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EFFECTS OF THE VOLUMETRIC STRAIN DUE TO PRE-SHAKING ON LIQUEFACTION RESISTANCE

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Abstract

The resistance of sandy soil to liquefaction is influenced not only by relative density and particle gradation (e.g. fine content) but also by many factors including aging effects. Previous researches pointed out that sandy soils resting for several thousand years should have a greater resistance to liquefaction because of improved interlocking and cementation of neighboring sand grains associated with their extended time under a static pressure and being subjected to many earthquake shakings (i.e. pre-shearing). The interest of this study is pre-shearing effects on the liquefaction resistance. Some researchers have pointed out that pre-shearing effects on liquefaction resistance depends on the cyclic shear strain, numbers of cycles and the cyclic shear stress of the pre-shaking, but none of these factors can be used to assess the pre-shearing effect on liquefaction resistance. Besides those factors, it is considered that volume of contraction during and after pre-shearing might be an influential factor to rise the liquefaction resistance. This assumption is made because volumetric strain plays dominant role of controlling the liquefaction resistance when volumetric contraction can occur during cyclic shearing. Undrained cyclic shear of unsaturated sand, membrane penetration and system compliance effects and partial drainage during shaking may be the cases. In order to assess the effect of the volumetric strain due to pre-shearing on the liquefaction resistance series of cyclic triaxial testing with pre-shearing histories were conducted. The volumetric strain due to pre-shearing was measured and the liquefaction resistance ratio, that is the ratio of the liquefaction resistance of a sand with pre-shaking history to that without pre-shaking, was obtained. Test results show that liquefaction resistance ratio increases with increasing in the volumetric strain in a unique way regardless of the relative density, number of cycles and stress level of the pre-shaking. The relationship between liquefaction resistance ratio and the volumetric strain for the tests are compared with those for undrained cyclic tests on unsaturated sand and on saturated sand with membrane penetration effect. It is found that all those results agree quite well, which strongly suggest that the volumetric strain is the only parameter which plays the dominant role of controlling the enhancement of liquefaction resistance due to pre-shearing.

Keywords: Liquefaction, aging, volumetric strain, triaxial test

1. Introduction

It has been pointed out that sandy soils resting for several thousand years have a significantly greater resistance to liquefaction because of improved interlocking and cementation of neighboring sand grains developed after the deposition, associated with their extended time under static pressured and being subjected to many earthquake shakings [1,2], hereafter in this study, called pre-shearing. In this study, the aging effect considered is the improvement on the inter-locking between adjacent soil grains due to pre-shearing. Significant attempts have been made to better understand the effects of pre-shearing on the liquefaction resistance and found that the pre-shearing effect on liquefaction resistance depends on shear strain level [3, 4], number of cycles and cyclic stress ratio [5] of the pre-shearing, but none of those parameters can quantify the improvement of the liquefaction resistance due to pre-shaking. On the other hand, volumetric strain plays dominant role of controlling the enhancement of liquefaction resistance when volumetric contraction occurs during cyclic shearing and it was used to quantify the improvement on the liquefaction resistance. Undrained cyclic shearing of unsaturated sands [6], membrane penetration and system compliance effects in triaxial testing [7] and partial drainage during shaking [8] are the cases. Since dissipation of the excess pore pressure during or after pre-shearing both results in the volume contraction, it may have similar effect on the liquefaction resistance. This study aims at investigating the pre-shearing effects on liquefaction resistance, assuming the volumetric strain during pre-shearing as controlling factor to enhance the liquefaction resistance. A series of cyclic triaxial tests were conducted in this study on clean sand samples with and without pre-shaking history and results are summarized together with tests in the literature to verify the assumption.

2. Triaxial Test

Goto and Towhata [5] conduted undrained cyclic triaxial tests on sand with pre-shaking history. They prepared medium dense and dense sand specimens (Dr = 59 ~ 91%), subjected to pre-shaking with a cyclic stress ratio (0.11 ~ 0.33) and number of cycles (1~10, 000) in the drained condition, and finally conducted the liquefaction test. In this study, similar tests were conducted on medium loose sand specimens (Dr = 38 ~ 45%).

