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LIQUEFACTION STRENGTH OF COARSE-GRAINED SOILS AS DETERMINED BY LARGE TORSIONAL TEST AND THE MEMBRANE PENETRATION EFFECT ON THE STRENGTH

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SUMMARY

The liquefaction strength of coarse-grained soil was investigated by using a large torsional hollow cylinder test and a medium size triaxial test, and the membrane penetration effect on the strength during the liquefaction test was also investigated. The results of liquefaction tests were discussed with the following two aspects; 1) The applicability of existing strength correction method for membrane penetration effect that uses the test results without the membrane penetration correction. 2) The difference between the liquefaction strengths that are obtained from the hollow cylinder test and the triaxial test.

As to the applicability of existing strength correction method for the membrane penetration effect, it was concluded that the existing method underestimates somewhat the strength in both type of tests. For the comparison of the liquefaction strengths between the two types of test method, it was found that the liquefaction strength obtained from the large torsional hollow cylinder test is higher than that from the medium triaxial test. Review is made on the past studies of liquefaction strength difference between the hollow cylinder and triaxial tests on clean sands, and it was shown that the existing method to convert the triaxial test result to that of torsional hollow cylinder test based on the studies with clean sand is not applicable to the coarse-grained soil tested in this work.

INTRODUCTION

Liquefaction strength of soil has been studied extensively in the past, but the experiments have been mainly for clean sands as the many of liquefied sites are located at coastal areas or alluvial deposits consisting of clean sand. But in Hansin-Awaji Earthquake, not only the clean sand but also the coarse-grained soil, especially of fill material at man-made islands near Kobe-port[1)], liquefied extensively causing a heavy damage to harbor facilities of Kobe Port. Because of such liquefaction of fill material that contains a large size aggregates and with a well grade characteristics, investigations on the liquefaction characteristics of coarse-grained soil became one of the major research item of soil liquefaction. The liquefaction characteristics of coarse-graind soil have been investigated in our laboratory,

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and a special apparatus of large torsional hollow cylinder test[2] was constructed to simulate the deformation condition that prevails during the earthquake in the field. Usually the liquefaction strength of coarse-grained soil is studied by performing a large size triaxial test, but it is known that there is a difference between the strengths obtained from the triaxial test and the torsional hollow cylinder test. The strength difference between the two types of test may be due to these two different modes of shearing with respect the soil structure or the orientation of soil depositional direction, and the anisotropic properties of soil would play a major role in this aspect of soil behavior. The difference of soil strength among the different types of soil testing has been studied mostly on static strength properties of soil, but there is a need to correlate the liquefaction strengths obtained from these two types of test as the use of triaxial test would be more conventional for usual soil investigations.
Another problem associated with the liquefaction strength of coarse-grained soil is the need to consider the membrane penetration effect. Membrane penetration occurs in a great extent for the specimens consisting of large size particles. It is well known that the membrane penetration effect increases with the mean diameter of soil particle[3]. Several studies have been made to correct the membrane penetration effect on the liquefaction strength, either directly correcting during the test or correcting indirectly by applying a correction factor on the test result that was obtained without membrane correction. In this study, a special device was used to correct membrane penetration effect during liquefaction test, and the difference of corrections between the direct and the indirect methods of correcting the membrane penetration effect on the liquefaction strength was examined.

EXPERIMENTAL PROCEDURE

Test Apparatus

Fig. 1 shows a large hollow cylinder test apparatus developed herein. As to the size of specimen, outside and inside diameters of the specimen were 50cm and 30cm, and the height was 60cm. The axial force to specimen is given through the piston via the air cylinder placed above the apparatus, and the torsional force to the specimen is given by two horizontal arms connected to the air cylinders placed at upper edge of outer circular frame. The air pressure to these cylinders was controlled by electro-pneumatic regulators which were in turn operated by personal computer. Measurements of axial and torsional forces on the specimen were made by a two-directional-load-cell that is placed just above the specimen cap, and cell pressure and pore pressure were measured by pressure transducers. Measurements of axial displacement and volume change of the specimen were made by LVDT and load cell to measure the volume of water expelled from the specimen. A membrane penetration correction device is attached at the drainage line from the specimen, and its function will be described in details later.
The medium size triaxial test apparatus is seen in Fig. 2. The diameter of the specimen was 10cm and its height was 20cm. Loading and measurement systems are almost the same with those of the large torsional hollow cylinder test apparatus. In case of the triaxial test, the volume change was measured by an electronic balance for better accuracy and the membrane correction devise with finer adjustment was used as will be shown later.

