EFFECTS OF OVERCONSOLIDATION ON LIQUEFACTION STRENGTH OF SANDY SOIL SAMPLES

H NAGASE[1], K SHIMIZU[2], A HIRO-OKA[3], S MOCHINAGA[4] And M OHTA[5]

SUMMARY

It is known that sandy soil generally has physical properties similar to overconsolidated soil due to sedimentation. And it was reported that soil improvement with a sand drain or preloading decreased ground subsidence due to liquefaction during the 1995 Hyogoken-nambu earthquake. Therefore, it is significant to investigate effects of overconsolidation on the liquefaction strength of sandy soil deposit improved with a sand drain or preloading, or sedimented for a long time. In order to examine the effects of consolidation and restricted displacement on liquefaction strength of overconsolidated sandy soil, several series of cyclic torsional shear tests were performed on clean Toyoura sand. Furthermore, several series of cyclic triaxial tests were conducted on undisturbed samples and reconstituted samples which were overconsolidated, in order to investigate the effects of sedimentary age and overconsolidation on the liquefaction strength.

From the former tests, it was clarified that the liquefaction strength increased due to overconsolidation in proportion to OCR^n where OCR denotes overconsolidation ratio and the value of n was almost unchanged even when the vertical displacement was restricted during cyclic loading. Moreover, in the tests on sand overconsolidated under Ko-condition, the liquefaction strength ratio decreased when (OCR)v determined by effective vertical stress was large. In the latter tests on some samples, there was a relatively good correlation between the sedimentary ages and overconsolidation ratio.

INTRODUCTION

It is clear in Schnertmann (1992) etc. that sandy soil generally has physical properties similar to soil overconsolidated due to sedimentation. That effect is called aging and it is clarified in Seed (1979) that the liquefaction strength of sandy soil increases due to the effect. And, it is considered that the liquefaction strength of sandy soil increases when the ground is overconsolidated by soil improvement. For example, it was reported in Yasuda et al. (1996) that soil improvement with a sand drain or preloading decreased subsidence at the ground surface of reclaimed lands due to liquefaction during the 1995 Hyogoken-nambu earthquake. One reason is believed to be that the liquefaction strength increased since the ground was overconsolidated by soil improvements executed to prevent consolidation settlement. Although a secondary effect, it is significant that earthquake damage decreased as a result of the effect. However, another reason could be that the coefficient of earth pressure at rest, Ko, in the ground increased due to the soil improvements. Thus, it is necessary to evaluate the aging effect or overconsolidation effect to assess the liquefaction strength of sandy soil deposits in in-situ conditions, since the liquefaction strength increases due to these effects.

Nagase et al. (1996) clarified the effects of density and confining stress on the liquefaction strength of overconsolidated sand using a cyclic triaxial test apparatus. It is pointed out in Kato et al. (1984) that the increase in the liquefaction strength due to overconsolidation is affected by test condition, testing apparatus, and the condition of stress applied to specimens. Although Ishihara et al. (1979) studied the effects of overconsolidation on the liquefaction strength under Ko-consolidation, it was not enough to clarify the effects. In the present study, several series of cyclic torsional shear tests on clean Toyoura sand were performed to

[1] *Department of Civil Engineering, Kyushu Institute of Technology (E-mail:nagase@tobata.isc.kyutech.ac.jp)*
[2] *Department of Civil Engineering, Kyushu Institute of Technology*
[3] *Department of Civil Engineering, Kyushu Institute of Technology*
[4] *Nagasaki Prefectural Office*
[5] *Muramoto Construction Co., Ltd.*

examine the effects of consolidation and restricted displacement on the liquefaction strength of overconsolidated sandy

soil. Moreover, several series of cyclic triaxial tests were conducted on four kinds of undisturbed samples and reconstituted samples, which were overconsolidated, in order to measure the effects of sedimentary age and overconsolidation on the liquefaction strength.