2.1 Test procedures and conditions

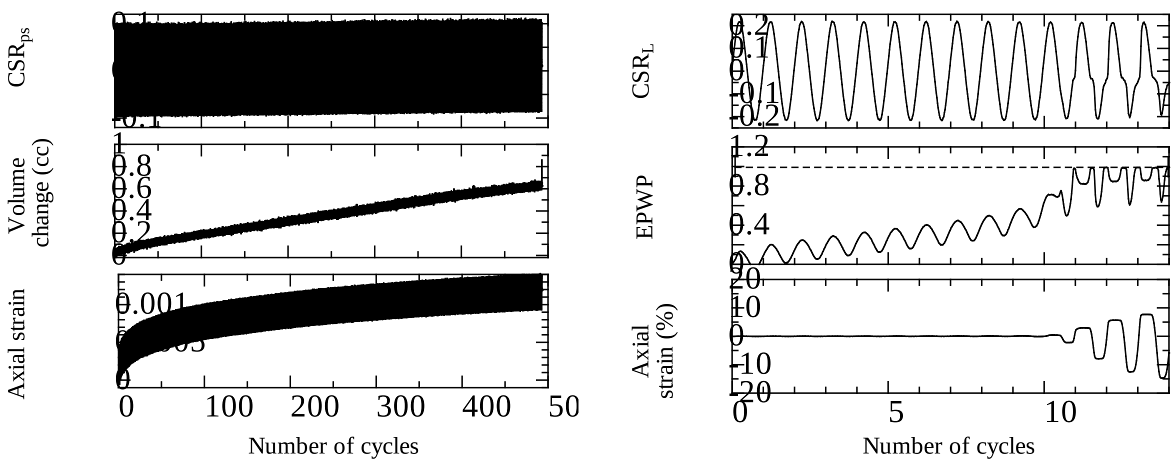
Toyoura Sand was used in the test of which specific gravity is 2.64 and the minimum and maximum void ratios are e_{min} = 0.609 and e_{max} = 0.973, respectively. All the specimens were prepared by pluviating sand through air to a target relative density of Dr = 40 %. The specimen's dimensions were 50 mm in diameter and 100 mm in height. After saturation and confirming the *B* value higher than *0.96*, the specimens were subjected an isotropic effective confining pressure of 50 kPa. At pre-shearing, the specimens were subjected to a constant cyclic stress ratio, CSR_{PS}, of 0.05, 0.1, 0.15, 0.2, 0.25, 0.28 or 0.29 and a frequency of 0.01Hz in the drained condition. This frequency was slow enough to prevent any excess pore pressure to build up. The volume change in the samples during the pre-shearing was continued until the target volume change was achieved. Four target volumetric strain in the pre-shaking were set in this study, that is, ε_v=0 (without pre-shaking history), 0.9×10^{-4}, 2.6×10^{-3} and 7.6×10^{-3}.The target volumetric strain were set to cover the ranges tested in the previous researches [5,7]. After pre-shearing, undrained cyclic shear test was conducted.

Table 1 – Summary of test conditions and results

		Pre-shearing					**Liquefaction test**	
Test No.	**Dr (%)**	**Target vol. strain εv**	**Cyclic stress ratio, CSR_{PS}**	**No. cycles, N_{ps}**	**Measured vol. strain ε_v**	**Dr (%) after pre-shearing**	**Cyclic stress ratio, CSR_L**	**No. Cycles, N_L**
1	40		-	-	-	-	0.19	2
2	44	0	-	-	-	-	0.18	2
3	45		-	-	-	-	0.14	16
4	43		-	-	-	-	0.12	53
5	38		0.1	NR	0.0009	39	0.18	15
6	43	0.0009	0.1	318	0.0011	44	0.17	29
7	42		0.05	652	0.0008	42	0.16	36
39	45		0.15	11	0.001	46	0.19	8
40	45		0.15	11	0.00094	45	0.17	20
41	45		0.13	21	0.00085	46	0.18	12
42	40		0.14	22	0.00095	41	0.17	15
8	42		0.2	35	0.0031	43	0.22	11
9	43		0.25	8	0.003	44	0.21	12
10	43		0.15	375	0.0031	44	0.22	9
11	44	0.003	0.1	493	0.003	45	0.22	11

