EXPERIMENTAL STUDY ON LIQUEFACTION OF SATURATED SOILS USING A SHAKING TABLE

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SUMMARY

The liquefaction tests for comparatively large specimen are performed using a shaking table. In this paper, the following three subjects are investigated and the results are reported. 1) Comparison of liquefaction test results obtained by this shaking table test with those obtained by other tests. 2) Reliquefaction characteristics of soils. 3) Liquefaction characteristics under drainage condition.

INTRODUCTION

Generally, the liquefaction tests are performed by dynamic triaxial test apparatus or dynamic simple shear test apparatus. On the other hand, a few liquefaction tests using shaking table are carried out for comparatively large specimen (Ref. 1), 3), 4)).

The liquefaction test apparatus used in this studies is shown in Fig.1. A size of specimen is 60 cm in diameter and 4 cm in height. To similar to shear deformation of ground during earthquake as simply as possible, polyvinyl chloride rings having smooth surface are stacked around the specimen. Because the diameter of the specimen is large, it is considered that liquefaction tests can be performed for not only sand, but also for soils such as gravel and Masado (the decomposed granite soil) consists of large grain size. Experiments are performed to clarify the reliquefaction characteristics of saturated soils mentioned above, and liquefaction characteristics of saturated sand under drainage condition. The results obtained by the former experiments are compared with those obtained by other tests.

EXPERIMENTAL APPARATUS

Experimental apparatus is shown in Fig.1. This apparatus is made up shearing box fixed on a shaking table ⑥ and equipment for measuring drainage volume. The bottom plate of the shaking table is made from a stainless steel plate, having 5 mm in thickness, and rim ⑪, having 60 cm in outer diameter and 3 cm in height welded to the base plate. Four polyvinyl chloride rings are stacked around the specimen, having 60 cm in diameter and 4 cm in height covered by rubber membrane. A size of each ring is 1 cm in thickness, and inner- and outer diameters are 60.6 cm, 76.0 cm, respectively.

Vertical stress is applied to the specimen by weight of loading plate (2.5 kN), and its magnitude at surface of the specimen is 8.8 kN/m^2. Cyclic shear stress is applied to the specimen by horizontal inertia force of loading plate, specimen and rings during shaking.

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SOILS

Soils used in this experiments are Toyoura sand, Shingu sand, Masado (decomposed granite) and gravel. The grain size distribution curves and the physical properties for each soil are shown in Fig.2 and in Table 1, respectively. Toyoura sand, Shingu sand and gravel are uniformity in grain size, but a uniformity coefficient of Masado is equal to 8.9.

SPECIMEN AND EXPERIMENTAL PROCEDURE

(1) SPECIMEN

The saturated specimen, having about 50% relative density $(D_r)_{av}$ for each sample was prepared. The saturated specimen is prepared by carefully pouring wet sample into water stored in a rubber membrane fixed around a rim. Subsequently the specimen is compacted by a tamper to obtain a required density and then loading plate is set on the specimen. The specimen thus prepared is 60 cm in diameter, and 4 cm in height which causes the substantial shear deformation. The coefficient of pore pressure B was above 0.95 after consolidation.
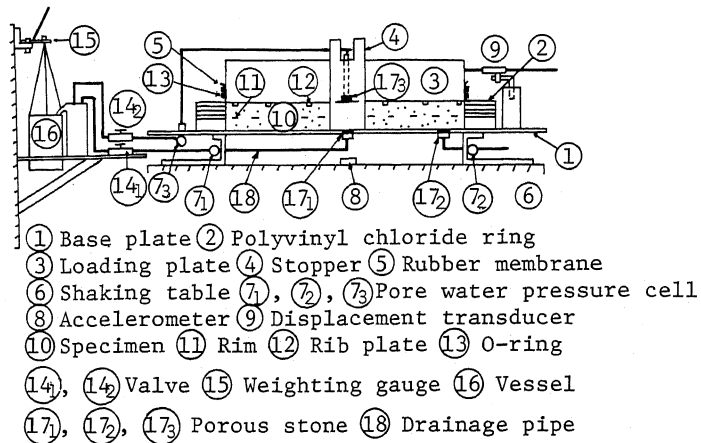
(2) RELIQUEFACTION TEST

