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EFFECT OF TWO-DIRECTIONAL INPUT MOTION ON CHARATERISTICS OF SANDS LIQUEFACTION BASED ON PSEUDO-DYNAMIC TESTS

Noriaki SAKO[1] and Toshio ADACHI[2]

SUMMARY

In this study, pseudo-dynamic tests were conducted to investigate the response properties of saturated sands focusing on the pore water pressure (p.w.p.) subjected to horizontal one-directional and two-directional earthquake waves. The apparatus was simple shear test device incorporating two cyclic loaders. The direction of maximum pore water pressure obtained from the tests was not the same as the direction of maximum acceleration and velocity of the input motions, but corresponded to the direction of maximum response velocity. That is, for the evaluation of the liquefaction potential, the direction of major axis can not be evaluated by the characteristics of input earthquake ground motion, but it is necessary to consider the predominant period of surface layers. When the results for two-directional inputs were compared with that of the major axis inputs for the same maximum p.w.p., the accelerations by the two-directional inputs were 10 to 20 percent lower than those of the major axis inputs.

INTRODUCTION

Earthquake ground motions causing soil liquefaction are mainly multi-directional horizontal components. Some studies have been reported that investigated the dynamic behavior of the saturated sands subject to liquefaction under multi-directional loading. Test results of a multi-directional shaking table test performed by Pyke et al.[1] and Seed et al. [2] showed that the liquefaction resistance of saturated sand under multidirectional shaking becomes about 10 per cent lower than that under one-directional shaking. Ishihara et al. [3] examined the effect of multi-directional cyclic loading on liquefaction resistance based on laboratory element tests with harmonic waves, and showed that the descent ratio of liquefaction resistance depended on patterns of multi-directional shear, and that the maximum descent ratio was about 35 per cent. Nagase [4] examined the effect of multi-directional shear on liquefaction resistance based on laboratory element tests with random waves, and showed the effect coefficient did not depend much on relative density, and that the value was about 0.8. Fujikawa et al. [5] showed from the shaking table tests with random wave that the amplitude of one-directional input was 1.6 times as large as two-directional input that built up the pore water pressure. Endo et al. [6] performed shaking table tests with harmonic

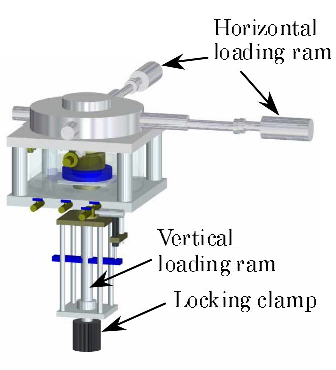
[1] Graduate Student, Nihon University, Tokyo, Japan. Email: d032002@edu.cst.nihon-u.ac.jp
[2] Professor, Nihon University, Tkyo, Japan. Email: adachi@arch.cst.nihon-u.ac.jp

waves. The results showed the amplitude of the input acceleration that caused liquefaction became smaller in the order of circular shaking, elliptical shaking and one-directional shaking.
However, according to the various kinds of earthquake motion records, there is a major axis and a minor axis in the orbit of acceleration or velocity on the horizontal plane (Matsushima [7]). Studies by Seed et al. [2] and Fujikawa et al. [5] with actual earthquake waves did not seem consider the effect of the major axis, while studies of Ishihara et al. [3] and Endo et al. [6] with harmonic waves did not clearly show how the test results correspond to those of randomly variable earthquake waves. In addition, the major axis was defined as the direction of maximum acceleration in the study by Nagase [4], but the principal axis direction of a horizontal earthquake motion by eigen value analysis does not always agree with the direction of maximum acceleration.
In this study, pseudo-dynamic tests were conducted to investigate the response properties of saturated sands focusing on the pore water pressure subjected to horizontal one-directional and two-directional earthquake waves. The pseudo-dynamic testing method for a geotechnical system was a hybrid experiment combining earthquake response analysis with a laboratory dynamic soil test using a computed on-line data processing system.

