Copyright © 1996 Elsevier Science Ltd
Paper No. 388. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

PSEUDO-DYNAMIC TEST ON INTENSITY OF EARTHQUAKE GROUND MOTIONS AT OCCURRENCE OF LIQUEFACTION

T. ADACHI, H. SEKIHARA, M. YAMADA and A. ENAMI

Department of Architecture, College of Science and Technology, Nihon University
1-8, Kanda surugadai, Chiyoda-ku, Tokyo, 101, Japan

ABSTRACT

The intensities of earthquake ground motions at occurrence of liquefaction were estimated by the pseudo-dynamic test using a torsional shear test apparatus. The maximum velocity at liquefaction is about 15 kine, and the scatter is small compared with that of the maximum acceleration at liquefaction. Furthermore, the excess pore water pressure correlates better with the maximum velocity and the spectrum intensity than the maximum acceleration. These results agree fairly well with previous findings on the basis of observations of strong ground motions, and they verify that maximum velocity is a more appropriate measure for evaluating liquefaction potential than maximum acceleration, which has commonly been used.

KEYWORDS

Liquefaction; Intensity of earthquake ground motions; Pseudo-dynamic test; Torsional shear test apparatus Maximum acceleration; Maximum velocity; Spectrum intensity; Excess pore water pressure; Subsurface layers

INTRODUCTION

It has recently been pointed out from seismic observations that maximum velocity is more appropriate than maximum acceleration as a measure of earthquake ground motion intensity. Yanagisawa *et al.* (1986), for example, indicated that the maximum velocity of the surface ground correlates better with the pore water pressure developed in the ground during an earthquake than the maximum acceleration of the surface ground. Furthermore, Midorikawa and Wakamatsu (1988) investigated the observed and estimated intensities of earthquake ground motions at about 130 liquefied and non-liquefied sites during 19 Japanese earthquakes. It is shown that the maximum acceleration at the border between the sites where liquefaction occurred and didn't occur ranged from 70 to 300 gal and the maximum velocity meanwhile ranged from 10 to 20 kine. Furthermore, the scatter of the maximum velocity was small compared with that of the maximum acceleration. These results indicate that maximum velocity is a more appropriate measure for evaluating liquefaction potential of subsurface layers than maximum acceleration, which has commonly been used.

The objectives of this study were : (1) To reproduce the liquefaction process of subsurface layers by conducting a pseudo-dynamic test using a torsional shear test apparatus. (2) To investigate appropriate measures for evaluating liquefaction potential by estimating maximum ground motion intensities at occurrence of liquefaction. (3) To investigate the correlation between excess pore water pressure ratio and seismic responses.

PSEUDO-DYNAMIC TESTING METHOD

The pseudo-dynamic method for testing a geotechnical system is a hybrid experiment which combines an earthquake response analysis with a laboratory dynamic soil test with a computer on-line data processing system (Kusakabe *et al.*, 1995). The test procedure is outlined below. (1) An analytical layer is modelled into a lumped mass model, and an earthquake motion with minute time intervals is input from its base. (2) The displacement response is calculated by solving the equation of motion of the lumped mass model which is expressed as :

$$m\ddot{x}+c\dot{x}+kx=m\ddot{y} \tag{1}$$

where, m, c and k are the mass, damping and stiffness, respectively. (3) A shear strain corresponding to the calculated displacement response is imparted to the soil specimen by a strain control method, and the restoration force of the soil specimen is measured at the same time. (4) The displacement response in succeeding steps is calculated by adopting this restoration force. The earthquake response behavior of the ground is simulated by repeating this procedure within the duration of an earthquake motion. Therefore, this testing method can estimate not only nonlinear behavior of the ground such as seismic response, strength, deformation characteristics, *etc.* but also the behavior of pore water pressure directly and simultaneously.