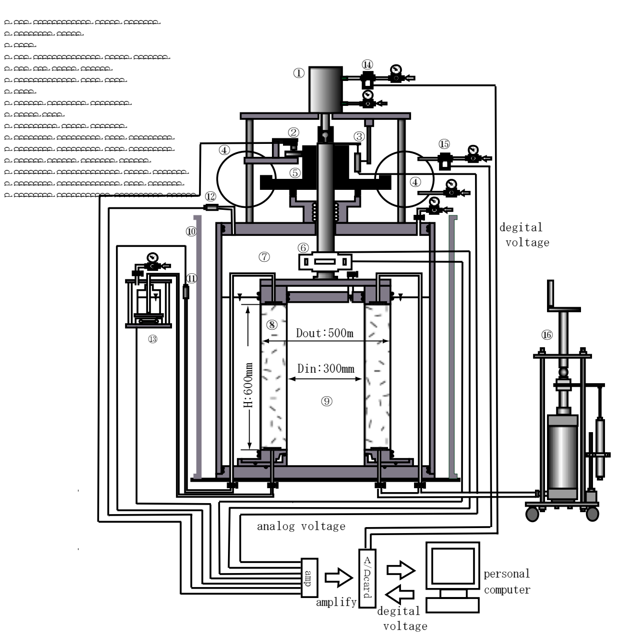


Fig.1 Large hollow cylinder test apparatus

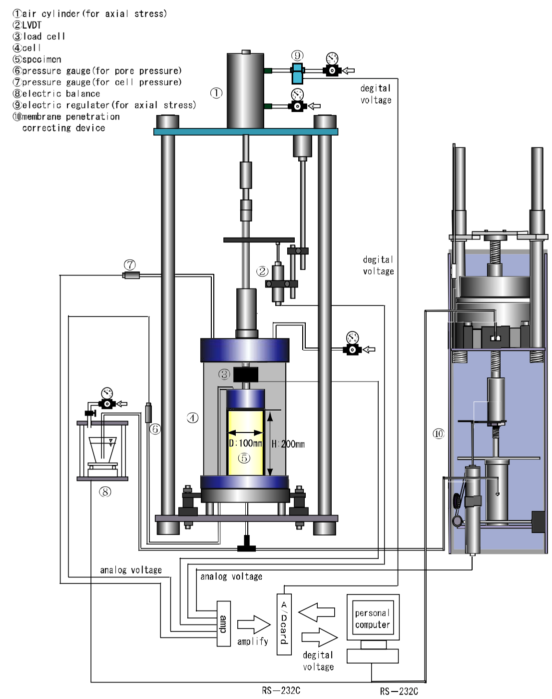


Fig.2 Medium size triaxial test apparatus

Test Materials and Sample Preparation

The experimental material was a coarse-grained gravelly sand taken from a construction site at Nishi-Ward of Kobe City (hereafter it will be called as Nishi-soil). The maximum grain size of the sample was adjusted to 19mm. The gradation curve is shown in Fig. 3, and it is seen that the Nishi-soil is well-graded material. The physical properties of the soil are shown in Table 1.

Sample preparations for both the large hollow cylinder and the medium size triaxial tests are the same as described in the followings. All specimens were prepared by pulverizing soil into a mold and the density of soil was set to a relative density of 60% by adjusting falling height of air-pulverization. For saturating the specimen, a specimen was given an ample amount of CO_2 flow from the bottom, while maintaining a confining pressure of 0.04Mpa to the specimen. Then enough flow of de-aired water was introduced into the specimen, and then a back-pressure of 0.1Mpa was given to the specimen to increase the degree of saturation. Before the test, the measurement of "B" value was

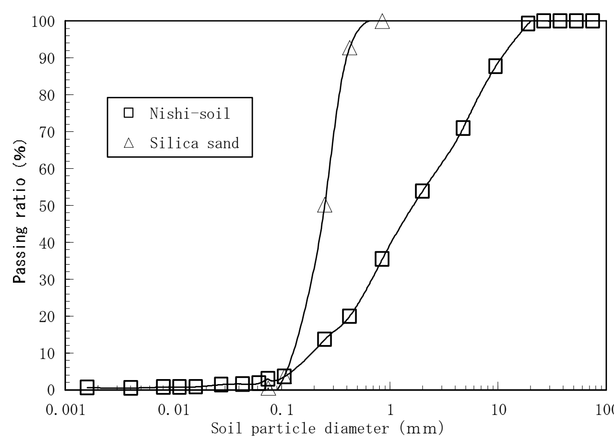


Fig.3 Gradation curve

Table 1: Physical Properties of material

material	Nishi-soil	Silica sand
$\rho_s (t/m^3)$	2.67	2.62
$\rho_{max} (t/m^3)$	1.95	1.57
$\rho_{min} (t/m^3)$	1.54	1.25
D_{max} (mm)	19	0.85
D_{mean} (mm)	1.7	0.22
U_c	15	2.0
U_c'	0.82	1.1

made for each specimen, and only those specimens with B value of greater than 0.95 were used for the liquefaction test. It may be noted that all specimens were consolidated to the effective confining pressure of 0.1MPa that was achieved by applying a cell pressure of 0.2MPa with a back pressure of 0.1MPa.

Liquefaction Strength Test

In liquefaction test, a sinusoidal cyclic of shear stress was applied to the specimen in undrained condition. In the case of large torsional hollow cylinder test, a sinusoidal cyclic shear stress was applied by giving a rotational twist to the specimen while keeping the isotropic confining stress. A maximum shear stress is applied on horizontal plane of the specimen. In the case of the triaxial test, a sinusoidal cyclic deviator stress was given by increasing and decreasing the axial stress and the maximum shear stress acts on 45° plane from the horizontal. The large torsional hollow cylinder test was terminated when the excessive pore pressure exceeds 95% of the confining pressure, while the triaxial test was terminated when the excessive pore pressure exceeds 95% limit and DA exceeds 5%.