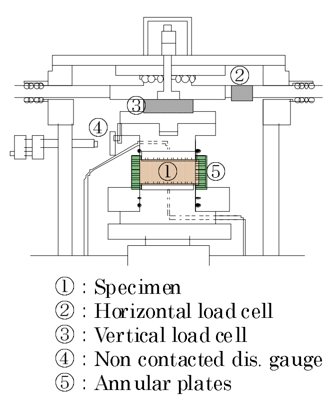
TWO-DIRECTIONAL INPUT FOR PSEUDO-DYNAMIC TEST

Test apparatus and specimen

The test apparatus was a simple shear test device incorporating two mutually perpendicular cyclic loaders. A schematic diagram and a section diagram are shown in Fig.1 (a), (b). Vertical stress was applied to the specimen by a vertical loading ram, and specimen could be deformed under simple shear mode with fixing the vertical rocking clump. A stack of 35 Teflon coated annular plates was used to prevent lateral displacement during cyclic shear. A non-contacted displacement transducer with high resolve potential was used to measure the horizontal displacement. This transducer could measure from 10^{-5} to 10^{-2} order shear strain.
The specimen was columnar, 7.0 cm in diameter and 3.5 cm high. The sample for the test was Toyoura sand and specimens were produced with relative density of approximately 70 % by the air pluviation method. Carbon dioxide and de-aired water were percolated through the specimen to be saturated, and after confirming B value above 0.9, specimens were consolidated under the required effective vertical stress. Decrease of vertical stress during cyclic shear was regarded as increase in pore water pressure since the test was conducted at of K_0-consolidation.



(a) Schematic diagram



(b) Section diagram

Fig.1 Bi-directional simple shear test apparatus

Test algorithm

As the liquefaction characteristics with the two-directional input were examined in this study, an analytical saturated sand layer was modeled as a single mass model with two degrees of freedom, as illustrated in Fig.2. The mass of the lumped mass model was determined for the primary natural frequency of the analytical layer coinciding with the frequency of the lumped mass model, which is expressed as:

$$m = 4H\rho/\pi^2 \qquad (1)$$

where, H is thickness and ρ is density.

The equation of motion for the two-directional input is expressed by:

$$\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix} \begin{Bmatrix} \ddot{x}_{NS} \\ \ddot{x}_{EW} \end{Bmatrix} + \begin{bmatrix} c & 0 \\ 0 & c \end{bmatrix} \begin{Bmatrix} \ddot{x}_{NS} \\ \ddot{x}_{EW} \end{Bmatrix} + \begin{Bmatrix} R_{NS} \\ R_{EW} \end{Bmatrix} = -\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix} \begin{Bmatrix} \ddot{y}_{NS} \\ \ddot{y}_{EW} \end{Bmatrix} \qquad (2)$$

Consequently, the viscous damping was negligible (c=0) in this study, since the predominant damping in sands is hysteretic. Newmark's β-method was utilized to solve Eq.(2) numerically. A linear acceleration method (β=1/6) was applied to the first time step and an impulse acceleration method (β=0) was applied to the subsequent time steps. The error correction method developed by Kusakabe [8] was introduced to this testing method

In order to verify the test algorithm, a test was conducted with a dummy specimen. The strong motion records, Hachinohe-EW (1968 Tokachi-Oki Earthquake) was used for the input earthquake motion. The response acceleration was then analyzed with an elastic calculation as a comparison. Fig.3 compares the response acceleration orbit of the test and the analysis, and shows that they corresponded.

