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A SIMPLIFIED CORRECTION FOR MEMBRANE COMPLIANCE IN LIQUEFACTION TESTS

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ABSTRACT

A concept to account for the effect of membrane penetration on the generation of pore pressure in liquefaction tests was demonstrated based on experimental studies. The major effect of membrane penetration was to increase the number of cycles to cause liquefaction. The cycle ratio was defined as a ratio between numbers of cycles causing liquefaction with and without compliance at the same stress ratio. The cycle ratio was found to be a unique function of membrane compliance ratio, and independent of applied shear stress. A careful review of the previous study (Martin et al., 1978) yielded the same result, indicating the validity of the concept.

Based on the findings, a simplified method was presented for correcting liquefaction test results for the membrane penetration effects. Several previous studies concerning the effects of specimen diameter were used to validate the proposed method, since the resulting difference in the liquefaction strength mainly reflects the membrane penetration effects. The liquefaction strength curves for different diameter specimens after membrane correction were almost coincident, showing a considerable potential of the proposed method.

Key words : gravel, laboratory test, liquefaction, membrane penetration, sand, shear strength, undrained test (**IGC** : D 7/D 6)

INTRODUCTION

In undrained cyclic tests, the membrane penetration has a significant influence on the liquefaction characteristics of coarse materials. Since the resulting errors in the measured strength are on the unsafe side, appropriate measures must be taken when membrane compliance are significant. Despite many studies concerning this subject, there seems no reliable method to minimize or compensate for such effects.

Recently Tokimatsu and Nakamura (1986) devised a system which could compensate for the volume change caused by membrane penetration while the liquefaction test is in progress. It sometimes desirable, however, to correct such effects either empirically or analytically without using such a special devise. This type of correction appears indispensable when the effects have become only known to be significant after the test. For

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this purpose, Martin et al. (1978) proposed a simplified method of correction based on the results of simple shear tests. Their method of correction, however, yields overcompensation of strength in cyclic triaxial tests (Banerjee et al., 1979), which restricts its general application.

It is the purpose of this paper to clarify the membrane penetration effects in liquefaction tests and then to propose a simplified method of correction to the test result.

REVIEW OF PREVIOUS STUDIES

Compliance Ratio

To normalize volume changes due to system compliance in simple shear tests, Martin et al. (1978) defined the compliance ratio, C_R, as :

$$C_R=K_c/E_r \qquad (1)$$

in which K_c=pressure required for unit volume increase of the confining system including membrane, and E_r=tangent modulus of the one-dimensional rebound or unloading curve of the sand for the corresponding pressure change. Similarly the compliance ratio for triaxial or torsional specimens may be defined as :

$$C_R=K_c/K_s \qquad (2)$$

in which K_s is bulk modulus of the sand. Eq. (2) can be rewritten as :

$$C_R=(d\varepsilon_{vm}/d\sigma_c')/(d\varepsilon_v/d\sigma_c')=d\varepsilon_{vm}/d\varepsilon_v \qquad (3)$$

in which ε_{vm} is volumetric rebound strain due to membrane penetration, ε_v is that due to soil skeleton rebound, and σ_c' is the effective confining pressure.

Providing that the pore water is incompressible, the increment of pore water pressure under undrained conditions could be expressed by (Martin et al., 1978) :

$$\Delta u=K_s\Delta\varepsilon_{vd}/(1+C_R) \qquad (4)$$

in which $\Delta\varepsilon_{vd}$=the volumetric strain increment corresponding to the decrease in volume occurring during a drained load cycle, having the same shear strain amplitude and initial effective stress conditions.

The pore pressure increment for non-zero compliance, Δu_c, can therefore be defined as

$$\Delta u_c=\Delta u_0/(1+C_R) \qquad (5)$$

in which Δu_0 is the pore pressure increment for zero compliance. Thus the greater the compliance ratio, the smaller the pore pressure generation. If the system compliance is solely due to the volume change caused by membrane penetration, the compliance ratio may be called the membrane compliance ratio and defined by C_{RM}.

Method of Correction

There are basically two methods to eliminate or compensate for the membrane penetration effects in liquefaction tests :

1) Corrections to the test result. Martin et al. (1978) proposed this type of correction in which the error due to membrane compliance is defined in terms of stress ratio.

2) Elimination or minimization of membrane penetration in the test. A treated membrane (e. g., Kiekbusch and Schuppener, 1977), fine particles smeared on the soil surface, or a compensation system such as proposed by Tokimatsu and Nakamura (1986) may serve this purpose.

Unlike Method 2, Method 1 does not require any special test condition and therefore appears attractive despite the lack of experimental verification. In reality, the Martin's method was based on limited data in simple shear tests, and would result in overcompensation of the strength in cyclic triaxial tests (Banerjee et al., 1979). Further studies seem therefore necessary concerning the membrane correction in liquefaction tests.

TEST APPARATUS AND TEST PROCEDURE

Test Apparatus

Liquefaction tests were performed with a conventional cyclic triaxial test apparatus coupled with the membrane compensation system proposed by Tokimatsu and Nakamura (1986). Fig. 1 schematically shows the principal elements of the system which can adjust, through Pressure B, the specimen volume monitored in Burette 1. By means

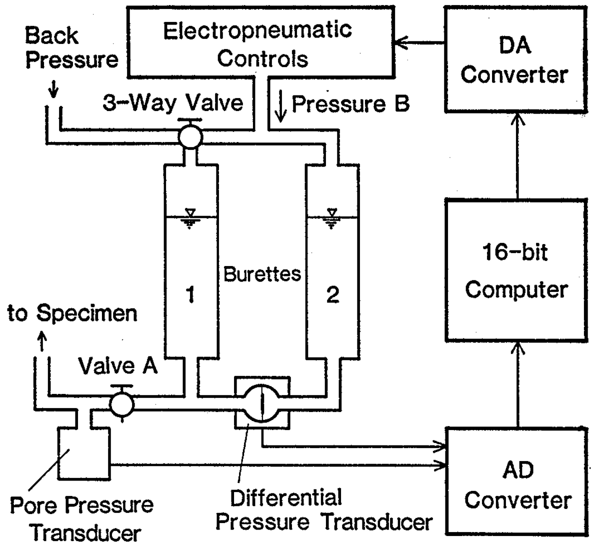

Fig. 1. Schematic diagram of the membrane compensation system (after Tokimatsu and Nakamura, 1986)

of this adjustment, the system enables one to carry out a constant volume liquefaction test in which the adverse effects of membrane penetration are minimized.

