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Liquefaction Resistance versus S-wave Velocity for Intact and Reconstituted Sands by Bender Element Triaxial Tests

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ABSTRACT

A series of experimental study by means of bender element tests and subsequent undrained cyclic loading liquefaction tests in the same triaxial test specimens were carried out. Test results on reconstituted sands indicated that the cyclic resistance ratio (R_L) is not uniquely but differently correlated with shear-wave velocity (V_s) for different soils. Accelerated tests by mixing a small amount of cement to simulate the geological aging effect on liquefaction resistance in a short time demonstrated that V_s, though not being a sensitive indicator, can serve as a convenient parameter to roughly evaluate R_L for an individual soil. It was also found that not only the geological age but also the fines content are the keys of the aging effect on R_L, which was also demonstrated by a series of tests using intact samples recovered from several sites.

Introduction

In the current practice of liquefaction potential evaluation, the more fines content Fc is, the higher the liquefaction resistance RL becomes under the same penetration resistance qt. However, Kokusho et al. (2012) showed by lab tests on reconstituted samples that the RL~qt curve is uniquely determined despite the difference in Fc. The same authors further indicated by accelerated lab tests mixing the tested sand with a small amount of cement that a cementation effect simulating an aging effect in a short period changes the RL~qt curve in the same manner as that employed in the current practice. Thus, the aging effect may be a key factor in evaluating liquefaction potentials in in situ soils by SPT or CPT. These penetration tests are destructive tests which tend to destroy delicate soil fabrics induced by aging. In contrast, shear-wave velocity Vs readily measured in a non-destructive test may potentially serve as an indicator detecting a subtle difference in soil fabrics to evaluate in situ liquefaction resistance RL reflecting the aging effect.

In this research, bender-element triaxial tests are carried out to investigate the RL~Vs relationship for reconstituted sands with variable relative densities containing various amounts of fines. Then, accelerated tests adding a small amount of cement to fines-containing sands are conducted to examine the cementation effect on the RL~Vs relationship. Finally the intact samples recovered from in situ sandy deposits at several places are tested and compared with reconstituted soils from the same samples to examine the aging effect on the liquefaction resistance of in situ soils.

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Test Method and Results for Reconstituted Sands with Various D_r & F_c

A specimen size of the bender element triaxial test is 50mm in diameter and 100mm in height. All the samples were prepared by the dry tamping method to target prescribed relative densities D_r. Then, the sample was saturated with de-aired water. The pore-pressure coefficients B were higher than 0.95. After isotropically consolidated by effective stress σ_c'=98kPa and with back pressure of 196 kPa, the bender element (BE) test and liquefaction test was carried out sequentially in the same specimen. In the BE test using S-wave travelling from the bottom to the top of the specimen, the S-wave velocity V_s was calculated by $V_s = H'/\Delta t$ where H' = BE tip to tip distance (the height of specimen minus 14mm) and Δt = the S-wave travelling time. In the liquefaction test, the specimen was loaded cyclically in undrained condition with frequency 0.05Hz, and the cyclic resistance ratio R_{L10} for double amplitude strain ε_{DA}=5% and the number of cycles N_c=10 was determined from a series of tests.

Two kinds of reconstituted sands were tested; Futtsu and Urayasu sand, with various D_r or F_c. The mean grain sizes are D_{50}=0.197 mm and 0.176 mm, and their uniformity coefficients are C_u=2.0 and 2.2, respectively. The fines mixed in the two sands are distinctively different; the fines in the Futtsu sand was originally sieved out from decomposed granite soil, 25% clay content of total fines and low plasticity index (I_p=6), while that in the Urayasu sand was originally contained in the same soil, 10% clay content and non-plastic.

Figure 1 (a) shows a cyclic stress ratio R_L versus N_c chart for reconstituted Futtsu and Ura- yasu sands on the semi-log scale for ε_{DA} =5%. The plots are approximated by the formula $R_L = aN_c{}^{-b}$ with positive constants a and b as illustrated with a set of curves in the diagram. It is obviously seen that R_L tends to increase with increasing D_r and decrease with increasing F_c for the same D_r. From the chart, the cyclic resistance ratio (CRR) R_{L10} corresponding to N_c =10 is read off to use in the following discussions.