PROCEDURES FOR CORRECTING MEMBRANE PENETRATION

Correction of membrane penetration

The amount of membrane penetration (MP) to be corrected for hollow cylinder sample and triaxial sample is obtained by the following procedure suggested by Vaid & Negussey[4]. As indicated below, the volumetric strain of soil skeleton is assumed to be three times of soil axial strain that is measured in the unloading procedure:

$$\varepsilon_V = 3 \times \varepsilon_a$$

$$\Delta V_s = V \times \frac{\varepsilon_V}{100}$$

ε_a : axial strain(%)

ε_V : volumetric strain of soil skeleton(%)

ΔV_s : volume change of soil skeleton (cm^3)

V : initial volume(cm^3)

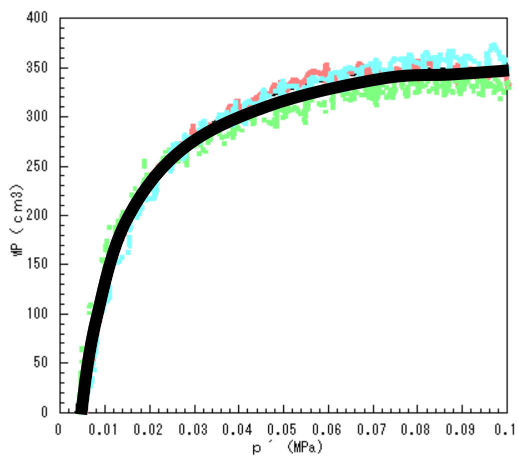
Measured volume change is composed of not only the volume change of soil skeleton but also of the change due to MP. Therefore change of membrane penetration can be obtained by subtracting the volume change of soil skeleton from the measured volume change:

$$MP = \Delta V - \Delta V_s$$

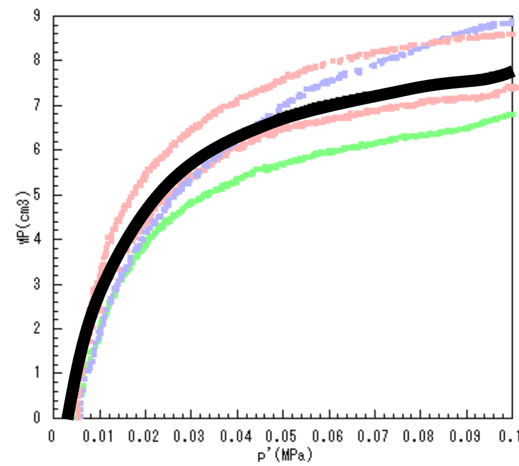
MP : amount of MP (cm^3)

ΔV : measured volume change (cm^3)

By applying the above method, the relationship between MP and the effective confining pressure, p', can be obtained. Since the amount of MP correction should be unique for the soil with same gradation, a single correction curve for MP and p' is determined by averaging the measured MP vs. p' relationships. Fig.4 shows the obtained correction curves for both types of tests.



a)



b)

Fig.4 Correction Curves for Membrane penetration effect,
a) large torsional hollow cylinder test, b) medium size triaxial test

Other system compliances

In addition to the MP correction, there are two other system compliances to be corrected for the test apparatus. One is the system compliance of drainage tube and the other is that of MP correction cylinder, both being function of confining pressure changes. It was found that these system compliances are much smaller than that of MP of specimen[5), 6)], but these were also corrected by using the MP correction device during liquefaction test.

METHOD TO CORRECT MP

Direct correction method

The MP device used in the large torsional hollow cylinder test is shown in Fig.5 and one used in the triaxial test is shown in Fig.6. In both devise, a minute amount of water is injected in or out of the specimen by horizontal displacement of piston which is generated by rotation of mega-torque motor through a screw gear[5), 6)]. The amount of injected water is the product of cylinder's section area and the piston displacement which is measured by LVDT. By applying the measured p' value on the MP correction curve of Fig.4, the amount of water to be injected is calculated and then the MP correction device is operated to give the necessary volume of water. Fig.7 shows a schematic of automatic MP correction procedure in the triaxial test. In the triaxial test, the accuracy of correction was 0.0088% of the maximum amount of MP. On the other hand, the MP correction device for hollow cylinder test is operated manually[5)].

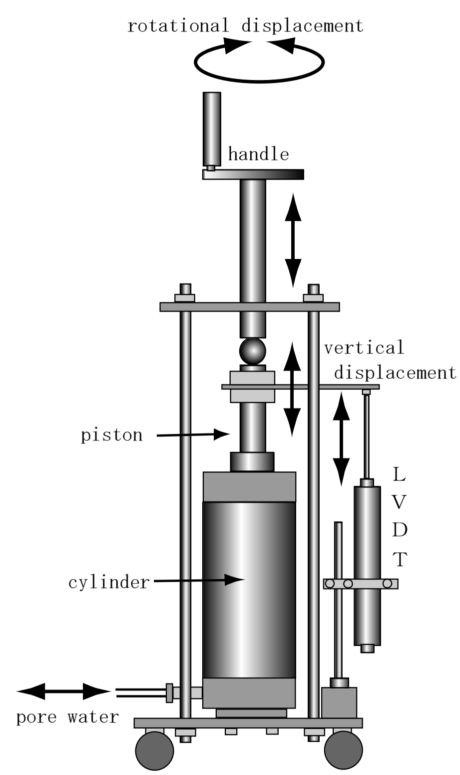


Fig.5 MP device
(Hollow cylinder test)