The working principle of this system is that the volume change measured in Burette 1 is the volume change due to both membrane penetration and soil skeleton rebound or consolidation. Thus, to maintain a constant volume condition of the soil skeleton, the water level must be adjusted by an amount of volume equal to that due to membrane penetration. Further details of the system were described by Tokimatsu and Nakamura (1986).

Soil Used

The grain size is the most significant factor controlling membrane penetration when using specimens of the same size. Several soils with different mean grain sizes were then used to quantify the effects of membrane penetration.

The soils used included Toyoura sand and size fractions of Kinugawa sand. The physical properties of these soils are summarized in Table 1 and Fig. 2. All materials are poorly graded soils with the uniformity coefficient of 1.5, and their mean grain sizes range from 0.17 to 1.0 mm.

Test Procedure

An air-pluviation method was used to form four type of specimens, as listed in Table 2, which include three $D_r=65\%$ specimens and one $D_r=85\%$ specimen. The size of the specimens was approximately 150 mm high and 75 mm in diameter.

All specimens were consolidated at an effective confining pressure of 1 kgf/cm² (98 kPa). Volume changes caused by membrane penetration to be corrected in the constant volume liquefaction test were first evaluated by conducting unloading tests. This evaluation at the same time provides the membrane compliance ratio of the specimen for a conventional liquefaction test without membrane correction. The detailed procedure of this evaluation has been described elsewhere (Vaid

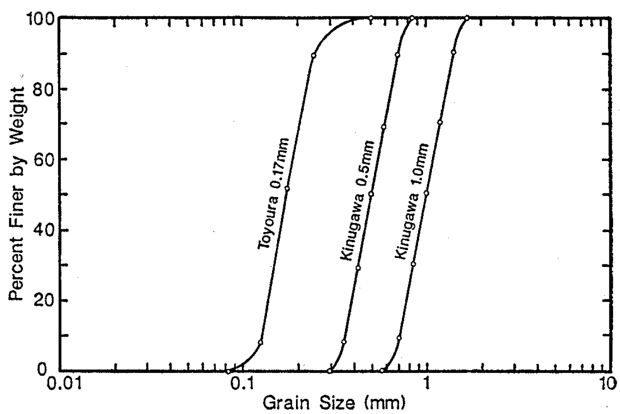

Fig. 2. Grain size distribution curves for soils used

Table 1. Physical properties of soils used (1Mg/m³=1g/cm³)

Soil	Specific gravity of solids G_s	Mean grain size D_{50} (mm)	Effective grain size D_{10} (mm)	Coefficient of uniformity U_c	Maximum dry density ρ_{max} (g/cm³)	Minimum dry density ρ_{min} (g/cm³)
Toyoura sand	2.64	0.17	0.12	1.5	1.61	1.34
Kinugawa sand	2.65	0.5	0.36	1.5	1.60	1.32
Kinugawa sand	2.63	1.0	0.72	1.5	1.61	1.37

Table 2. Physical properties of test specimens

Soil	D_{50} (mm)	D_r (%)	C_{RM}
Toyoura sand	0.17	65	0.2
Kinugawa sand	0.5	65	0.6
Kinugawa sand	0.5	85	0.6
Kinugawa sand	1.0	65	1.2

and Negussey, 1984; Tokimatsu and Nakamura, 1986).

Two series of liquefaction tests, one with using the compensation system and the other without it, were performed on each specimen listed in Table 2. The effective confining pressure, σ_0', and the back pressure were 1 kgf/cm² (98 kPa) and 2 kgf/cm² (196 kPa), respectively. The axial stress was cyclically loaded at a frequency of 0.01 Hz while keeping the cell pressure constant. The slow loading rate was selected to ensure good performance of the system.

EFFECTS OF MEMBRANE PENETRATION ON LIQUEFACTION STRENGTH

Membrane Compliance Ratio

The volume change caused by membrane penetration and that due to soil skeleton rebound in unloading for the test specimens are summarized in Figs. 3 and 4, respectively. Note that the grain size has a strong influence on the volume change due to membrane compliance in Fig. 3, but little influence on the volume change of the soil skeleton in Fig. 4.

