LIQUEFACTION STRENGTH CHARACTERISTICS OF OVERCONSOLIDATED SAND SAMPLES

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ABSTRACT

In order to study the effects of density and confining stress on the liquefaction strength of overconsolidated sand, several series of cyclic undrained triaxial tests were performed on specimens of a poorly-graded clean sand called Toyoura sand. Moreover, similar tests were conducted on undisturbed specimens of two other sands to investigate the liquefaction strength of overconsolidated sand with grain size distributions different from that of Toyoura sand. These tests showed that the liquefaction strength increased as the overconsolidation ratio, (O.C.R.), increased and the ratio of increase in the liquefaction strength was expressed by $(O.C.R.)^n$. The power n firmly depended on relative density, initial effective confining stress and fine contents and gravel fractions in sand specimens. The cyclic undrained triaxial tests were also carried out on reconstituted sand specimens with a relative density of about 0 %, to study the increase in liquefaction strength due to repeated overconsolidation. It was found that the liquefaction strength increased as overconsolidation was repeated.

KEYWORDS

Liquefaction strength, Overconsolidation, Relative density, Confining stress, Reconstituted sand sample, Undisturbed sample

INTRODUCTION

There is a countermeasure against liquefaction which utilizes the effects of overconsolidation on the liquefaction strength of sand deposits. For example, this countermeasure can be realized by pre-loading or dewatering a loose sand deposit. Several studies have been performed on the effects of overconsolidation in laboratories. It is clear from these studies that the liquefaction strength increases as the overconsolidation ratio increases and the ratio of increase in the liquefaction strength, which is defined by the liquefaction strength ratio of overconsolidated sand samples divided by that of normally consolidated sand samples, can be shown as $(O.C.R.)^n$. The character of (O.C.R.) denotes the overconsolidation ratio. Ishihara and Takatsu (1979) conducted several series of cyclic torsional shear tests to evaluate the effect of overconsolidation on the liquefaction strength of Fuji river sand with a relatively well-graded grain size distribution. The results showed that the liquefaction of the sand with a relative density of 55% increased approximately in proportion to the square root of overconsolidation ratio, which means that the power n is equal to 0.5. On the contrary, Tatsuoka *et al.* (1988) carried out a series of cyclic triaxial tests on Toyoura sand with a poorly-graded grain size distribution and on Sengenyama sand including some fines, in order to evaluate the effects of overconsolidation on the liquefaction strength. It was clarified in the tests that the power n was 0.25 for Toyoura sand with a relative density of about 50% and 0.5 for Sengenyama sand with a relative density of about 80%. It seems that the power n can be very different for different sands.

In the present study, several series of cyclic undrained triaxial tests under three initial effective confining stresses of 19.8, 49.0 and 98.0kPa were conducted on reconstituted specimens made of Toyoura sand with relative densities of 0%, 30% and 50%, in order to investigate the power n showing the effects of overconsolidation on the liquefaction strength. Moreover, similar tests under initial effective confining stresses of 49.0 and 98.0kPa were performed on undisturbed specimens of two other sands to investigate the liquefaction strength of overconsolidation sand with grain-size distributions different from that of Toyoura sand. The overconsolidation ratios used in the tests were 1, 2 and 4. The number of cycles for repeated overconsolidation was also changed from 1, to 4 and 10. From the results obtained in the tests described above, it will be discussed how the density of samples, the initial confining pressure and the number of cycles for repeated overconsolidation affect the increase in liquefaction strength of the overconsolidated sand samples.