In this study, the pseudo-dynamic test was conducted using a torsional shear test apparatus. If an analytical layer was one layer of saturated sand of thickness, H, it was modelled as a lumped mass model with a single degree of freedom. Consequently, it doesn't matter that the viscous damping of Eq.(1) is negligible (c=0), since the predominant damping in sand is hysteretic. The mass of a lumped mass model, m, was determined for the condition of primary natural frequency of analytical layer coinciding with the frequency of a lumped mass model, which is expressed as :

$$m=4H\rho/\pi^2 \tag{2}$$

where, ρ is the density of an analytical layer. Newmark's β -method was utilized to solve Eq.(1) numerically. That is, 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.

TEST CONDITIONS

Three kinds of sand samples were used for the test : Toyoura sand, Niigata sand and Kasumigaura sand. Their physical properties and the grain size distribution curves are shown in Table 1 and Fig. 1, respectively. The specimens were produced by the air pluviation method (height, 100mm, outer diameter, 100mm, and inner diameter, 60mm), and isotropically confined. The confining pressure was reproduced by the effective overburden pressure at the middle point of the layer. To reproduce an simple shear deformation mode, the test was conducted under plane strain conditions. Figure 2 shows the relations between cyclic shear stress ratio and number of cycles of each sand, which were obtained from the cyclic undrained torsional shear test under plane strain conditions. The input earthquake waves were five earthquake records : El Centro-NS (1940 Imperial valley earthquake), Taft-EW (1952 Kern county, California earthquake), Niigata-EW (1964 Niigata earthquake), Hachinohe-EW (1968 Tokachi-Oki earthquake) and Kobe-NS (1995 Hyogoken-Nanbu earthquake). The duration of the input earthquake waves were 15 seconds for El Centro(NS), Taft(EW) and Niigata(EW), and 10 seconds for Hachinohe(EW) and Kobe(NS). The time intervals of all earthquake records were 0.01 seconds.

Table 1. Physical properties of sands

Sand	Specific gravity of soil particles G_s	Void ratio in loosest state e_{max}	Void ratio in densest state e_{min}	Uniformity coefficient U_c	Mean grain size D_{50} (mm)
Toyoura sand	2.63	0.969	0.621	1.59	0.171
Niigata sand	2.69	1.068	0.650	1.86	0.220
Kasumigaura sand	2.76	0.944	0.605	2.47	0.562