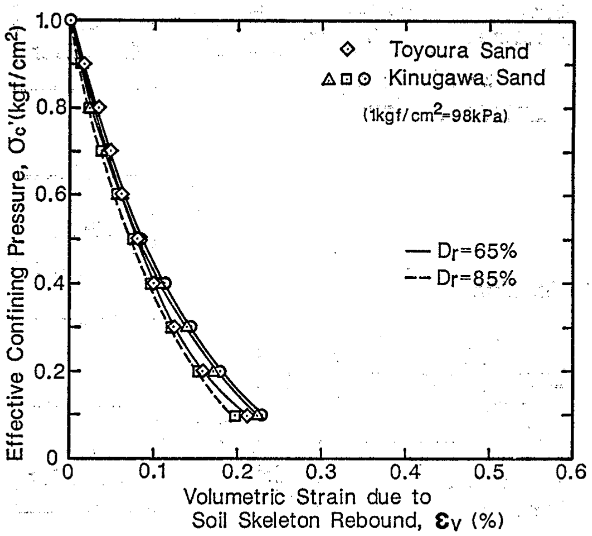

Fig. 4. Volume change due to soil skeleton rebound for test specimens

The membrane compliance ratios of each specimen at various confining pressures were determined from Figs. 3 and 4, and shown in Fig. 5. The membrane compliance ratio of each specimen seems practically constant over the confining pressures tested. Thus the average value listed in Table 2 will be used to represent membrane compliance characteristics of each specimen. Note that the

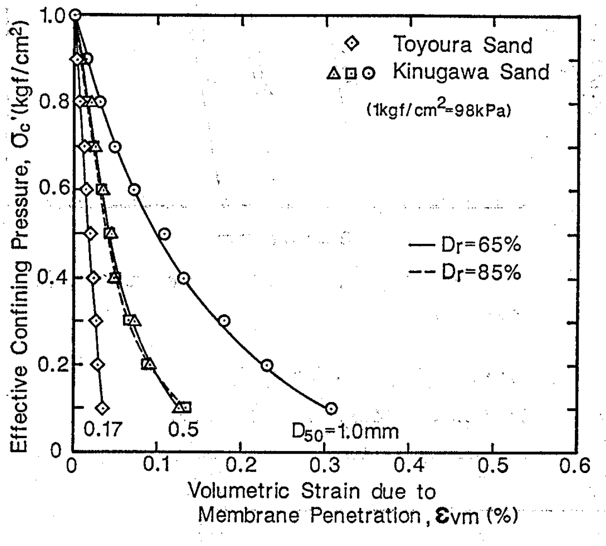

Fig. 3. Volume change due to membrane penetration for test specimens

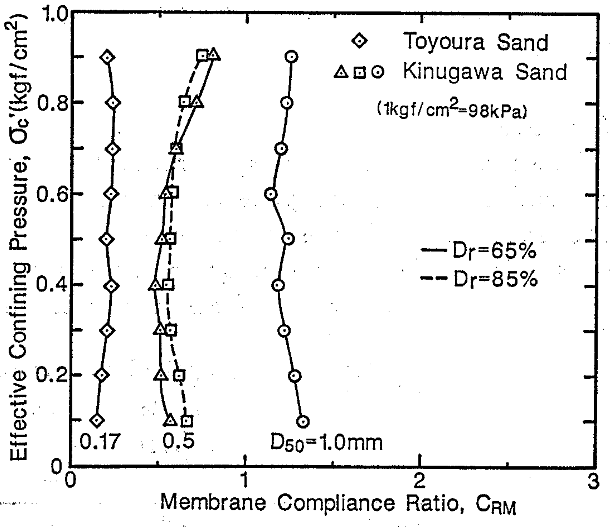

Fig. 5. Membrane compliance ratios for test specimens

difference in relative density of Kinugawa sand with $D_{50}=0.5$ mm has little influence on their compliance ratios.

Effects of Grain Size

In each of Figs. 6 to 8, two liquefaction strength curves with and without membrane compliance for each soil are compared. In the figures, "initial liquefaction" denotes a condition where the peak pore pressure becomes nearly equal to the applied confining pressure. It also corresponds to a condition in which a double amplitude axial strain of about 2.5% develops.

Figs. 6 and 7 indicate that the membrane penetration effects on the measured strength would be negligibly small for fine to medium sands. Fig. 8, in contrast, shows a significant increase in the measured strength as a result of membrane compliance of the coarse sand.

The errors in stress ratio to cause liquefaction for given numbers of cycles may be obtained from Figs. 6 to 8, and are shown in Fig. 9. The error can be defined by

$$(R_c-R_o)/R_o \qquad (6)$$

in which R_c is the stress ratio to cause liquefaction for non-zero compliance, and R_o for zero compliance at the same number of cycles. Although the magnitude of error varies slightly with the number of cycles, increased errors with mean grain size seem

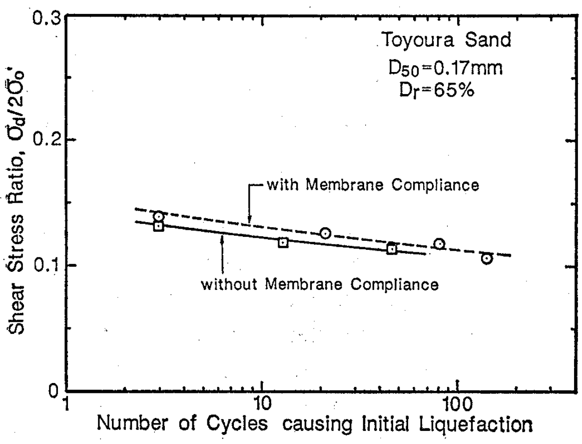

Fig. 6. Effects of membrane penetration on liquefaction strength for sand with $D_{50}=0.17$ mm (after Tokimatsu and Nakamura, 1986)

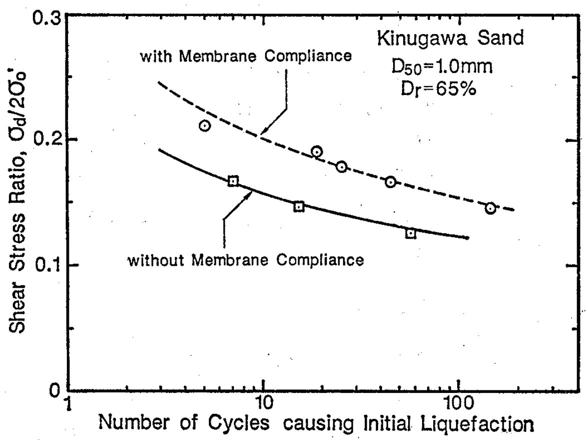

Fig. 8. Effects of membrane penetration on liquefaction strength for sand with $D_{50}=1.0$ mm (after Tokimatsu and Nakamura, 1986)