TESTING METHODS

Three sand samples with different grain-size distributions, as shown in Fig.1, were used as test materials. Toyoura sand is a clean sand used as the reconstituted sample. The specific gravity, Gs, is 2.637. The maximum and minimum void ratios, e_{max} and e_{min}, obtained by the method specified in Chapter 8 of Soil Testing Method, published by the JSSMFE, are 0.973 and 0.609, respectively. The other sand samples shown in Fig.1 were obtained from reclaimed land at Kobe Port Island before the Hyogoken-nanbu Earthquake of 1995 and an alluvial sand layer consisting of fluvial deposit in Narashino City, Chiba Prefecture, Japan. These undisturbed samples were carefully obtained using thin-walled tubes, and were named Kobe P.I. sand (Gs=2.651, e_{max} =1.098, e_{min},=0.526) and Narashino alluvial sand (Gs=2.677,e_{max} =1.148, e_{min},=0.703). The specific gravity and the maximum and minimum void ratios of the two undisturbed samples were measured using the sand samples from which gravel fractions, of more than 2.0mm had been removed on the basis of the Soil Testing Method. Therefore, it may be seen that the relative densities of the undisturbed sand specimens should be evaluated from the void ratios of samples with sand particle of less than 2mm in diameter. In this study, the relative densities were obtained by the following method. (1) The volume and dry weight of the gravel fraction of the tested specimens are calculated from the specific gravity and data obtained by a sieve analysis of the specimen, (2) the volume and dry weight of the parts of specimens with soil particles of less than 2mm are also calculated by subtracting the volume and dry weight of the gravel fractions from those of the specimens measured just before the cyclic test, respectively, (3) the void ratio to evaluate the relative density is obtained from the volume and dry weight of the specimen without gravel.

For Toyoura sand, cylindrical specimens of 7.5cm in diameter and 15cm in height were used as the reconstituted samples in the tests. The relative density, Dr, employed in the test were 0%, 30% and 50%. The specimen with Dr=0% was made by freezing the unsaturated sand; refer to Nagase *et al.* (1995) for detailed information. The specimens with Dr=30%, 50% were made by the air-pluviation method. For Kobe P.I. sand and Narashino alluvial sand, cylindrical specimens of 7.5cm in diameter and 15cm in height were also used in the tests, although the specimens of 5cm in diameter and 10cm in height were tested under 49.0kPa initial effective confining stress using Narashino alluvial sand samples. After the specimen was placed in the cell, carbon dioxide (CO_2) gas was percolated through it to ensure a desired degree of saturation.

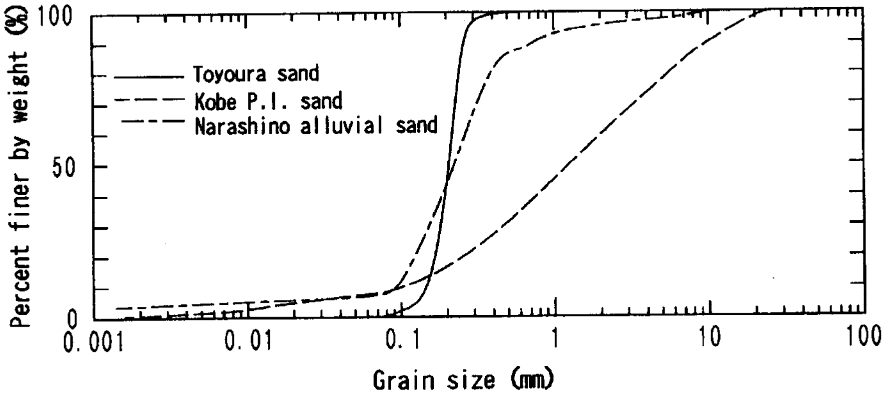

Fig.1. Grain size distribution curves of Toyoura sand, Kobe P.I. sand and Narashino alluvial sand

Deaired water was circulated and a back pressure of 198 kPa was applied to achieve a B-value in excess of 0.95. The specimen was then isotropically consolidated under pressures of 19.8, 49.0, and 98.0 kPa which are equal to the initial effective confining stresses, σ_0'. Then, a stress history of overconsolidation was applied to the specimen as follows, (1) confining pressure was isotropically applied to the specimen until the overconsolidation ratio, (O.C.R.), reached 2 or 4, (2) after finishing the consolidation, the pressure was isotropically decreased to the value of the initial effective confining stress. In the tests on effects of repeated overconsolidation, the confining pressure was applied again to the specimen with a relative density of 0% after the unloading. The number of cycles for repeated overconsolidation was 4 and 10 under (O.C.R.)=4. Following the overconsolidation, cyclic undrained triaxial tests were carried out at a frequency of 0.1 Hz for all series of tests while keeping the confining pressure constant.