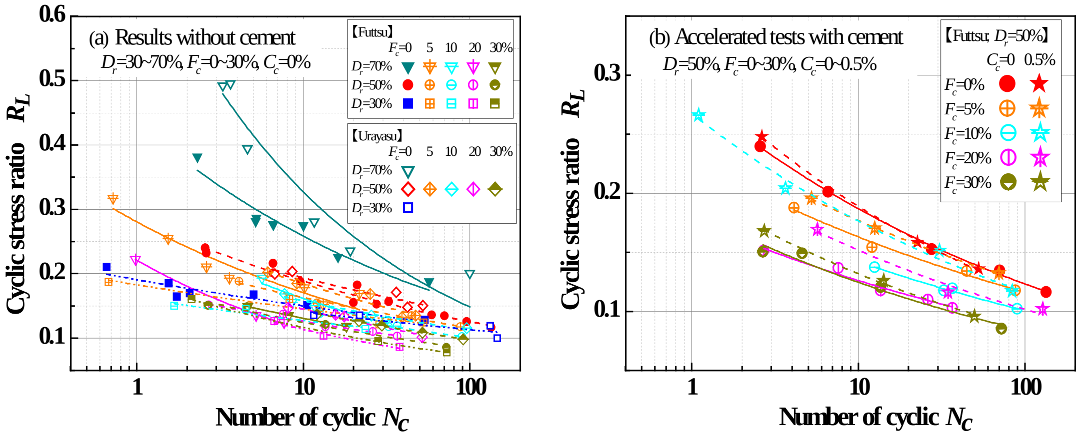

Figure 1: Cyclic stress ratio R_L versus number of cyclic N_c for reconstituted sands: (a) normal tests with various D_r and F_c, (b) accelerated tests with cement content C_c=0~0.5%.

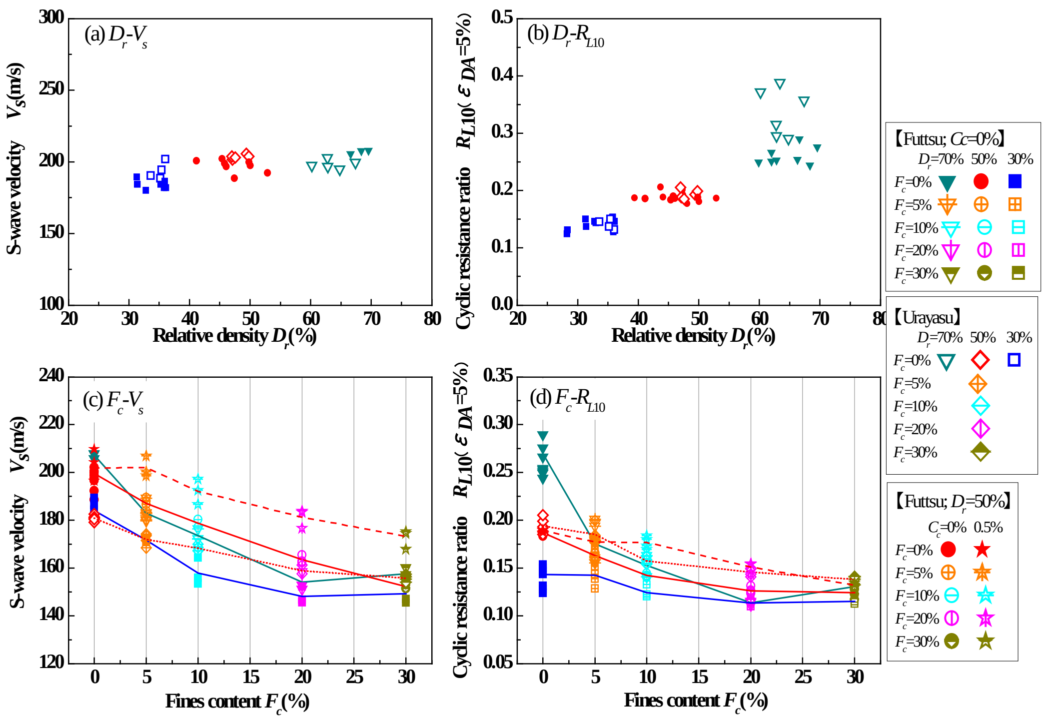

Figure 2: V_s or R_{L10} versus D_r plots (a), (b), and V_s or R_{L10} versus F_c plots (c), (d) for reconstituted soils with various relative densities D_r and fines contents F_c.