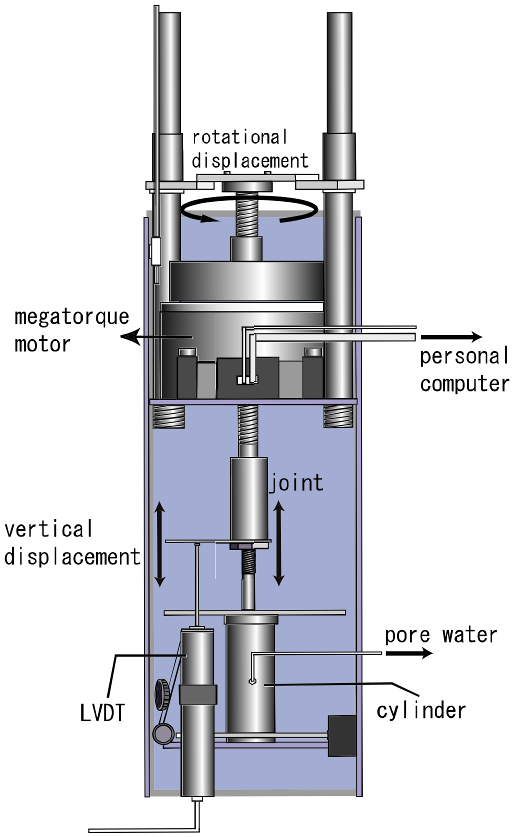


Fig.6 MP device
(Triaxial test)

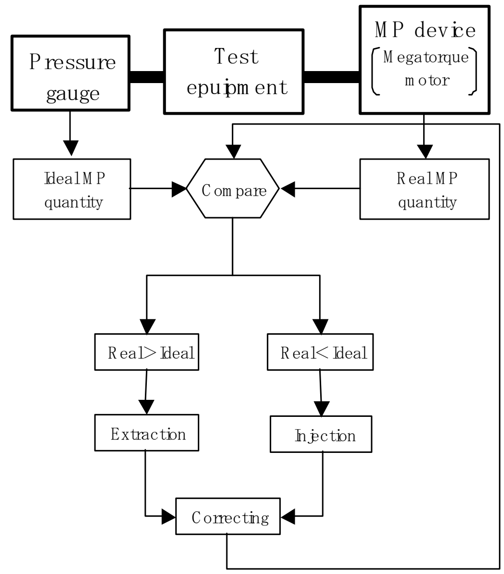


Fig.7 Correction procedure(Triaxial test)

Indirect correction method

As already stated, there is an indirect MP correction method which modifies the liquefaction test result without MP correction. Martin et al.[7] has proposed a correction coefficient of C_{RM} which is a relationship between MP and the volume change of soil skeleton. Nakamura et al.[8] has studied the liquefaction strength of various types of soils whose by using a MP correction device developed by Tokimatsu et al.[9]. From test results, they proposed a strength correction curve by using C_{RM} value as shown in Fig.8. In the figure, the vertical axis, C_N=R/R*, represents a correction ratio to be applied on the liquefaction strength curve that is obtained without MP correction. For the same level of cyclic stress, the liquefaction strength curve without correction yields the number of cycles R, while the strength curve with MP correction yields the R* cycles. Since the liquefaction strength is overestimated with the tests without MP correction, the liquefaction strength curve should be shifted horizontally towards the origin by the ratio given as C_N.

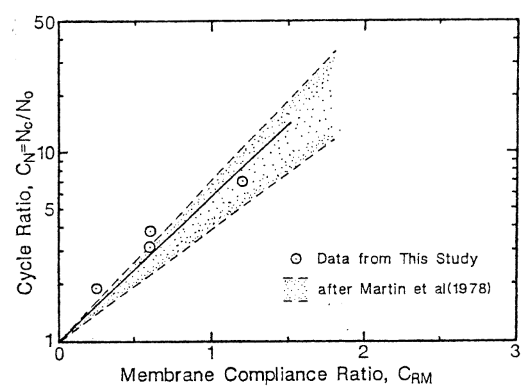


Fig.8 C_N vs.C_{RM} curve[7]

TEST RESULTS

Tables 2 and 3 show the torsional hollow cylinder and the triaxial test series performed in this study. As can be seen from the tables, four tests in each test series were performed by either applying the MP corrections or without the correction.

Table 2 Hollow Cylinder Test Series

H series	τ_c/σ_c'	τ_c	D_r(%)
H-0.35	0.35	0.035	62.82
H-0.25	0.25	0.025	54.01
H-0.20	0.20	0.020	64.46
H-0.15	0.15	0.015	62.18
H-0.35-MP	0.35	0.035	62.14
H-0.25-MP	0.25	0.025	63.44
H-0.20-MP	0.20	0.020	62.76
H-0.15-MP	0.15	0.015	59.29

Table 3 Triaxial Test Series

T series	$\sigma_d/2\sigma_c'$	σ_d	D_r(%)
T-0.30	0.30	0.060	59.52
T-0.25	0.25	0.050	57.56
T-0.20	0.20	0.040	62.08
T-0.15	0.15	0.030	61.86
T-0.30-MP	0.30	0.060	59.32
T-0.25-MP	0.25	0.050	62.02
T-0.20-MP	0.20	0.040	61.55
T-0.15-MP	0.15	0.030	59.24

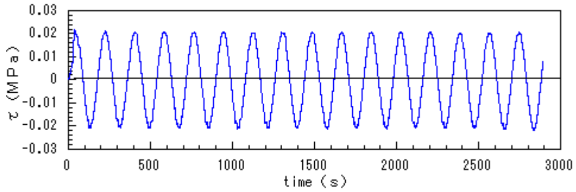
Undrained Cyclic Loading Test Results With or Without MP Correction