12	39		0.15	36	0.0024	40	0.18	39
33	41		0.28	2	0.00283	42	0.21	8
34	41		0.19	29	0.003	42	0.18	37
35	43		0.24	19	0.0031	44	0.18	91
36	42		0.24	15	0.00307	43	0.18	68
37	43		0.28	2	0.00288	44	0.18	22
14	41		0.15	10239	0.0078	45	0.23	26
15	42		0.2	990	0.0076	46	0.23	52
16	42		0.35	2	0.01	46	0.22	4
17	44		0.25	124	0.0079	48	0.23	72
22	44	0.0077	0.25	201	0.0074	48	0.27	26
24	42		0.25	149	0.0077	46	0.28	78
25	43		0.29	4	0.0075	48	0.21	15
26	41		0.28	69	0.0077	45	0.22	124
27	46		0.2	1045	0.00805	50	0.27	6
28	44		0.27	96	0.0076	48	0.22	126
29	45		0.29	3	0.00815	49	0.22	4
31	44		0.24	308	0.0077	47	0.27	18
32	42		0.28	86	0.00765	46	0.28	16
38	43		0.21	883	0.0077	47	0.23	60
43	41		0.2	989	0.00765	45	0.27	6

NR – not recorded



a) pre-shearing histories of cyclic stress ratio, volumetric strain and axial strain, respectively

b) Typical time histories during theundrained liquefaction test

Fig. 1 – Typical time histories from test with pre-shearing

2.2 Test results

Fig. 1a shows typical time histories obtained during pre-shearing for test no.11 (ε_v = 0.003). The volumetric strain increased with the number of cycles, with the increment ratio being slow down as the number of cycles increased. This indicates that the ability of the sand of generating excess pore pressure or volumetric strain decreases with the number of cycles. Typical time histories of the undrained liquefaction test are shown in Fig.

1b. Excess pore pressure ratio ($\Delta u/\sigma'_c$), EPWP, increased with the number of cycles and axial strain started to increase swiftly as soon as the excess pore pressure approached its maximum value. This response is typical of fully saturated loose sand.

Fig. 2 depicts the relationship between cyclic stress ratio of the liquefaction tests, CRS_L, and the number of the cycles to attain DA of 5% for all tests, with and without pre-shearing histories. CSR_L increased with an increase in ε_v. A slight volumetric strain of 7.6×10^{-3} almost doubled the CSR_L of the medium dense sand. It should be mentioned that the plots in the figure for the same target volumetric strain almost lies practically on the same line, although they were subjected to pre-shearing with different CSR_{PS} and N_{PS}.

The liquefaction strength curves in the figure are more or less parallel to each other. The same has been reported for the case of unsaturated sand [6] and test of sand with membrane penetration and system compliance effects [7].

Finn et al. [4] stated that the beneficial effect of pre-shaking on liquefaction resistance became less as shear strain amplitude during pre-shaking increased. It is presumed that a small shear strain amplitude of the pre-shearing improves soil grain contacts and enhances stability of soil skelton, resulting in higher liquefaction resistance, while a larger shear strain amplitude degrades, on the contrary, the stability of soil skelton. The threshold shear strain amplitude above which the beneficial effect ceases was approximately 0.5%. Shear strain amplitude at pre-shaking in this study was in a range between $2.5*10^{-5}$ and $5*10^{-3}$. On test 25 and 29 the shear strain amplitude was approximately 0.5% due to relatively higher CSR_{PS} imposed to the samples. On those tests, 25 and 29, the improvement on liquefaction resistance was smaller comparing with the others with the same target volumetric strain as shown on fig. 2.