TEST RESULTS

The results of the cyclic undrained triaxial tests on the reconstituted specimens made of Toyoura sand are listed in Table 1. On the basis of the test results shown in Table 1, relationships between cyclic stress ratio, $\sigma_d/2\sigma_0'$, and number of cycles required to cause double amplitude axial strain, DA, of 5% are drawn as shown in Fig.2, when the relative density, Dr, was about 0% and the initial effective confining stress, σ_0', was 49.0 kPa. It can be seen in Fig.2 that the liquefaction strength increased as the overconsolidation ratio, (O.C.R.), increased. Similar plots were also made using other series of test results. Table 1 also shows liquefaction strength ratios in 20 cycles, $R\ell_{20}$, obtained from average lines on the basis of the plots. The liquefaction strength ratio was plotted versus the average relative density in each series of the tests. Fig.3 indicates typical plots of the results of the tests under σ_0'=49.0 kPa. Similar plots were also made using the data for σ_0'=19.8, 98.0 kPa. It is clear from the data shown in Fig.3 that the liquefaction strength was great as the overconsolidation ratio was large.

To investigate the effects of overconsolidation on the liquefaction strength, the ratio of increase in liquefaction strength due to overconsolidation, R_{oc}, was defined as follows,

$$R_{oc}=\frac{\text{Liquefaction strength ratio in 20 cycles, } R\ell_{20}\text{, of overconsolidated specimen}}{\text{Liquefaction strength ratio in 20 cycles, } R\ell_{20}\text{ ,of normally overconsolidated specimen}}$$

The liquefaction strength ratio for relative densities, Dr, of 0%, 30%, and 50%, which was read off from the average line shown in Fig.3, was substituted into Eq.(1). Fig.4 shows the relationships between the ratio of increase in liquefaction strength, R_{oc}, and the overconsolidation ratio, (O.C.R.), for Dr=0%, 30%, and 50%, respectively. It may be seen in Fig.4 that the ratio of increase in liquefaction strength, R_{oc}, is expressed by $(\text{O.C.R.})^n$. For the data on specimens with Dr=50%, the power n is equal to 0.25. This trend coincides with the test results of Tatsuoka *et al.* (1988) where Toyoura sand was used. However, when the relative density, Dr, was reduced to 30% and the initial effective confining stress, σ_0', was raised to 98 kPa, the power n increased to 0.35. When Dr was 0% and σ_0' was 49.0, 98.0 kPa, the power n was 0.4 and 0.45, respectively. Therefore, it can be seen that the power n increased as the relative density decreased or the initial effective confining stress increased and was equal to 0.25 to 0.45. The ratio of increase in liquefaction strength, R_{oc}, for (O.C.R.)=4 was plotted versus the relative density in Fig.5. It can clearly be seen that the ratio of increase, R_{oc}, firmly depended on the values of relative density and initial effective confining stress.

The liquefaction strength of overconsolidated sand specimens varied from 1.4 to 1.8 times as large as that of normally consolidated sand specimens when the overconsolidation ratio, (O.C.R.), was 4. It was observed that the increase in relative density due to overconsolidation, which may depend on the test conditions, was at most 3%. Therefore, the increase in liquefaction strength due to an increase in relative density is not supposed to be large, as shown in Fig.3. It may be noted that the liquefaction strength increase due to overconsolidation was induced principally by a slight change in the arrangement of sand particles in the specimen, due to a small contraction of the volume. Fig.6 indicates the relationships between the ratio of increase in liquefaction strength, R_{oc}, and the volumetric strain, $\Delta V_{oc}/V_c$, due to overconsolidation, for Dr=0%, 30%, 50%, respectively. ΔV_{oc} and V_c, denote the amount of volume change due to overconsolidation and the volume of the specimen during cyclic loading. In Fig.6, the ratio, R_{oc}, linearly increased as the volumetric strain, $\Delta V_{oc}/V_c$, increased. The incline of the straight line was great when the relative density was large. It may be noted that a slight contraction of the specimen made the arrangement of the particles more stable as the density was large.

