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EFFECTS OF OVERECONSOLIDATION ON LIQUEFACTION STRENGTH CHARACTERISTICS OF SAND SAMPLES UNDER K_0-STRESS CONDITION

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SUMMARY

It is widely known that if sandy soil deposits are overconsolidated, their liquefaction strength increases. However, only a few studies have investigated the effects of overconsolidation by means of element tests to simulate the in-situ ground condition more correctly. In the present study, the liquefaction strength characteristics of overconsolidated sand samples were investigated under K_0-stress condition using a hollow cylindrical torsional shear apparatus, based on the supposition that earthquake excitations apply to the horizontal ground. Furthermore, two methods, preloading and dewatering, were believed to simulate the stress histories of overconsolidation. Toyoura clean sand was used as a sample. The following behaviors were observed in the tests; 1) The liquefaction strength was greater in the tests under K_0-consolidation than under isotropic and anisotropic consolidations. 2) There is a possibility that the liquefaction strength increased more remarkably in the sandy soil deposits that were subjected to the preloading method than to the dewatering method.

INTRODUCTION

It is widely known that if sandy soil deposits are overconsolidated, their liquefaction strength increases. Several laboratory element tests have been performed to understand the tendency to quantitatively increase the liquefaction strength, e.g., in Tatsuoka et al. (1988) and Nagase et al. (1996). However, the cyclic triaxial test was the typical element test conducted in the previous studies, and the stress conditions in the deposits during earthquakes could not be simulated exactly in these tests. For example, stress histories of overconsolidation and cyclic shear stresses are applied to the horizontal ground in a state in keeping with K_0-stress condition. Cyclic torsional tests have been conducted to clarify the effects of overconsolidation on liquefaction strength by Ishihara et al. (1979). However, the overconsolidation effects are not perfectly clear.

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There are two methods, preloading and dewatering, which provide the stress histories of overconsolidation when applied to the horizontal ground. It is supposed that the stress histories applied to the ground during overconsolidation get altered in the two methods, respectively. Therefore, it is essential to study the increase in the liquefaction strength by simulating the stress histories in these methods.

In the present study, the liquefaction strength characteristics of overconsolidated sand samples were investigated under K_0-stress condition using a hollow cylindrical torsional shear apparatus, based on the supposition that earthquake excitations are applied to the horizontal ground. Furthermore, the two methods of preloading and dewatering were assumed to simulate the stress histories of overconsolidation. Toyoura clean sand was used as a sample. The vertical or horizontal displacement of the specimen was restricted in the cyclic loading. The stress histories and overconsolidation effects observed in the sandy soil deposits that were subjected to the above two methods will be discussed in the following sections.

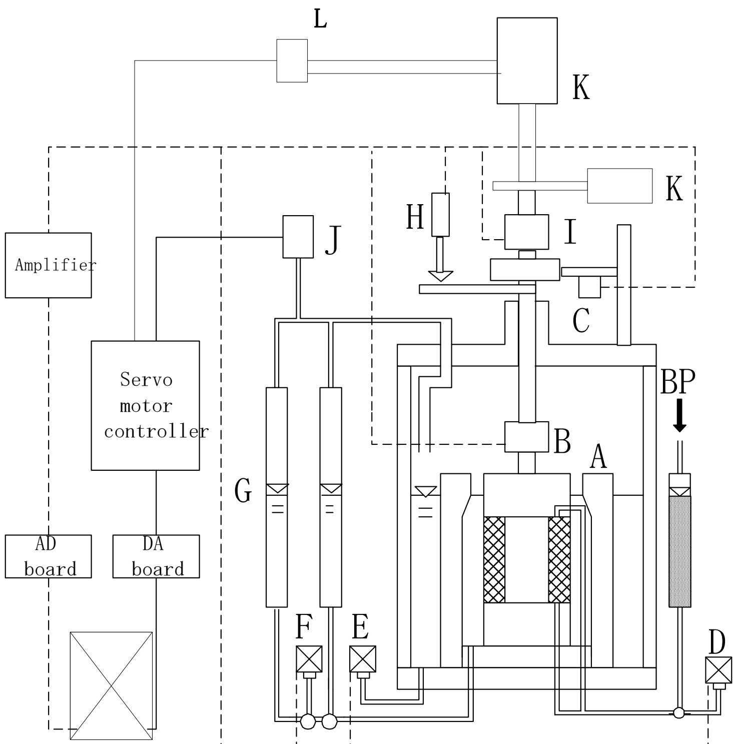
SAMPLES AND TEST PROCEDURES

Toyoura clean sand was used as a sample material. The soil particle density, ρ_s, is 2.637 and the maximum and minimum void ratio, e_{max} and e_{min}, are 0.973 and 0.609, respectively. Hollow cylindrical specimens of 10 cm in outer diameter, 6 cm in inner diameter, and 10 cm in height were used in cyclic torsional shear tests. The specimens with a relative density of 30% were prepared by an air-pluviation method. In all the tests, the specimen was saturated in excess of a B-value of 0.95 by circulating carbon dioxide, CO_2, and deaired water.