The specimen obtained by above method was subjected to sinusoidal acceleration with constant amplitude and frequency (f)=3.1 Hz under undrained condition. After pore pressure generated in the specimen became equal to effective vertical stress, vibration of about 20 pulses was applied to the specimen. Subsequently shaking table was stopped, then pore water was drained from upper surface of the specimen for 15 minutes. After the drainage completed, the
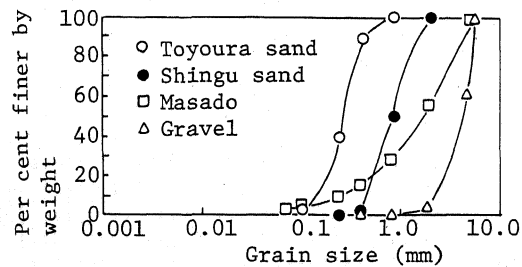

① Base plate ② Polyvinyl chloride ring
③ Loading plate ④ Stopper ⑤ Rubber membrane
⑥ Shaking table ⑦₁, ⑦₂, ⑦₃ Pore water pressure cell
⑧ Accelerometer ⑨ Displacement transducer
⑩ Specimen ⑪ Rim ⑫ Rib plate ⑬ O-ring
⑭₁, ⑭₂ Valve ⑮ Weighting gauge ⑯ Vessel
⑰₁, ⑰₂, ⑰₃ Porous stone ⑱ Drainage pipe

Fig.1 Test apparatus.

Fig.2 Grain size distribution curves.

Table 1 Physical properties of samples.

	Toyoura sand	Shingu sand	Masado	Gravel
G_s	2.63	2.64	2.63	2.76
D_{max}(mm)	0.84	2.00	5.66	5.66
D_{50}(mm)	0.27	0.83	1.75	4.40
U_c	1.6	1.7	8.9	2.1
e_{max}	1.028	0.890	1.062	0.853
e_{min}	0.678	0.540	0.597	0.638

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vibration having required acceleration was applied to the specimen to cause liquefaction again. Thus the liquefaction tests were carried out for the same specimen three times by same procedure.

The acceleration of the shaking table, pore pressure at three positions of the specimen and amplitude of shear deformation of the specimen were measured. These measured values were recorded in pen-written oscillograph.

(3) LIQUEFACTION TEST UNDER DRAINAGE CONDITION

In contrast with the liquefaction tests under complete undrained condition, the liquefaction tests under drainage condition were performed. Horizontal seismic coefficient (k_h) was nearly 0.05, 0.08 and 0.10, and frequency (f) was changed to 1.5 Hz, 3.1 Hz and 5.1 Hz for each k_h. Drainage volume of pore water during the vibration was controlled by a valve (14) in advance. The drainage volume was stored in a vessel (16) and was measured by weighting gauge (15). Other measurements are the same as reliquefaction test.

RESULTS AND CONSIDERATIONS

(1) COMPARISON OF TEST RESULTS OBTAINED BY SHAKING TABLE TESTS WITH THOSE OBTAINED BY OTHER TESTS

In this paper, occurrence of liquefaction was defined as a point of state where the amplitude of shear strain increased rapidly as shown in Fig.9. Number of cycles of acceleration to cause liquefaction was designated by n_L.

In this shaking table, as the required acceleration cannot be displayed from first pulse functionally, corrected pulse n_p been equivalent to the required acceleration was obtained from Eq.1 (Ref. 5)).

$$n_p=(k_h)_i \cdot n_i/k_h \qquad (1)$$

in which $(k_h)_i$: the horizontal seismic coefficient, n_i: the number of cycles during increase of acceleration, k_h: the required horizontal seismic coefficient.

Vertical stress $(\sigma_v)'_m$ was calculated from Eq.2 by referring to Fig.3.

$$(\sigma_v)'_m=(\sigma_v)'_o-M \cdot c/2I \qquad (2)$$

in which $(\sigma_v)'_o$: vertical stress distributed on a bottom of specimen without considering rotational moment, M: moment occurred by the loading plate and the specimen, I: moment of inertia, c: diameter of the specimen. Shear stress (τ) was calculated from Eq.3.

$$\tau=k_h \cdot W/A \qquad (3)$$

in which W: the sum total of weights of specimen, loading plate and rings, A: cross-sectional area of the specimen.