Table 1. Test results

(O.C.R.)	Dr(%)	R	N_ℓ	$R_{\ell 20}$
σ_0'=19.8 (kPa)				
1	-3.2	0.153	3.1	0.106
	0.4	0.103	37	
	5.3	0.105	80	
2	-6.3	0.173	3.1	0.123
	4.2	0.123	18	
	5.4	0.115	23	
4	0.4	0.163	14	0.151
	1.6	0.126	47	
	4.3	0.113	48	
1	35.4	0.188	1.7	0.137
	40.0	0.182	2.7	
	40.9	0.190	2.7	
	34.8	0.135	17	
	36.0	0.115	330	
2	28.3	0.261	1.7	0.158
	36.0	0.162	18	
	27.8	0.121	148	
4	25.7	0.289	1.6	0.184
	35.7	0.227	4.7	
	27.1	0.186	23	
	28.1	0.133	143	
1	43.2	0.233	2.5	0.160
	49.9	0.153	27	
	46.6	0.129	152	
2	49.2	0.246	7.2	0.200
	49.1	0.229	8.2	
	53.2	0.205	20	
	51.9	0.137	128	
	54.2	0.182	196	
4	50.4	0.287	6.8	0.236
	49.6	0.248	19	
	49.8	0.200	64	
σ_0'=49.0 (kPa)				
1	-5.0	0.071	39	0.077
	6.6	0.077	18	
	5.4	0.079	55	
2	2.8	0.123	4.6	0.106
	-2.2	0.135	5.6	
	-2.2	0.095	32	
	8.0	0.101	53	
4	-1.1	0.163	2.7	0.133
	-0.6	0.138	8.7	
	1.4	0.146	10	
	2.0	0.131	25	
1	36.6	0.139	2.0	0.102
	28.3	0.100	18	
	33.5	0.097	42	
	35.4	0.092	68	
σ_0'=49.0 (kPa)				
2	36.0	0.106	24	0.125
	34.6	0.097	40	
	38.0	0.128	47	
	39.2	0.121	58	
4	35.0	0.166	3.1	0.149
	35.3	0.159	7.2	
	35.4	0.155	32	
	31.0	0.115	129	
1	45.9	0.135	5.6	0.118
	44.6	0.123	22	
	45.6	0.122	31	
	48.1	0.117	32	
	45.1	0.094	313	
2	46.7	0.168	10	0.147
	46.8	0.164	12	
	44.3	0.124	71	
	46.5	0.143	112	
4	56.0	0.224	10	0.189
	58.2	0.199	11	
	52.8	0.177	24	
	53.5	0.160	207	
σ_0'=98.0 (kPa)				
1	2.9	0.090	6.7	0.074
	4.5	0.077	4.5	
	-0.2	0.063	62	
2	3.2	0.135	5.7	0.100
	0.5	0.102	20	
	3.5	0.088		
4	4.4	0.145	11	0.132
	-1.9	0.139	12	
	1.5	0.122	36	
1	28.7	0.108	5.6	0.089
	28.9	0.093	13	
	29.2	0.086	27	
4	35.1	0.157	15	0.149
	35.2	0.129	65	
	33.2	0.133	81	
1	47.6	0.138	5.7	0.122
	47.9	0.123	18	
	48.3	0.114	63	
4	50.0	0.224	9.6	0.202
	48.5	0.198	17	
	48.7	0.171	41	
	49.3	0.161	58	