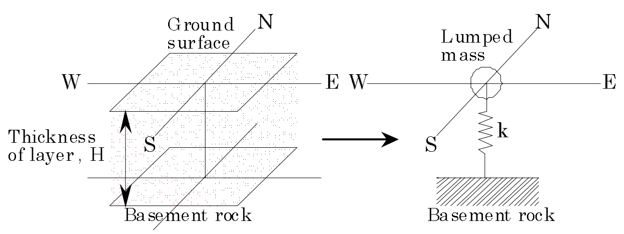


Fig.2 Lumped mass model

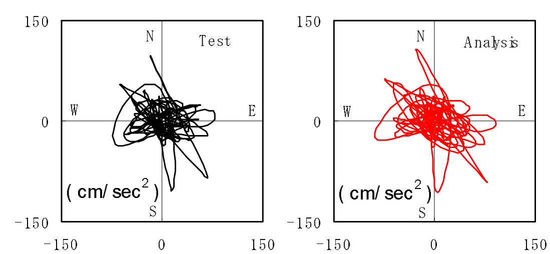


Fig.3 Comparison of test with analysis

EXAMINATION OF MAJOR AXIS DIRECTION

Test condition

This section examines the major axis direction in the earthquake motion. Tests were conducted with one-directional and two-directional inputs. For the one-directional inputs, as summarized in Fig.4, accelerations was composed every 30 degrees of rotation coordinate from NS direction for the input in order to verify the major axis direction giving influence in pore water pressure. EW direction corresponds to 90 degrees. The acceleration due to the rotation coordinate is calculated by:

$$\alpha'(t) = \cos\theta \times \alpha_{NS}(t) + \sin\theta \times \alpha_{EW}(t) \qquad (3)$$

where, $\alpha(t)$ is acceleration and θ is rotation angle.

The earthquake waves for the input motion were Taft (1952 Kern country, California earthquake) and Hachinohe. These earthquake waves are typical strong motions that are used for earthquake-resistant design, but have different predominant period. Fourier spectra are shown in Fig.5. The acceleration orbits of Hachinohe and Taft, velocities orbits obtained from a linear acceleration method, are shown in Fig. 6(a) and Fig. 6(b). From these figures, it is found that the directions of maximum acceleration and maximum velocity (45-55 degrees) correspond in Taft, but are mutually perpendicular in Hachinohe.

Table 1 lists the test conditions. The name “ Specimen No. ” in Table 1 represents the test case as the direction by one-directional input or two-directional input. For one-directional input, tests were added with input waves every 15 degrees from the direction of maximum or minimum in pore water pressure in order to examine the effect in detail.

Effective vertical stress for the test was used as equivalent to the center of gravity point of vertical stress distribution. When the depth was 5m, the center of gravity position was 3.33m, so the vertical stress was 33 kN/m^2 since unit volume weight was about 19.2 kN/m^2. The initial natural period of the ground is given by:

$$T_0 = 4H / V_s \qquad \left(V_s = \sqrt{G_0 / \rho}\right) \tag{4}$$

where, G_0 is initial shear modulus. G_0 was measured before the pseudo-dynamic test.

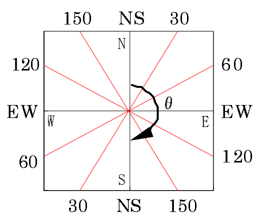


Fig.4 Definition of rotational direction

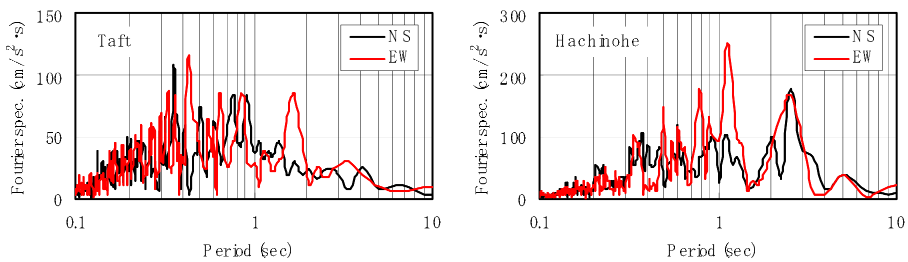
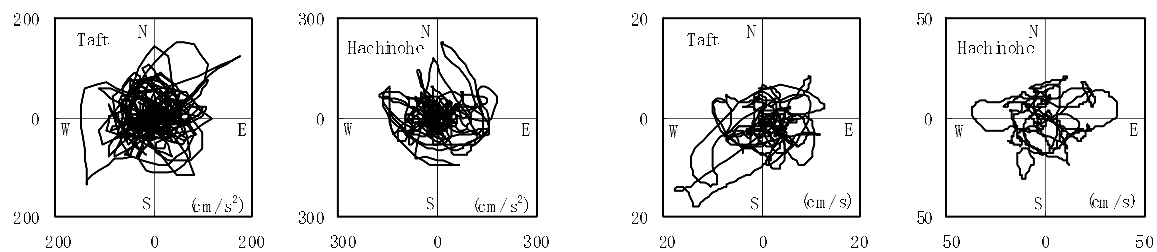