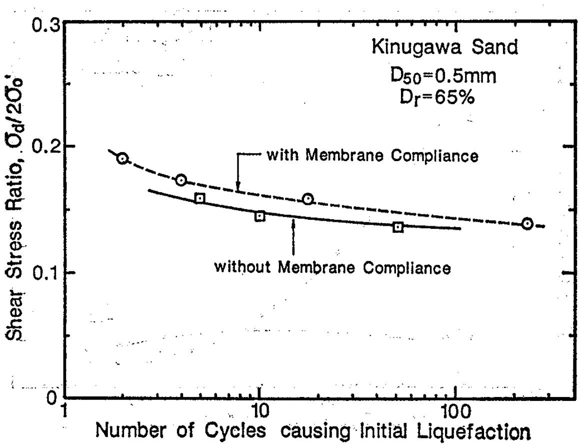

Fig. 7. Effects of membrane penetration on liquefaction strength for sand with $D_{50}=0.5$ mm

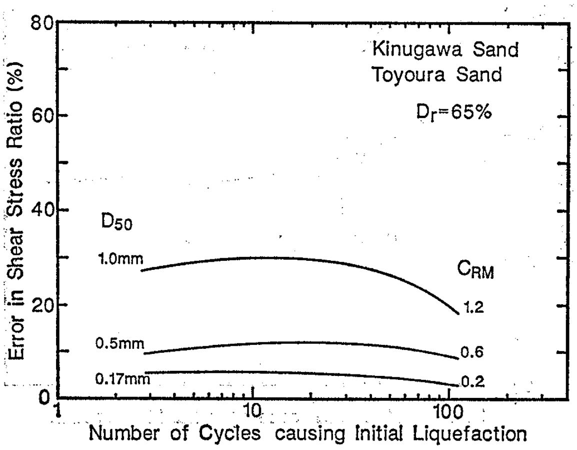

Fig. 9. Error in stress ratio to cause liquefaction due to membrane compliance for medium dense specimens

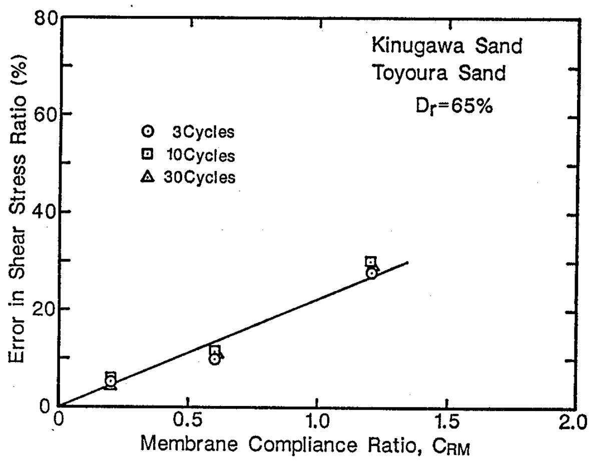

Fig. 10. Error in stress ratio to cause liquefaction in 3, 10 and 30 cycles due to membrane compliance

to be primarily due to the effects of membrane penetration.

To confirm the above findings, the errors after 3, 10 and 30 cycles are read from Fig. 9 and plotted in Fig. 10 against the membrane compliance ratio. Note that the magnitude of errors increases linearly with the membrane compliance ratio.

Effects of Soil Density

Fig. 11 shows the effects of membrane penetration on the liquefaction strength curve of $D_{50}=0.5$ mm Kinugawa sand at $D_r=85\%$.

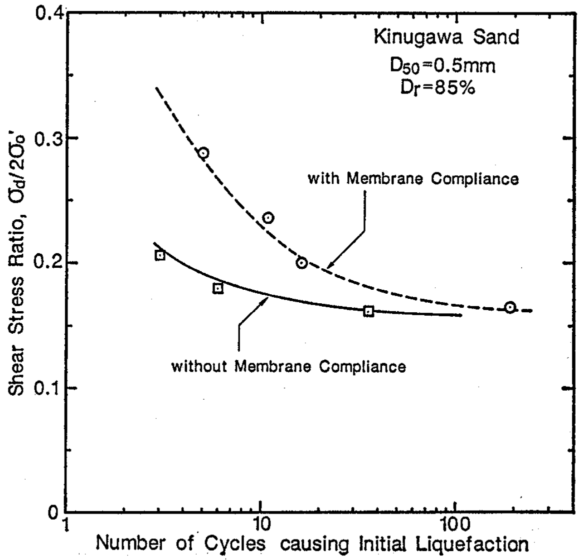

Fig. 11. Effects of membrane penetration on liquefaction strength of dense sand with $D_{50}=0.5$mm

The compliance ratio of this dense specimen is very close to that of the same sand but having a relative density of 65%. The membrane penetration of the dense sand, however, increases the liquefaction strength in 10 th cycle by approximately 30% which is considerably higher than the error for the specimen with $D_r=65\%$. Thus, as far as the errors are expressed in terms of stress ratio, the membrane penetration effects become pronounced as the soil density increases.

The errors in stress ratio due to membrane compliance of the dense sand read off from Fig. 11 are shown in Fig. 12. To investigate the effects of soil density in further detail, the errors for the specimen having $D_r=65\%$ are also shown in the figure. While the error for the $D_r=65\%$ specimen is insensitive to the change in the number of cycles, the error for the dense specimen varies considerably. The smaller the number of cycles, the greater becomes the error in the stress ratio.

