Effect of Membrane Penetration on Liquefaction Resistance

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Abstract

The liquefaction of saturated sand is due to a negative dilatancy. In the cyclic triaxial test, a part of pore water squeezed from sample is transformed into the reduction of membrane penetration and so the perfect undrained test can not be performed. Consequently, the liquefaction resistance obtained by the cyclic triaxial test is evaluated apparently larger than true value. In this paper, the method of correction of the liquefaction resistance is proposed by consideration of various experimental results.

It is clear that the volume change of sample obtained by the undrained cyclic triaxial test is nearly equal to the expansive volume change of sample due to the decrease of effective stress. According to this relation, we considered that the liquefaction resistance obtained by the cyclic triaxial test can be corrected by means of the obtaining volumetric strain of sand structure concerned with the increase of pore pressure as the difference between expansive volume change and volume change been equivalent to the membrane penetration. This procedure is explained in Fig. 9 schematically.

Introduction

There are many studies on liquefaction of a saturated sand layer due to earthquake and we have known the character of liquefaction, the experimental method and the method for evaluation of liquefaction resistance.

H. B. Seed[1),2)] carried out these experimental studies systematically, using the dynamic triaxial compression test and the dynamic simple shear test. He pointed out that the liquefaction resistance obtained by the dynamic triaxial compression test is larger than it obtained by the dynamic simple shear test, because of stress concentration induced in the simple shear box.

After that, the ring shear apparatus, the hollow cylinder torsion apparatus and Kjellman type simple shear apparatus were developed by Y. Yoshimi[3)], K. Ishihara[4)] and S. O-hara[5)], and the many detailed results were obtained.

On the other hand, the shaking table tests, having large scale sand layer, were carried out by W. D. L. Finn[6)], S. O-hara[5)] and De Alba[7)]. In this experiments, a surface of sand layer was covered by rubber seat to provide effective normal pressure. At recently the dynamic simple shear tests with large diameter specimen were performed by T. Harada[8)], O. Matsuo[9)] and S. O-hara[10)].

These results were compared with it obtained by the dynamic triaxial compression test. Consequently, the liquefaction resistance obtained by the shaking table tests is smaller than its obtained by the cyclic triaxial tests. Martin et al.[11)] presumed that this fact was caused by the difference of coefficient of earth pressure at rest acting on the sample and the

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effect of a membrane.

They corrected their results by a system compliance and a membrane compliance.

It has been clear that the liquefaction of saturated sand is due to a negative dilatancy. During the cyclic triaxial test, a part of pore water squeezed from sample is transformed into the reduction of membrane penetration and so the perfect undrained test can not be performed.

Consequently, the liquefaction resistance obtained by the cyclic triaxial test is evaluated apparently larger than true value. On the other hand, the effect of membrane penetration on the experimental results is small in the simple shear test without cell pressure.

At present, a cyclic triaxial test apparatus is more useful than other apparatus structurally because of a convenient operation. In this paper, the method of correction of the liquefaction resistance is proposed by consideration of various experimental results.

Soils

Three kinds of sands, Toyoura sand, Shingu sand and Masado (the decomposed granite soil) were used in this experiment.

The grain size distribution curves and the physical properties of sands are shown in Fig. 1 and in Table 1 respectively.

Toyoura sand and Shingu sand are uniformly but a uniformity coefficient of Masado is equal to 5.11. It was judged by Tsuchida's proposition that these soils have the possibility of liquefaction.

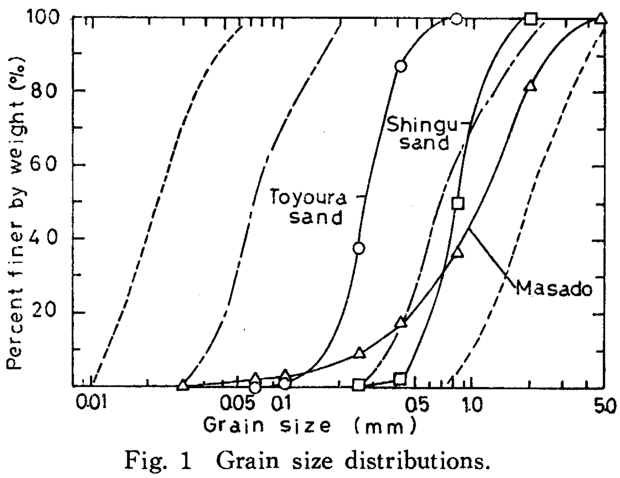

Fig. 1 Grain size distributions.