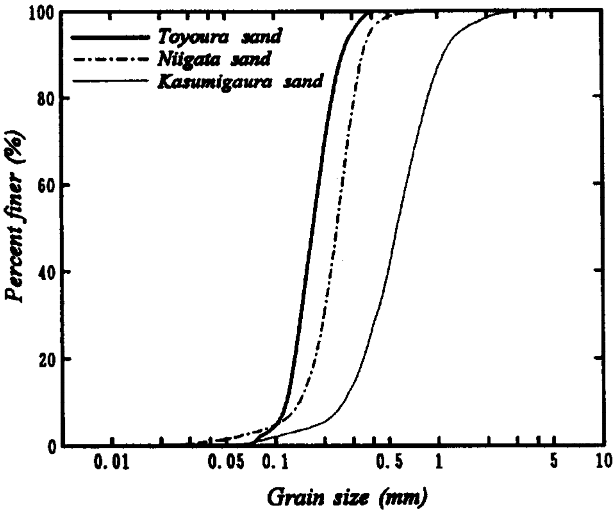


Fig. 1 Grain size distribution curve

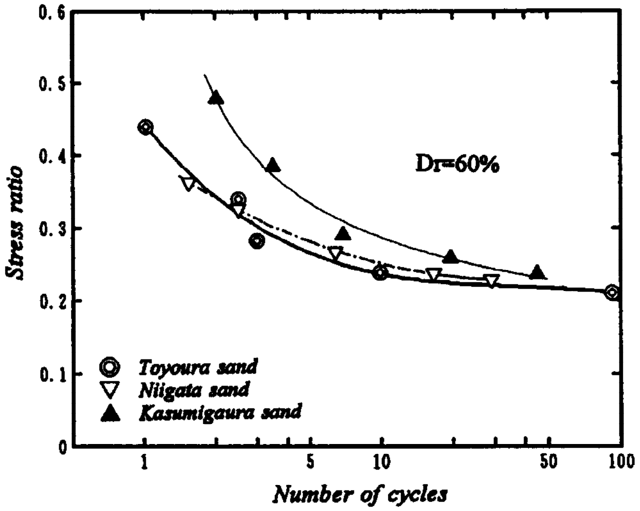


Fig. 2 Relation between cyclic stress ratio and number of cycles to $u/\sigma_0'=0.95$

To verify the reproducibility of the liquefaction process by means of the pseudo-dynamic testing method, the test was conducted on the three kinds of sands shown above. The input earthquake wave used for the test was El Centro(NS). The test conditions are shown in Table 2. After the reproducibility was verified, the test was conducted following the conditions for Case 1 ~ Case 3 on Toyoura sand to determine the most appropriate measure for evaluating liquefaction potential from maximum acceleration, maximum velocity and spectrum intensity. In Case 1, the effect of the relative density of the sand specimen was investigated. In Case 2, the effect of input earthquake wave form was investigated. In Case 3, the effect of layer thickness was investigated. The test conditions for Cases 1 ~ 3 on Toyoura sand are shown in Table 3.

Table 2. Test conditions for verification of reproducibility

Sand	Relative density (%)	Input earthquake wave	Thickness (m)
Toyoura sand	60	El Centro(NS)	10, 5
Niigata sand			5
Kasumigaura sand			5

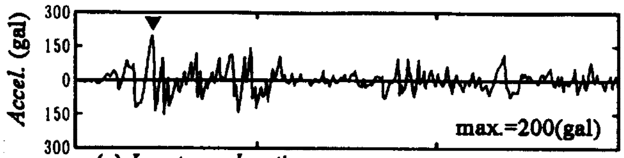
Table 3. Test conditions for Cases 1 ~ 3 on Toyoura sand

Case No.	Relative density (%)	Input earthquake wave	Thickness (m)
1	60 45	El Centro(NS)	10
2	60	El Centro(NS) Taft(NS) Niigata(EW) Hachinohe(EW) Kobe(NS)	10
3	60	El Centro(NS)	10 8 6 5

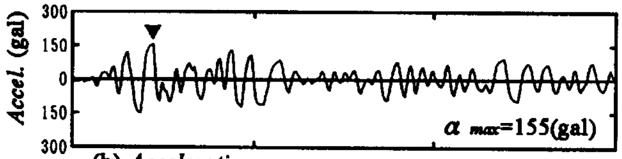
TEST RESULTS

Reproducibility of Liquefaction Process

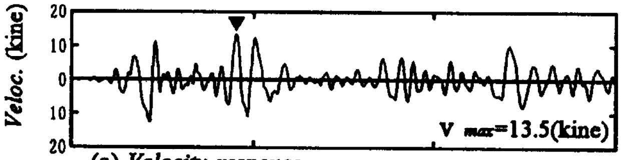
Figure 3 shows an example (see *Note* of Figs. 3 and 4) of the time histories of ground responses. In Fig. 3, (a) ~ (d) show the time histories of the input acceleration, the acceleration response, the velocity response and the excess pore water pressure ratio, respectively. The ▼ marks in each time history display the maximum values. Figure 4 shows the effective stress path. Figure 4 indicates the tendency which the shear stress ratio decreases and the effective stress path goes toward the origin as the excess pore water pressure increases.