TEST PROCEDURES

Toyoura clean sand was used in the study on the effects of consolidation and restricted displacement on the liquefaction strength of overconsolidated sand. Undisturbed samples obtained by an in-situ freezing sampling method and reconstituted samples of Edo river sand, Natori river sand, Muko river sandy gravel and Kuzuryu river sandy gravel were used in the study on the effects of sedimentary ages on the liquefaction strength. Figure 1 shows typical grain size distribution curves of those samples. Edo and Natori river sands included 5% to 10% fine contents and Muko and Kuzuryu river sandy gravels contained 50% to 65% gravel contents, respectively. Table 1 indicates the physical properties of samples used in the tests. The dry density was measured on undisturbed samples, while the relative density of Toyoura sand was 30% in all the tests. The maximum void ratios of Muko and Kuzuryu river sandy gravels were not measured, because these samples included much gravel. The initial mean effective confining pressure, $\sigma_0{}'$, was equal to the vertical effective stress, $\sigma_v{}'$, which was evaluated from the depth of sampling and the density of the upper layer. The sedimentary age of Natori river sand was assessed by a radiocarbon dating of the fragment of shells included in the sand. For the other sample, the sedimentary ages were evaluated from topographic maps, soil boring logs and sedimentary depths. The sedimentary age of Natori river sand was also evaluated from the latter method and it almost corresponded with that obtained by radiocarbon dating.

Hollow cylindrical specimens of 10cm in outer diameter, 6cm in inner diameter and 10cm in height were used in cyclic torsional shear tests. Two sizes of cylindrical specimens, one of 5cm in diameter and 10cm in height, and

Table 1 Physical properties of sample used in this study

sample	Toyoura sand	Edo river sand	Natori river sand	Muko river sandy gravel	Kuzuryu river sandy gravel
Dry density (g/cm^3)		1.511	1.331	1.662	1.980
Maximum void ratio	0.997	0.995	1.243		
Minimum void ratio	0.605	0.573	0.773		
Density of soil particle (g/cm^3)	2.637	2.600	2.653	2.600	2.691
Initial effective confining pressure (kPa)		58.8	88.2	179.3	137.2
Depth of sampling (m)		G.L–4.00 –4.30	G.L–8.70□ –9.00	G.L–10.32□–11.62	G.L–7.00 –8.10
Sedimentary age (year)		2000 3000	2740 2820	100 150	50 100

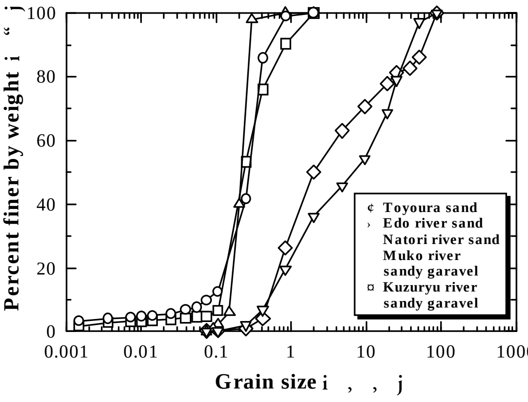

Fig.1 Typical grain size distribution curves of samples used in this study

Table 2 Test condition

Case	Consolidation method	Overconsolidation ratio, OCR or $(OCR)_v$	Initial vertical effective stress, σ_{v0}' (kPa)
(A)	Isotropic consolidation	1,2,4	49.0
(B)	Isotropic consolidation	1,2,4	49.0
(C)	Anisotropic consolidation	1,2,4	49.0
(D)	K_o–consolidation	1,2,4	76.2
(E)	K_o–consolidation	1,2,4,6	42.2

the other of 15cm in diameter and 30cm in height, were used in the cyclic triaxial tests. The specimens were prepared by the air-pluviation method to obtain the desired dry density for Toyoura sand and the reconstituted samples. Table 2 shows the conditions of tests on Toyoura sand. Three kinds of consolidation methods, isotropic, anisotropic and Ko-consolidation, and two conditions, with and without restriction of the vertical displacement, were applied to the specimens in the series of tests. Isotropic consolidation was utilized in the tests on undisturbed and reconstituted samples.

A stress history of overconsolidation was applied to the specimens in the following procedure. In the case of isotropic consolidation, the specimens were at first consolidated by a desired initial mean effective confining pressure, σ_0', and then it was consolidated by effective confining pressures which were twice or four times the initial effective confining pressure to simulate an overconsolidation ratio of 2 or 4. After the consolidation, the confining pressure was decreased to the initial mean effective confining pressure, σ_o', isotropically. In the tests on sand consolidated anisotropically, the confining pressure was increased and decreased to simulate an overconsolidation ratio of 2 or 4, which was equal to the ratio of the maximum vertical effective stress,σ_v', to the initial vertical effective stress,σ_{vo}', keeping the ratio of the horizontal effective stress,σ_h', to the vertical effective stress,σ_v', 0.5. At that time, the overconsolidation ratio was also equal to the ratio of the maximum horizontal effective stress,σ_h', to the initial horizontal effective stress,σ_{ho}'. In the tests on sand consolidated under Ko-condition, the specimens were at first consolidated by the initial vertical and horizontal effective confining pressures, σ_{vo}'andσ_{ho}', whereσ_{ho}' was equal to Ko□σ_{vo}', while preventing lateral displacement. Then, the vertical effective confining pressure,σ_v', was increased to twice or four times the value ofσ_{vo}'. After the consolidation,σ_v' was decreased toσ_{vo}', restricting the lateral displacement of the specimens. In the Ko-consolidation, the lateral displacement was controlled to a value smaller than±0.05%.