Hollow Cylinder Test Series

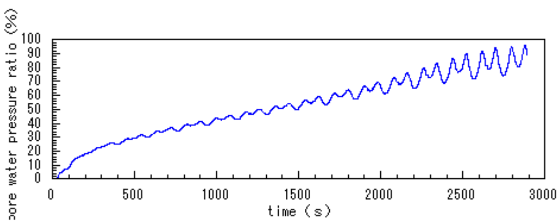
Fig.10 shows typical results of liquefaction test by using hollow cylinder test apparatus, Test [H-0.20] for one without MP correction and Test [H-0.20-MP] for one with MP correction. In correcting the MP effect, the test [H-0.20-MP] is performed by manually adjusting the correction device, and the obtained effective stress path shows some scattering. It can also be seen that the number of cycles to liquefy the specimen in Test [H-0.20-MP] is much less than that of Test [H-0.20], and thus the effect of MP on liquefaction strength is clear demonstrated.

Triaxial Test Series

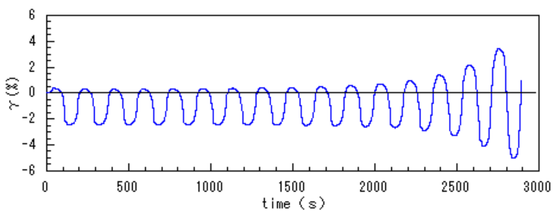
Fig.11 shows typical results of liquefaction test by using medium size triaxial test apparatus, Test [T-0.20] for one without MP correction and Test [T-0.20-MP] for one with the MP correction. In contrast to the manually controlled adjustments for the membrane correction for the hollow cylinder tests as above, automatic adjustment of membrane correction device is used for the triaxial tests, and the stress path of Test [T-0.20-MP] is very smooth compared with the one for hollow cylinder test, for example Test [H-0.20-MP]. Thus it can be concluded that the automatic correction of MP is very effectively achieved. It can also be seen that the number of cycles to liquefy the specimen in Test [B- 0.20-MP] is much less than that of Test [B-0.20], and therefore the effect of MP on the liquefaction strength is also significant in the medium size triaxial test series.



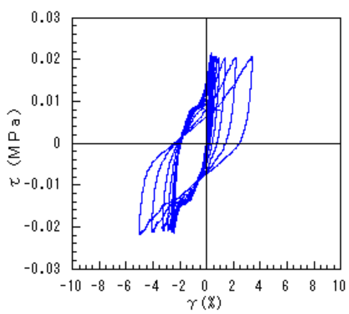
a) shear stress vs.time(Test: H-0.20)



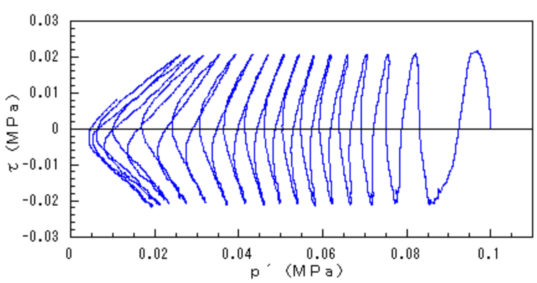
b) pore water ratio vs.time(Test: H-0.20)



c) γ vs.time(Test: H-0.20)

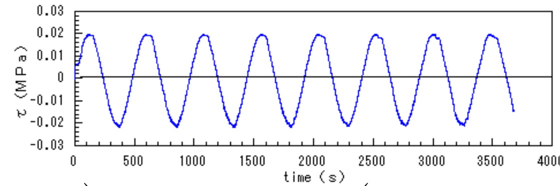


d) τ vs. γ (Test: H-0.20)

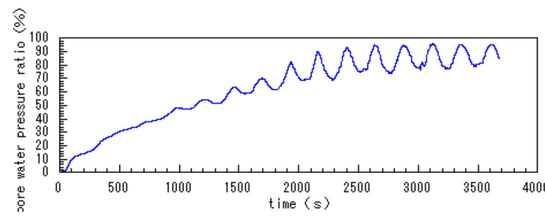


e) stress path (Test: H-0.20)

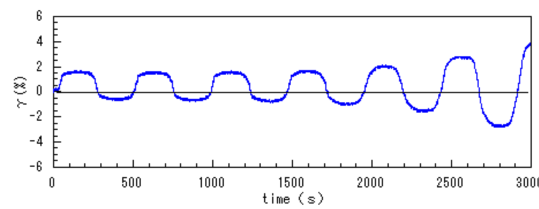
a)



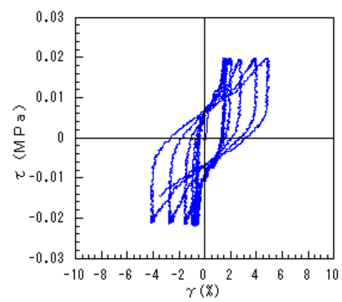
a) shear stress vs.time(Test: H-0.20-MP)



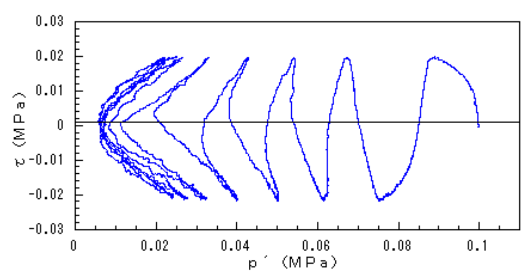
b) pore water ratio vs.time (Test: H-0.20-MP)



c) γ vs.time(Test: H-0.20-MP)



