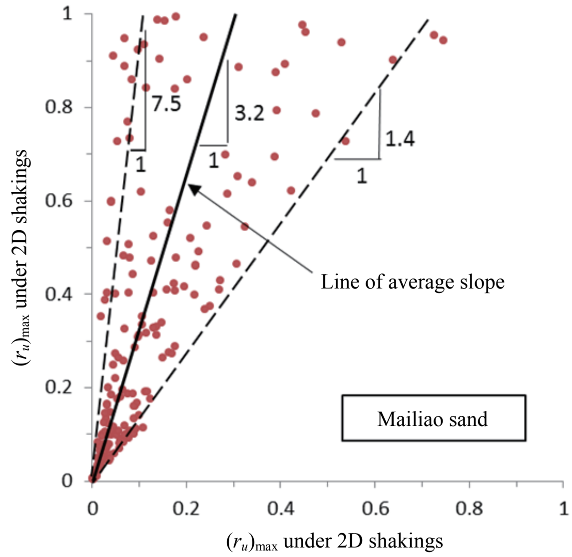


Fig. 10 **Correlation of $((r_u)_{max})_{2D}$ versus $((r_u)_{max})_{1D}$ for Mailiao sand**

4. EFFECT OF 2D SHAKING ON LIQUEFACTION RESISTANCE

To evaluate the effect of 2D shakings on the resistance based on the aforementioned results of the pore water pressure generations under 2D shakings obtained in this study, the procedures developed by Seed *et al.* (1978) in their estimating the effect of 2D shaking on the liquefaction resistance of Monterey sand are adopted. First, the rate of pore pressure ratio increase induced by cyclic shear stresses is assumed following that proposed by Seed *et al.* (1975). That is,

$$\frac{N}{N_L} = \left[\frac{1}{2}(1-\cos \pi r_u)\right]^{\alpha} \tag{1}$$

or

$$r_u = \frac{1}{\pi}\cos^{-1}\left[1 - 2\left(\frac{N}{N_L}\right)^{1/\alpha}\right] \quad (2)$$

where N = number of applied stress cycles,

N_L = number of cycles required to cause liquefaction,

α = a parameter depending on soil properties and test conditions.

Figure 11 shows the relation of pore pressure ratio increase versus N/N_L according to Eq. (1) for $\alpha = 0.7$, 1.0 and 1.5. $\alpha = 0.7$ was suggested for the best fit of the data by Seed *et al.* (1975) and was used in this study. Eq. (1) is assumed applicable to both 1D and 2D shaking situations.

Under a given number of loading cycles N, if the pore pressure ratio induced by 1D shaking, $(r_u)_{1D}$, and that induced by 2D shaking, $(r_u)_{2D}$, are known, then the numbers of cycles required to cause liquefaction under 1D and 2D shakings, $(N_L)_{1D}$ and $(N_L)_{2D}$, respectively can be calculated by Eq. (1). The effect of 2D shakings on the liquefaction resistance of a soil can be considered based on the following relation:

$$\frac{(N_L)_{2D}}{(N_L)_{1D}} = \frac{\left[\frac{1}{2}\left(1 - \cos\pi(r_u)_{1D}\right)\right]^{\alpha}}{\left[\frac{1}{2}\left(1 - \cos\pi(r_u)_{2D}\right)\right]^{\alpha}} \quad (3)$$

where $(r_u)_{1D}$ and $(r_u)_{2D}$ are the pore pressure ratio induced at the same number of stress cycles under 1D and 2D shakings, respectively.

Let Rru = $(r_u)_{2D}/(r_u)_{1D}$. According to the shaking table test results and analyses discussed in Section 3, the values of Rru are estimated to be about 5.0 and 3.0 for Vietnam sand and Mailiao sand, respectively. Since Eq. (3) is a complex equation, $(N_L)_{2D}/(N_L)_{1D}$ for various values of Rru were obtained by the following procedures: (1) give a value of $(r_u)_{1D}$ and a value of $(r_u)_{2D}$ = Rru × $(r_u)_{1D}$ in Eq. (3) to get a value of $(N_L)_{2D}/(N_L)_{1D}$; (2) repeat step (1) by giving different sets of values of $(r_u)_{1D}$ and $(r_u)_{2D}$ in Eq. (3) to get values of $(N_L)_{2D}/(N_L)_{1D}$ for increasing r_u with the same Rru until $(r_u)_{2D}$ approaching 1.0. Slightly different values of $(N_L)_{2D}/(N_L)_{1D}$ are obtained for different r_u but the spreading is small. Therefore, the mean value of $(N_L)_{2D}/(N_L)_{1D}$ can be used for this assigned value of Rru; For other values of Rru, $(N_L)_{2D}/(N_L)_{1D}$ can be obtained by the same procedures. The values of $(N_L)_{2D}/(N_L)_{1D}$ for Rru = 2.0, 3.0, and 5.0 thus obtained are 0.46, 0.26, and 0.14, respectively. For Rru = 2.0, Seed *et al.* (1978) gave an estimated value of $(N_L)_{2D}/(N_L)_{1D} = 0.5$ for Monterey sand which is close to the value obtained in this study.