Result obtained by this shaking table test was close to that obtained by De Alba et al. (1976). Fig.4 shows the relation between stress ratio $\tau/(\sigma_v)'_m$ and n_L for each sample. Similar results obtained by the dynamic triaxial test and the dynamic simple shear test etc. are shown in this figure. It is seen in
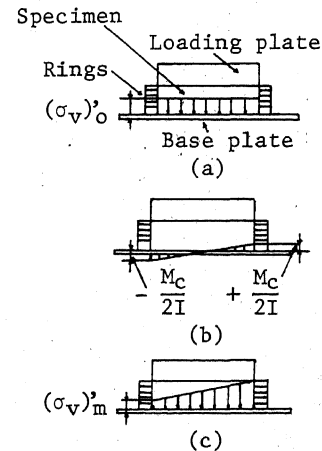

Fig.3 Vertical stress distributed on a bottom of specimen under shaking.

---·--	Toyoura sand($(D_r)_{av}$=51.8%)	—— Masado($(D_r)_{av}$=51.3%)
---	Shingu sand ($(D_r)_{av}$=48.1%)	--- Gravel($(D_r)_{av}$=52.5%)

Other studies

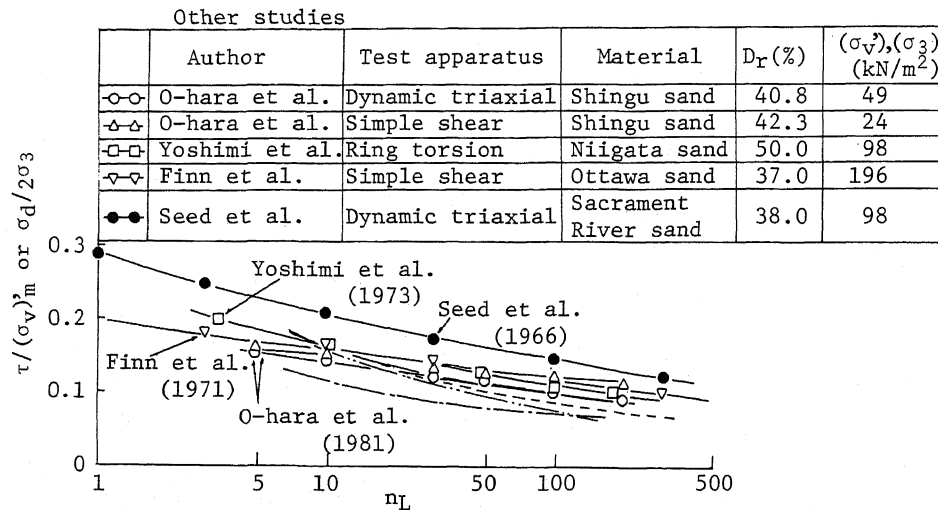|	Author	Test apparatus	Material	D_r(%)	$(\sigma_v'),(\sigma_3)$ (kN/m^2)
-o-o-	O-hara et al.	Dynamic triaxial	Shingu sand	40.8	49
-△-△-	O-hara et al.	Simple shear	Shingu sand	42.3	24
-□-□-	Yoshimi et al.	Ring torsion	Niigata sand	50.0	98
-▽-▽-	Finn et al.	Simple shear	Ottawa sand	37.0	196
-●-●-	Seed et al.	Dynamic triaxial	Sacrament River sand	38.0	98

Fig.4 Comparison of results obtained by shaking table tests with those obtained by other tests.

this figure that the stress ratio (the resistance to liquefaction) for saturated soils measured by the shaking table tests is a little smaller than those obtained by the dynamic triaxial test apparatus or the dynamic simple shear test apparatus etc.. Also, it is note worthy that the resistance to liquefaction of gravel is the most smallest.

Fig.5 Reliquefaction test results obtained by shaking table test.