Thus the errors in stress ratio due to membrane penetration depend not only on membrane compliance ratio, but also on such factors as relative density and number of cycles. It seems therefore that the error chart in terms of stress ratio such as Fig. 10 has a restricted application. Described in the following is an alternative method of correction in which the error caused by membrane compliance is uniquely determined.

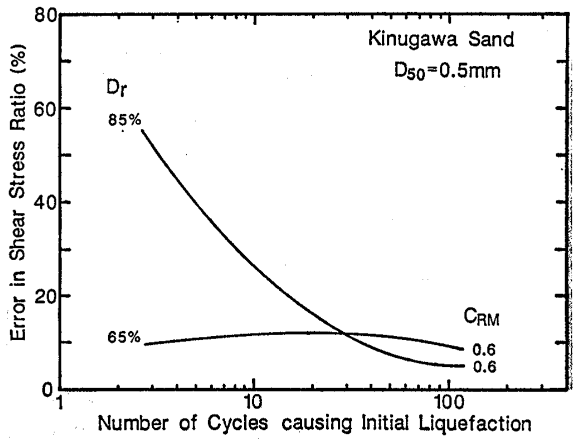

Fig. 12. Effects of soil density on error in stress ratio to cause liquefaction due to membrane compliance

CORRECTION FOR MEMBRANE PENETRATION IN TERMS OF NUMBER OF CYCLES

Evaluation from Experiment

Figs. 6 to 8, and 11 show that the liquefaction strength curve for the specimen with membrane compliance appears to shift rightward with respect to that without compliance. In other words, the presence of membrane penetration increases the number of cycles to cause liquefaction. As a result, the number of cycles causing liquefaction for non-zero compliance, N_c, is larger than would be for zero compliance at the same stress ratio. These effects on the liquefaction strength curve are schematically shown in Fig. 13.

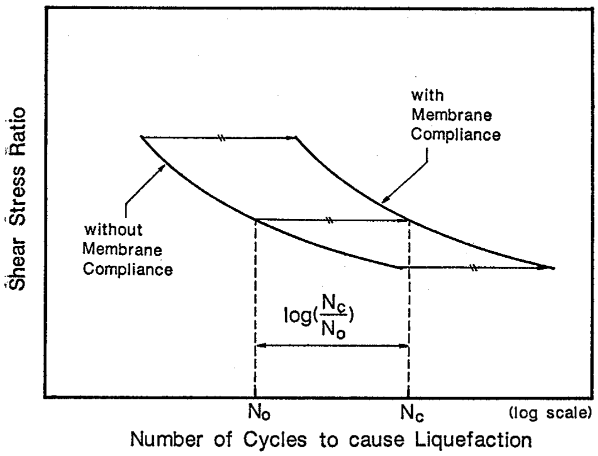

Fig. 13. Schematic diagram showing the effects of membrane penetration on liquefaction strength curve

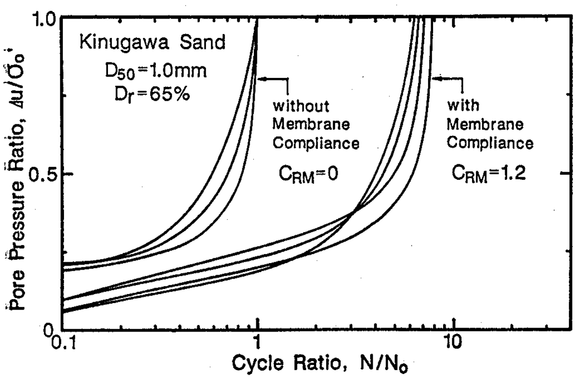

Fig. 14. Effects of membrane penetration on normalized pore pressure generation

As indicated by Lee and Albaisa (1974), pore pressure generation curves from specimens of one soil are similar in shape, and thus each curve can be described nondimensionally by plotting the abscissa as a cycle ratio of N/N_o in which N_o=the number of cycles to cause liquefaction for zero compliance at the same stress ratio.

Fig. 14 shows a typical example of such curves from the test results shown in Fig. 8. As expected, not only the normalized curves for zero compliance but those for non-zero compliance fall within a narrow band, respectively. Consequently the cycle ratios to cause liquefaction for non-zero compliance, N_c/N_o, are almost identical for any applied shear stress. This means that differences between N_c and N_o on a logarithmic scale, i.e., $\log (N_c/N_o)$, are almost the same for any stress ratio as shown in Fig. 13.

Fig. 13 thus indicates that the presence of membrane compliance would displace the strength curve with zero compliance to the right, keeping the shape of the curve unchanged. Conversely, shifting the strength curve with compliance to the left by an appropriate distance, can provide the curve with zero or smaller compliance.

The cycle ratios to cause liquefaction for non-zero compliance, $C_N=N_c/N_o$, are determined from Figs. 6 to 8 and 11, and plotted in Fig. 15 against the membrane compliance ratio. Note that the cycle ratio increases

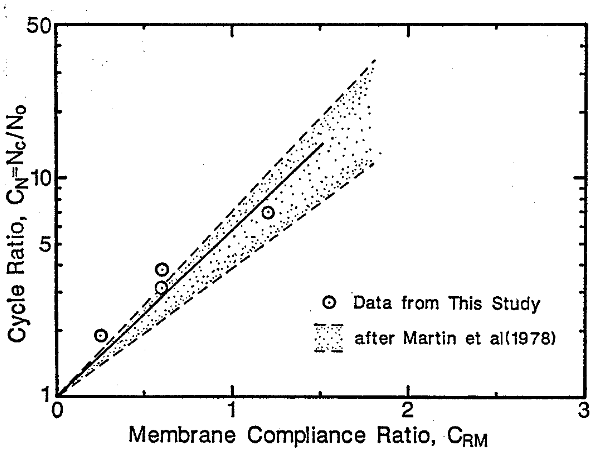

Fig. 15. Error in number of cycles to cause liquefaction due to membrane compliance

with increasing membrane compliance ratio. Unlike Fig. 12 where the error in stress ratio varies with number of cycles and soil density, the error function shown in Fig. 15 appears independent of such factors as soil density and applied shear stress.