Fig.5 Fourier spectrum (Input motion)



(a) Acceleration

(b) Velocity

Fig.6 Orbit of input motion (Taft and Hachinohe)

Table1 Pseudo-dynamic test conditions

Input motion	Specimen No.	Relative density Dr (%)	Max acc. (input) α (cm/s^2)	natural period T_0 (sec)	Thickness h (m)	Initial vertical stress σ_{v0}'(kN/m^2)
	NS <0>	73	65	0.246		33.0
	30	75	83	0.246		33.5
	45	74	90	0.252		33.5
	60	72	91	0.245		33.0
TAFT	EW <90>	71	75	0.250	5	33.5
	120	74	63	0.248		32.8
	135	72	60	0.246		33.0
	150	72	60	0.249		33.0
	Two-direc.	74	NS:65、EW:75	0.246		33.5
	NS <0>	73	75	0.246		33.3
	30	74	68	0.246		32.8
	60	72	63	0.250		32.8
	75	73	64	0.248		33.3
八戸	EW <90>	74	61	0.250	5	33.3
	120	74	62	0.252		33.5
	150	74	63	0.250		33.5
	165	72	71	0.247		33.0
	Two-direc.	74	NS:75、EW:61	0.248		33.5

Major axis direction for liquefaction

Fig.7 shows the histories of pore water pressure ratio. With two earthquake waves, pore water pressure with two-directional input increased most. The directions that show maximum and minimum in pore water pressure were mutually perpendicular. Fig.8 shows the relationship between maximum of pore water pressure ratio summarized in Fig.7 and rotational angle for input earthquake motion. In this study, the buildup of pore water pressure was used as an evaluation criterion of earthquake motion intensity that produced liquefaction damage of ground. From this viewpoint, the major axis direction was 45 degrees in Taft and 165 degrees in Hachinohe.

Fig.9 shows the variation of maximum acceleration and velocity of input earthquake wave due to rotation coordinates, where the ordinates axes were normalized with the mean. By comparing Fig.8 with Fig.9, it is found that variation of pore water pressure resembled that of maximum acceleration and velocity for Taft, but did not for Hachinohe. In particular, the difference between the rotation angles of maximum pore water pressure and velocity was 90 degrees. This means that the major axis direction that influences buildup of pore water pressure cannot be decided only by the characteristics of the input earthquake motion. The orbit of response velocity obtained from pseudo-dynamic tests are shown in Fig.10 and variation of response velocity due to rotation coordinates are shown in Fig.11. It is found that the variation of response velocity resembled that of maximum pore water pressure ratio (Fig.8) for both Taft and Hachinohe, and the direction of the response velocity and pore water pressure corresponded in maximum and minimum. Thus in evaluation the major axis direction for the liquefaction potential, it is necessary to consider the predominant period of the surface layers.