Undrained cyclic loading tests were performed using sine wave loads with a frequency of 0.1 Hz, after the stress histories of overconsolidation were applied to the specimens. In all tests, the specimens were saturated in excess of a B-value of 0.95 by circulating carbon dioxide, CO_2, and deaired water.

EFFECTS OF CONSOLIDATION AND RESTRICTED DISPLACEMENT ON LIQUEFACTION STRENGTH OF OVERCONSOLIDATED SAND

Figures 2 and 3 show relationships between the cyclic stress ratio, $R=\tau/\sigma_0'$, and the number of cycles, Nc, to a double amplitude shear strain, DS, of 7.5%, obtained from cyclic torsional shear tests on Toyoura sand overconsolidated to an overconsolidation ratio, OCR of 1, 2 and 4. Figure 2 indicates the results of tests with and without restriction of vertical displacement of the specimen. Figure 3 shows the results of tests on sand overconsolidated isotropically and anisotropically. σ_0', σ_{vo}'andσ_{ho}'denote initial effective confining pressure, initial vertical effective confining pressure and initial horizontal effective confining pressure, respectively, which show the values just before cyclic loading. These are satisfied with the following equation;$\sigma_0' = (\sigma_{vo}' + 2\sigma_{ho}')/3$. It can be seen from these figures that □ the liquefaction strength increased as the overconsolidation ratio, OCR,

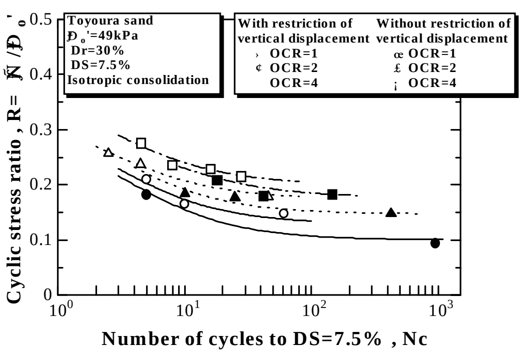

Fig.2 Cyclic stress ratio , R , versus number of cycles, Nc, to DS=7.5% relationships obtained from cyclic torsional shear tests on Toyoura sand under isotropic condition

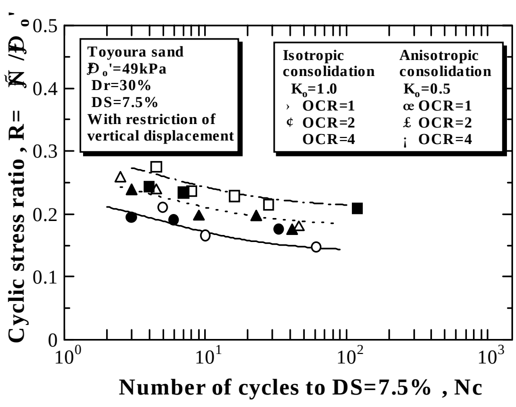

Fig.3 Cyclic stress ratio , R , versus number of cycles, Nc, to DS=7.5%; relationships obtained from cyclic torsionalshear tests on Toyoura sand

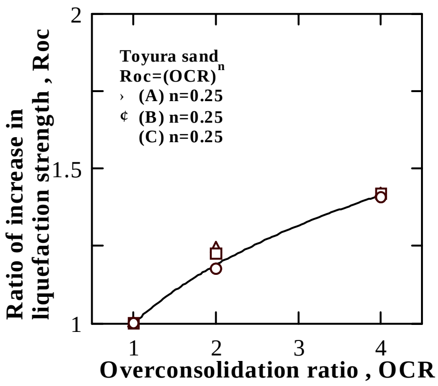

Fig.4 Ratio of increase in liquefaction strength, Roc, versus overconsolidation ratio, OCR, relationships