(a) *Input acceleration*



(b) *Acceleration response*



(c) *Velocity response*

(d) *Excess pore water pressure ratio*

Fig. 3 Time histories of ground responses

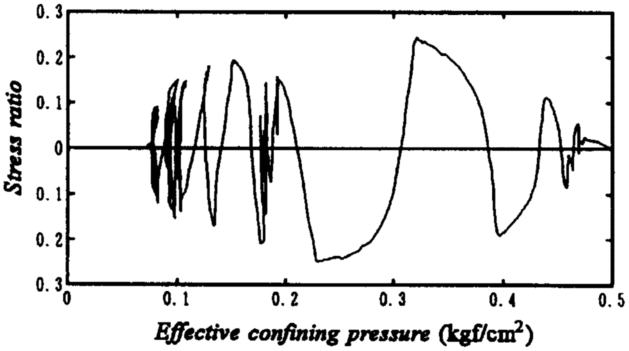
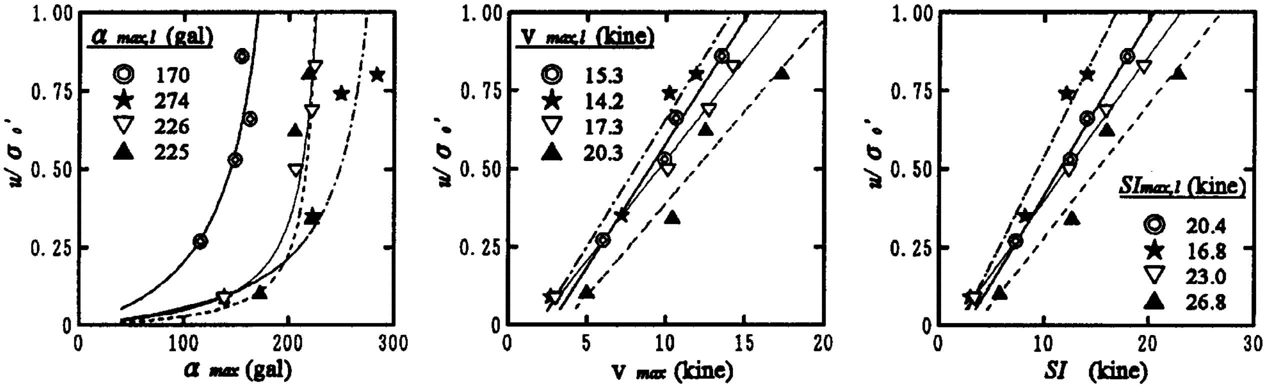


Fig. 4 Effective stress path

Note : *Figures. 3 and 4 are the test results for the conditions below.*

Sand : Toyoura sand
Relative density : 60%
Thickness : 10m
Input earthquake wave : El Centro(NS)
Input maximum acceleration : 200gal

Figure 5 shows the relation between the excess pore water pressure ratio, u/σ_o', and each maximum ground response of the subsurface layers for the different kinds of sands. Figure 5(a) shows the relation between u/σ_o' and the maximum acceleration response, α_{max} ; (b) shows the relation between u/σ_o' and the maximum velocity response, v_{max} ; and (c) shows the relation between u/σ_o' and the spectrum intensity, *SI*. In Fig. 5(c), *SI* is defined as the average value under the velocity response spectrum with 0.2 damping ratio between the periods 0.1 and 2.5 seconds (Housner, 1952). In this study, the moment when u/σ_o' reaches 1.0 from the upward tendency of u/σ_o' is defined as the occurrence of liquefaction, and the maximum ground response at liquefaction is expressed along with the suffix "*max,l*". From Fig. 5(a) ~ (c), α_{max}, v_{max} and *SI* of each sand sample at the occurrence of liquefaction, i.e., $\alpha_{max,l}$, $v_{max,l}$ and $SI_{max,l}$ were estimated. These estimated values are shown in Fig. 5(a) ~ (c) respectively. The relation between u/σ_o' and α_{max} in Fig. 5(a) was approximated by a regression equation of a hyperbola, since the tendency which α_{max} asymptotes its upper limit has been pointed out. The relation between u/σ_o' and v_{max} in Fig. 5(b) and the relation between u/σ_o' and *SI* in Fig. 5(c) were approximated by a linear regression equation. From Fig. 5(a), the maximum acceleration responses at liquefaction for the three sands, $\alpha_{max,l}$, ranged from 170 to 274 gal. From Fig. 5(b) and (c), the maximum velocity responses at liquefaction, $v_{max,l}$, ranged from 14.2 to 20.3 kine, and the spectrum intensity at liquefaction, $SI_{max,l}$, ranged from 16.8 to 26.8 kine. These results agreed fairly well with previous findings (Midorikawa and Wakamatsu, 1988). The reproducibility of the liquefaction process was verified qualitatively and quantitatively by the response results obtained from the pseudo-dynamic test on three kinds of sands.