Table 1 Physical properties of sands.

	Toyoura sand	Shingu sand	Masado
G_S	2.63	2.64	2.63
D_{50} (mm)	0.27	0.83	1.13
U_C	1.64	1.70	5.11
e_{max}	1.028	0.859	1.091
e_{min}	0.678	0.623	0.549

Experimental apparatus

In this experiments, the cyclic triaxial compression test apparatus, the dynamic simple shear test apparatus and the shaking table were used. They have been used in our previous experiment and their detail was described in our previous paper. So, an outline of the cyclic triaxial compression apparatus was only described in this paper, because it was mainly used in present experiments.

A size of sample is cylindrical shape 5.0 cm in diameter, about 12 cm in height. The sample was isotropically consolidated to the required confining pressure and the sample as confined was then subjected to repeated deviator stress of a given amplitude at 2.0 sec. period (Fig. 2).

For this purpose, the spindle to which top cap is connected is joined to the piston rod of an air cylinder: compressed air is introduced in or removed from the upper and lower chambers alternately.

The time intervals of this feed and exhaust are controlled by means of a solenoid valve and the associated relay circuit. The air pressure introduced into the cylinder is regulated in advance by a reducing valve.

The air cylinder used is bellophragm cylinder. Its effective sectional area is 17.7cm^2. Amplitude of the deviator stress is measured by a load cell of the wire strain gauge type which is attached to a spindle supporting the top cap. For the measurement of pore pressure in the sample, the pressure water penetrating through a porous plate in the pedestal is led to a suitable point through a polyethylene pipe. The measurement is made with a pressure cell of diaphragm 6 mm in diameter. This pressure cell is also of the wire strain gauge type.

Axial displacement is measured by displacement transducer of the wire strain gauge type.

The various quantities such as deviator stress, axial displacement and pore pressure are recorded in pen-written oscillograph.

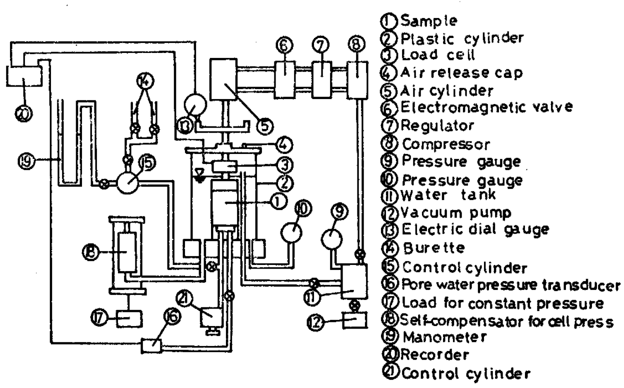

Fig. 2 Cyclic triaxial test apparatus.

Sample and Experimental Method

This studies were carried out in order to investigate the effect of the membrane penetration on the experimental results obtained by the cyclic triaxial test. So, three kinds of experiments were carried out by the using of the cyclic triaxial test apparatus, including the liquefaction test.

The preparation of sample and the experimental procedure are follows.

(1) Sample

Size of a sample is 5.0 cm in diameter and about 12 cm in height. Samples were prepared in a medium compacted state and loose compacted state.

In order to prepare perfect saturated sample, sand of weights 320~360 gf is placed in a beaker filled with deaired water and then it is boiled for about one hour to removed completely air bubbles from the sand. In forming the final sample, the sand already prepared is poured into the rubber sleeve set in the split mould stood on the pedestal. The mould is then filled with deaired water. The sand is compacted to obtain the required void ratio by means of the shock. After the placing of the top cap on top of the sample, pressure in the sample is adjusted to a negative pressure of about 0.054 kgf/cm^2, so that the sample stands by itself. The mould is removed and the dimension of the sample is measured.