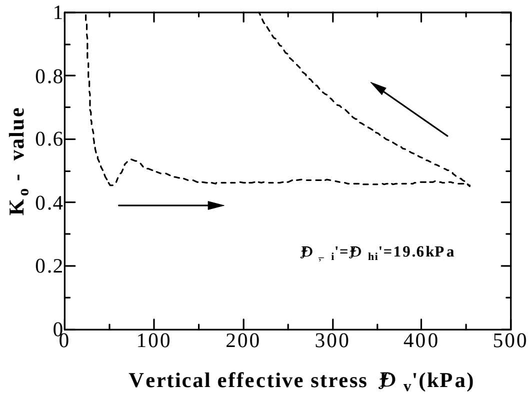

Fig.5 Coefficient of earth pressure at rest , K_o, versus vertical effective stress , σ_v' , relationship

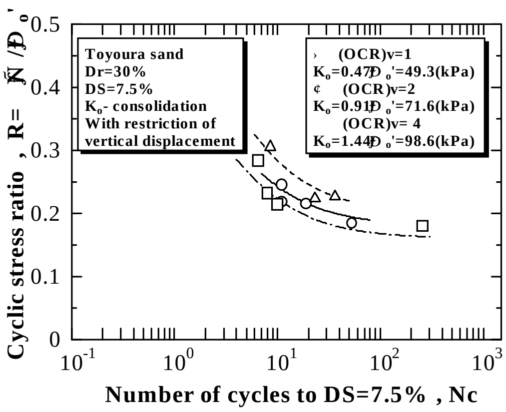

Fig.6 Cyclic stress ratio , R , versus number of cycles, Nc, to DS=7.5% relationships obtained from cyclic torsional shear tests on Toyoura sand under K_o-condition

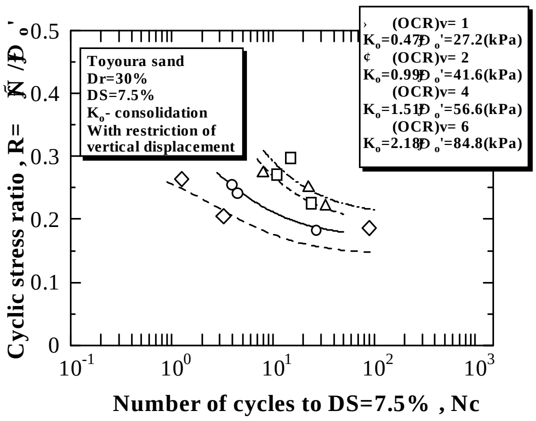

Fig.7 Cyclic stress ratio , R , versus number of cycles , Nc, to DS=7.5% relationships obtained from cyclic torsional shear tests on Toyoura sand under K_o- condition

increased, □ the liquefaction strength increased to about 8% due to the restriction of vertical displacement, and □ the liquefaction strength did not change in the tests on sand overconsolidated isotropically and anisotropically. For the trend on □, it can be considerated that the shear deformation of the specimen was somewhat restrained during cyclic loading, because a suspected plane strain condition was simulated by the restriction of vertical displacement. The cyclic stress ratio at the twenty cycles, which is called the liquefaction strength ratio, R_{l20}, was read from Figs.2 and 3, to obtain the ratio of increase in liquefaction strength due to overconsolidation, R_{oc}. R_{oc} was defined as the ratio of the liquefaction strength ratio of overconsolidated sand to that of nomally consolidated sand. Figure 4 indicates R_{oc} versus OCR relationships. It can be seen from Fig.4 that the ratio of increase in liquefaction strength, R_{oc} , was equivalent to $(OCR)^n$ and the value of n was almost equal to 0.25 in cases of (A), (B) and (C), independent on the restriction and consolidation condition. It may also be noted that the value of n, 0.25, corresponded with that obtained by the cyclic triaxial tests which were performed by Tatsuoka et al. (1988) and that seems to be the peculiar value for Toyoura sand.

Figure 5 shows the coefficient of earth pressure at rest, Ko, versus vertical effective stress, σ_v', in Ko-consolidation test, where the vertical load was increased and decreased from the initial state of$\sigma_{vi}'=\sigma_{hi}'$= 19.6 kPa. The Ko-value at first decreased, as the vertical effective stress,σ_v', increased to about 50kPa and kept a constant value of 0.45 to 0.50 in the region of vertical effective stress greater than 50kPa. In this test, the average Ko- value was about 0.47. In the process of unloading, the Ko-value increased as the vertical effective stress,σ_v', decreased, along a path different from that in loading. Therefore, it can be considered that the Ko-value and the initial mean effective stress,σ_0', just before cyclic loading increases as the overconsolidation ratio increases in the process of overconsolidation.