Evaluation from Theoretical Study

Martin et al. (1978) analytically evaluated membrane penetration effects on simple shear liquefaction test results as a function of C_{RM} as shown in Fig. 16. The stress ratio in this case is defined by a ratio between cyclic shear stress amplitude, τ_{hv}, and the initial vertical effective stress, σ_{co}'. The liquefaction strength curve shown in the figure appears to shift rightward as the compliance ratio increases. This trend is consistent with the experimental results mentioned previously.

For comparison, the error functions in terms of number of cycles to cause liquefaction were read from Fig. 16 and the possible range is shown in Fig. 15. The theoretical estimations by Martin et al seem insensitive to the change in stress ratio and show a good agreement with the experimental results. Also noted in the figure is a well-defined trend in which the logarithm of the cycle ratio increases linearly with the membrane compliance ratio. The good agreement and well-defined trend confirm that the membrane correction be made to the number of cycles rather than to the stress ratio.

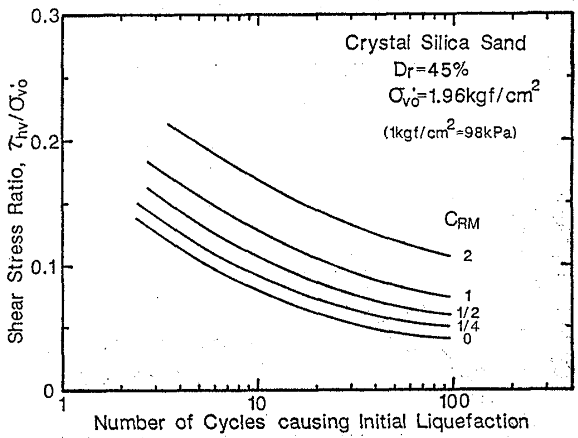

Fig. 16. Effects of system compliance on stress ratios causing liquefaction in cyclic simple shear tests (after Martin et al., 1978)

A SIMPLE METHOD TO CORRECT FOR MEMBRANE PENETRATION EFFECTS

Based on the above findings, the error due to membrane penetration in the liquefaction strength curve of a specimen plotted in a semilog chart, may be corrected in the following manner.

Empirical Evaluations of Membrane Compliance Ratio

Evaluate, either experimentally or empirically, the membrane compliance ratio of the specimen. Since experimental evaluations have been described elsewhere (Banerjee et al., 1979 ; Tokimatsu and Nakamura, 1986), only an empirical evaluation will be described herein.

As stated previously, the membrane compliance ratio for a specimen is defined as a ratio between volumetric rebound strain due to membrane penetration, ε_{vm}, and that of the soil skeleton, ε_v, for the same stress reduction. Thus the evaluation of membrane compliance ratio initiates the determination of the two strains.

The normalized membrane penetration, S, is given by :

$$S=\Delta v_m/\Delta \log \sigma_c' \qquad (7)$$

in which σ_c'=effective confining pressure, and v_m is unit membrane penetration and defined by

$$v_m=\varepsilon_{vm}V/A_m \qquad (8)$$

in which V=volume of the soil skeleton, and A_m=surface area covered by membrane. Substitution of Eq. (7) into Eq. (8) leads to

$$\Delta\varepsilon_{vm}=S(A_m/V)\Delta\log\sigma_c' \qquad (9)$$

The terms in the parentheses indicate the surface area to volume ratio of which values for conventional test specimens are listed in Table 3. Based on the previous studies, the possible relation of S with mean grain size is shown in Fig. 17.

Similarly, the volumetric strain due to

Table 3. Surface area to volume ratios for specimens in conventional tests

Test Apparatus	Triaxial Shear	Torsional Shear
Specimen Geometry	Solid Cylinder	Hollow Cylinder
A_m/V(1/cm)	$4/D$	$4/(OD-ID)$

D: Diameter, OD: Outside diameter, ID: Inside diameter (in cm)

soil skeleton rebound may be defined as :

$$\Delta \varepsilon_v = C \Delta \log \sigma_c' \qquad (10)$$

in which C is swelling index or rebound index. Fig. 18 shows the variation of C with relative density for several clean sands with poor gradation under confining pressure less than 2 kgf/cm² (196 kPa).

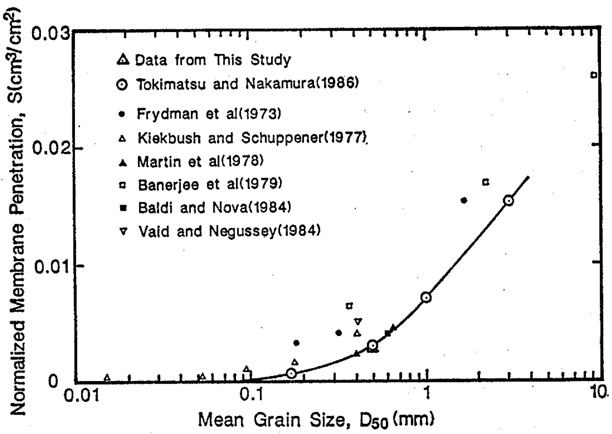

Fig. 17. Relationship between normalized membrane penetration and mean grain size (after Tokimatsu and Nakamura, 1986)