Then void ratio of the sample is confirmed.

(2) Experimental procedure

We describe the procedures of three kinds of experiments in order.

a) Liquefaction test

The triaxial cell is assembled and the sample is consolidated for 15 minutes by means of the confining pressure.

Before consolidation, the pore pressure is measured at subjecting to confining pressure. The coefficient of pore pressure was above 0.96.

A connection is then made from the top cap to the load cell connected to the piston rod of the air cylinder.

By manipulation of the reducing valve, the pressure of compressed air to the air cylinder is adjusted. Adjustments are made of the deviator stress transducer, displacement transducer and pore pressure transducer etc. Finally, by actuating the solenoid valve, deviator stress is applied repeatedly to the sample until liquefaction takes place in the sample.

b) Drained cyclic compression test

In this experiment, the volumetric change of sample produced by cyclic compression stress was measured by means of the measurement of a drainage volume of pore water.

The sample was prepared by the same method above mentioned. A drainage volume of pore water of sample was measured by the burette. At this test, cyclic axial stress which was subjected to sample, was determined equal to it of the liquefaction test performed previously and also the measurement of a drainage volume was performed until the same number of cycles to cause liquefaction. The experimental results were discussed by a volumetric strain obtained from the drainage volume of a pore water.

c) Rebound test

The relations between the coefficient of volumetric expansion of sample and the decrement of the cell pressure (effective pressure) were obtained by means of the measurement of water level change in burette.

An expansion of a sample produced the decrease of water level in a burette, which is equivalent to the expansive volume of sample ΔVr, because the pore water in sample penetrating through a porous plate in the pedestal is led to a burette through a vinyl tube. But, this measured value consists of the expansive volume of soil structure ΔVs and the reduced volume accompanying a recovery of the membrane penetration ΔVrm.

Therefore, the rebounded volume of soil structure ΔVs is equal to $(\Delta Vr - \Delta Vrm)$.

In this experiment, ΔVrm was measured by means of the rod method. The detail was explained in other paper[12].

Experimental results

Fig. 3 shows the typical liquefaction test result of Toyoura sand obtained by cyclic triaxial test. It is clear in Fig. 3 that stress ratio to cause liquefaction is in proportion to a number of cycles to cause liquefaction in semi-logarithmic graph.

The test results of three kinds of sands were shown together in Fig. 4. These results

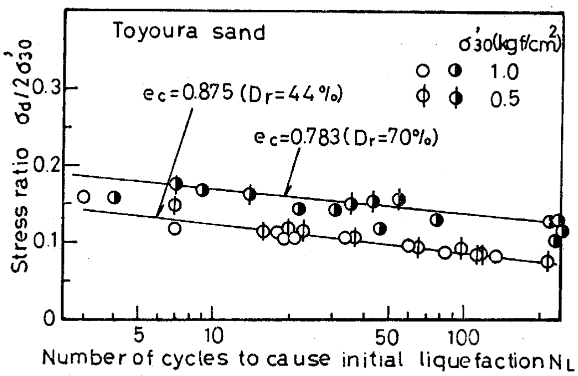

Fig. 3 Relations between stress ratio and number of cycles (Toyoura sand).

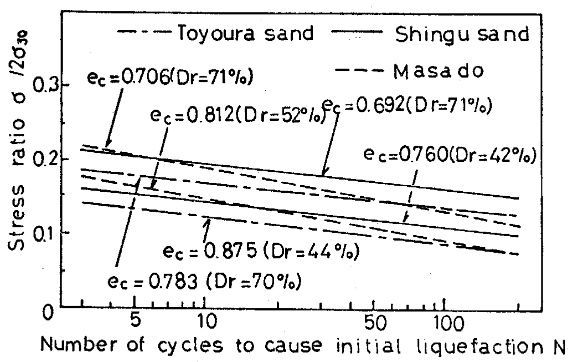

Fig. 4 Relations between stress ratio and number of cycles.

were summarized by an initial liquefaction and an initial liquefaction was defined as following condition in this paper.

$$\frac{\sigma_d}{2} = (\sigma'_3 - u) \; tan \phi \tag{1}$$

where σ_d : Amplitude of cyclic deviator stress
σ_3' : Initial effective stress
ϕ : Angle of internal friction
u : Pore pressure

Practically, an occurrence of initial liquefaction was considered as axial strain of sample began to increase rapidly.