Figures 2 (a), (b) show V_s versus D_r and R_{L10} versus D_r relationships, respectively, for the two kinds of reconstituted clean sands of F_c=0. Both V_s and R_{L10} tend to increase with increasing D_r in a slightly different manner depending on the sands. Note that V_s is far more insensitive to the change in D_r than R_{L10} (the change D_r =30% to 70% increases V_s only by 15% in contrast to R_{L10} by 150%, all very roughly). In Figures 2 (c), (d), circle plots connected with solid lines show V_s versus F_c and R_{L10} versus F_c relationships for Futtsu sand without adding cement (cement contente C_c=0). Under the same D_r, both V_s and R_{L10} tend to decrease monotonically as F_c increases, and their decrements become prominent with increasing D_r for R_{L10} in particular. This trend in R_{L10} is compatible with what has been found in previous similar test results (e.g. Kokusho 2007). Urayasu sand shown in Figures 2 (c), (d) with rhomboid symbols connected by dotted lines exhibits a similar but more moderate F_c-dependent changes. For the two sands, V_s and R_{L10} tend to arrive at some minimum or stable values around F_c over 20% corresponding presumably to the critical fines content CF_c (Kokusho 2007).

Figure 3 shows direct relationships between R_{L10} and V_s for the two reconstituted sands with various D_r and F_c. Two thin solid curves in the chart represent previous research results by Kayan et al. (1992) and Andrus & Stokoe (2000), which are based on liquefaction case histories combined with in situ V_s-measurements. Note that CRR for their original curves was determined as τ_{av}/σ'_v, where τ_{av}=uniform cyclic shear stress with its amplitude and number of cycles equivalent to M_w7.5 earthquakes and σ'_v=effective overburden stress. Considering the earth pressure coefficient K_0=0.5 used in the previous research, the CRR for the two dashed curves have been multiplied by $3/(1+2K_0)=3/2$ to compare with R_{L10} in the present triaxial test results under the isotropic stress condition. The present lab test results show a fair agreement not only qualitatively but quantitatively as well with the field-based curves despite some differences in defining CRR. It should also be pointed out that the two sands used in the lab tests for F_c=0 tend to show different trends (thick solid and dotted curves, respectively), implying that the R_L~V_s relationship may not be uniquely applicable to any sand in general but only to a particular sand individually. In the same context, it is also seen that if the fines is added to the same sand, the R_L~V_s curve tends to slightly shift leftward as indicated by the plots in Figure 3 particularly for the Futtsu sand with fines of some plasticity. This trend is not so clear in the same diagram for the Urayasu sand with non-plastic fines.