(a) u/σ_o' *versus* α_{max} (b) u/σ_o' *versus* v_{max} (c) u/σ_o' *versus SI*

Fig. 5 Relation between u/σ_o' and each maximum ground response for the different the kinds of sands

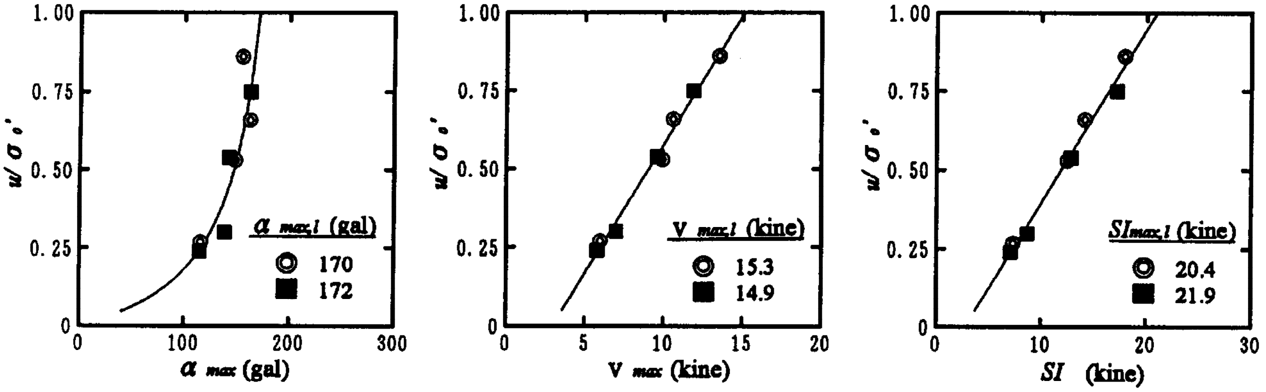
Intensity of Ground Motions at Liquefaction

Case 1 (Effect of Relative Density). Figure 6 shows the relation between u/σ_o' and each maximum ground response for the relative densities of sand specimens of about 60% and 45%. As shown in Fig. 6(a) ~ (c), $\alpha_{max,l}$, $v_{max,l}$ and $SI_{max,l}$ for each relative density at the occurrence of liquefaction were estimated, and the estimated values are shown in Fig. 6(a) ~ (c). As shown in Fig. 6(a) ~ (c), for the two relative densities of sand specimens, $\alpha_{max,l}$ were 170 and 172 gal ; $v_{max,l}$ were 15.3 and 14.9 kine ; and $SI_{max,l}$ were 20.4 and 21.9 kine.

Case 2 (Effect of Earthquake Wave Form). Figure 7 shows the relation between u/σ_o' and each maximum ground response for the five input earthquake waves. As shown in Fig. 7(a) ~ (c), $\alpha_{max,l}$, $v_{max,l}$ and $SI_{max,l}$ for each input earthquake wave at the occurrence of liquefaction were estimated, and the estimated values are shown in Fig. 7(a) ~ (c). As shown in Fig. 7(a) ~ (c), for the five input earthquake waves, $\alpha_{max,l}$ ranged from 170 to 216 gal ; $v_{max,l}$ ranged from 14.0 to 17.2 kine ; and $SI_{max,l}$ ranged from 20.4 to 23.4 kine.