The effect of the rate of pore water pressure generation on the liquefaction resistance depends on the relation of the cyclic stress ratio (CSR) versus N_L of a sand. For Vietnam sand with Dr = 39%, CSR versus N_L under 1D shaking obtained in the laboratory liquefaction tests is shown in Fig. 12 (Chiang 2000). Under 2D shakings, another relation of CSR versus N_L for Rru = 5.0 can be obtained by reducing the values of N_L by 0.14 for the same CSR as shown in Fig. 12. Considering an equivalent number of cycles of 20, corresponding to an earthquake of approximately $M_w \approx 7.5$ (Kishida and Tsai 2014), the liquefaction resistance stress ratio (CRR) reduces from 0.153 under 1D shakings to 0.111 under 2D shakings, approximately 75% of that

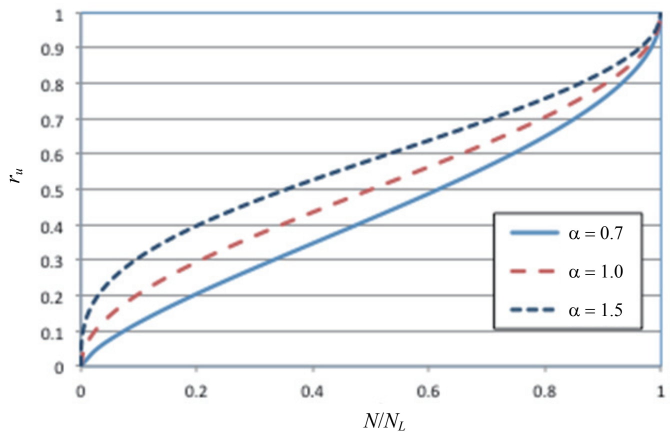


Fig. 11 Rate of pore pressure built-up versus stress cycles according to Eq. (2)

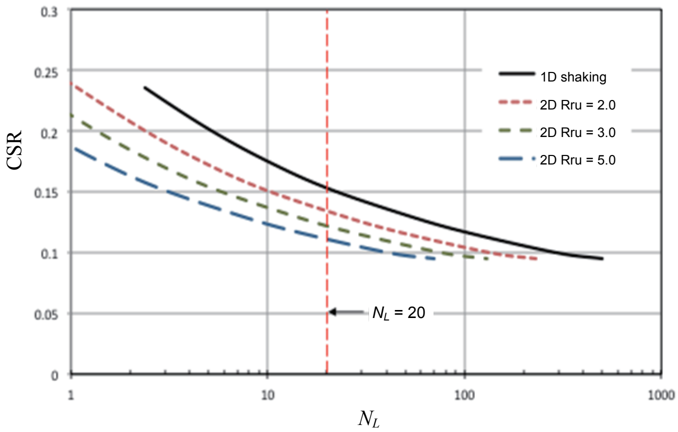


Fig. 12 Liquefaction resistances of Vietnam sand (D_r = 39%) under 1D (data from Chiang 2000) and 2D shakings

under 1D shakings. For Rru = 2.0 and 3.0, the CRRs under 2D shakings are about 87% and 80%, respectively, of those under 1D shakings as shown in Fig. 12. Similarly, for Mailiao sand with fines content FC = 15% and void ratio e = 0.80 (Kuo 2004), the liquefaction resistances under 2D shakings are approximately 0.90, 0.85 and 0.77 of that under 1D shakings with Rru = 2.0, 3.0 and 5.0, respectively (Fig. 13).