In other definition, an occurrence of initial liquefaction may be defined as a state where a pore pressure increased to equal to an initial effective pressure.

A number of cycles to cause liquefaction under our definition was less in 2~3 cycles than it under other definition.

Fig. 5 shows the path of a pore pressure change in process of liquefaction. The ordinate and the abscissa indicate the pore pressure ratio u/σ'_3 and ratio of number of cycles N/N_L (N: repeated cycles, N_L: number of cycles to cause initial liquefaction). As may be seen in Fig. 5, the initial liquefaction occurs at about certain pore pressure ratio generally, independent of value of stress ratio $\sigma_d/2\sigma'_{30}$. Black points indicate mean values of pore pressure ratio.

Fig. 6 shows the results of drained cyclic shear test and indicates the change of the volumetric strain of sample subjected to cyclic deviator axial stress with the required amplitude.

This results are of Shingu sand ($e_c=0.765$) under $\sigma'_{30}=1.0$ kgf/cm². Also in this figure, black points indicate mean values of volumetric strain. The number of cyclics used in this experiments, adopted equal to it to cause liquefaction, corresponding to a stress ratio.

Therefore, the volumetric strain at $N/N_L=1.0$ obtained in Fig. 6 is considered to be equal to the volumetric strain of sand structure produced at initial liquefaction.

Comparing the volumetric strains produced at same number of cycles, it is decreasing in the order of Masado, Shingu sand, Toyoura sand and especially, the volumetric strain

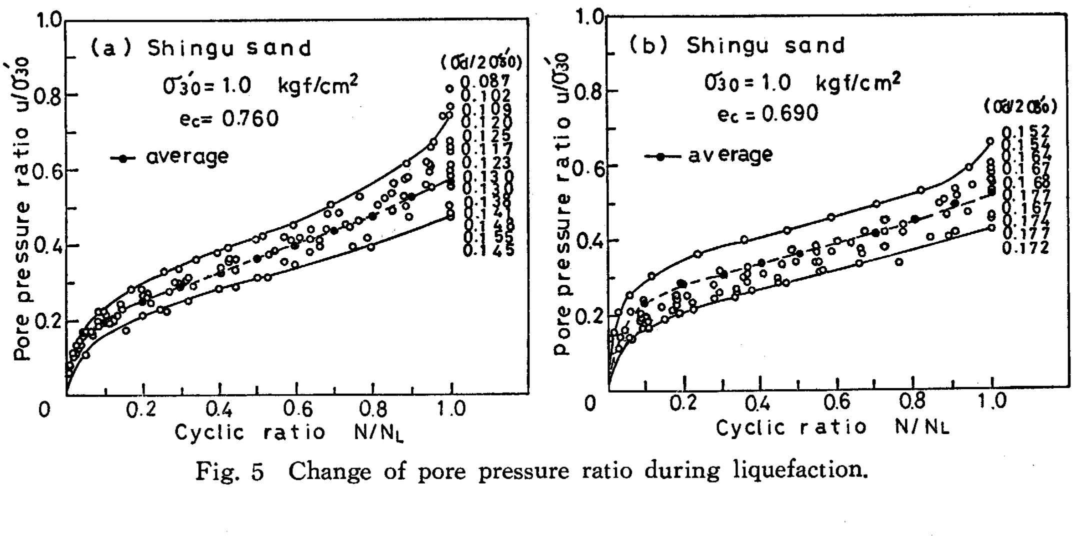

Fig. 5 Change of pore pressure ratio during liquefaction.