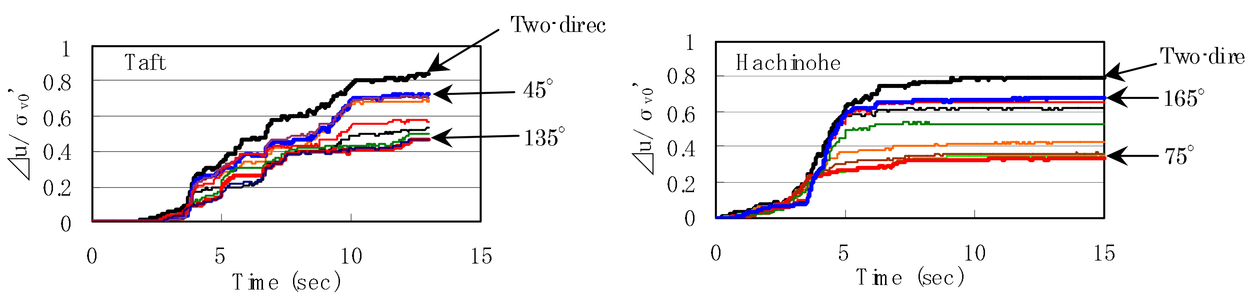


Fig.7 Time histories of pore water pressure ratio

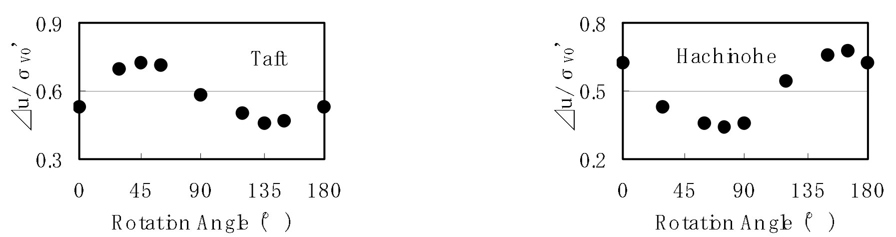


Fig.8 Correlation between maximum pore water pressure ratio with rotation angle

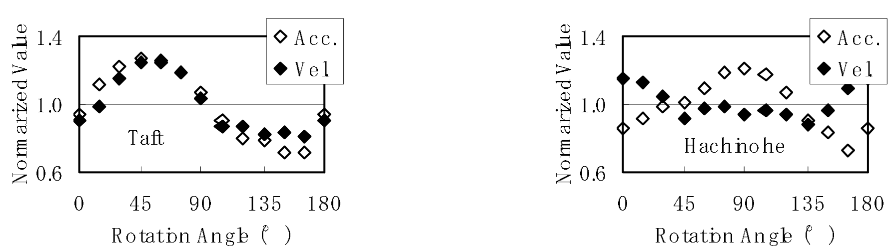


Fig.9 Variation maximum acceleration and velocity due to rotation coordinates

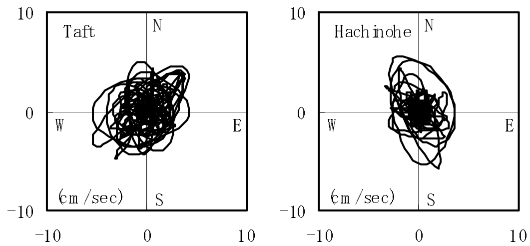


Fig.10 Orbit of response velocity

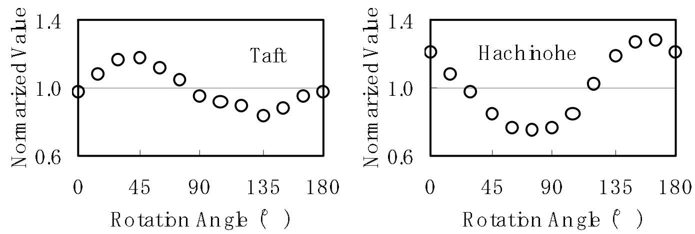


Fig.11 Variation maximum response velocity due to rotation coordinates (Taft and Hachinohe)

INFLUENCE OF TWO-DIRECTIONAL INPUT ON PORE WATER PRESSURE

Differences were shown in pore water pressure obtained by one-directional and two-directional input with Taft and Hachinohe, as summarized in Fig.7. This section describes additional tests conducted with some different earthquake wave and examines the influence of two-directional input on pore water pressure. The additional input earthquake wave for the tests were Kushiro (1993 Kushiro-oki earthquake), Kansai E.P. (1995 Hyogoken-Nambu Earthquake) and Kobe P.I. (1995 Hyogoken-Nambu Earthquake). Fig.12 shows the orbit of input earthquake motion.