(2) RELIQUEFACTION CHARACTERISTICS

Fig.5 shows an example of reliquefaction test results. Sample is Toyoura sand. The symbols ○, ● and ◑ represent first-, second-, and third liquefaction test results, respectively. The horizontal seismic coeffient written on both ends in each curve indicate those maximum and minimum values. It is clarified in Fig.5 that the resistance to reliquefaction increases with increasing a relative density by drainage after liquefaction.
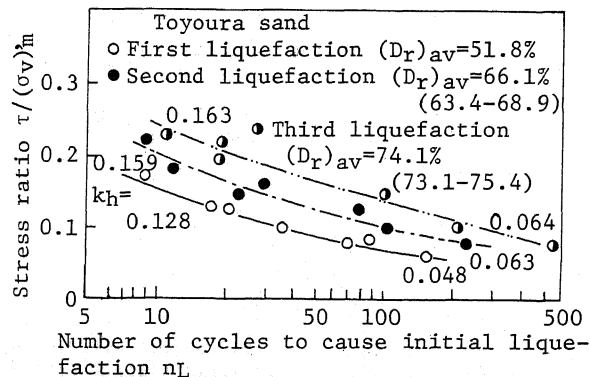
Fig.6 shows the reliquefaction test results for Toyoura sand performed by the dynamic triaxial test. A size of the specimen is 5 cm in diameter and

about 12 cm in height. σ_3, σ_d represent initial effective stress and amplitude of repeated deviator stress, respectively. In this dynamic triaxial test result, the resistance to second liquefaction is larger than the resistance to first liquefaction, and this result coincides with result of the shaking table test shown in Fig.5. It is noticed that this result differs from that of Finn et al. (1971). Finn et al. obtained the result that resistance to liquefaction of the specimen after liquefaction is smaller than that of the specimen before liquefaction in spite of increasing density. Though detail of the dynamic triaxial test method by Finn et al. is not clarified, we performed the triaxial tests by removing a constriction induced on upper part of the specimen by liquefaction.

(3) COMPARISON OF RESISTANCE TO RELIQUEFACTION WITH ORDINARY RESISTANCE TO LIQUEFACTION

Fig.7 shows the relation between stress ratio $\tau/(\sigma_v)'_m$ and n_L for Toyoura sand specimen reliquefied and not liquefied. Relative density for each specimen is 66.1% and 67.2%, respectively. The former is the specimen having initial relative density 51.8% before liquefied.

It is seen in this figure that the resistance to reliquefaction of specimen subjected to large strain such as 10% during first liquefaction is almost coincident with that of the virgin specimen which has almost same relative density.

Fig.8 shows the results of second and third liquefaction tests for specimens shown in Fig.7. It is noticed that the
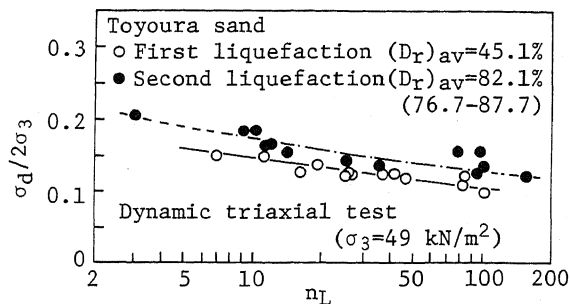

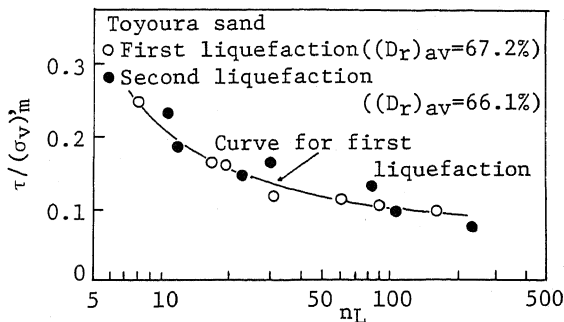Fig.6 Reliquefaction test results obtained by dynamic triaxial test.

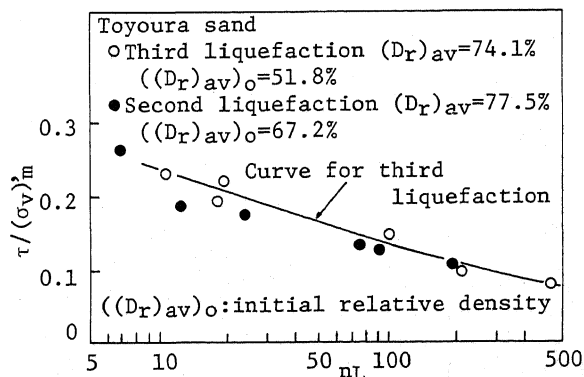Fig.7 Comparison of stress ratio for specimen liquefied once with that for virgin specimen.