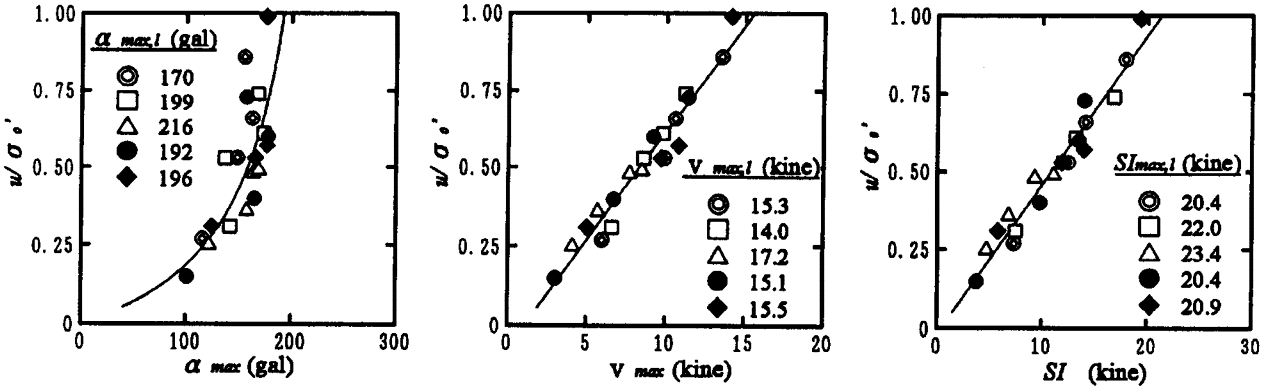
Case 3 (Effect of Layer Thickness). Figure 8 shows the relation between u/σ_o' and each maximum ground response for the four layer thicknesses. As shown in Fig. 8(a) ~ (c), $\alpha_{max,l}$, $v_{max,l}$ and $SI_{max,l}$ of each layer thickness at the occurrence of liquefaction were estimated, and the estimated values are shown in Fig. 8(a) ~ (c). As shown in Fig. 8(a) ~ (c), for the four layer thicknesses, $\alpha_{max,l}$ ranged from 170 to 274 gal ; $v_{max,l}$ ranged from 14.2 to 15.3 kine ; and $SI_{max,l}$ ranged from 16.8 to 20.4 kine. As is clear from Fig. 8, the maximum acceleration responses became larger as layer thickness became smaller. Meanwhile, the maximum velocity responses and the spectrum intensities in relation to u/σ_o' remained almost constant in spite of the change in layer thickness.

The test results of Cases 1 ~ 3 on Toyoura sand are summarized in Table 4. The average values and the coefficient of variation for each maximum ground response are also shown in Table 4. As shown, $\alpha_{max,l}$ ranged from 170 to 274 gal ; $v_{max,l}$ ranged from 14.0 to 17.2 kine ; and $SI_{max,l}$ ranged from 16.8 to 23.4 kine. In the coefficient of variation, $\alpha_{max,l}$ was 15.8% ; $v_{max,l}$ was 5.2% ; and $SI_{max,l}$ was 8.7%. It is evident from the coefficient of variation that the scatter of $v_{max,l}$ is smaller than that of $\alpha_{max,l}$.