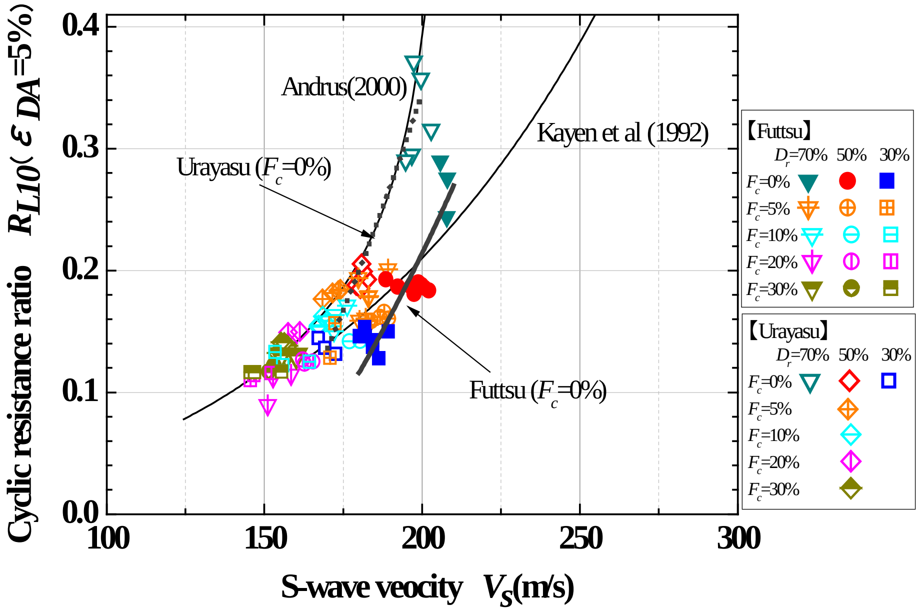

Figure 3. V_s versus R_{L10} plots for reconstituted specimens of Futtsu and Urayasu sands with various D_r and F_c compared with previously proposed curves based on case histories.

Test Method and Results on Accelerated Tests with a Small Amount of Cement

In order to simulate the cementation effect in a short-term lab test, a series of accelerated triaxial tests were carried out by adding a small amount of Portland cement to the Futtsu sand of D_r≒50% with various fines content. The test method was exactly the same as in the normal test without cement mentioned above, except that the tested dry sand was uniformly mixed in advance to have a cement content C_c=0.5% of the total dry weight. After dry-tamped to a target D_r, the specimen was saturated and isotropically consolidated with σ'_c=98 kPa for exactly 24 hours after wetting to have an identical curing/cementation time before testing.

Figure 1 (b) shows the cyclic stress ratio R_L versus N_c chart on the semi-log scale for ε_{DA}=5%. For the same F_c values, R_L tends to increase with increasing cement content C_c, though the increment in R_L seems different for different F_c. In Figures 2 (c), (d), star symbols connected with dashed lines show relationships, V_s versus F_c and R_{L10} versus F_c, respectively, for sands mixed with 0.5% cement. Both V_s and R_{L10} tends to become larger to a certain extent than those for C_c=0. The increments by adding the same amount of cement become greater with increasing F_c, up to some F_c-value (presumably around the critical fines content CF_c) reflecting a strong effect of F_c on the cementation.

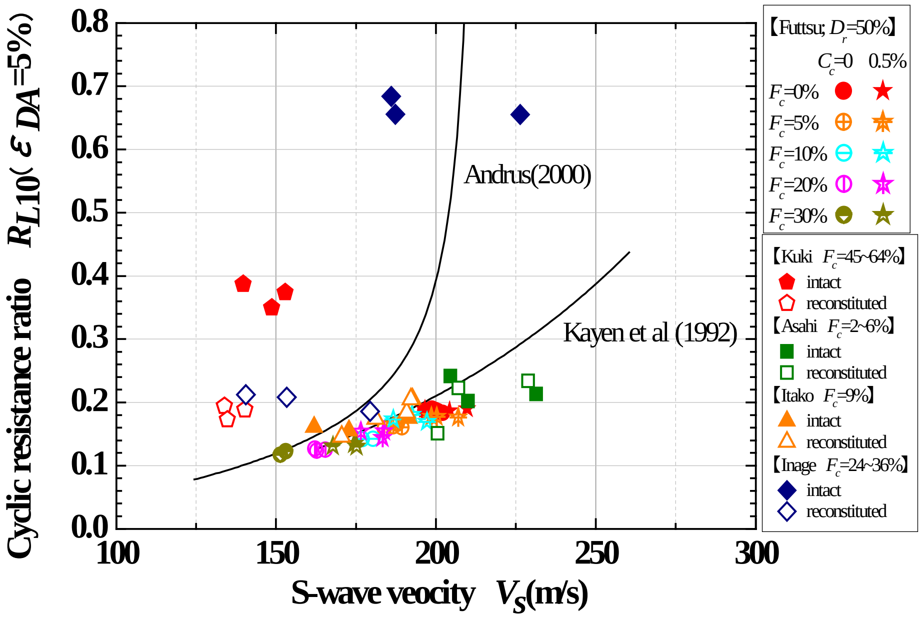

Figure 4: V_s versus R_{L10} plots for Futtsu sands (D_r=50%) mixed with a little cement superposed by similar plots for intact and reconstituted soils sampled from 4 sites.