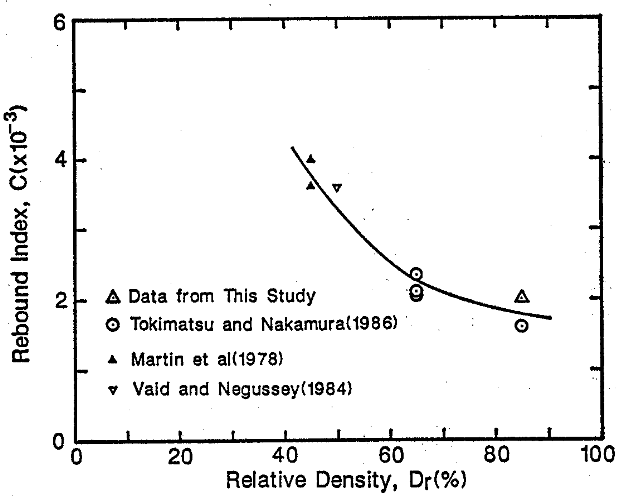

Fig. 18. Relationship between rebound index and relative density for poorly graded soils

Thus knowing ε_v and ε_{vm}, the membrane compliance ratio of the specimen is evaluated from Eq. (3) as

$$C_{RM} = d\varepsilon_{vm}/d\varepsilon_v = S(A_m/V)/C \qquad (11)$$

Note that C_{RM} is independent of the confining pressure as indicated in Fig. 5. The values of S and C given in Figs. 17 and 18 are mainly for poorly graded soils, and may not be suitable for well graded materials. For such materials, membrane compliance ratios should be evaluated by experiment.

Correction of Liquefaction Strength Curve

(1) Determine the cycle ratio, C_N, for the given membrane compliance ratio, C_{RM}, from Fig. 15.

(2) To obtain the strength curve for zero compliance, divide the number of cycles to cause liquefaction by C_N. In other words, shift the original curve in the semilog chart to the left by a distance of log (C_N).

(3) The liquefaction curve for a different compliance ratio, C_{RM2}, may be also obtained by dividing the number of cycles to cause liquefaction by C_N/C_{N2} in which C_{N2} is the cycle ratio corresponding to C_{RM2}. Shifting the original curve horizontally by a distance of log (C_N/C_{N2}) can also yield the same result.

VALIDATION OF THE METHOD OF CORRECTION

Wong et al. (1975) indicated that variations in sample size might have considerable influence on the results of cyclic loading tests for two reasons :

"1. Stress concentrations associated with the cap and base might be different in samples having different diameters. However, if the height/diameter ratio of the samples is maintained constant, this effect should not differ significantly.

2. The effects of membrane compliance will vary as the diameter and thickness of membranes are varied from one test to an-

other. Since the ratio between the surface area covered by membrane and the specimen volume is inversely proportional to the specimen diameter, the membrane penetration effects increase with decreasing specimen diameter."

For triaxial specimens with the same height-to-diameter ratio, the major cause of variations in the measured strength therefore might be primarily due to the membrane penetration effects. As far as the authors know, there have been three studies concerning the effects of specimen size on the liquefaction strength of sands.

Test Results by Wong et al.

Wong et al. (1975) are probably the first to investigate the membrane penetration effects on liquefaction strength by conducting cyclic triaxial tests on sand specimens with diameters of 71 mm and 305 mm. The sand used was Monterey sand with the mean grain size of 0.58 mm and the uniformity coefficient of 1.8. The test results for the two specimens having relative densities of 60% are plotted in Fig. 19. The smaller specimen shows about 15% greater strength in 10th cycle than the larger specimen. This tendency corresponds to the membrane penetration effects.

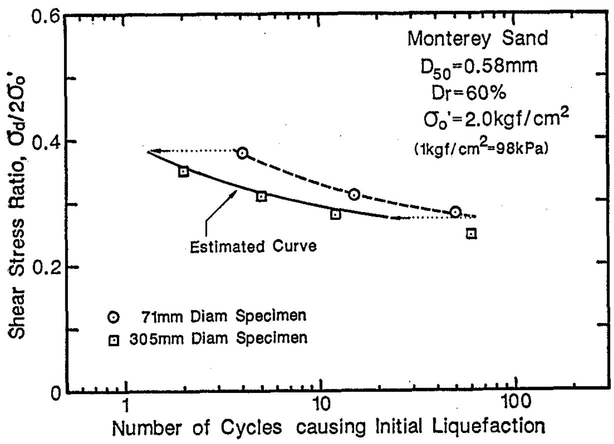

Fig. 19. Cyclic triaxial test results showing effectiveness of the proposed method (Data from Wong et al., 1975)

Taking into account the difference in the membrane penetration, the liquefaction strength curve for the 71 mm diameter specimen can be converted to that for the 305 mm diameter specimen. Summarized in Table 4 are the membrane compliance ratios and the cycle ratios for the two specimens. The correction factor to convert the strength curve from the smaller specimen to the larger specimen would be 3. This means that the difference in membrane compliance between the two specimens increases the number of cycles to cause liquefaction by a factor of 3. The strength curve determined experimentally for the 71 mm diameter specimen is then shifted leftward by log 3 to obtain that for the 305 mm specimen.

The curve for the 305 mm specimen thus estimated is also shown in Fig. 19. The estimated curve is in good agreement with the experimental result for the specimen with the same diameter, suggesting that the proposed method is effective for membrane correction in liquefaction tests.