Table 1 shows the test conditions used in the present study. The isotropic and anisotropic consolidations as well as the K_0-consolidations were individually applied to the specimens in the tests. The vertical or horizontal displacement of the specimen was restricted in the cyclic loading. The stress histories of overconsolidation were applied to the specimens in the following manner. In the case of isotropic consolidation, the specimens were initially consolidated by a desired initial mean effective confining pressure, σ_0' and subsequently consolidated by effective confining pressures, which were twice or four times the initial mean effective confining pressure, to simulate an overconsolidation ratio, $(OCR)_v$, of 2 or 4. After the consolidation, the confining pressure was isotropically decreased to the initial mean effective confining pressure, σ_0'. In the tests on sand consolidated anisotropically, the confining pressure was increased and decreased to simulate the overconsolidation ratio, $(OCR)_v$, of 2 or 4, which was equal to the ratio of the maximum vertical effective stress, σ_{vmax}', to the initial vertical effective stress, σ_{v0}', keeping

Table 1 Test conditions

Cace	Consolidation method	Restriction of specimen	Initial vertical effective stress σ_{v0}' (kPa)	Ratio of overconsolidation$(OCR)_v$
(A)	Isotropic consolidation	Vertical displacement	49.0	1,2,4
(B)	Anisotropic consolidation	Vertical displacement	73.5	1,2,4
(C)	Anisotropic consolidation	Lateral displacement	73.5	1,2,4
(D)	K_0-consolidation (Axial pressure control)	Vertical displacement	75.8	1,2,4
(E)	K_0-consolidation (Axial pressure control)	Lateral displacement	75.8	1,2
(F)	K_0-consolidation (Backpressure control)	Vertical displacement	75.8	1,2,4



A : Inner cell
B : Inner torque meter
C : Rotation angel gauge
D : Pore water pressure gauge
E : Lateral pressure gauge
F : Differential pressure gauge
G : Tube of reference water level
H : Axial displacement gauge
I : Load cell
J : E/P transducer
K : Bellofram cylinder
L : E/P transducer

Fig.1 The schematic illustration of the cyclic torsional shear apparatus

the ratio of the horizontal effective stress, σ_h', to the vertical effective stress, σ_v', equal to 0.5. Simultaneously, the overconsolidation ratio was also equal to the ratio of the maximum horizontal effective stress, σ_h', to the initial horizontal effective stress, σ_{h0}'. In the tests on sand consolidated under K_0-stress condition, the specimens were initially consolidated by the initial vertical and horizontal effective confining pressures, σ_{v0}' and σ_{h0}', respectively, where σ_{h0}' was equal to $K_0 \cdot \sigma_{v0}'$, in the case where the lateral displacement was prevented. After the consolidation, σ_v' was decreased to σ_{v0}', restricting the lateral displacement of the specimen. The horizontal effective stress, σ_h', ordinarily changes keeping the K_0-consolidation condition, while the vertical effective stress, σ_v', increases or decreases. The overconsolidation ratio, $(OCR)_v$, was defined as the ratio of the maximum vertical effective stress, σ_v', to the initial vertical effective stress, σ_{v0}', although the ratio, $(OCR)_v$, ordinarily does not correspond to the ratio of the maximum horizontal effective stress, σ_h', to the initial horizontal effective stress, σ_{h0}', during overconsolidation under K_0-stress condition. The initial mean effective confining pressure, σ_0', is expressed as $(\sigma_{v0}' + 2\sigma_{h0}')/3$, using the initial vertical effective stress, σ_{v0}', and the initial horizontal effective stress, σ_{h0}'.

The K_0-consolidation and cyclic shear tests under K_0-consolidation were performed due to the following procedure. In the K_0-consolidation tests, the vertical stress was applied to the specimen at a rate of 1.96 kPa/min and the lateral displacement was restricted to a value smaller than $\pm 0.05\%$. Figure1 indicates the schematic illustration of the cyclic torsional shear apparatus, which is capable of controlling the horizontal displacement of the specimen. In the cyclic shear tests, under the condition where the lateral displacement is restricted, the difference between the water level around the specimen in the inner cell and the reference water level in the bullet with a differential pressure gauge was restricted to a value smaller than ± 0.05 ml, using the lateral pressure. The differential water level was equivalent to the controlled value during K_0-consolidation.

Cyclic shear tests were conducted using a sine wave load with a frequency of 0.1 Hz under no vertical displacement, and 0.01 Hz under no horizontal displacement. The cyclic tests with no vertical displacement were performed keeping the upper clamp of the cell closed.

K_0-VALUE DURING OVERCONSOLIDATION UNDER K_0-STRESS CONDITION

Figures.2 and 3 show the relationship between the coefficient of earth pressure at rest, K_0, and the vertical effective stress, σ_v', observed in K_0-consolidation tests involving cases where the preloading and dewatering methods are individually applied to the horizontal ground. The data have been obtained from the K_0-consolidations under axial pressure - or backpressure control.

In the K_0-consolidation test under axial pressure control, the K_0-value was equal to 1.0 in the initial state, where both the vertical and horizontal effective stresses, σ_{vi}', and, σ_{hi}', were equal to 19.6 kPa. Initially, the K_0-value decreased when the vertical effective stress, σ_v', increased to 50 kPa. Its value remained constant from 0.45 to 0.50 in the region where the vertical effective stress was greater than 50 kPa. In this test, the average K_0-value was approximately 0.47. In the process of unloading, the K_0-value increased when the vertical effective stress, σ_v', decreased. However, the path of decrease was different from that of loading. This may have occurred because the lateral displacement did not undergo any change during the unloading, and the lateral effective stress also remained almost unchanged. Therefore, it can be considered that the K_0-value and the initial mean effective stress, σ_0', increase just before cyclic loading when the overconsolidation ratio increases.