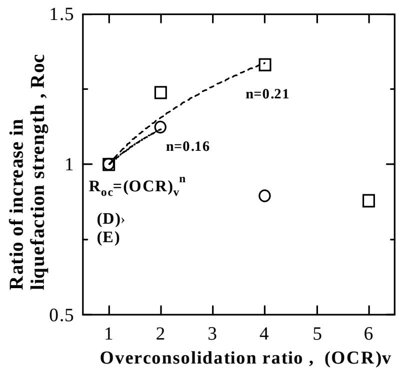

Fig.8 Ratio of increase in liquefaction strength , Roc ,versus overconsolidation ratio , $(OCR)_v$, relationships

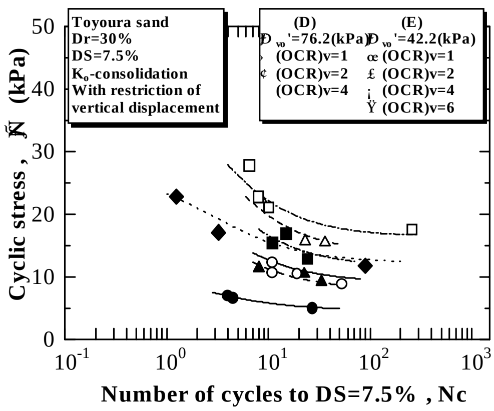

Fig.9 Cyclic stress , τ , versus number of cycles , Nc, to DS=7.5% relationships obtained from cyclic torsional shear tests on Toyoura sand under K_o-condition

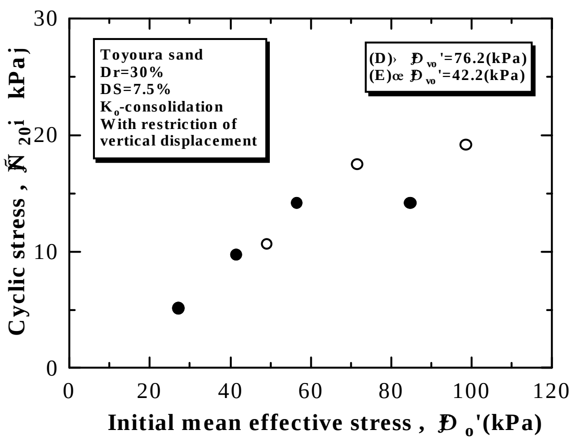

Fig.10 Cyclic stress at twentieth cycle , τ_{20} , versus initial mean effective stress ,σ_0' , relationships

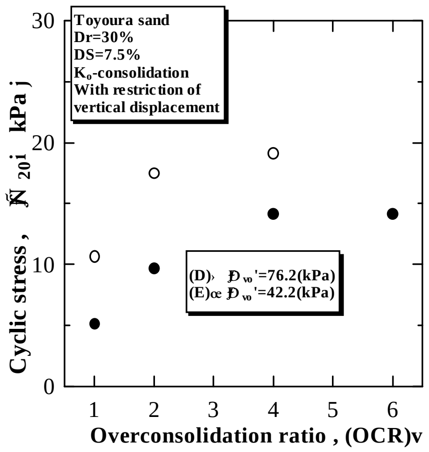

Fig.11 Cyclic stress at twentieth cycle ,τ_{20} , versus overconsolidation ratio, $(OCR)_v$, relationships