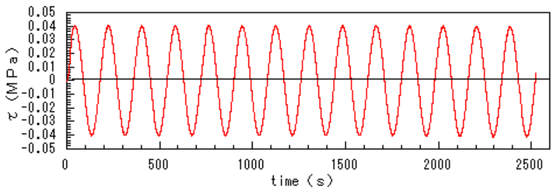
d) τ vs. γ (Test: H-0.20-MP)



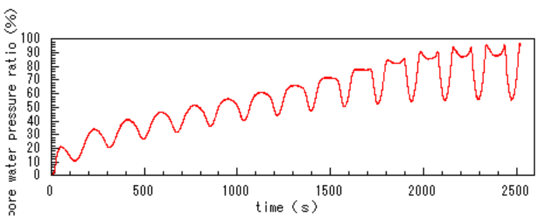
e) stress path (Test: H-0.20-MP)

b)

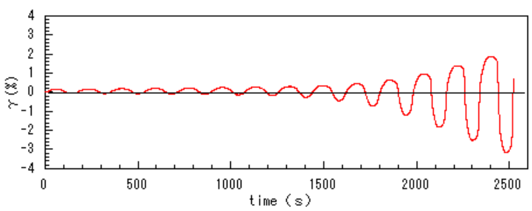
Fig.10 Large Hollow Cylinder Test Results, a) Test [H-0.20], b) Test [H-0.20-MP]



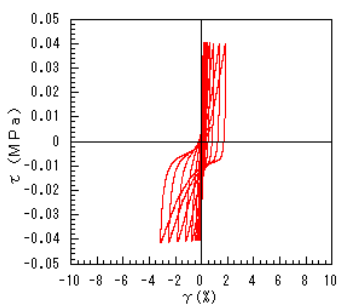
a) shear stress vs.time(Test: T-0.20)



b) pore water ratio vs.time(Test: T-0.20)



c) γ vs.time(Test: T-0.20)



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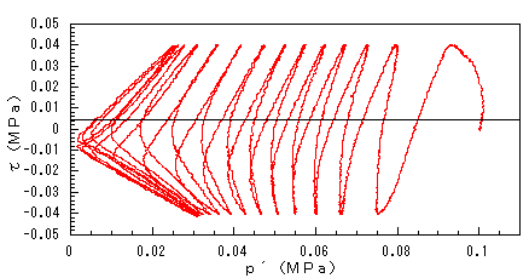
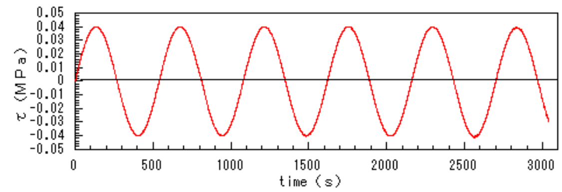
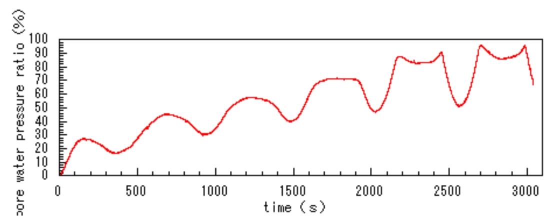


e) stress path (Test: T-0.20)

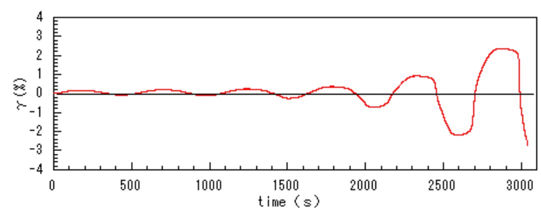
a)



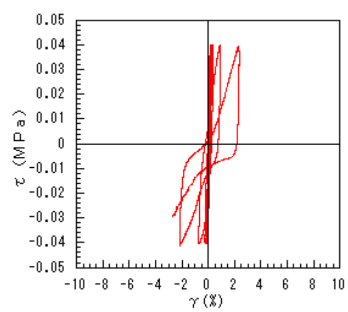
a) shear stress vs.time(Test: T-0.20-MP)



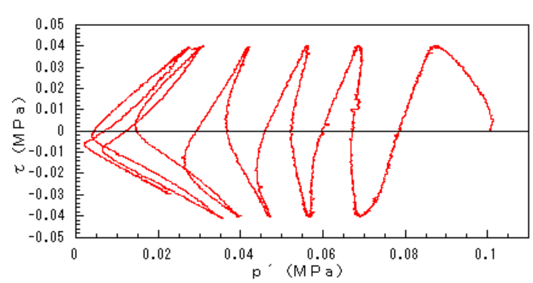
b) pore water ratio vs.time (Test: T-0.20-MP)



c) γ vs.time(Test: T-0.20-MP)



d) τ vs. γ (Test: T-0.20-MP)



e) stress path (Test: T-0.20-MP)

b)

Fig.11 Medium Size Triaxial Test Results, a) Test [T-0.20], b) Test [T-0.20-MP]