In the K_0-consolidation test under backpressure control, the K_0-value was equal to 1.0 in the initial state, as that under axial pressure control. Further, the vertical effective stress, σ_v', increased to the level of the initial vertical effective stress, σ_{v0}', before the backpressure decreased. Although the trace of K_0-value was the same as that under axial pressure control until the backpressure control began to decrease, the trace under backpressure control was extremely different from that under axial pressure control in the process of controlling backpressure. As seen in Fig.3, the K_0-value increased due to the unloading of backpressure and it decreased due to the reloading of backpressure, and both the traces were almost the same during normal consolidation and overconsolidation under backpressure control. It can be considered that the unloading and reloading of backpressure were applied isotropically to the specimen and at that time both the vertical and horizontal effective stresses, σ_v', and , σ_h', were equally varied within a region similar to the one controlled by the backpressure, because the lateral displacement was restricted. It can be noted that the K_0-value and the mean effective confining pressure, σ_0', did not change during overconsolidation by means of backpressure control.

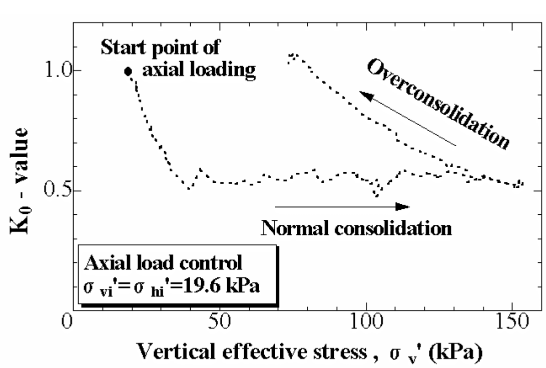


Fig.2 Coefficient of earth pressure at rest, K_0, versus vertical effective stress, σ_v'

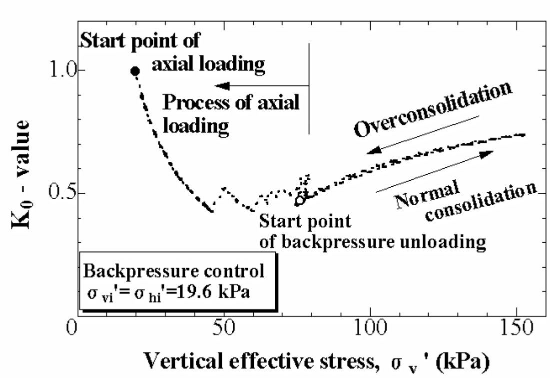


Fig.3 Coefficient of earth pressure at rest, K_0, versus vertical effective stress, σ_v'

TIME HISTORIES OBSERVED IN CYCLIC SHEAR TESTS

Typical time histories of the cyclic stress ratio, τ/σ_0', the shear strain, γ, the excess pore water pressure ratio, $\Delta u/\sigma_{h0}'$, or , $\Delta u/\sigma_{v0}'$, the vertical total stress, σ_v, or horizontal total stress, σ_h, and the vertical and horizontal effective stresses, σ_v', and , σ_h', are illustrated in Figs.4 and 5 using the data obtained from Cases (D) and (C), respectively. Figures.4 and 5 show the results observed under K_0-consolidation and the restriction of vertical displacement, and under anisotropical consolidation and the restriction of lateral displacement, respectively, where K_c signifies a ratio of the initial horizontal effective stress, σ_{h0}', to the initial vertical effective stress, σ_{v0}'. The value of K_c was 0.5 in all the tests conducted under anisotropical consolidation.

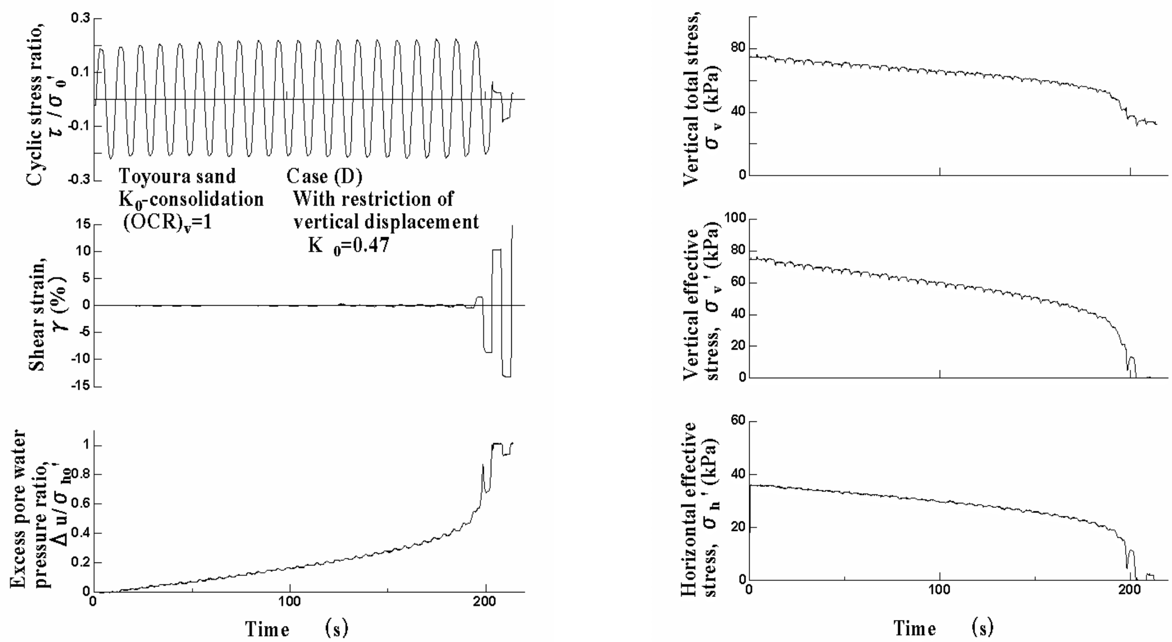


Fig.4 Typical time histories of test results observed in Case(D)