NOTE

σ_0': Initial effective confining stress

(O.C.R.): Overconsolidation ratio

Dr: Relative density

R: Cyclic stress ratio

N_ℓ: Number of cycles to double amplitude axial strain of 5%

$R_{\ell 20}$: Liquefaction strength ratio in 20 cycles

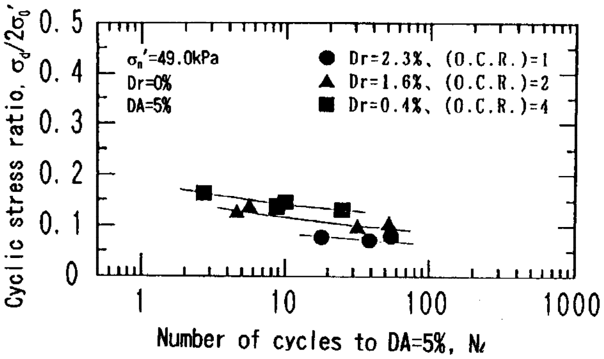

Fig.2. Cyclic stress ratio versus number of cycles required to cause double amplitude axial strain of 5%

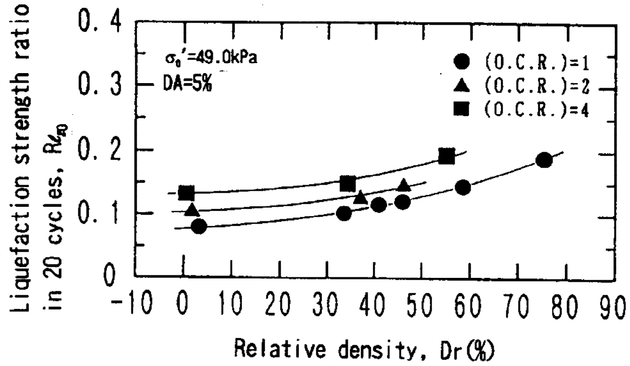

Fig.3. Relationships between liquefaction strength ratio in 20 cycles and relative density

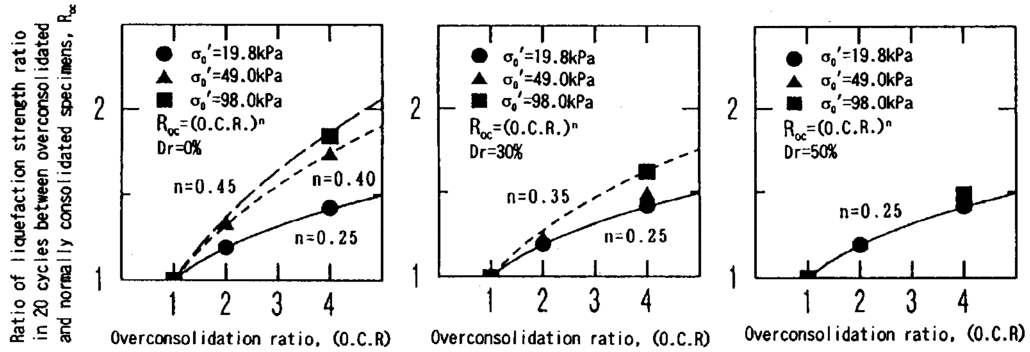

Fig.4. Liquefaction strength increase due to overconsolidation for (a) Dr=0%, (b) Dr=30% and (c) Dr=50%

The relationships between the cyclic stress ratio, $\sigma_d/2\sigma_0'$, and the number of cycles required to cause double amplitude axial strain, DA, of 5% are shown in Fig.7, using the results of the tests on the repeated overconsolidated sand specimens with a relative density of 0%. The tests were performed under initial effective confining stresses, σ_0'=19.8, 49.0 kPa. It can be seen in Fig.7 that the cyclic stress ratio increased a the number of cycles for repeated overconsolidation, N_{oc}, increased. The ratio of increase in liquefaction strength, R_{oc}, obtained from the data shown in Fig.7 were plotted versus the number of cycles for repeated overconsolidation, N_{oc}, in Fig.8. The ratio of increase, R_{oc}, increased as the value of N_{oc} increased. This tendency seemed to be marked when the initial effective confining stress, σ_0', was large. However, the ratio of increase, R_{oc}, did not increase remarkably after the 4th cycle.