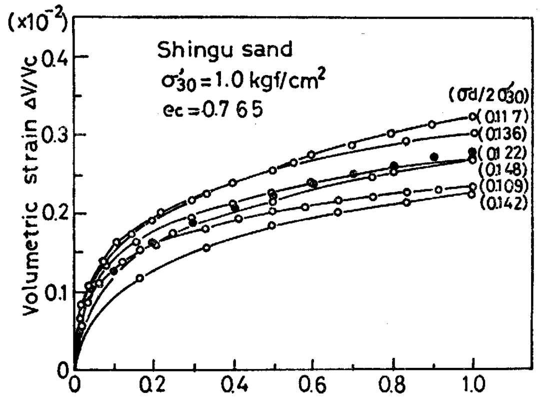

Fig. 6 Results of drained cyclic triaxial test.

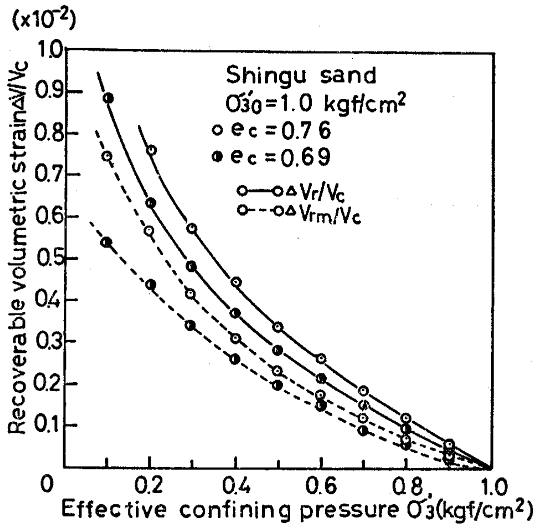

Fig. 7 Results of rebound test.

of Masado sample was two times as large as its of other sand sample. Fig. 7 shows the relation between the rebounded volume of sample and the decrease of effective stress. This typical result is of Shingu sand under $\sigma'_{30}=1.0$ kgf/cm². The solid line shows total rebounded volume of sample and the dotted line shows the decrease of membrane penetration. From these results, the rebounded volume of sand structure is equal to the difference between both lines.

Considerations of Experimental Results

From above mentioned experimental results, the correction of the liquefaction resistance obtained by the cyclic triaxial test was considered as follows:

A volume of sample is kept constant under the process of liquefaction because the contraction of sand structure due to cyclic axial stress is canceled by the expansion of sample due to a reduction of effective stress.

Both phenomena induce simultaneously.

N. Yagi[13] proposed Eq. (1) for the relation between the increase of pore pressure Δu and the volumetric strain of sample $\Delta\varepsilon_V$.

$$\Delta u = \frac{\Delta\varepsilon_V}{m_S} \qquad (1)$$

where, m_s is coefficient of volume expansibility.

But the sample used in the cyclic triaxial test is covered by rubber membrane and the penetration of rubber membrane decreases in process of liquefaction.

Therefore, in the cyclic triaxial test, a strict undrained test can not be performed because volume expansion of sample is permitted and from result, the liquefaction resistance is estimated larger than true value.

According to this consideration, the relation between the pore pressure and volumetric strain can be introduced as follows.

The volume change of saturated sand in unit volume caused by pore pressure change Δu is given by $\Delta u \cdot m_w \cdot n$. Here m_w is coefficient of volume compressivility of pore water and n is porosity.

On the other hand, the volume expansion of sample caused by the decrease in effective stress is given by $m_s \cdot \Delta u$ and the volume expansion of membrane is given by $m_m \cdot \Delta u$ (m_m: coefficient of volume expansion of membrane).

Finally, the following equation may be obtained.

$$\Delta \varepsilon_V - m_s \cdot \Delta u - m_m \cdot \Delta u = \Delta u \cdot m_w \cdot n$$

Thus, Eq. (2) is obtained

$$\Delta u = \frac{\Delta \varepsilon_V}{m_s + m_m + m_w \cdot n} \tag{2}$$

Here, $m_s \gg m_w$, $m_m \gg m_w$, $n < 0.5$

Eq. (3) is deduced from Eq. (2) as follow.

$$\Delta u \fallingdotseq \frac{\Delta \varepsilon_V}{m_s + m_m} \tag{3}$$

$\Delta u \cdot (m_s + m_m)$ is the volumetric expansive strain of sample caused by the increase in pore pressure Δu (i.e. the decrease in effective stress).