Firstly, the major axis direction was estimated from the orbit of response velocity obtained from two-directional input. Variation of response velocity due to rotation coordinates for Kushiro, Kansai E.P. and Kobe P.I. are shown in Fig.13. The directions that indicate maximum and minimum were mutually perpendicular for each earthquake wave, and the rotation angle indicating maximum was 75 degrees for Kushiro, 120 degrees for Kansai E.P. and 135 degrees for Kobe P.I.. Secondly, based on the conclusion that the major axis direction corresponds to the maximum response velocity direction, more tests were conducted by one-directional input with acceleration composed from the above rotation coordinates. From these test results, the differences between maximum pore water pressures obtained from one-directional and two-directional inputs are shown for all cases (Fig.14). The maximum pore water pressure obtained from the two-directional input was simulated by the test with a one -directional input of the major axis multiplied by a modification coefficient step by step. Fig.14 shows time histories of pore water pressure ratio obtained from the tests and Table 2 lists the modification coefficients.

Ishihara et al. [3] conducted cyclic simple shear tests on saturated sand in multi-directional loading and indicated that liquefaction resistance was decreased gradually so that the amplitude ratio of cyclic stress ratio in two mutually perpendicular directions approached 1.0. This study focused on the maximum and minimum response velocities shown in Fig.11 and Fig.13. Fig.15 shows that the axis of the ordinates the expresses reciprocal of the modification coefficient 1/a (that is, the modification coefficient affected by a two-directional input if a one-directional input was considered to be the basis), and the axis of the abscissa expresses the ratio of minimum to maximum in response velocity. It is found that 1/a was smaller as the axis of the abscissa approached 1.0. This means that the shape of the orbit became close to round as the ratio approached 1.0, and the amplitude of the one-directional input in the major axis direction then became larger and equivalent of that of the two-directional input then. In other words, liquefaction of sand due to two-directional input was influenced more, so that the ratio of minimum to maximum in response velocity was large. This tendency was similar to that derived by Ishihara et al. [3]. The values of 1/a were within the range from 0.79 to 0.93, and were 0.86 on average. For the present evaluation of liquefaction resistance provided by the relationship between cyclic stress ratio and cyclic number when the amplitude of shear strain generates several per cent, 0.9-1.0 are used for the modification coefficient for multi-directional characteristics in the horizontal plane of the earthquake motion. Thus, the modification coefficient obtained from the tests in this study is smaller than that commonly used in Japan, which implies the possibility of underestimating the liquefaction potential.

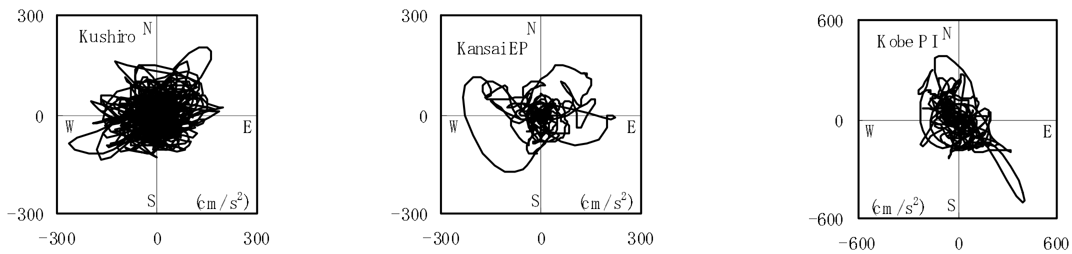


Fig.12 Orbit of input motion (Kushiro, Kansai EP and Kobe PI)

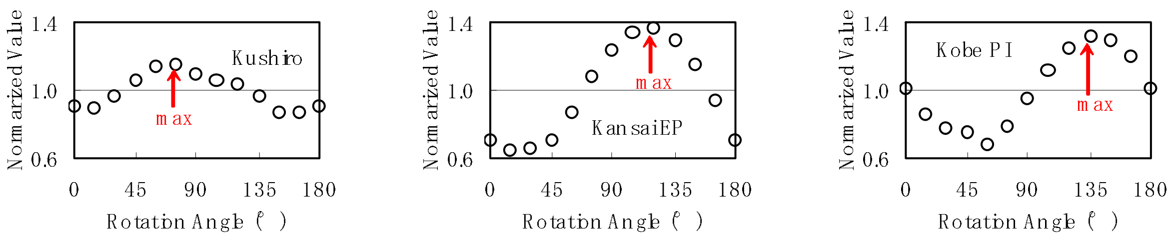


Fig.13 Variation response velocity due to rotation coordinates (Kushiro, Kansai EP and Kobe PI)