Fig.8 Comparison of stress ratio for specimen liquefied two times with that for specimen liquefied three times.

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resistance to reliquefaction of both specimens are almost indentical. The same results as mentioned in Figs.7 and 8 were also obtained for Masado which considerably differs with Toyoura sand in grain size distribution. Accordingly, it is concluded from this studies that the resistance to liquefaction should be determined by a relative density of the specimen irrespectively whether the specimen has reliquefied or not previously.

(4) EFFECT OF DRAINAGE ON RESISTANCE TO LIQUEFACTION

To use a convenient index representing degree of drainage, we defined the following index v_t obtained by Eq.4.

$$v_t = (\Delta V/V_w)/n \qquad (4)$$

in which ΔV: drainage volume of pore water from the specimen during shaking, V_w: initial volume of pore water contained in the specimen, n: number of cycles. n is defined by n_L described previously in a case of the specimen liquefied as shown in Fig.9, otherwise defined by number of cycles of shear stress until pore pressure reaches to maximum value. The reason for use of V_w instead of initial volume of the specimen is that the effect of density on results shown later may be ignored.

Fig.9 shows a typical test record performed with $v_t = 9.65 \times 10^{-6}$ and frequency of 3.1 Hz. The record lines represent acceleration of shaking table, pore pressure, shear strain and drainage volume of pore water, in oder.

Before the liquefaction tests are carried out, the effect of frequency on the resistance to liquefaction was examined under undrained condition. Frequencies are 1.5 Hz, 3.1 Hz and 5.1 Hz. As shown in Fig.10, the resistance to liquefaction is not affected by frequency under undrained condition. This result agrees with the result obtained by ring torsional test by Yoshimi et al. (1980).

Fig.11 shows the relation between pore pressure ratio $u/(\sigma_v)'_0$ and number of cycles n at each drainage v_t. Here, u represents pore pressure. $v_t = 0$ means undrained condition. Each curve shows average curve obtained by three tests carried out under
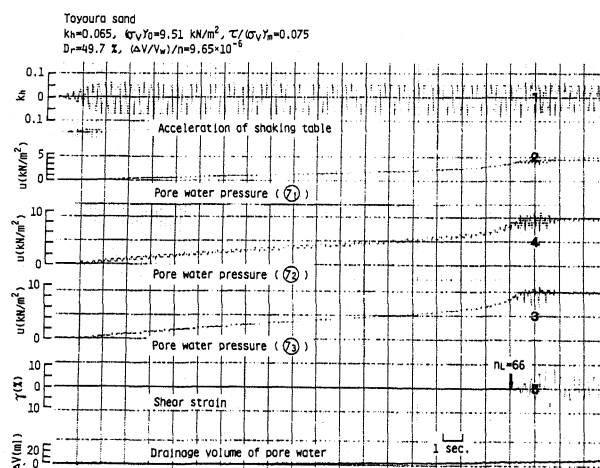

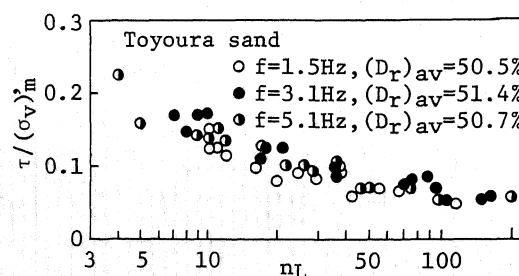Fig.9 Typical record of liquefaction test under drainage.

Fig.10 Relation between stress ratio and number of cycles to cause liquefaction.

almost same conditions.
It is seen in this figure
that liquefaction does not
occur when v_t is larger
than a certain value.
Same results are obtained
by experiments with fre-
quency of 1.5 Hz and 5.1
Hz.

Test results are
plotted in relation be-
tween $\tau/(\sigma_v)'_m$ and v_t in
Fig.12. For test at each
frequency, solid and open
symbols represent the re-
sult liquefied and not li-
quefied, respectively. It
is interesting to note
that there exist lower
boundary for stress ratio
which liquefaction occurs
under drainage condition.
Also, the effect of drain-
age on liquefaction is ir-
respective of frequency.
Same results were also ob-
tained for Shingu sand
shown in Fig.13. Both
straight lines shown in
Figs.12 and 13 almost agree.