The effect of 2D shakings on the liquefaction resistance of other types of sand was also investigated with the same procedures. For Maoluo River sand at Nantou, Taiwan (Yeh 2005), where liquefaction occurred during the 1999 Chi-Chi earthquake, with fines content FC = 48% and dry density γ_d = 1400kg/m^3, the liquefaction resistances under 2D shakings are approximately 0.90, 0.80 and 0.75 of those under 1D shakings with Rru = 2.0, 3.0 and 5.0, respectively (Fig. 14). For Monterey sand used by Seed *et al.* (1978), shown in Fig. 15, the liquefaction resistances under 2D shakings with Rru = 2.0, 3.0 and 5.0 are approximately 0.90, 0.85 and 0.82, respectively, of those under 1D shakings.

Therefore, for the ratio of pore pressure ratio induced by 2D shakings to that induced by 1D shakings Rru ranging between 3.0 and 5.0 as obtained in this study, the liquefaction resistance under 2D shakings can reasonably be between 0.75 to 0.85 of that under 1D shakings.

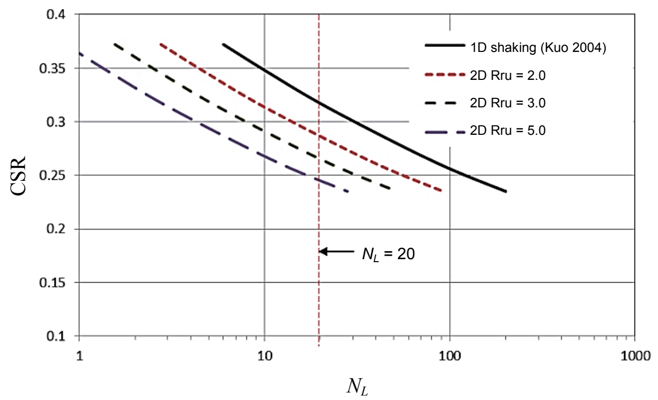


Fig. 13 Liquefaction resistances of Mailiao sand (FC = 15%, *e* = 0.80) under 1D (data from Kuo 2004) and 2D shakings

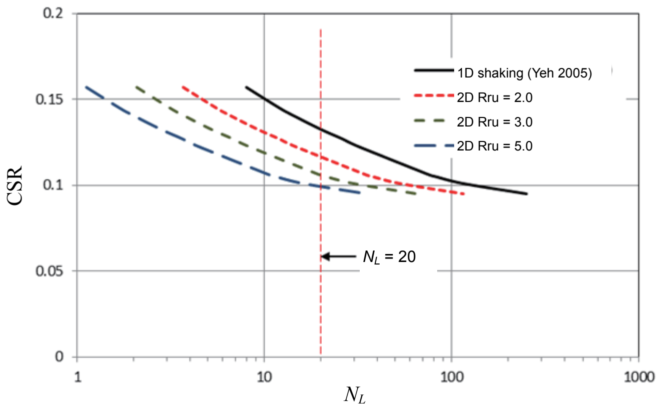


Fig. 14 Liquefaction resistances of Maoluo River sand (FC = 48%, γ_d = 1400kg/m^3) under 1D and 2D shakings

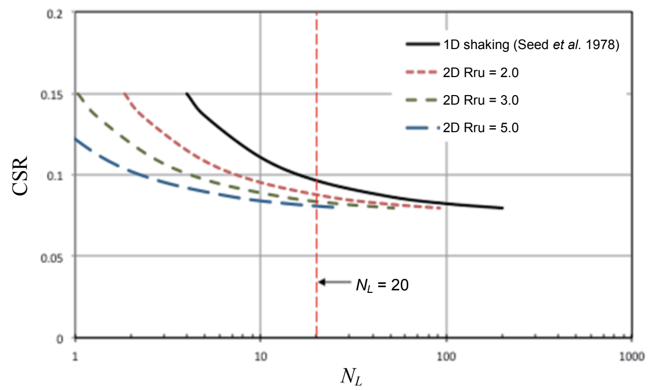


Fig. 15 Liquefaction resistances of Monterey sand (D_r = 60%) under 1D and 2D shakings

5. CONCLUSIONS

This study compiles the results of pore water pressure generations measured during the 1D and 2D shaking table tests at NCREE for Vietnam sand and Mailiao sand. It was found that the pore pressure generations in sand under 2D shakings were always higher than those under 1D shakings and the ratios of the excess pore pressures induced by 2D shakings to those induced by 1D shakings measured at different locations throughout the sand specimen were about the same. The excess pore water pressures in Vietnam sand and Mailiao sand induced by 2D shakings are approximately 5.0 and 3.0 times, respectively, in average of those generated during 1D shakings. Based on these findings, the resistance to liquefaction under 2D shakings was evaluated to be about 0.75 to 0.85 of that under 1D shakings.

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