Using Symbols,

$$\left.\begin{aligned} \Delta \varepsilon_V &= \Delta V / V_c \\ \Delta u \cdot (m_s + m_m) &= \Delta V r / V_c \\ \Delta u \cdot m_m &= \Delta V r m / V_c \end{aligned}\right\} \tag{4}$$

Therefore, we obtained

$$\Delta V / V_c \fallingdotseq \Delta V r / V_c \tag{5}$$

The mean values of $\Delta V/Vc$ and $\Delta Vr/Vc$ at $N/N_L = 1.0$ were obtained from their experimental results as same as Fig. 6 and Fig. 7.

Both values relate to the pore pressure at initial liquefaction. Fig. 8 shows the relation between $\Delta V/Vc$ and $\Delta Vr/Vc$. Comparing $\Delta V/Vc = \Delta Vr/Vc$ line with the experimental values, the fact $\Delta V/Vc = \Delta Vr/Vc$ was confirmed in experimental results generally.

By obtaining the fact shown in Fig. 8, we considered that the volumetric strain of sand structure, which is produced by cyclic shear stress, takes part in the decrease of pore pressure and in the expansion of membrane.

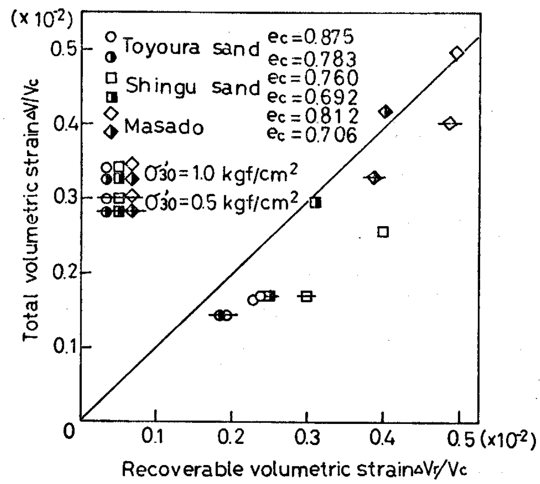

Fig. 8 Relation between $\Delta V/Vc$ and $\Delta Vr/Vc$.

Correction of Liquefaction Resistance

We considered the following method for the correction of liquefaction resistance. We explain this method by way of example, Shingu sand ($e_c=0.76$) under $\sigma'_{30}=1.0$ kgf/cm^2.

Fig. 9 (a) shows the results of rebounded test and of membrane penetration test, as same as Fig. 7.

Fig. 9 (b) shows the mean curve of the result of drained cyclic shear test. First, the mean value of pore pressure ratio u/σ'_{30} is obtained 0.560 at $N/N_L=1.0$ from Fig. 5. Then the effective stress σ'_3 becomes 0.440 kgf/cm^2. In Fig. 9 (a), we can obtain the