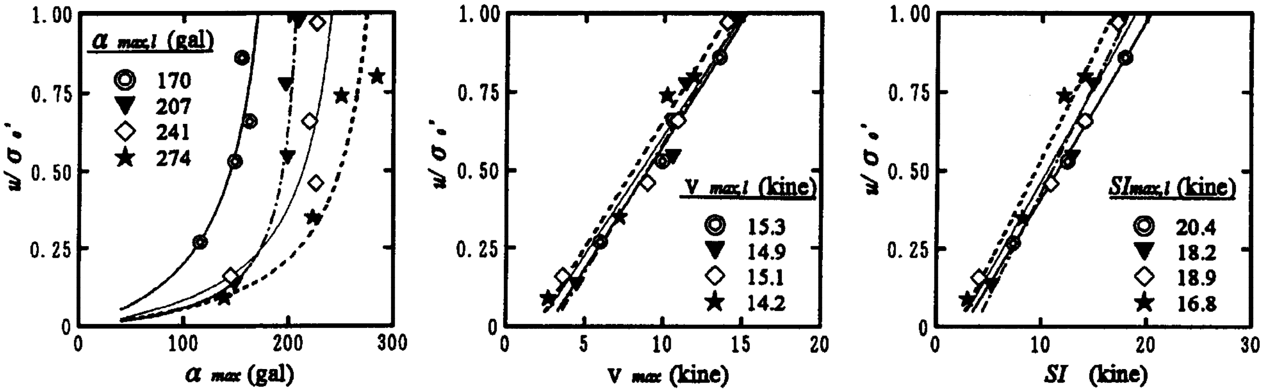
(a) u/σ_o' versus α_{max} (b) u/σ_o' versus v_{max} (c) u/σ_o' versus SI

Fig. 6 Relation between u/σ_o' and each maximum ground response for two relative densities of sand specimens



(a) u/σ_o' versus α_{max} (b) u/σ_o' versus v_{max} (c) u/σ_o' versus SI

Fig. 7 Relation between u/σ_o' and each maximum ground response for five input earthquake waves

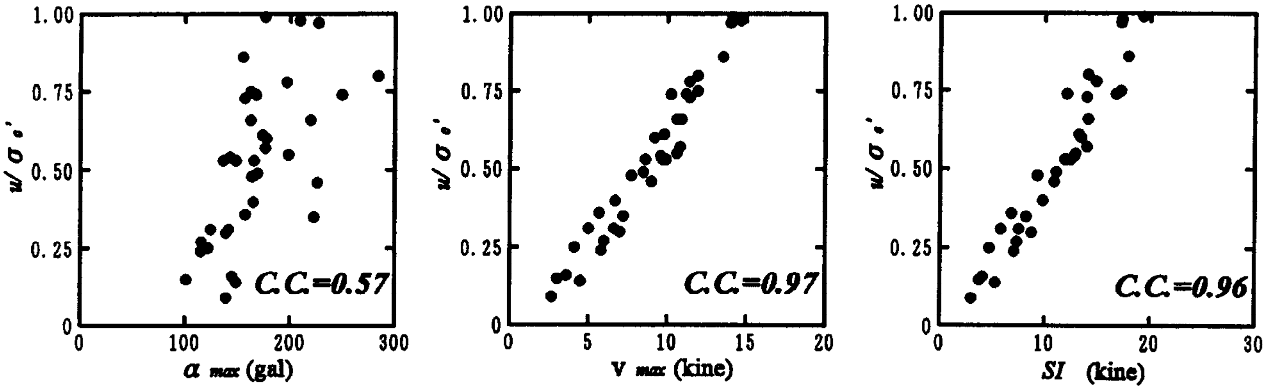


(a) u/σ_o' *versus* α_{max} (b) u/σ_o' *versus* v_{max} (c) u/σ_o' *versus* SI

Fig. 8 Relation between u/σ_o' and each maximum ground response for four layer thicknesses

