Aging Effect on Liquefaction Resistance versus S-wave velocity by means of Laboratory Triaxial Tests with Bender Element

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ABSTRACT
Previous studies about liquefaction resistance have indicated that soil fabric in natural sand deposit is stabilized due to "aging effect": chemical reaction of minerals and various loading history, leading to an increase of in situ liquefaction resistance. It is thus significant to take aging effect into account in evaluating liquefaction potential in engineering design. For that goal, shear-wave velocity is supposed to be promising to serve as a convenient in situ index. In this research, liquefaction resistance R_L versus shear-wave velocity V_s relationships of sand are investigated by a series of triaxial liquefaction tests and bender element tests on the same specimens.

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 by cementation 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 and chemical properties 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.

1 INTRODUCTION

Previous studies about liquefaction resistance have indicated that soil fabric in natural sand deposit is stabilized due to "aging effect": chemical reaction of minerals and various loading history, leading to an increase of in situ liquefaction resistance. Thus, it is significant to consider the aging effect in evaluating liquefaction resistance. On the other hand, the mechanism or influencing factors of the aging effect have not been made clear yet. Further, it is difficult to evaluate the aging effect in triaxial tests on specimens reconstituted in the laboratory.

In situ tests such as Standard Penetration Tests (SPT) or Cone Penetration Tests (CPT) may not fully evaluate the aging effect because they belong to a sort of destructive tests difficult to detect subtle soil fabric as it is. On the other hand, non-destructive tests such as elastic wave velocity measurements may be able to discern the in situ soil fabric and detect the aging effect (e.g. Andrus and Stokoe 2000).

In this research, shear-wave velocity versus liquefaction resistance relationships of various sands are investigated by conducting cyclic triaxial tests together with bender element tests to develop R_L versus V_s relationships focusing on the aging effect. In this paper, R_L is defined as cyclic stress ratio $\sigma_d/2\sigma'_c$ for double amplitude strain ε_{DA}=5%, and V_s is defined as a velocity at which shear-wave travels from bottom to top of a specimen.

Not only reconstituted but intact soils from in situ were tested to know the applicability of the V_s measurement to assess the in situ liquefaction potential of aged soils with various fines contents and plasticities.

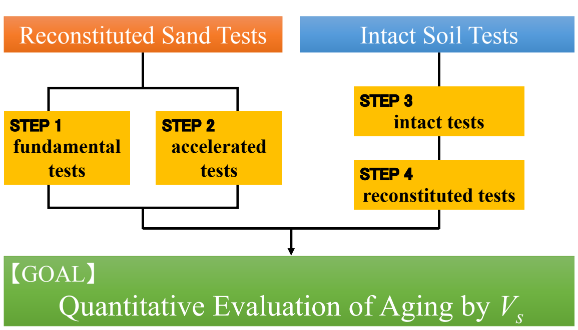


Figure 1. Research flow

2 TRIAXIAL TEST METHOD AND CONDITION

Figure 1 shows a research flow, wherein R_L versus V_s relationships focusing on the aging effect are investigated in two series of tests, "Reconstituted Sand Tests" and "Intact Soil Tests". In the former, reconstituted specimens with various relative density D_r or fines content F_c (STEP 1) and farther adding a small amount of cement (STEP 2) were tested. In the latter (STEP 3 and STEP 4), intact specimens sampled from several sites and specimens reconstituted from them were tested by the same method, and the two results were compared.

For all the tests, the specimen size was 50 mm in diameter and 100 mm in height. In Reconstituted Sand Tests (STEP 1 and STEP 2), the specimens were prepared by dry tamping to target prescribed relative densities D_r. In Intact Soil Tests, the specimens (STEP 3) were prepared by trimming intact soils sampled from in situ natural deposits of given ages and tested. After that, the soils were completely remolded and dried in the oven. Then, specimens (STEP 4) were reconstituted by compacting the remolded soils with natural water contents to target relative densities D_r of the intact specimens. All of the specimens were saturated with de-aired water before the tests to satisfy the pore-pressure coefficients B higher than 0.95. After isotropically consolidating with the effective stress σ'_c=98 kPa and the back pressure of 196 kPa, the bender element (BE) tests and liquefaction tests were carried out sequentially on the same specimens. 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' = the BE tip to tip distance (the height of specimen minus 14 mm) and Δt = the S-wave travelling time. In the liquefaction test, the specimen was loaded cyclically in the undrained condition with the frequency 0.05 Hz, 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.