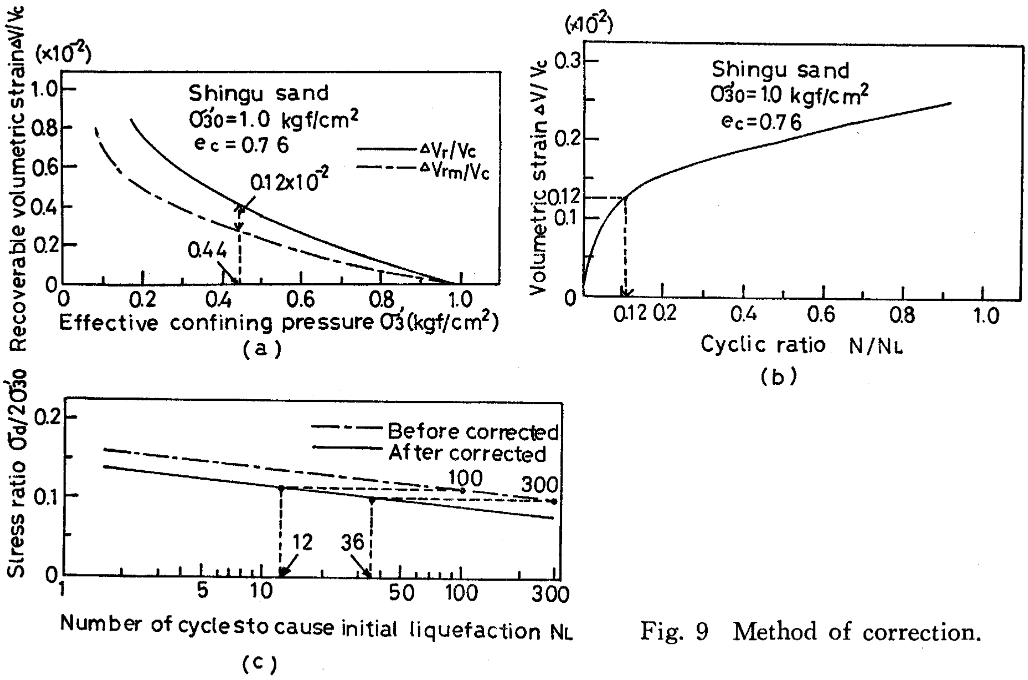

Fig. 9 Method of correction.

volumetric strain of sand structure $\Delta Vs/Vc$ at $\sigma'_3=0.440$ kgf/cm² by $\Delta Vr/Vc-\Delta Vrm/Vc=0.12\times10^{-2}$.

We considered that the volumetric strain $\Delta Vs/Vc$ determines the increase of pore pressure. Therefore, the value $N/N_L=0.12$ is obtained by the correspondence to $\Delta Vs/Vc=0.12\times10^{-2}$.

Because $\Delta Vs/Vc$ shown in Fig. 9 (b) is the volumetric strain without the influence of membrane penetration, the time at the occurrence of liquefaction was corrected as from $N/N_L=1.0$ to $N/N_L=0.12$ by corresponding $\Delta V/Vc$ to expansive strain of sand structure $\Delta Vs/Vc=0.12\times10^{-2}$ obtained from Fig. 9 (a). Consequently, it can be presumed that the initial liquefaction may occur at $N=0.12$ N_L.

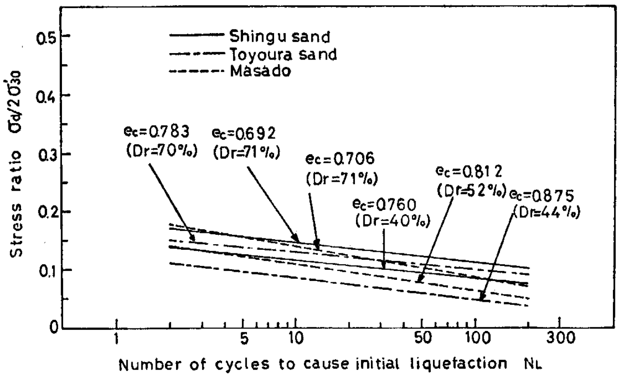

Fig. 10 Relations between stress ratio and number of cycles after correction.

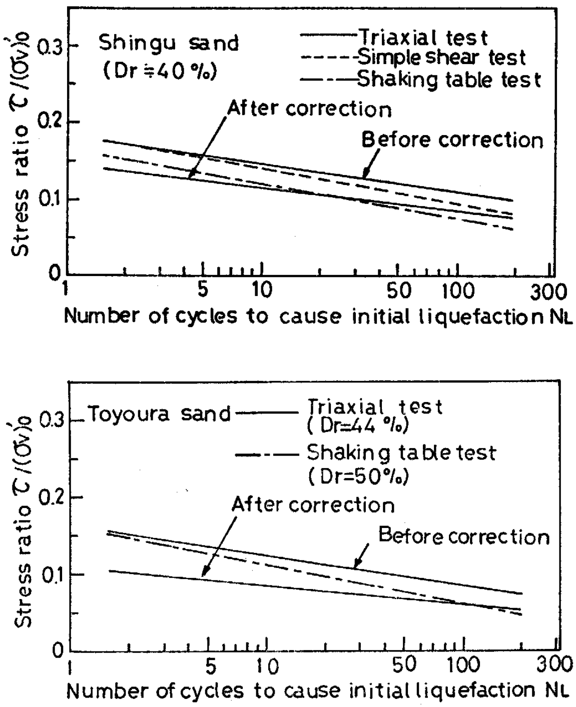

Fig. 11 Evaluation of correction.