Table 4. Summary of the test results for Cases 1 ~ 3 on Toyoura sand

Case No.	Parameter		$\alpha_{max,l}$ (gal)	$v_{max,l}$ (kine)	$SI_{max,l}$ (kine)
1	Relative density(%)	60	170	15.3	20.4
		45	172	14.9	21.9
2	Wave	El Centro(NS)	170	15.3	20.4
		Taft(NS)	199	14.0	22.0
		Niigata(EW)	216	17.2	23.4
		Hachinohe(EW)	192	15.1	20.4
		Kobe(NS)	196	15.5	20.9
3	Thickness (m)	10	170	15.3	20.4
		8	207	14.9	18.2
		6	241	15.1	18.9
		5	274	14.2	16.8
	Average values		201	15.2	20.3
	Coefficient of variation		15.8%	5.2%	8.7%



(a) u/σ_o' *versus* α_{max} (b) u/σ_o' *versus* v_{max} (c) u/σ_o' *versus* SI

Fig. 9 Correlation between u/σ_o' and each maximum ground response

Correlation Between Excess Pore Water Pressure Ratio and Ground Responses

The correlation between maximum ground responses and excess pore water pressure ratio was investigated on the basis of the pseudo-dynamic test results of Cases 1 ～ 3 on Toyoura sand. Figure 9 shows the correlation between u/σ_0' and each maximum ground response. In Fig. 9(a) ～ (c), *C.C.* denotes correlation coefficient. The *C.C.* of α_{max}, v_{max} and *SI* were 0.57, 0.97 and 0.96, respectively. That is, excess pore water pressure ratio correlated better with v_{max} and *SI* than with α_{max}

CONCLUSIONS

The conclusions obtained from this study are summarized as follows :

(1) The reproducibility of the liquefaction process was verified qualitatively and quantitatively by the response results obtained from the pseudo-dynamic test on three kinds of sands : Toyoura sand, Niigata sand and Kasumigaura sand.

(2) The maximum intensities of earthquake ground motions at occurrence of liquefaction were estimated from the Toyoura sand test results. When relative density, earthquake wave form and layer thickness were the test parameters, the maximum acceleration responses at liquefaction ranged from 170 to 274 gal, and the scatter was not small. However, the maximum velocity responses at liquefaction lay within a narrow band from 14.0 to 17.2 kine, and the scatter was small compared with the maximum acceleration responses. The spectrum intensities at liquefaction ranged from 16.8 to 23.4 kine, and the scatter was small. This tendency was similar to the maximum velocity responses.

(3) The pseudo-dynamic test results indicated that excess pore water pressure developed in the ground correlated better with the maximum velocity responses and the spectrum intensity than the maximum acceleration responses, which has commonly been used for evaluating soil liquefaction potential.

Conclusions (2) and (3) agree fairly well with the previous findings (Midorikawa and Wakamatsu, 1988 ; Yanagisawa *et al.*, 1986) on the basis of strong ground motion observations. These conclusions indicate that the maximum velocity is a more appropriate measure for evaluating liquefaction potential of subsurface layers than the maximum acceleration which has commonly been used. Furthermore, the possibility that the spectrum intensity might be a measure for evaluating liquefaction potential is confirmed. However, the maximum velocity obtained directly from observation records is more practical measure than the spectrum intensity. These conclusions are obtained from limited data by a laboratory dynamic soil test. Therefore, further investigation is necessary.

REFERENCES

Housner, G.W. (1952). Spectrum intensities of strong motion earthquakes. *Proc. 1952 Symposium on earthquake and blast effects on structure*, Earthquake engineering institute, 20-36.

Kusakabe, S. and S. Morio (1995). The development of a substructure on-line testing system for seismic response analysis of geotechnical system. *Soil and Foundations*, Vol. 35, No. 2, 117-125.

Midorikawa, S. and K. Wakamatsu (1988). Intensity of earthquake ground motion at liquefied sites. *Soil and Foundations*, Vol. 28, No. 2, 73-84.

Yanagisawa, E., A. Shimizu, H. Ohmiya (1986). Wave-induced pore water pressure in surface sand layer. *Proc. 7th Japan earthquake engineering symposium*, 589-594. (in Japanese with English abstract).