Test Results by Lade and Hernandez

Lade and Hernandez (1977) performed cyclic triaxial loading tests on Monterey sand specimens with diameters of 36 mm and 71 mm. The mean grain size and uniformity coefficient of the sand are 0.62 mm and 1.4. The relative density of the test specimens is 50%. The results shown in Fig. 20 again indicate that the smaller specimen yields about 20% higher strength than the larger one, probably reflecting the membrane pene-

Table 4. Physical properties of soils

Soil	D_{50} (mm)	U_c	D_r (%)	D (cm)	C	S (cm)	C_{RM}	C_N / C_{N2}	C_N/C_{N2}	Reference
Monterey Sand	0.58	1.8	60	7.1 30.5	0.0026	0.004	0.76 0.20	4.0 1.4	3	Wong et al. (1975)
Monterey Sand	0.62	1.4	50	3.6 7.1	0.0033	0.0045	1.52 0.77	16 4.0	4	Lade and Hernandez (1977)
Toyoura Sand	0.17	1.4	80	5.0 30.0	0.0020	0.001	0.40 0.07	2.0 1.1	2	Tatsuoka et al. (1986)

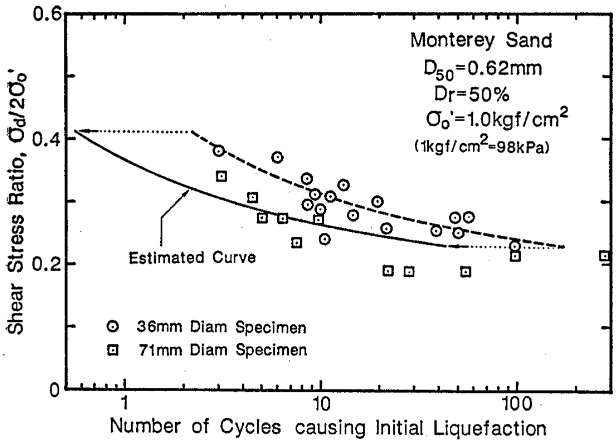

Fig. 20. Cyclic triaxial test results showing effectiveness of the proposed method(Data from Lade and Hernandez, 1977)

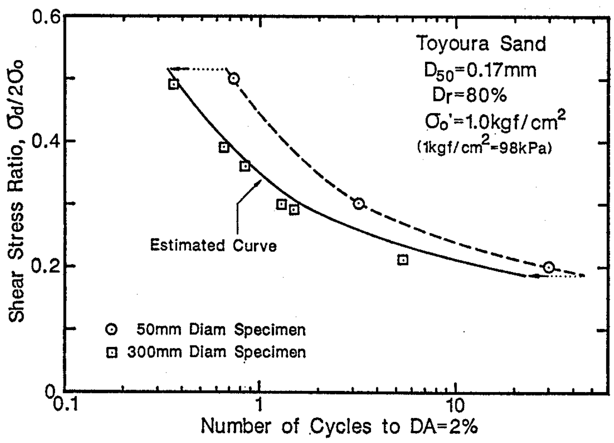

Fig. 21 Cyclic triaxial test results showing effectiveness of the proposed method (Data from Tatsuoka et al., 1986)

tration effects. Considering relatively small specimen diameter compared to the coarse grained material, the membrane penetration effects in the 36 mm diameter specimen can be significant. The estimated values of C, S, and C_{RM} for each specimen are listed in Table 4. The membrane compliance ratio of the 36 mm diameter specimen is estimated to be 1.52, resulting in an enormously large cycle ratio of 16.

The strength curve for the larger specimen is again estimated based on the result for the smaller specimen and shown in Fig. 20. The correction factor in this case is 4. The estimated curve is again in good accord with the experimental results, showing that the proposed method is effective.

Test Results by Tatsuoka et al.

Tatsuoka et al. (1986) conducted cyclic triaxial loading tests on Toyoura sand specimens with diameters ranging from 50 to 300 mm. The mean grain size, the coefficient of uniformity, and the relative density are 0.17 mm, 1.4, and 80%.

Fig. 21 shows the test results for the 50 mm and 300 mm diameter specimens. In spite of its small mean grain size, the smaller specimen shows a considerably higher strength than the larger specimen as the number of cycles gets small. This may be indicative of a severe effect of membrane penetration for dense specimens.

The membrane compliance ratio and the cycle ratio for each specimen are listed in Table 4. The liquefaction strength curve for the 300 mm diameter specimen was estimated based on the test results for the 50 mm diameter specimen and shown in Fig. 21. The estimated curve and the experimental results for the 300 mm diameter specimen are almost coincident.

Different soil type, different specimen geometry, different sample preparation method, and different density would result in different membrane compliance, and thereby yielding different errors in liquefaction strength. The above mentioned evaluation can therefore be approximate. However, the comparison with the several test results indicates that the proposed method shows a considerable potential for membrane compliance correction in liquefaction tests.

CONCLUSIONS

A concept to account for the effect of membrane penetration on the generation of pore pressure in liquefaction tests was demonstrated based on experimental studies. The major effect of membrane penetration was to increase the number of cycles to cause liquefaction. The cycle ratio was defined as a ratio between numbers of cycles causing liquefaction with and without compliance at the same stress ratio. The cycle ratio was found to be a unique function of membrane compliance ratio, and independent of applied shear stress. A careful review of the previous study (Martin et al., 1978) yielded the same result, indicating the validity of the concept.

Based on the findings, a simplified method was presented for correcting liquefaction test results for the membrane penetration effects. Several previous studies concerning the effects of specimen diameter were used to validate the proposed method, since the resulting difference in the liquefaction strength mainly reflects the membrane penetration effects. The liquefaction strength curves for different diameter specimens after membrane correction showed a good agreement.

Since the presence of membrane penetration increases both the number of cycles and stress ratio to cause liquefaction, the test error is on the unsafe side. It is therefore necessary to assess the effects of membrane penetration, and appropriate corrections must be taken. It is believed that the proposed method will provide adequate assessment and correction for this purpose.

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