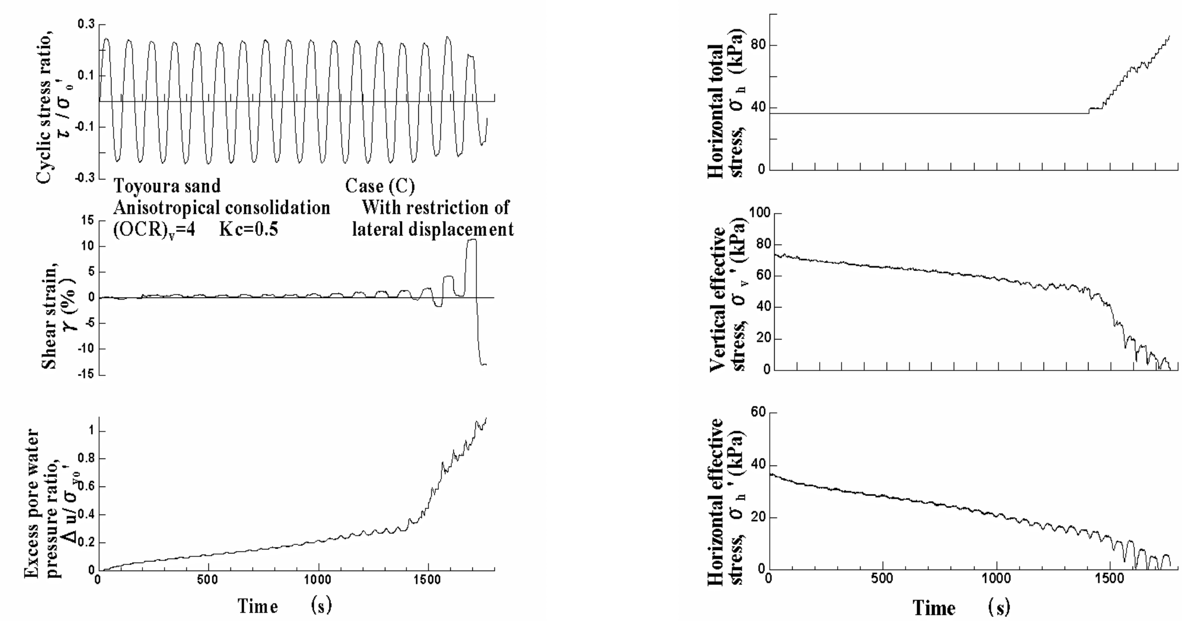


Fig.5 Typical time histories of test results observed in Case(C)

When the excess pore water pressure ratio, $\Delta u/\sigma_{h0}'$, increased in the process of cyclic loading and attained a value of 1.0, the shear strain, γ, suddenly increased in Fig.4. This phenomenon shows that the specimen was liquefied during the test. In the liquefaction stage, the vertical total stress, σ_v, corresponded to the initial horizontal effective stress, σ_{h0}', and both the vertical and horizontal effective stresses, σ_v', and, σ_h', coincided with zero. Based on these results, it can be realized that an isotropic stress state was simulated after the specimen was liquefied. On the contrary, in Fig.5, liquefaction occurred and the horizontal total stress, $\sigma_{h,}$ corresponded with the initial vertical effective stress, σ_{v0}', and both σ_v' and σ_h' coincided with zero. It can also be seen in Fig.5 that liquefaction occurred and an isotropic stress state was simulated under the restriction of a horizontal displacement.

LIQUEFACTION STRENGTH CHARACTERISTICS OF SAND OVERCONSOLIDATED UNDER SEVERAL CONDITIONS

Figure.6 shows the relationships between the cyclic stress ratio, R= τ/σ_0', and the number of cycles, N_c, to a double amplitude shear strain, DA, of 7.5% obtained from the cyclic torsional shear tests in Cases (A) and (B) on Toyoura sand overconsolidated to an overconsolidation ratio of 1, 2, and 4. This figure compares the results of the tests on isotoropically and anisotropically overconsolidated sand. σ_0', σ_{v0}', and σ_{h0}' denote the initial mean effective confining pressure, initial vertical effective confining pressure, and initial horizontal effective confining pressure, respectively, which correspond with the values just before cyclic loading. These values are also called the initial mean effective stress, initial vertical effective stress, and initial horizontal effective stress. It can be seen from Fig.6 that ① the liquefaction strength increased as the overconsolidation ratio, $(OCR)_v$, increased. ② The liquefaction strength remained unchanged in the tests on isotoropically and anisotropically overconsolidated sand.

Similarly, the relationship between the cyclic stress ratio, R= τ/σ_0', and the number of cycles, N_c, to a double amplitude shear strain, DA, of 7.5% is plotted in Fig.7 using the data obtained from the tests in Case (C) under anisotropic consolidation with restricted horizontal displacement. The cyclic stress ratio increased as the overconsolidation ratio, $(OCR)_v$, increased, independent of the number of cycles, $N_{c.}$ The effect of overconsolidation on the increase in liquefaction strength is shown in Fig.7. Furthermore, it can be seen that the cyclic stress ratio in Fig.7 is slightly smaller than that indicated in Fig.6, in comparison to the data of $(OCR)_v$ = 1. This may be the reason because of which the restriction conditions were quite different in Cases (B) and (C).