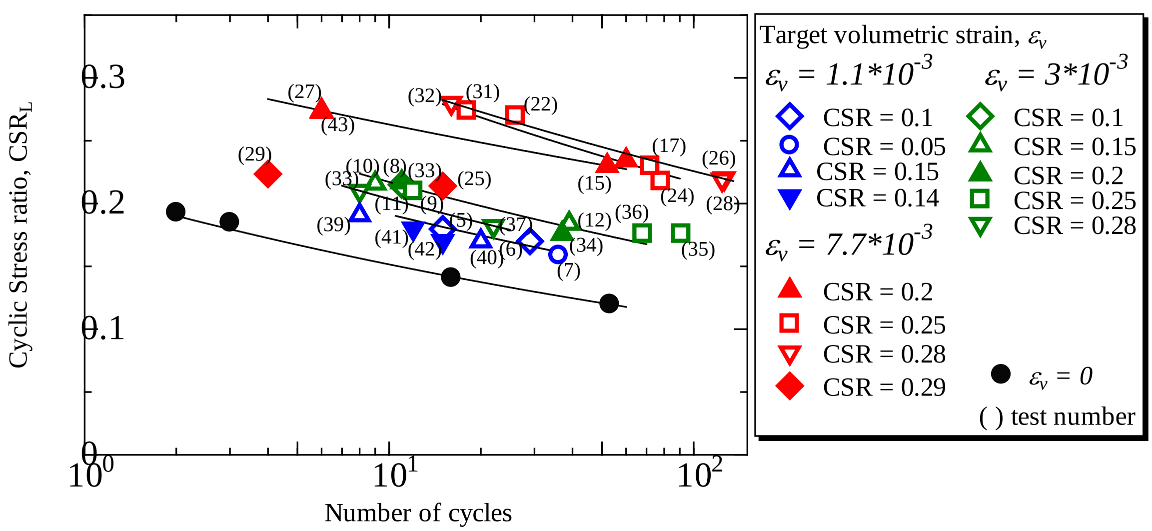


Fig. 2 – Relationship between cyclic stress ratio and number of cycles

3. Volumetric strain due to pre-shearing

The test results described above strongly suggests that the volumetric strain is the main parameters that rule the improvement on the liquefaction resistance due to pre-shaking. The liquefaction resistance increased with increasing volumetric strain regardless the number of cycles and the cyclic stress ratio as shown in Fig. 2. Increases in liquefaction resistance due to volumetric strain have also been observed in studies related to air bubble compressibility during shaking and membrane penetration and system compliance.

For the case of unsaturated soil, many researchers consistently reported that the liquefaction resistance increases with decreasing the degree of saturation. The underlying mechanism is that air bubbles absorb generated excess pore pressures by contracting its volume during cyclic shearing. Okamura and Soga [6] have carried out triaxial tests on unsaturated sandy soils extensively and found a unique relationship between liquefaction resistance ratios, *LRR*, which stands for the ratio of liquefaction resistance of a sand to that of a fully saturated sand, and the potential volumetric strain as shown in figure 3. They defined potential volumetric strain as the volumetric strain that will be attained when the excess pore pressure reaches its maximum value.

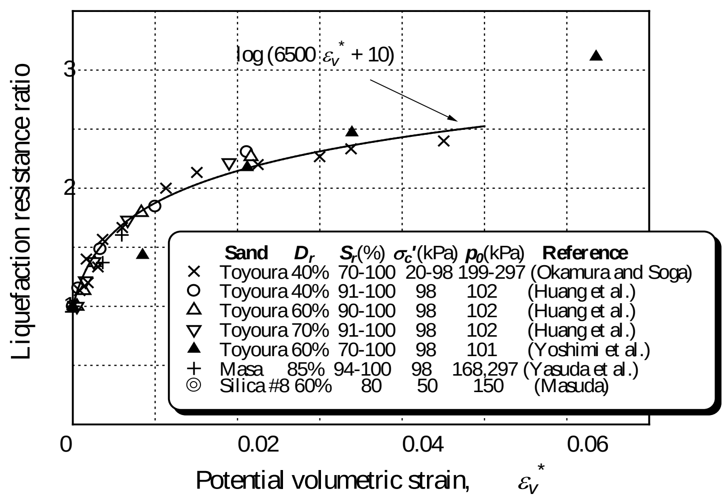


Fig. 3– Relationship between potential volumetric strain and liquefaction resistance ratio of partially saturated sand (after Okamura and Soga [6])

For the case of membrane penetration compliance, Tokimatsu and Nakamura [7] found that volume change due to membrane penetration increased the number of cycles to liquefy through series of triaxial testing on specimens with zero membrane compliance and non-zero membrane compliance.