3 TEST RESULTS OF RECONSTITUTED SANDS

3.1 Samples

Two kinds of reconstituted sands were tested; Futtsu sand 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, 28% clay content of the total fines and low plasticity index (I_p=6), while that in the Urayasu sand was originally contained in the same soil, 19% clay content of the total fines and non-plastic.

3.2 Reconstituted Sand Tests (STEP 1)

Figure 2 shows cyclic stress ratio R_L for ε_{DA}=5% versus number of cycles N_c plots for the reconstituted Futtsu and Urayasu sands on the semi-log chart. 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.

In Figures 3 (a) and (b), the plots connected with solid and dotted lines show F_c versus V_s and F_c versus R_{L10} relationships for the Futtsu and Urayasu sands. For the clean sand (F_c=0%), both V_s and R_{L10} tend to increase with increasing D_r in a slightly different manner depending on the two sands. Note that V_s is far less sensitive to the change in D_r than R_{L10} (in case of the Futtsu sand, the change in D_r from 30 to 70% increases V_s only by 15% in contrast to R_{L10} by 150%, all very roughly). Under the same D_r, both V_s and R_{L10} tend to decrease monotonically as F_c increases, and their decrements of R_{L10} become prominent for higher D_r in particular. This decreasing trend in R_{L10} is compatible with what has been found in previous similar test results (e.g. Kokusho 2007). The Urayasu sand shown in Figures 3(a) and (b) with plots connected by dotted lines exhibits a similar but more

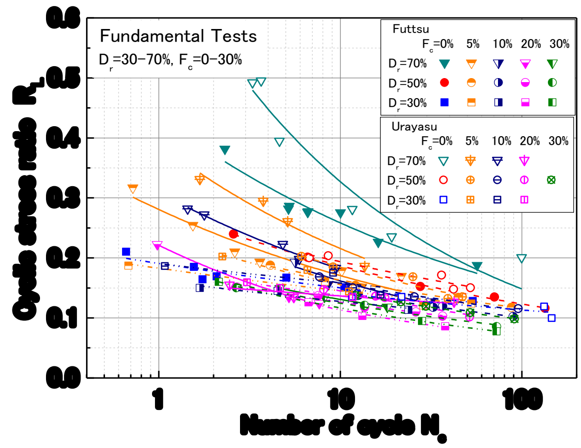
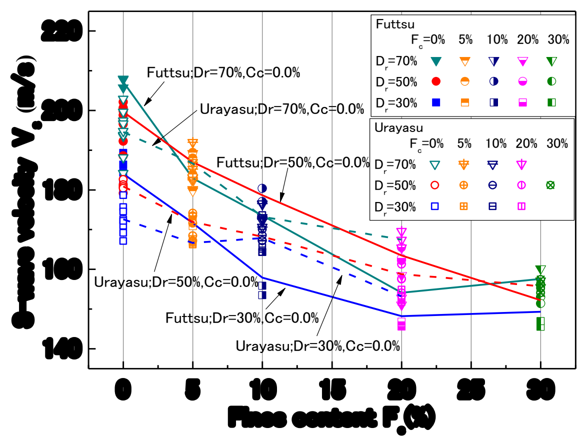
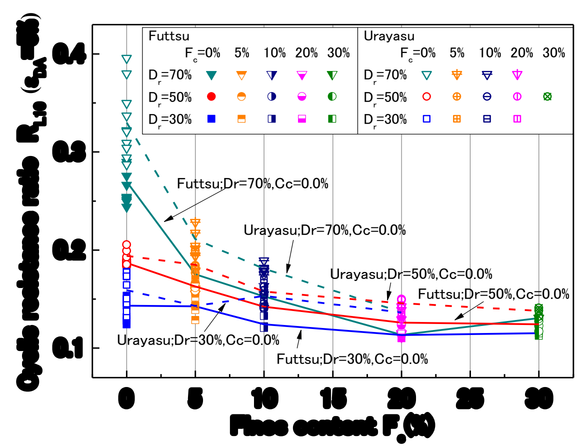