Figures 6 and 7 show the relationships between the cyclic stress ratio, $R=\tau/\sigma_0'$, and the number of cycles, Nc, to a double amplitude shear strain, DS, of 7.5%, obtained in the tests on Toyoura sand consolidated under Ko-condition where the initial vertical effective stresses were 76.2 kPa and 42.2 kPa, respectively, as shown in Table 2. The cyclic stress ratio increased when the overconsolidation ratio, $(OCR)_v$, increased from 1 to 2, in spite of the number of cycles, where $(OCR)_v$ denotes the ratio of the maximum vertical effective stress, σ_v, to the initial vertical effective stress,σ_{vo}'. And the cyclic stress ratio was greater under Ko-consolidation than under isotropic consolidation when OCR was equal to 1 and 2. It may be considered that the particle structure in the specimen was stabilized due to Ko-consolidation, in which the lateral displacement was restrained and the vertical displacement only took place during the consolidation. In a manner similar to Fig.4, the ratio of increase in liquefaction strength due to overconsolidation, which was obtained from Figs.6 and 7, was plotted against the overconsolidation ratio, $(OCR)_v$, in Fig.8. R_{oc} decreased when $(OCR)_v$ exceeded 2 in case (D) and 4 in case (E), respectively. The value of n was 0.16 in case (D), when $(OCR)_v$ was lower than 2, and 0.21 in case (E), when $(OCR)_v$ was lower than 4. In order to clarify the reason why R_{oc} was lower than 1.0, the cyclic stress, τ, versus number of cycles, N_c, relationship was plotted in Fig.9. The cyclic stress at the twentieth cycle,τ_{20}, read from Fig.9 was plotted against the initial mean effective stress,σ_o', in Fig.10 and the overconsolidation ratio, $(OCR)_v$, in Fig.11. It can be seen from Figs.10 and 11 that the shear stress,τ_{20}, approached constant values in cases (D) and (E), respectively, asσ_o' or $(OCR)_v$ was increased. Therefore, it can be considered that there is a limitation of the increase in the cyclic stress,τ_{20}, when the overconsolidation ratio, $(OCR)_v$, is increased in the tests on sand overconsolidated under Ko-condition. It can also be considered that the cyclic stress ratio decreased as $(OCR)_v$ increased, because the initial mean effective stress,σ_o', which is the denominator of cyclic stress ratio shown in Figs.6 and 7, was increased by the fact that the Ko-value increased during unloading in the process of overconsolidation controlling only vertical effective stress.

EFFECTS OF SEDIMENTARY AGE AND OVERCONSOLIDATION ON LIQUEFACTION STRENGTH

Figures 12 to 15 show the relationships between the cyclic stress ratio, R, and the number of cycles, Nc, to a double amplitude axial strain, DA, of 2% or 5%, obtained by the cyclic triaxial tests on the undisturbed and reconstituted samples of Edo river sand, Natori river sand, Muko river sandy gravel and Kuzuryu river sandy gravel. These figures also show the results of the tests on overconsolidated reconstituted samples. The reason why DA=2% was used as a criterion to determine the liquefaction strength of sandy gravel is that the specimen did not deform uniformly if the double amplitude axial strain was larger than 2%, as described in Nagase et al. (1999). For Edo and Natori river sand, the relationships between the cyclic stress ratio, $R=\sigma_d/2\sigma_0'$, and the number of cycles, Nc, on the undisturbed and reconstituted samples are almost parallel lines and the liquefaction strength of the reconstituted sample apparently increased due to overconsolidation. On the other hand, for Muko river sandy gravel, there is a large scattering in the data on liquefaction strength of undisturbed samples, and the liquefaction strength of reconstituted samples clearly increased due to overconsolidation. It may be considered that the scattering was induced by the fact that the dry density of undisturbed sample was varied widely, especially for Muko river sandy gravel. The average curve drawn by thick solid line in Fig.14 indicates the liquefaction strength curve of undisturbed samples, which had the same dry density as that of the reconstituted sample. The liquefaction strength curve of the undisturbed sample is almost parallel to that of the reconstituted sample. In the data on Kuzuryu river sandy gravel, the trend of liquefaction strength curve is quite different from those of the other samples. The liquefaction strength curve of the undisturbed sample stands up sharply in

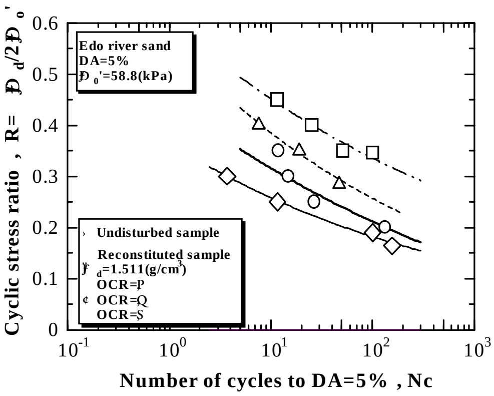

Fig.12 Cyclic stress ratio, R, versus number of cycles, Nc, to DA=5% relationships obtained from cyclic triaxial tests on Edo river sand