The cyclic stress ratio at the twentieth cycle, which is called the liquefaction strength ratio, R_{l20}, was obtained from Figs.6 and 7, to obtain the ratio of increase in liquefaction strength due to

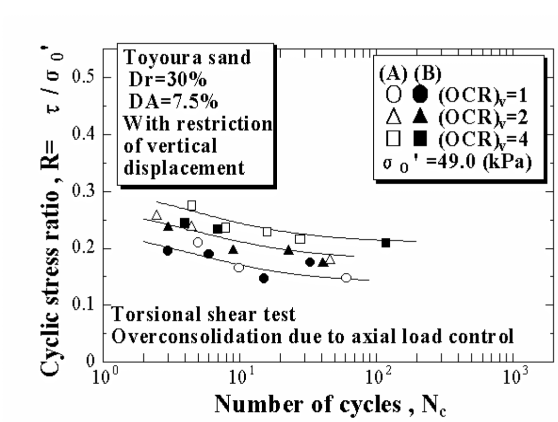


Fig. 6 Cyclic stress ratio, R, versus number of cycles, N_c, to DA=7.5%

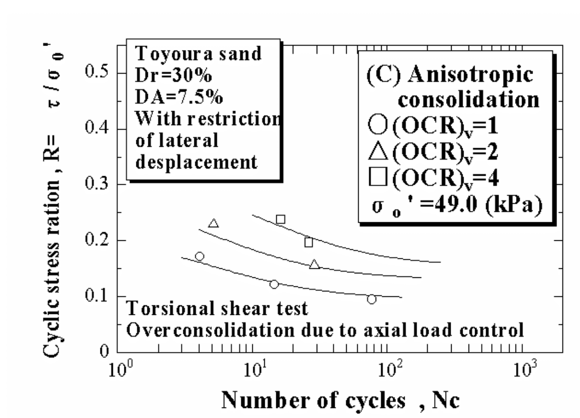


Fig. 7 Cyclic stress ratio, R, versus number of cycles, N_c, to DA=7.5%

overconsolidation, R_{oc}. R_{oc} was defined as the ratio of the increase in liquefaction strength ratio of overconsolidated sand to that of normally consolidated sand. Figure.8 indicates the relationship between R_{oc} and $(OCR)_v$. It can be seen from Fig.8 that the ratio of increase in liquefaction strength, R_{oc}, is equivalent to $(OCR)_v^n$, and the value of n was within a narrow range of 0.25 to 0.35 in Cases (A), (B), and (C), independent of the restriction and consolidation conditions. It may also be noted that the value of n relatively corresponds with that obtained from the cyclic triaxial tests, which were performed by Tatsuoka et al. (1988).

Figures.9 and 10 show the relationship between the cyclic stress ratio and the number of cycles to DA = 7.5% obtained from the tests in Case (D) under K_0-consolidation. The cyclic stress ratio was expressed as τ/σ_0' in Fig.9 and τ/σ_{v0}' in Fig.10. In Fig.9, it can be seen that the liquefaction strength ratio, R_{l20}, increased as the overconsolidation ratio, $(OCR)_v$, increased, when (OCR)v was 1 to 2. On the other hand, the values of R_{l20} inversely decreased as $(OCR)_v$ increased, when $(OCR)_v$ was 2 to 4. On the contrary, the liquefaction strength ratio, R_{l20}, always increased with an increase in the overconsolidation ratio, $(OCR)_v$, as seen in Fig.10. This may be considered as the reason that the initial mean effective stress, σ_0', was greater than the initial vertical effective stress, σ_{v0}', because the K_0-value was high when the overconsolidation ratio, $(OCR)_v$, was large during K_0-consolidation. Additionally, in order to estimate the liquefaction strength in in-situ ground, it can be assumed that the cyclic stress ratio can be more preferably expressed as τ/σ_{v0}' than τ/σ_0'. Furthermore, the liquefaction strength ratio was greater under K_0-consolidation than under isotropic and anisotropic consolidations when $(OCR)_v$ was equal to 1 and 2. It may be considered that the particle structure in the specimen was stabilized due to K_0-consolidation, in which the lateral displacement was restricted, because the vertical displacement occurred only during the consolidation.

Similarly, the relationship between the cyclic stress ratio and the number of cycles are shown by white marks in Figs.11 and 12, using the data obtained from the tests of Case (E) under K_0-consolidation and restriction of lateral displacement. The cyclic stress ratio was expressed by τ/σ_0' in Fig.11 and τ/σ_{v0}' in Fig.12. This tendency is similar to that observed in Figs.9 and 10. However, the magnitude of the

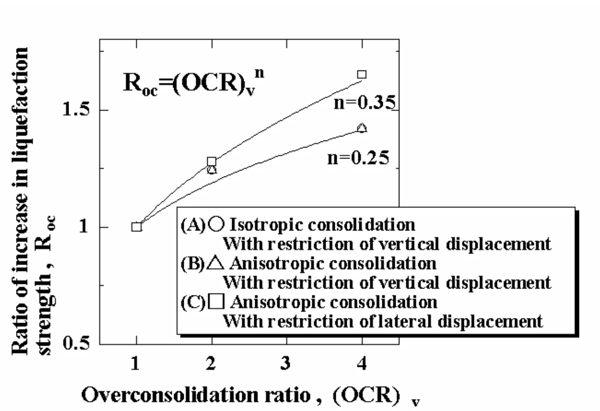


Fig. 8 Ratio of increase in liquefaction strength, R_{oc}, versus overconsolidation ratio, $(OCR)_v$