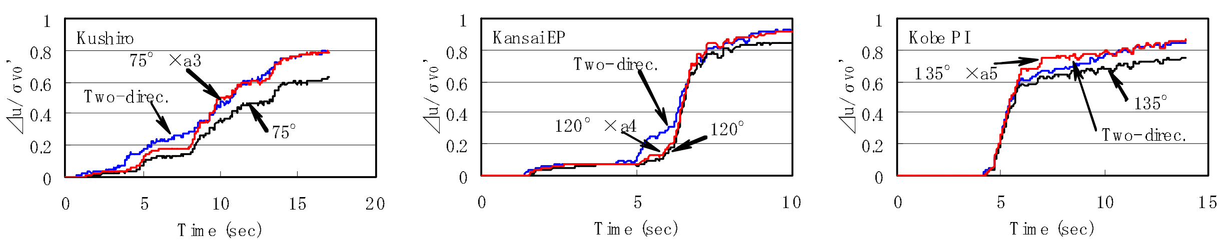


Fig.14 Comparison of pore water pressure ratio

Table2 List of modification coefficient

Input motion	case	Max.acc. (input) α (cm/s^2)	a	P.W.P ratio (max) $\Delta u/\sigma_{v0}'$
Taft	Two-direc. (45° direc.)	90	1.22	0.84
	45° - direc.			0.72
	(45° - direc.) $\times a_1$	110		0.84
Hachinohe	Two-direc. (165° direc.)	71	1.15	0.80
	165° - direc.			0.68
	(165° - direc.) $\times a_2$	82		0.83
Kushiro	Two-direc. (75° direc.)	95	1.26	0.80
	75° - direc.			0.63
	(75° - direc.) $\times a_3$	120		0.79
KansaiEP	Two-direc. (120° direc.)	102	1.08	0.93
	120° - direc.			0.85
	(120° - direc.) $\times a_4$	110		0.91
Kobe PI	Two-direc. (135° direc.)	166	1.08	0.85
	135° - direc.			0.75
	(135° - direc.) $\times a_5$	180		0.86

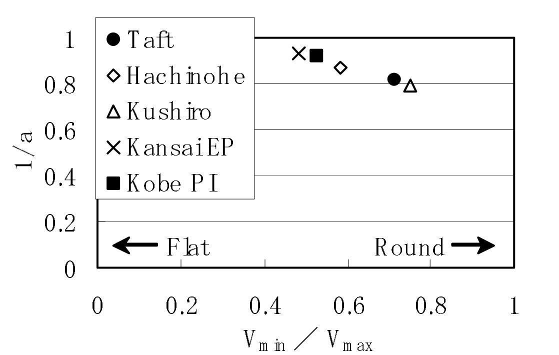


Fig.15 Relationship between 1/a and V_{min}/V_{max}

CONCLUSION

In this study, pseudo-dynamic tests were conducted to investigate the liquefaction potential of saturated sands focusing on the pore water pressure under horizontal one-directional and two-directional earthquake waves. The conclusions are summarized as follows:

1) The direction of maximum pore water pressure obtained from the tests was not the same as the direction of maximum acceleration and velocity of the input motions, but corresponded to the direction of maximum response velocity. That is, for evaluation of the liquefaction potential, the direction of the major axis can not be evaluated from the characteristics of input earthquake ground motion. It is necessary to consider the predominant period of the surface layers.

2) When the results for two-directional inputs were compared with that of the major axis inputs for the same maximum pore water pressure, the accelerations by the two-directional inputs were 10 to 20 percent lower than those of the major axis inputs. The value is smaller than the modification coefficient commonly used in Japan, which implies the possibility of underestimation of evaluation of liquefaction potential.

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