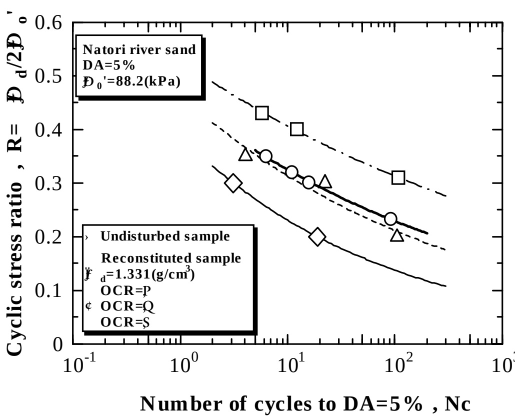

Fig.13 Cyclic stress ratio, R, versus number of cycles, Nc, to DA=5% relationships obtained from cyclic triaxial tests on Natori river sand

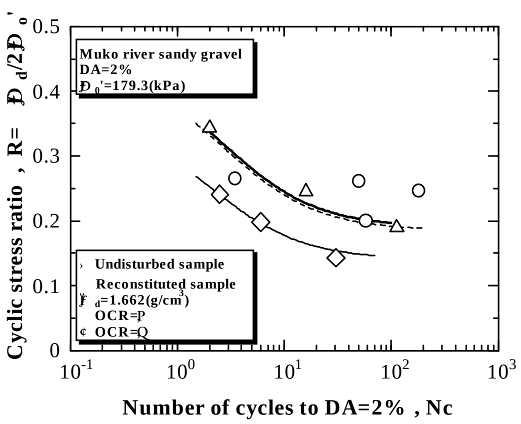

Fig.14 Cyclic stress ratio, R, versus number of cycles, Nc, to DA=2% relationships obtained from cyclic triaxial tests on Muko river sandy gravel

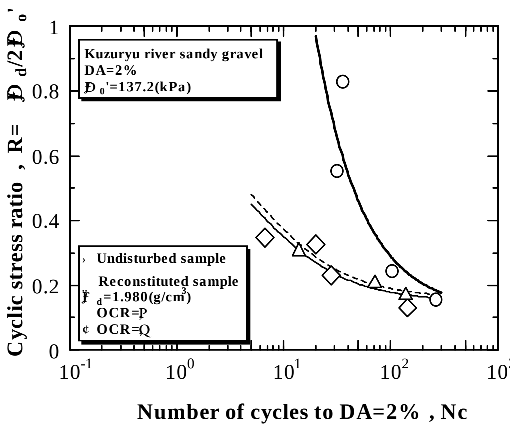

Fig.15 Cyclic stress ratio, R, versus number of cycles, Nc, to DA=2% relationships obtained from cyclic triaxial tests on Kuzuryu river sandy gravel

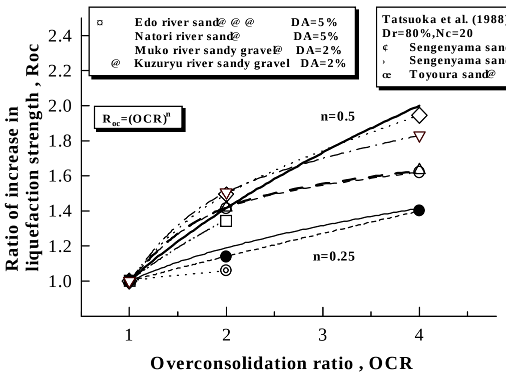

Fig.16 Ratio of increase in liquefaction strength, Roc, versus overconsolidation ratio , OCR , relationships

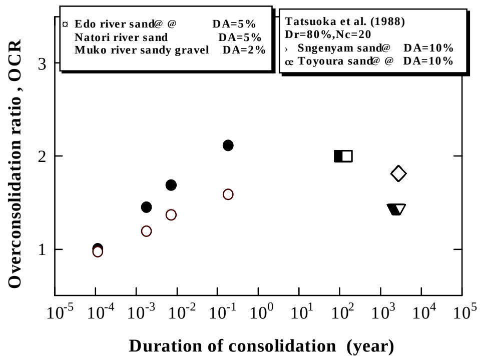

Fig.17 Overconsolidation ratio , OCR, Versus duration of consolidation relationships

the sphere within the one hundredth cycle, and the liquefaction strength of the reconstituted sample does not nearly increase due to overconsolidation. It can be considered that the liquefaction strength of the undisturbed sample was remarkably large because □ the gravel content ratio was larger than 65% and the skeleton of the specimen was formed by gravel particles, □ the dry density was quite large, □ the sand particles around the gravel, which was round, were angular, according to particle observations with the naked eye. The process of sedimentation of the sandy gravel layer may also explain the large liquefaction strength. It is necessary to study this point more. Furthermore, it may also be considered that the overconsolidation effect on liquefaction strength was not observed in the reconstituted sample of Kuzuryu river sandy gravel, because the skeleton was formed by gravel particles touching each other and the particle structure of sand and gravel hardly changed during overconsolidation.