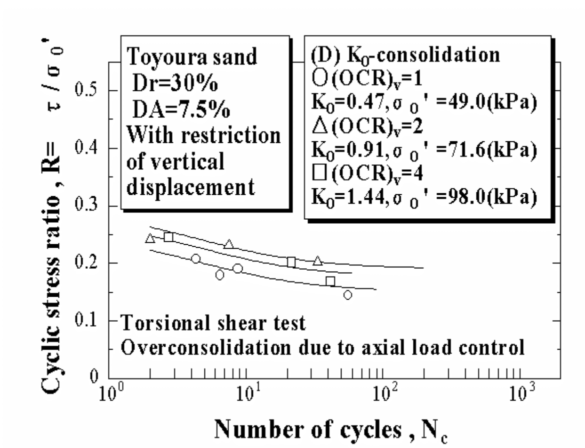


Fig. 9 Cyclic stress ratio, R, versus number of cycles, N_c, to DA=7.5%

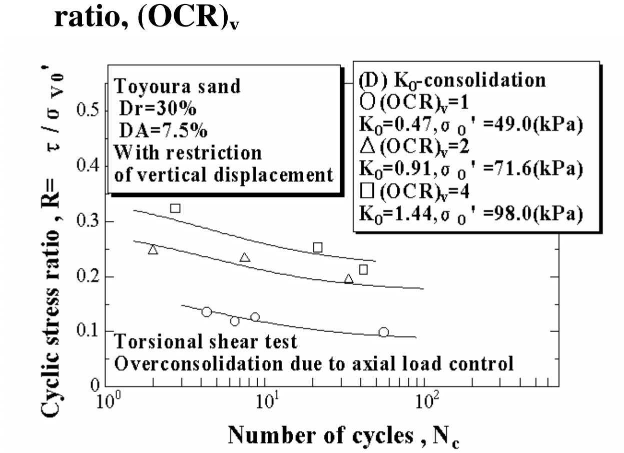


Fig. 10 Cyclic stress ratio, R, versus number of cycles, N_c, to DA=7.5%

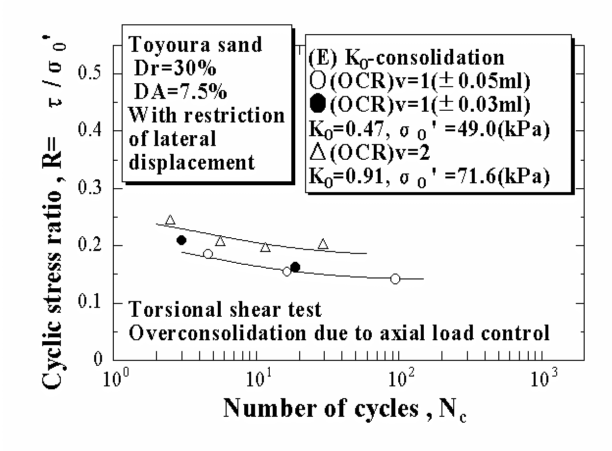


Fig. 11 Cyclic stress ratio, R, versus number of cycles, N_c, to DA=7.5%

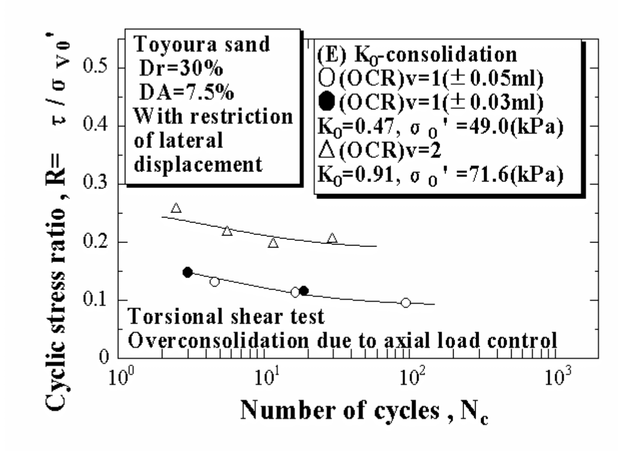


Fig. 12 Cyclic stress ratio, R, versus number of cycles, N_c, to DA=7.5%

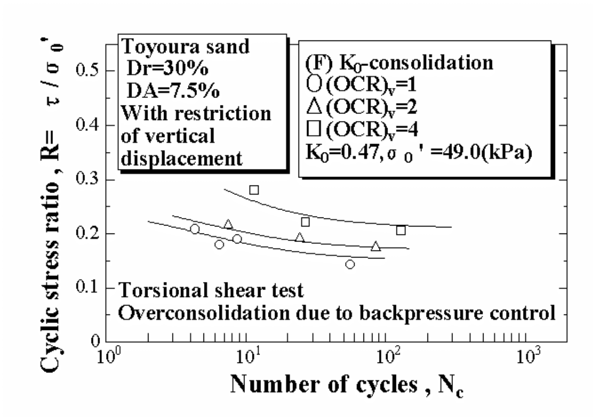


Fig. 13 Cyclic stress ratio, R, versus number of cycles, N_c, to DA=7.5%

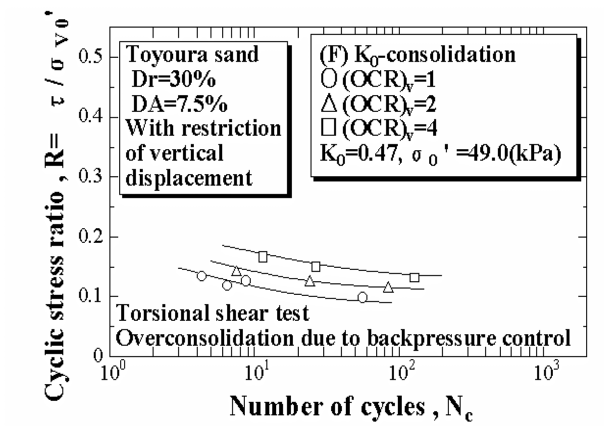


Fig. 14 Cyclic stress ratio, R, versus number of cycles, N_c, to DA=7.5%

cyclic stress ratio in Fig.9 under restriction of vertical displacement was greater than that in Fig.11 under the restriction of lateral displacement. This trend is almost the same as that observed in Figs.6 and 7. Based on these figures, it can be considered that the cyclic stress ratio is influenced by the difference between the restrictions of displacement in the specimens. Moreover, the black marks illustrated in Figs 11 and 12 show the data points obtained from the tests, in which the fluctuation of the water level was controlled within ±0.03 ml during cyclic loading. The liquefaction strength ratio, R_{120}, was large under the severe condition of restriction of lateral displacement, to simulate tests with a higher accuracy, in comparison to the data shown by the white marks in Figs.11 and 12.

Figures.13 and 14 indicate the relationships between the cyclic stress ratio and the number of cycles, using the test data obtained from the tests of Case (F), which are similar to those indicated in Figs.11 and 12. In Case (F), an overconsolidation history corresponding to the dewatering method was simulated due to backpressure control, maintaining the K_0-consolidation condition. The data at $(OCR)_v = 1$ shown in Figs.13 and 14 were the same as those at $(OCR)_v = 1$ shown in Figs.9 and 10, respectively. From these figures, it can be seen that the liquefaction