This method is illustrated in Fig. 9 (c) and the corrected line is shifted horizontally by 0.12 N_L.

Table 2 Corrected values.

Sample	σ'_{30} (kgf/cm^2)	e_c	u/σ'_{30} (Liquefaction test)	$\Delta V/V_c$ (Drained test)	$\Delta V_r/V_c$ (Rebound test)	$\Delta V_s/V_c$	N/N_L (Corrected value)
Toyoura sand	1.0	0.875	0.680	0.171	0.240	0.092	0.184
		0.783	0.680	0.165	0.230	0.103	0.167
	0.5	0.874	0.710	0.144	0.195	0.053	0.090
		0.788	0.730	0.145	0.185	0.061	0.063
Shingu sand	1.0	0.765	0.560	0.258	0.400	0.120	0.122
		0.696	0.520	0.299	0.310	0.092	0.030
	0.5	0.767	0.600	0.170	0.300	0.070	0.110
		0.704	0.580	0.170	0.250	0.062	0.024
Masado	1.0	0.805	0.710	0.501	0.495	0.145	0.052
		0.716	0.675	0.419	0.400	0.142	0.060
	0.5	0.816	0.720	0.404	0.485	0.190	0.155
		0.716	0.710	0.330	0.385	0.186	0.175

The corrected values of respective samples were shown in Table 2, obtained by above mentioned method.

Fig. 10 shows the corrected liquefaction resistance of respective sands. It is seen by the comparison between Fig. 6 and Fig. 10 that the corrected liquefaction resistance becomes less by 32~58% than the experimental value.

Fig. 11 shows the comparison between the corrected values indicated in Fig. 10 and other experimental values, obtained by a shaking table test and by a dynamic simple shear test.

The samples of the shaking table test and of the dynamic simple shear test place in a state of K_0-consolidation. Accordingly, it is said that their stress ratio to cause liquefaction becomes smaller than it obtained by the cyclic triaxial test. It may be seen in Fig. 11 that the corrected liquefaction resistances are close to the results of the shaking table test.

Conclusion

In order to correct the experimental results on liquefaction resistance, obtained by the cyclic triaxial test, eliminating the effect of membrane penetration, we performed three kinds of tests and proposed the method of correction by the consideration of experimental results.

First, it is clear that the volume change of sample, obtained by the undrained cyclic triaxial test is nearly equal to the expansive volume change of sample due to the decrease of effective stress. According to this relation, we considered that the liquefaction resistance obtained by the cyclic triaxial test can be corrected by means of the obtaining volumetric strain of sand structure, concerned the increase of pore pressure as the difference between expansive volume change and volume change been equivalent to the membrane penetration.

This procedure is explained in Fig. 9 schematically.

Also, this correction is examined by comparison between results of various tests.

Acknowledgement

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Symbols used in the paper

Δu : The increase of pore pressure
$\Delta \varepsilon_v$: The increase of volumetric strain
m_s : Coefficient of volumetric strain of sand structure
m_m : Coefficient of expansion of membrane
m_w : Coefficient of volumetric strain of pore water
n : Porosity
Vc : Initial volume of sample
ΔV : Total volume change of sample
ΔVr : Rebounded volume change of sample
ΔVrm : Expansive volume change of sample
ΔVs : Rebounded volume change of sand structure ($=\Delta Vr-\Delta Vrm$)
σ'_{30} : Initial effective stress
e_c : Initial void ratio
N : Number of cycles
N_L : Number of cycles to cause liquefaction
σ_d : Amplitude of repeated stress

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