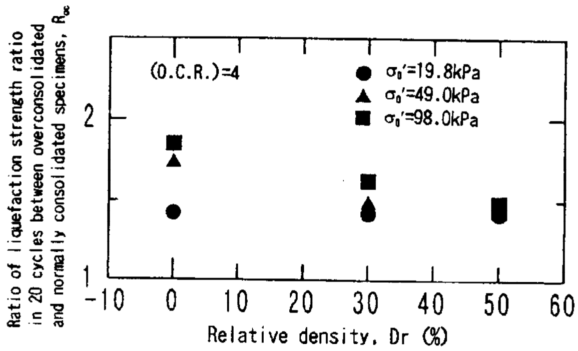

Fig.5. Ratio of increase in liquefaction strength versus relative density

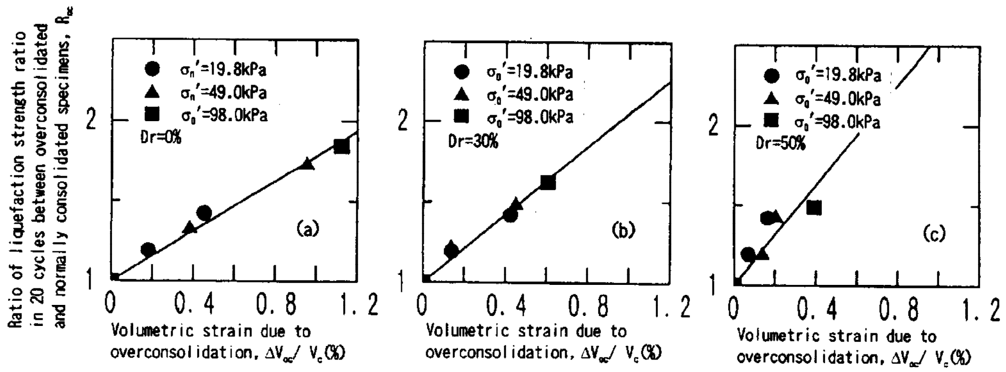

Fig.6. Ratio of increase in liquefaction strength versus volumetric strain due to overconsolidation for (a) Dr=0%, (b) Dr=30% and (c) Dr=50%

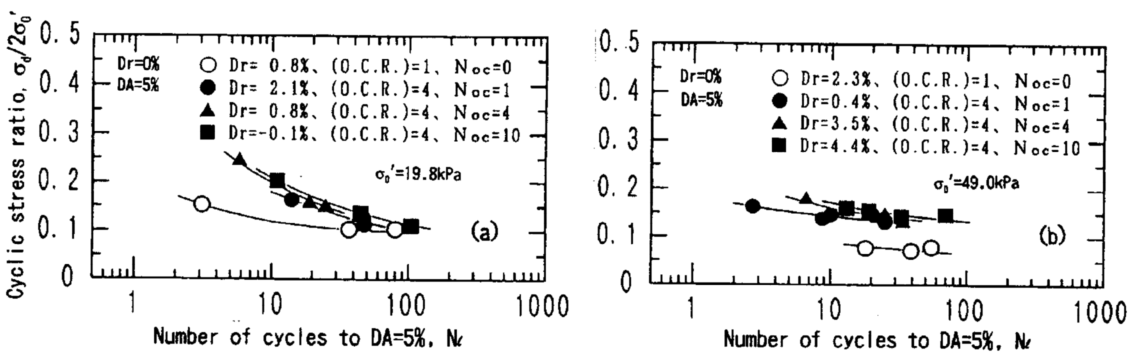

Fig.7. Cyclic stress ratio versus number of cycles required to cause double amplitude axial strain of 5% for (a) σ_0'=19.8kPa and (b) σ_0'=49.0kPa