The ratio of increase in liquefaction strength, R_{oc}, due to overconsolidation, which was obtained from Figs. 12 to 15, was potted against the overconsolidation ratio, OCR, in Fig.16. The data on Toyoura sand and Sengenyama sand, obtained by Tatsuoka et al. (1988), were also plotted in this figure. Sengenyama sand is well-graded and has about 2.4% fine contents. The results of sand and sandy gravel samples used in this study seem to approximate a line expressed in the formula of $R_{oc} = (OCR)^n$ when the value of n is almost equal to 0.5, except for the data on Kuzuryu river sandy gravel with a small value of n. Furthermore, these data corresponded with that of Sengenyama sand when OCR was smaller than 2, and this trend gradually disappeared as OCR increased. The value of n seems to be smaller than 0.5 for Sengenyama sand.

It is interesting to observe whether there is a unique relationship between the overconsolidation ratio, OCR, which offers the same magnitude of liquefaction strength as that of undisturbed samples to the reconstituted samples and the duration of consolidation in an in-situ condition or in the laboratory. Figure 17 shows the overconsolidation ratio versus the duration of consolidation, with the data obtained by Tatsuoka et al. (1988). It can be supposed that the overconslidation ratio showing how much the specimen stored overconcolidation effect increases as the duration of consolidation increases. It is recognized in Fig.17 that, for Toyoura sand and Sengenyama sand, there is a positive correlation and Toyoura sand preserved an overconsolidation effect equivalent to OCR□2 for about 0.1 year. It can also be seen that the results of the tests on Natori river sand and Muko river sandy gravel have a relatively good correlation with the data on Sengenyama sand. In all the data on undisturbed samples used in this study, however, the overconsolidation ratio increased to at most 1.4 – 2.0 even if the duration of consolidation was 100 – 3,000 years. It can also be pointed out that the undisturbed samples of Edo and Natori river sand were somewhat disturbed even using the in-situ freezing method to retrieve them, since the samples included 5% to 10% fine contents. Moreover, it seems to be difficult to find a clear relation between the liquefaction strengths obtained by laboratory tests and that in in-situ ground, and the overconsolidation effect on sandy soil corresponded with at most OCR=2 if the duration of consolidation is shorter than 3,000 years. It is necessary to accumulate more such data as that shown in Fig.17 to clarify the increase in liquefaction strength of sandy soil due to aging and overconsolidation.

CONCLUSIONS

Several series of cyclic torsional shear tests on Toyoura sand were performed to examine the effects of consolidation and restriction conditions on the liquefaction strength of overconsolidated sand. Moreover, in order to investigate the effects of sedimentary ages and overconsolidation on the liquefaction strength, several series of cyclic triaxial tests were conducted on four kinds of undisturbed and reconstituted samples, which were overconsolidated. The following behaviors were observed.

(1) The liquefaction strength of Toyoura sand increased due to overconsolidation in proportion to OCR^n. The value of n was equal when the vertical displacement was restricted during cyclic loading of specimens which were consolidated isotropically and anisotropically.
(2) The value of Ko increased in the unloading process during overconsolidation. Therefore, the cyclic stress ratio, τ/σ_0', decreased since the mean effective confining stress,σ_0', increased, and the cyclic shear stress,τ, approached a constant value as the overconsolidation ratio, $(OCR)_v$, on the vertical effective stress increased. It is necessary to investigate more how the overconsolidation ratio can be expressed when the specimen is overconsolidated under Ko-consolidation condition.
(3) The liquefaction strength of reconstituted samples also increased due to overconsolidation in proportion to $(OCR)^n$ and the value of n was nearly equal to 0.5, except for Kuzuryu river sandy gravel, which included a large gravel contents of 65% and had a great dry density of $1.98g/cm^3$. The overconsolidation ratio, OCR, which offered a liquefaction strength equal to that of the undisturbed samples, except for that of Kuzuryu river sandy gravel, to the reconstituted samples was at most 2.

In-situ ground conditions , for example, sedimentary environment, sedimentary deposit, environment of underground water and loading weight etc. after sedimenting are supposed to be multifarious and the liquefaction strength of sandy soil is considered to be influenced by these factors in the ground. It is also needed to investigate these effects to accurately access the liquefaction strength in in-situ ground.

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