In Figure 4, the R_{L10}-values are directly plotted versus V_s for the D_r=50% Futtsu sand of various F_c-values with C_c=0 (circle symbols) or C_c=0.5% (star symbols). It should be noted that, as the cement content C_c changes from 0 to 0.5%, the plots for larger F_c-values tend to shift in longer distance to right and upward. Also noted is that all the plots before and after the shift are located almost within a single unique narrow band. The gradient of the R_{L10} versus V_s band is much gentler than that in Figure 3 for the Futtsu sand, indicating that V_s may serve as a sensitive parameter detecting a small increment in liquefaction resistance of the same sand due to cementation. Hence, if the artificial cementation introduced by a small amount of cement can reproduce some pertinent aspect of the long-term geological aging effect, in situ V_s measurement may have a potential to roughly evaluate in situ liquefaction resistance reflecting the aging effect by cementation, though the R_L~V_s relationship is basically soil-specific as already indicated.

Test Methods and Results of Intact Soils Sampled In Situ

Intact samples taken from four different sites near Tokyo, Kuki, Asahi, Inage, and Itako, were tested and compared with the same soils reconstituted having similar densities. All the tests were conducted in the same way previously mentioned under the isotropic effective confining stress of σ_c'=98 kPa. Table 1 shows physical properties of the four intact soils. Kuki sand about 2000 years old was taken out by block sampling in a trench at a depth of about 6m. It contained the largest amount of fines (F_c=45~64%, I_p=7) among the four intact sands. Asahi sand of 4000~5000 years old sampled by a triple tube sampler from a depth of 6m had the smallest amount of fines of non-plasticity among the four sands. Inage sand with tens of thousands years old (Pleistocene age) containing a plenty of fines (F_c=32~36%) with I_p= 9 was sampled by Gel-Push (GP)-S Type Sampler by Kiso-Jiban Consultants Co. Ltd. Itako sand of 710~770 years old with F_c=9% was sampled by block sampling from natural Holocene deposits.

Table 1: Physical properties of intact samples recovered from 4 sites

		G.L. (m)	Age (yaer)	D_r (%)	F_c (%)	ρ_s (g/cm^3)	ρ_{dmax} (g/cm^3)	ρ_{dmin} (g/cm^3)	w_l (%)	w_p (%)	I_p (%)
Kuki	No1	-6.12	2000	76	64.0	2.605	1.118	0.842	48	41	7
	No2			58	45.0	2.573	1.082	0.803			
	No3			52	63.0	2.614	1.188	0.880			
Asahi	No1	-6.00	4000 ~5000	67	3.6	2.656	1.585	1.236	25	NP	-
	No2			77	2.2	2.659	1.643	1.321			
	No3			57	5.8	2.644	1.645	1.302			
Inage	No1	-6.31	tens of thousands	28	32.0	2.640	1.557	1.192	30	20	9
	No2	-6.19		46	23.8	2.625	1.711	1.303			
	No3	-6.43		42	36.2	2.659	1.564	1.189			
Itako	No1	-2.25	700	47	9.3	2.684	1.542	1.218	33	29	4
	No2			50		2.662	1.473	1.136			
	No3			75		2.658	1.433	1.099			
	No4			54		2.697	1.512	1.175			

Figures 5 (a), (b) show D_r versus V_s plots and D_r versus R_{L10} (ε_{DA} =5%) plots, respectively, with symbols associated with the four sites for intact samples and also for samples reconstituted from the same soils subsequently. Though the D_r-values in the reconstituted soils were not successfully controlled to be identical to the intact ones, it is remarkable that, in Kuki and Inage sands, R_{L10} and V_s are obviously higher for the intact specimens than for the reconstituted specimens in comparison to Asahi and Itako sands and their differences are particularly large in R_{L10} compared to V_s.