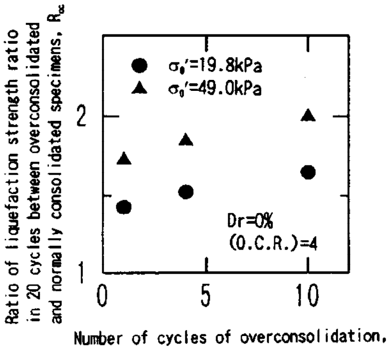

Fig.8. Increase in liquefaction strength due to repeated overconsolidation

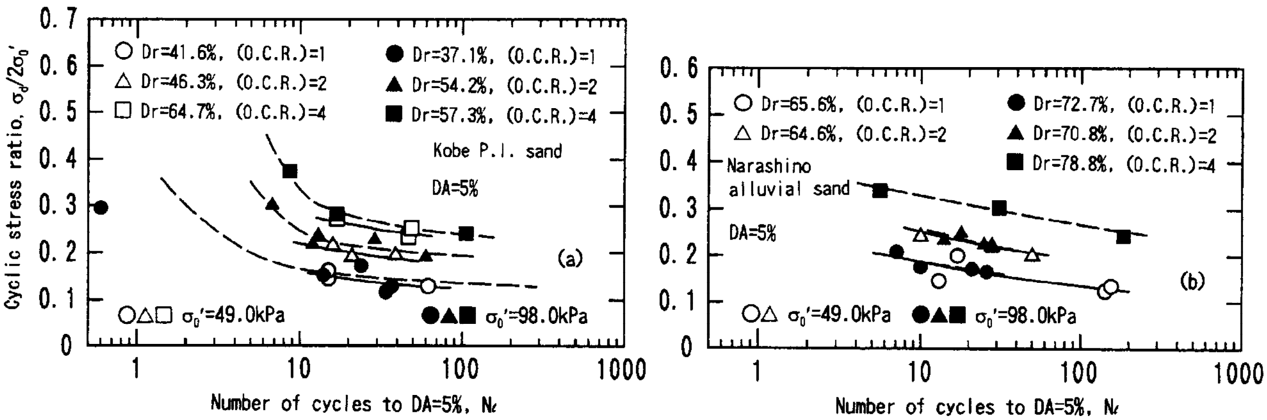

Fig.9. Cyclic stress ratio versus number of cycles required to cause double amplitude axial strain of 5% for (a) Kobe P.I. sand and (b) Narashino alluvial sand

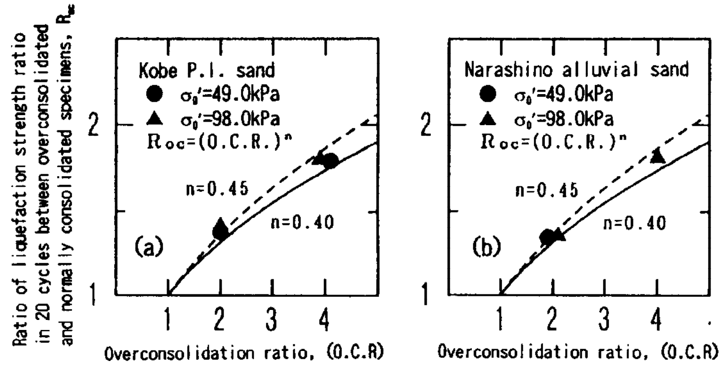

Fig.10. Liquefaction strength increase due to overconsolidation for (a) Kobe P.I. sand and (b) Narashino alluvial sand