strength ratio, R_{120}, increased with an increase in the overconsolidation ratio, $(OCR)_v$, even for the tests under backpressure control. However, when $(OCR)_v$ was equal to 2, the liquefaction strength ratio in Case (F) shown in Fig.13 was smaller than that in Case (D) shown in Fig.9. It can be considered that the particle structure in the specimen was not completely stabilized due to overconsolidation under backpressure control and K_0-consolidation, in which the effective stresses were isotropically changed in the vertical and lateral directions, and vertical displacement was not significant, although the stabilization of the particle structure was prominent in Case (D), as described above.

As seen in Fig.8, the ratio of increase in liquefaction strength due to overconsolidation, R_{oc}, which was obtained from Figs.6, 9, and 11, was plotted against the overconsolidation ratio, $(OCR)_v$, in Fig.15. These data were obtained from the tests of Cases (D), (E), and (A), in which the cyclic stress ratio was expressed by τ/σ_0'. In Case (D), the ratio of increase in liquefaction strength due to overconsolidation, R_{oc}, decreased as $(OCR)_v$ increased when $(OCR)_v$ was from 2 to 4, because the liquefaction strength ratio at $(OCR)_v = 4$ was smaller than that at $(OCR)_v = 2$, as shown in Fig.9. As described previously, it can be suggested that the value of initial mean effective confining pressure, σ_0', which is used in denominator of liquefaction strength ratio, is large when the overconsolidation ratio was high. Additionally, the horizontal axis in Fig.15 did not related with the K_0-value. Therefore, the overconsolidation ratio was tentatively expressed by means of the mean effective confining pressure. In this way, the overconsolidation ratio,

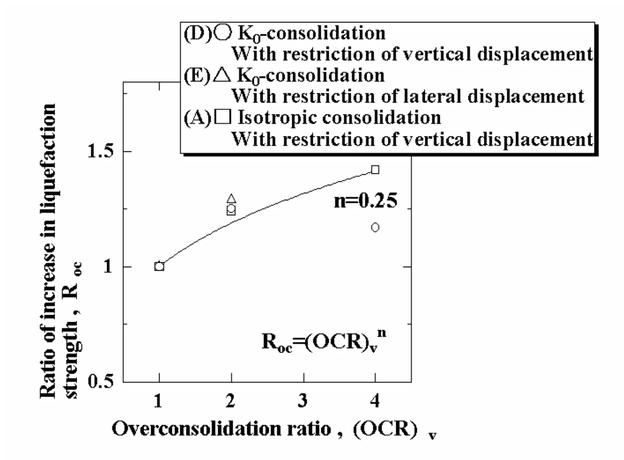


Fig. 15 Ratio of increase in liquefaction strength, R_{oc}, versus overconsolidation ratio, $(OCR)_v$

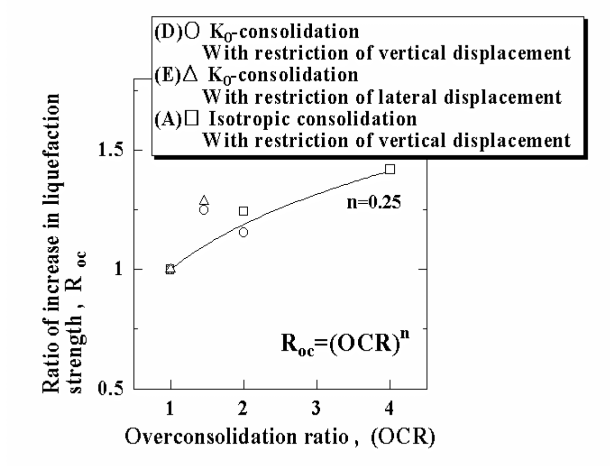


Fig. 16 Ratio of increase in liquefaction strength, R_{oc}, versus overconsolidation ratio, $(OCR)_v$