Figure 2. Relationship between N_c and R_L



(a) F_c versus V_s relationship



(b) F_c versus R_{L10} relationship

Figure 3. Relationships between F_c and V_s or R_{L10}

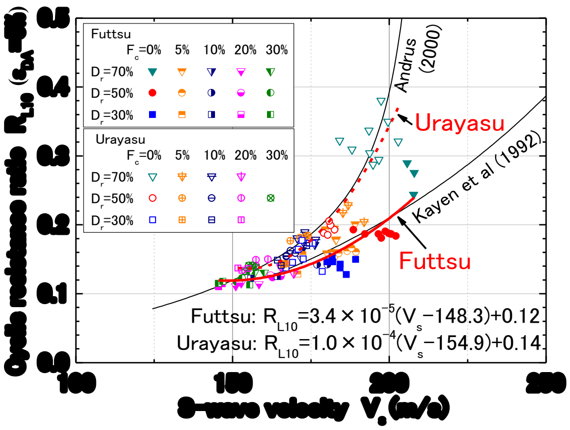


Figure 4. V_s versus R_{L10} relationship

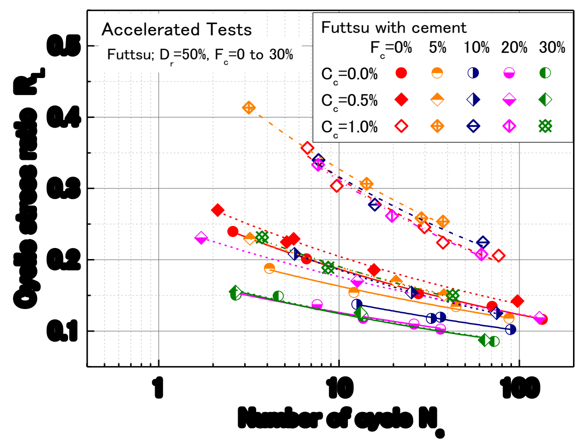


Figure 5. Relationship between N_c and R_L

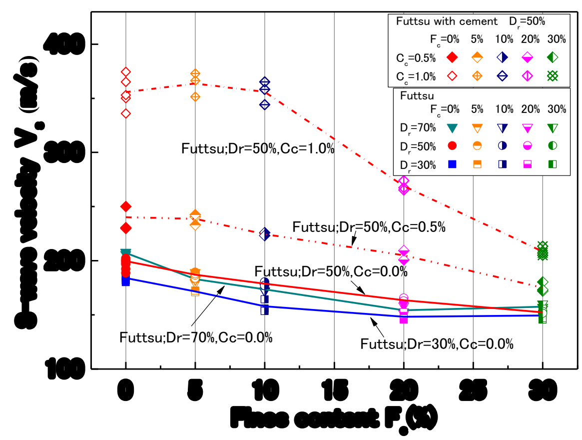
moderate F_c-dependent changes. For the two sands, V_s and R_{L10} tend to arrive at some minimum or stable values around F_c over 20% corresponding presumably to the critical fines content CF_c (Kokusho 2007).

Figure 4 shows direct relationships between R_{L10} and V_S for the two reconstituted sands with various D_r and F_c. It should be pointed out that the two sands used here in the lab tests show different trends approximated by the thick solid and dotted curves of parabolic functions, respectively. This implies that the R_L-V_s relationship may not be uniquely applicable to any sand in general but only to a particular sand individually. It is also observed that if the fines are added to the same sands, the R_L-V_s curve tends to slightly shift leftward as indicated in Figure 4 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.

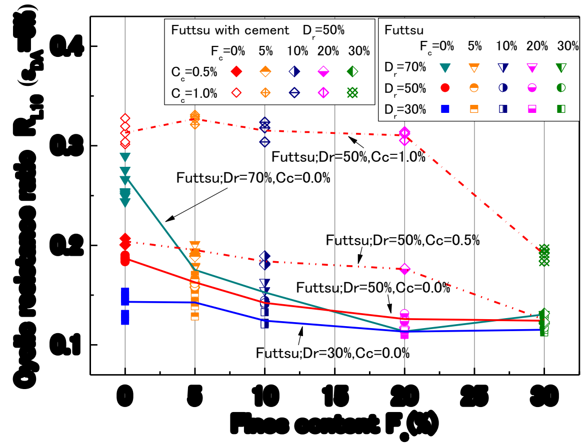
Two thin solid curves in Figure 4 represent previous research results by Kayan et al. (1992) and Andrus & Stokoe (2000), which are based on liquefaction case histories combined with in situ V_s-measurements. Note that the CRR-values for their original curves were determined as τ_{av}/σ'_v, where τ_{av}=uniform cyclic shear stress with its amplitude and number of cycles equivalent to M_w=7.5 earthquakes and σ'_v=effective overburden stress. Considering the earth pressure coefficient K_0=0.5 used in those researches, the CRRs 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 very accidentally not only qualitatively but quantitatively as well with the two separate field-based curves despite some differences in defining CRR.