Liquefaction Strengths Curves With or Without MP Correction

Fig.12 shows a comparison of the liquefaction strength curves of those tests with or without MP corrections based on the hollow cylinder tests. Similarly Fig.13 compares the liquefaction strength curves of those test results for the triaxial tests. As can be seen from these figures, there is a significant difference between the strength curves of with and without MP correction, and the horizontal distance between these curves are used to express the amount of correction needed to be applied to the test result obtained without MP correction. Also shown in Fig.12 and Fig.13 are the liquefaction strength curves that were obtained from the indirect correction of the test results without MP correction. These curves were obtained by applying C_N - C_{RM} curve as already shown in Fig.9. Calculated C_{RM} was 0.64, and corresponding value of C_N of 2.6 was obtained for correcting the number of cycles for the torsional hollow cylinder test. For the triaxial tests, C_{RM} was 1.43 and corresponding value of C_N was 3.0. From these figures, it is shown that directly corrected liquefaction strength is slightly higher than the ones with indirect correction irrespective of different testing methods. Therefore the correction curve as obtained from Fig.9 is not applicable to the coarse grained soil tested herein.

Based on the strength curves as obtained herein using the MP correction device, the values of C_N was reevaluated, and it is 1.43 for hollow cylinder test and 2.27 for triaxial test. These two C_N values have been plotted in Fig.14. As shown in the Figure, both values locate below the line determined by Martin et al.[7]. It also appears that C_N value of hollow cylinder test locates slightly lower than that of triaxial test.

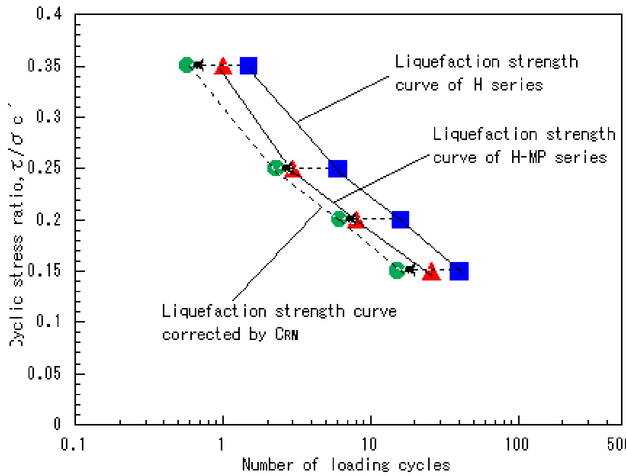


Fig.12 Liquefaction strength curve (H series)

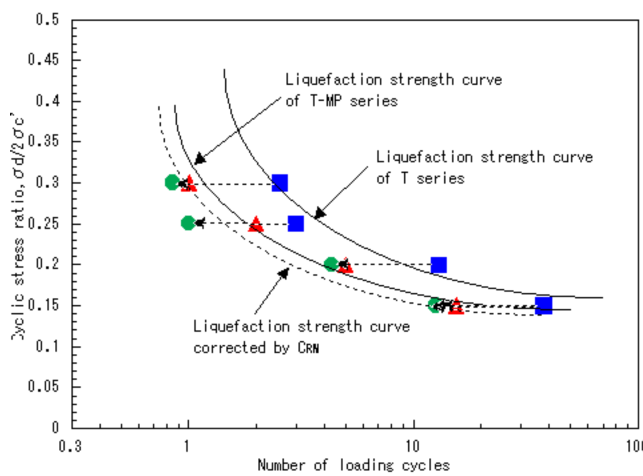


Fig.13 Liquefaction strength curve (T series)

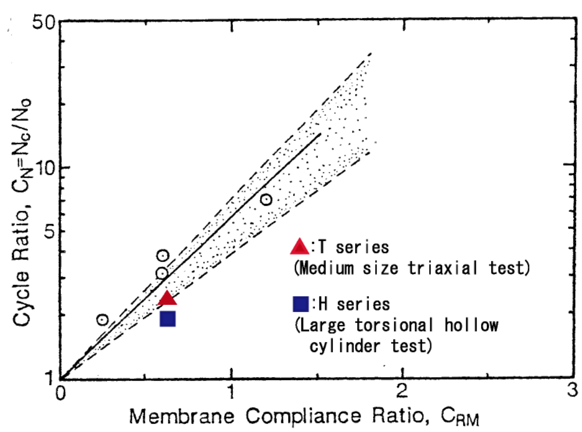


Fig.14 Ratios plotted on C_N - C_{RM} curve[7]

Comparison of liquefaction strength between the large torsional hollow cylinder test and the medium triaxial test

As have been shown previously, there is a significant difference in the direction of shearing relative to the bedding plane of specimen. The anisotropy of soil fabric would influence the deformation and the strength properties of soils. Toki et al.[10] have studied the difference of liquefaction strength between hollow cylinder test by noting the effect of soil fabric orientation on the liquefaction strength and they have examined the variations in liquefaction strength among the clean sand specimens that have been prepared by various specimen preparation methods. An example of Toki et al. results is shown in Fig.15. They concluded, based on the various sample preparation methods and strength difference between the two types of test, that the ratio of normalized strength $\{(\tau_c/\sigma_c')/(\sigma_d/2\sigma_c')\}$ between hollow cylinder and the triaxial tests depends on the degree of fabric anisotropy. They have expressed the degree of the anisotropy by a strain ratio between compression strain (ε_a comp) and double amplitude strain (DA) both measured during the triaxial testing. Fig.16 illustrates the definition of these strains, and the soil fabric response is isotropic when the ratio is 1/3. Thus they have demonstrated the strength difference between the two tests (i.e., $\{(\tau_c/\sigma_c')/(\sigma_d/2\sigma_c')\}$) varies with the anistropic fabric parameter (ε_a comp/DA), and their results are shown in Fig.17 by plotting the results on $\{(\tau_c/\sigma_c')/(\sigma_d/2\sigma_c')\}$ - (ε_a comp/DA) coordinates. Toki et al. results (Fig.17) which is basically for clean sands is used to compare the