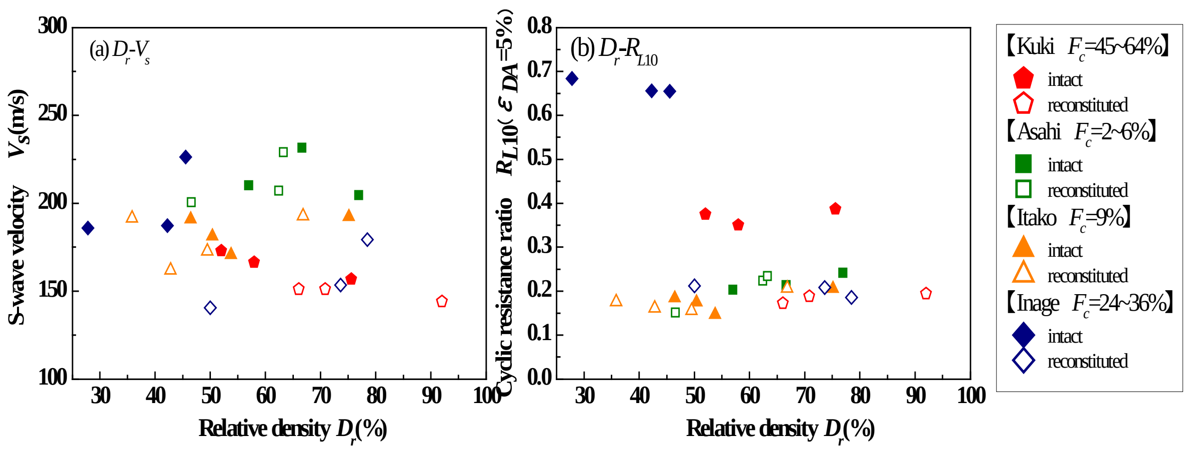

Figure 5: Cyclic stress ratio R_L versus number of cyclic N_c for intact and subsequently reconstituted soils sampled from 4 sites.

According to the accelerated test results by adding a small amount of cement as previously shown in Figures 2(c), (d), the cementation under the identical cement content C_c=0.5% tends to increase R_{L10} and V_s more significantly for sands containing fines than for clean sands. Hence, the larger values of R_{L10} and V_s in Kuki and Inage sands may presumably be attributed mainly to the higher F_c of non/low-plasticity fines (I_p=0~9) than in the Asahi and Itako sands between the two groups of sands. This further indicates that not only the geological age but also the fines content with a certain plasticity makes the difference in the liquefaction resistance R_L by the aging effect.

In Figure 4, the direct R_{L10} versus V_s plots for the intact (close symbols; see the legend for more details) and reconstituted (open symbols) specimens of the four sands recovered from in situ are superposed on the accelerated test results previously mentioned. Regarding relatively clean Asahi and Itako sands, the plots of both intact and reconstituted are located close to one of the previously proposed curves. Both V_s and R_{L10} of the two intact soils are not so much different from those reconstituted from the same soils, indicating minimal aging effects probably because F_c is low and geological age is relatively young. On the other hand, in Kuki and Inage sands, R_{L10} versus V_s plots are located quite differently, and the intact samples exhibit distinctively higher values than those of reconstituted from the same soils. This is presumably because these sands contain high fine contents of F_c=30~60% with plasticity of I_p =7~9, indicating a clear difference in manifestation of the aging effect due to differences in F_c and I_p.

Conclusions

1) Under the same relative density D_r, both S-wave velocity (V_s) and liquefaction resistance (R_{L10}) tend to decrease as fines content F_c increases up to 20%. The value of R_{L10} or V_s tends to converge to some values for F_c over 20% corresponding a critical fines content CF_c.
2) Though both R_{L10} and V_s increase with increasing D_r, R_{L10} tends to increase much more than V_s, indicating that V_s is not a sensitive parameter for liquefaction potential evaluation.
3) The R_{L10} versus V_s relationships for reconstituted specimens seem to be roughly compatible with previous research results based on liquefaction case histories. However, the present lab test demonstrates that the V_s - R_{L10} relationship is sand-specific, not applicable to any sands in general but only to specific sands individually.
4) The accelerated tests indicate that the cementation induced by a small amount of cement tends to increase R_L and V_s for sands with higher F_c in particular, indicating not only the geological age but also the amount of fines play a key role for manifestation of the aging effect on liquefaction resistance.
5) The test results on intact samples from in situ showed that, for soils with small F_c, the aging effects is hard to appear despite the geological age of thousands years, indicating that not only the geological age but also the fines content with a certain plasticity makes a difference in the aging effect, as implied by the accelerated tests using a little cement.

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