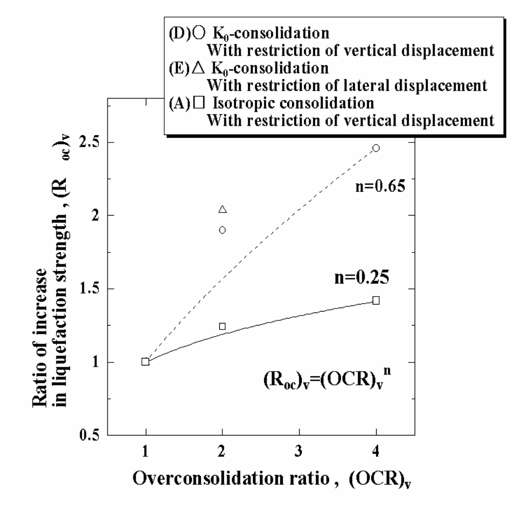


Fig. 17 Ratio of increase in liquefaction strength, $(R_{oc})_v$, versus overconsolidation ratio, $(OCR)_v$

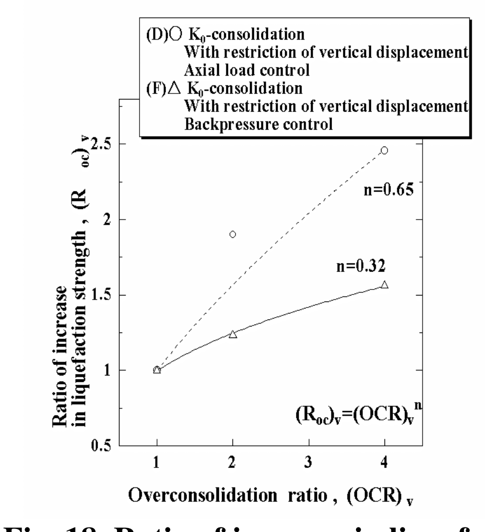


Fig. 18 Ratio of increase in liquefaction strength, $(R_{oc})_v$, versus overconsolidation ratio, $(OCR)_v$

(OCR), was expressed as the ratio of the maximum mean effective confining pressure during overconsolidation to the initial mean effective confining pressure. Figure.16 shows the relationship between the ratio of increase, R_{oc}, and the overconsolidation ratio, (OCR). In this figure, the data obtained from Cases (D) and (E) were not superimposed on the line formulated by $R_{oc}=(OCR)^n$. Therefore, it can be considered that the effects of overconsolidation on the liquefaction strength due to K_0-consolidation are essentially different from those due to isotropic consolidation. Figure.17 shows the ratio of increase, $(R_{oc})_v$, when plotted against the overconsolidation ratio, $(OCR)_v$, using the data indicated in Figs.6, 10, and 12, in which $(R_{oc})_v$ was calculated using the liquefaction strength ratio expressed by τ/σ_{v0}'. In Case (A), the liquefaction strength ratio, expressed by τ/σ_0', was equal to that obtained from τ/σ_{v0}'. It can be clearly recognized in Fig.17 that the ratio of increase in liquefaction strength due to overconsolidation, $(R_{oc})_v$, increased with the increase of the overconsolidation ratio, $(OCR)_v$, and the relationships can be expressed as $(R_{oc})_v = (OCR)_v^n$. The value of n would be a useful parameter in estimating the effects of overconsolidation on liquefaction strength in in-situ ground. Figure.18 compares the effects of overconsolidation on the liquefaction strength due to axial pressure and backpressure controls during K_0-consolidation, using the data from the tests of Cases (D) and (F). The value of n obtained under K_0-consolidation and backpressure control, which was much smaller than that under K_0-consolidation and axial pressure control, was 0.3 and almost equal to that under isotropic consolidation and axial pressure control. It can be noted that there is a possibility that the effects of overconsolidation on the liquefaction strength are greater due to the preloading method than due to the dewatering method in in-situ conditions.

CONCLUSIONS

Several series of cyclic torsional shear tests were performed on Toyoura clean sand under three consolidation and two displacement restriction conditions, in order to investigate the liquefaction strength characteristics of sand samples overconsolidated under K_0-stress condition. In the tests, the following behaviors were observed;

(1) The increase in liquefaction strength was greater in the test on sand overconsolidated under K_0-consolidation than that under isotropic and anisotropic consolidation. However, this trend was not observed in the test where the overconsolidation history was applied to the specimen due to backpressure control;

(2) The liquefaction strength was greater in the tests under the restriction of vertical displacement during cyclic loading than under the restriction of horizontal displacement during cyclic loading. This behavior was related to the difference in displacement restriction methods.

(3) Since the effective stress paths during overconsolidation and K_0-value after overconsolidation were supposed to be quite different in the ground subjected to the preloading and dewatering methods, the tendency of increase in liquefaction was supposed to be different in those cases. Therefore, there is a possibility that the effects of overconsolidation on liquefaction strength are higher in the ground subjected to the preloading method than that in the dewatering method.

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