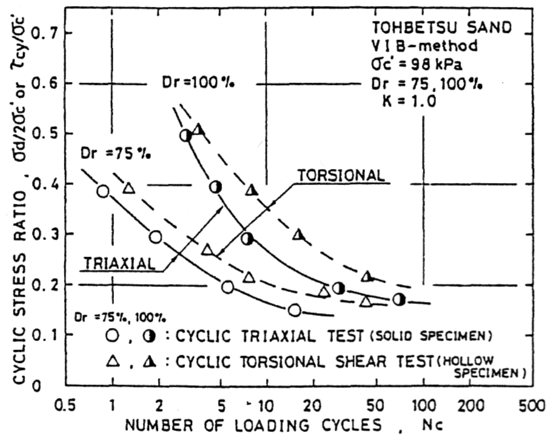


Fig.15 Two liquefaction strength curves[10]

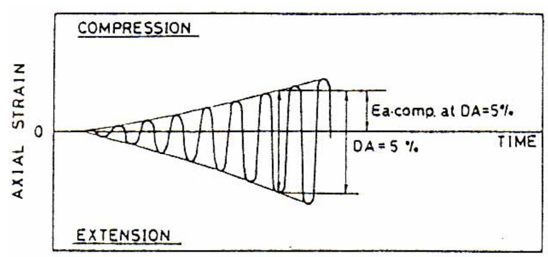


Fig.16 Definition of ε_a comp/DA[10]

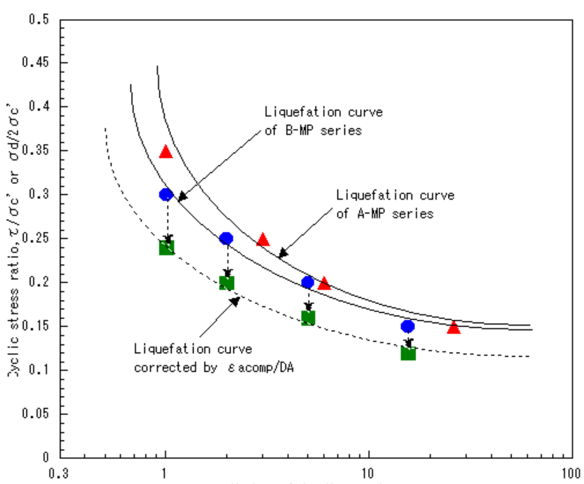


Fig.18 Liquefaction strength curve
(H-MP&T-MP series)

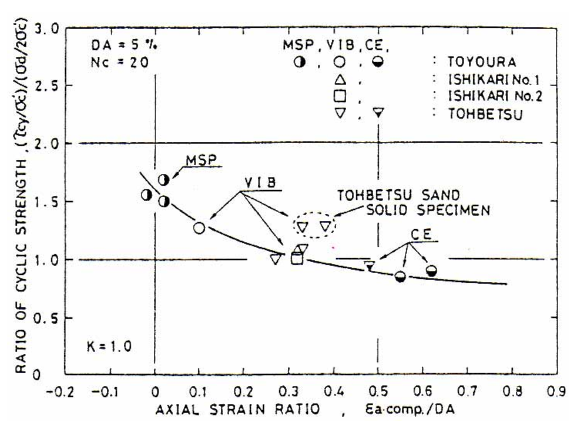


Fig.17 $\{(\tau_c/\sigma_c')/(\sigma_d/2\sigma_c')\}$ - (ε_a comp/DA) curve[8] results from the two types of tests in this study. The value of (ε_a comp/DA) from [T-MP] series was about 0.47 for the coarse grained soil in this study and thus the material shows nearly an isotropic deformation response. The correspond value of $\{(\tau_c/\sigma_c')/(\sigma_d/2\sigma_c')\}$ as suggested by Toki et al. is about 0.8, and this estimated strength difference is depicted in Fig.18. As can be seen in Fig.18, the liquefaction strength difference as obtained from this study is much less than that of Toki et al. study. It is quite possible that the difference of soil type (gradation or grain size) would influence the anisotropic response of soil. Further investigation is needed on how the difference of soil type would affect the anisotropic response such as (ε_a comp/DA) value. However, it is clear that the coarse-grained soil such as Nishi-soil behaves differently from the behavior of clean sand.

CONCLUSION

Based on the above test results, the following conclusions may be obtained for the liquefaction strength of coarse-grained soil like Nishi-soil that:

1) The effect of MP on the liquefaction strength of coarse-grained soil is very large irrespective of the different types of testing.
2) Existing indirect correction method of MP effect on the liquefaction strength somewhat overestimates the reduction of the liquefaction strength that is obtained from the tests without MP correction.
3) The difference of the liquefaction strengths of coarse grained soil as obtained from the torsional hollow cylinder and the triaxial tests is much smaller than the difference known for clean sand. Further investigation is needed on how the difference of soil type would affect the difference of liquefaction strengths as obtained from these two types of test.

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