Toyoura sand

$k_h \doteq 0.05$
$f = 3.1 Hz$

	$D_r(\%)$	$\tau/(\sigma_v)'_m$	$(\Delta v/v_w)/n$ $(\times 10^{-5})$
▲	51.4	0.057	0
□	52.0	0.057	0.228
●	50.7	0.061	1.361
△	50.2	0.058	2.500
○	52.5	0.056	1.457

Fig.11 Relation between pore pressure ratio
and number of cycles.

	1.5Hz	3.1Hz	5.1Hz
Liquefied	▲	●	■
Non liquefied	△	○	□
$(D_r)_{av}(\%)$	51.7	51.5	51.7

Fig.12 Lower boundary for stress ratio which
liquefaction occurred under drainage.

CONCLUSIONS

The main conclusions
obtained in this investiga-
tion are as follows.
(1) The resistance to li-
quefaction for satu-
rated sand obtained
by this shaking table
test is close to that
for saturated sand
obtained by the shak-
ing table test by De
Alba et al. and is a
little smaller than those obtained by the dynamic triaxial test or the
dynamic simple shear test etc..
(2) The resistance to reliquefaction for sand, gravel and Masado (the de-
composed granite soil) which increased a relative density by drainage
after liquefaction is larger than the resistance to first liquefaction.
The maximum shear strain during liquefaction is restricted to about 10%
in this test.
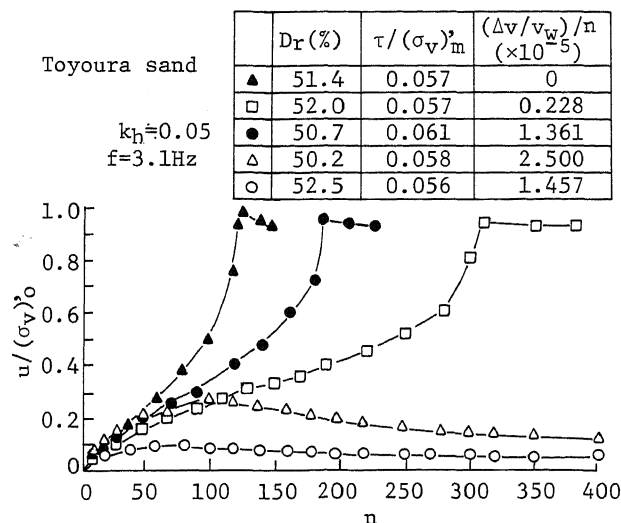(3) The resistance to reliquefaction of the specimen liquefied once or

twice is equal to the resistance to liquefaction of the virgin specimen having same relative density.

(4) It is shown that the lower boundary for stress ratio which liquefaction occurs under drainage condition is able to be represented by a straight line in relation between stress ratio and drainage. Drainage is able to be defined by a volumetric strain of the pore water per unit cycle.

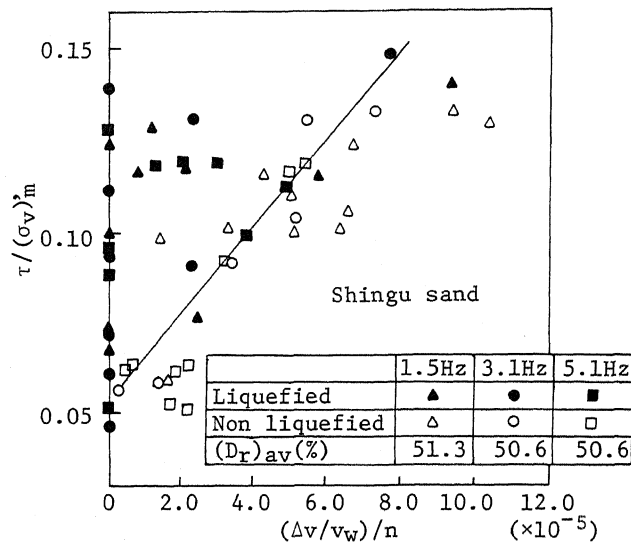|	1.5Hz	3.1Hz	5.1Hz
Liquefied	▲	●	■
Non liquefied	△	○	□
$(D_r)_{av}(\%)$	51.3	50.6	50.6

Fig.13 Lower boundary for stress ratio which liquefaction occurred under drainage.

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