For the results of the tests on two undisturbed sand specimens, the cyclic stress ratio, $\sigma_d/2\sigma_0'$, was plotted versus the number of cycles to DA=5% as shown in Fig.9. In the tests using undisturbed samples, the liquefaction strength also increased due to overconsolidation. On the basis of the data shown in Fig.9, relationships between the ratio of increase in liquefaction strength, R_{oc}, and the overconsolidation ratio, (O.C.R.), are shown in Fig.10. In the test results on two undisturbed sand specimens, the ratio of increase, R_{oc}, was also expressed by $(O.C.R.)^n$, scarcely depending on the initial effective confining stress, σ_0', and the power n was 0.40 to 0.45, which was equal to the value obtained by the tests on the reconstituted sand samples with a relative density of 0% and subjected to σ_0'=49.0, 98.0 kPa. In the tests on the undisturbed samples, the effects of an increase in relative density due to overconsolidation on the liquefaction strength was not clear because the density of the samples differed. However, the relative density increased by no more than 5%. Therefore, it may be noted that the main reason for an increase in liquefaction strength accompanying overconsolidation is a slight change in the arrangement of sand particles in the specimen and the formation of a more stable structure of the particles. Fig.11 shows the relationships between the ratio of increase in liquefaction strength, R_{oc}, and the volumetric strain, $\Delta V_{oc}/V_c$, due to overconsolidation, for the undisturbed sand specimens. The ratio of increase, R_{oc}, also linearly increased as the volumetric strain, $\Delta V_{oc}/V_c$, increased, while the incline seemed to be smaller for the undisturbed samples than for the reconstituted samples. It seems that the amount of the volumetric strain due to overconsolidation was larger for the undisturbed samples than for the reconstituted samples. It is supposed that the behavior of the volumetric strain was affected by fine contents and gravel fractions in the undisturbed samples.

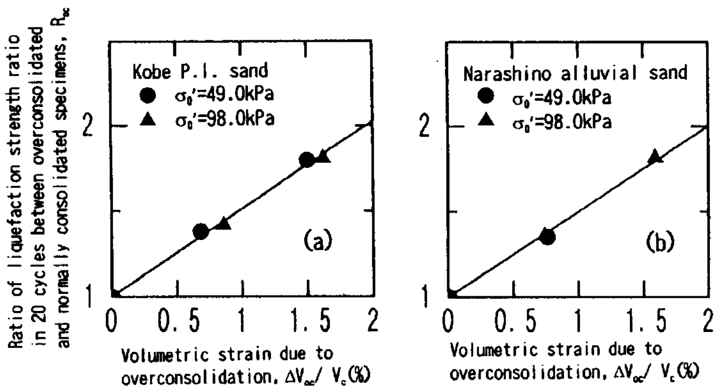

Fig.11. Ratio of increase in liquefaction strength versus volumetric strain due to overconsolidation for (a) Kobe P.I. sand and (b) Narashino alluvial sand

CONCLUSIONS

Several series of cyclic undrained triaxial tests were performed on reconstituted sand specimens of Toyoura sand in order to study the effects of density, confining stress and repeated overconsolidation on the liquefaction strength. Furthermore, similar tests were conducted on two undisturbed sand specimens with some fines and gravel fractions. From these test results, the following liquefaction strength characteristics were observed.

(1) The liquefaction strength increased as the overconsolidation ratio, (O.C.R.), increased. The ratio of increase in liquefaction strength was expressed by $(\text{O.C.R.})^n$. The power n, which increased as the density of a specimen decreased and the effective confining stress increased, was 0.25 to 0.45 for the reconstituted sand specimens and 0.40 to 0.45 for the undisturbed sand specimens.

(2) The ratio of increase in liquefaction strength increased as the number of cycles for repeated overconsolidation increased, although the ratio of increase did not considerably increase after the 4th cycle.

(3) The liquefaction strength increase due to overconsolidation was not supposed to be principally induced by the increase in density of the specimen, but by a slight change in the arrangement of sand particles in the specimen.

(4) The ratio of increase in liquefaction strength linearly increased as the volumetric strain due to overconsolidation increased.

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