In this study, the Liquefaction resistance ratio for pre-shearing case, LRR_p, which is the liquefaction resistance of sand to liquefy (DA=5%, N=20) normalized with respect to that without pre-shearing is calculate as follows:

$$LRR_p = CRR_{Np}/CRR_N \tag{1}$$

where, CRR_N and CRR_{Np} stand for cyclic resistance ratio for sand with and without pre-shearing histories, respectively. The LRR_p was plotted against volumetric strain due to pre-shearing together with Goto and Towhata's test results [5] in Fig. 4. The liquefaction resistance ratio increases with increasing volumetric strain uniquely regardless of the relative density, cyclic stress ratio and number of cyclic during pre-shearing. Additional data was provided by plotting together the empirical correlation obtain by Okamura and Soga [6] through series of undrained cyclic triaxial tests on unsaturated sands and the cyclic triaxial tests of Tokimatsu and Nakamura [7] to evaluate the membrane penetration effects on the liquefactions resistance ratio. Although the mechanism to cause small volumetric strain during shearing is different, it is of interest to compare the beneficial effects on liquefaction resistance of volumetric strain arisen in different causes. It is not unexpected that all the data in the figure agrees quite well. It is confirmed that small cyclic shearing induced volumetric strain and microscopic fabric rearrangement enhances liquefaction resistance of sand. The volumetric strain is the dominant factor which controls the liquefaction resistance ratio, *LRR*.

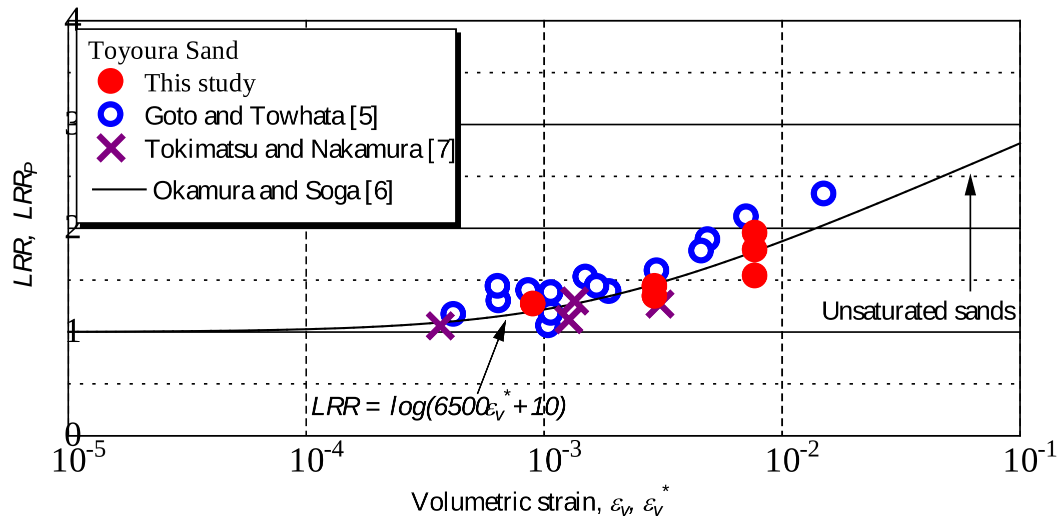


Fig. 4 – Relationship between rates of increase in *LRR* and volumetric strain: comparison of pre-shaking effects with unsaturated and membrane penetration effects

4. Conclusion

The effect of the pre-shearing on the liquefaction resistance was investigated through series of cyclic triaxial testing. The volumetric strain due to pre-sharing was assumed as the controlling factor to enhance the liquefaction resistance because it plays the dominant role of controlling the liquefaction resistance when volumetric contraction can occur.

The test results indicate that the liquefaction resistance increases with increasing the volumetric strain as expected. Volumetric strain is the only parameter dominating the beneficial effect of pre-shaking on the liquefaction resistance, with the effects of other parameters including relative density, cyclic stress ratio and number of cycles in pre-shaking being miner.

The liquefaction resistance ratio obtained in this study were compared with those from Okamura and Soga [6] on unsaturated sand and Tokimatsu and Nakamura [7] on the membrane penetration effect. The results shows that the data agrees quite well, suggesting that the volumetric strain plays the dominant role controlling the liquefaction resistance ratio.

5. Acknowledgements

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