3.3 Accelerated Test of Sands with Cement (STEP 2)

In order to simulate the geochemical aging effect (cementation) 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 sands of D_r≒50% with F_c=0 to 30%. The test way 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



(a) F_c versus V_s relationship



(b) F_c versus R_{L10} relationship

Figure 6. Relationships between F_c and V_s or R_{L10}

have a cement content C_c=0.5 or 1.0% of the total dry soil weight. After dry-tamped to a target D_r≒50%, 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 the BE and liquefaction tests.

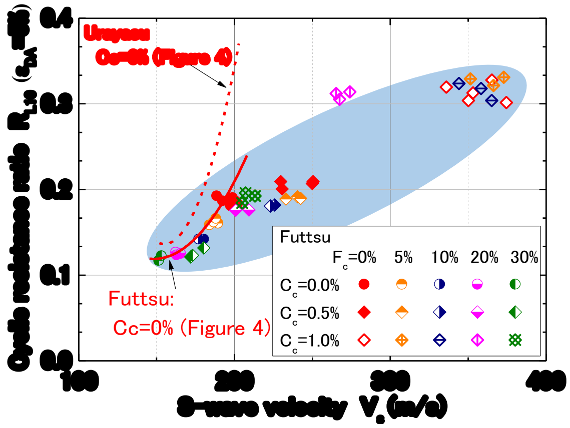


Figure 7. V_s versus R_{L10} relationship

Figure 5 shows the cyclic stress ratio R_L for ε_{DA}=5% versus N_c chart on the semi-log scale. 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 6 (a) and (b), various symbols connected with solid or dashed lines show relationships, F_c versus V_s and F_c versus R_{L10}, respectively, for sands without cement (C_c=0%) or with the cement mixture (C_c=0.5,1.0%). Both V_s and R_{L10} tend to decrease with increasing F_c under the same C_c. This F_c-dependent decreasing trend seems to slightly differ depending on C_c. For example, V_s starts to decrease at F_c=0% for C_c=0% but at around F_c=5% for C_c=0.5% and at around F_c=10% for C_c=1.0%. R_{L10} starts to decrease at F_c=0% for C_c=0% but at around F_c=10% for C_c=0.5% and at around F_c=20% for C_c=1.0%. These results indicate that fines content F_c is an important parameter for aging effect to manifest in increasing V_s or R_{L10} by the artificial cementation.

It can be read off from Figure 6 that the increment rate of V_s and R_{L10} due to increasing C_c tends to increase as F_c increases from 0% to higher values. However, that increment rate seems to be depressed as F_c approaches to 20% or 30%. This trend may be accounted for by the concept of “critical fines content” CF_c (Kokusho 2007). In the case of CF_c<F_c, a part of fines is considered to overflow the sand skeleton, changing the soil structure from coarse grain-supporting to matrix supporting. For Futtsu sand, CF_c=22 to 25%.

In Figure 7, 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, 0.5, 1.0%. It should be noted that, as the cement content C_c changes from 0 to 1.0%, the plots for larger F_c-values tend to shift far to the right and upward. Also noted is that most of 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 4 for the same sand without cement (red thick curve in Figure 7), 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 versus V_s relationship is basically soil-specific as already indicated.

Table 1. Physical properties of intact sands

		G.L. (m)	Age (yaer)	D_r (%)	F_c (%)	ρ_s (g/cm^3)	e_{max}	e_{min}	I_p (%)
Kuki	No1	-6.12	2000	76	64.0	2.605	2.094	1.330	7
	No2			58	45.0	2.573	2.204	1.378	
	No3			52	63.0	2.614	1.970	1.200	
Asahi	No1	-6.00	4000 to 5000	67	3.6	2.656	1.149	0.675	-
	No2			77	2.2	2.659	1.013	0.618	
	No3			57	5.8	2.644	1.031	0.607	
Inage	No1	-6.31	tens of thousands	28	32.0	2.640	1.215	0.695	9
	No2	-6.19		46	23.8	2.625	1.015	0.535	
	No3	-6.43		42	36.2	2.659	1.237	0.700	
Itako	No1	-2.25	700	47	9.3	2.684	1.204	0.741	4
	No2			50		2.662	1.344	0.807	
	No3			75		2.658	1.418	0.855	
	No4			54		2.697	1.295	0.784	

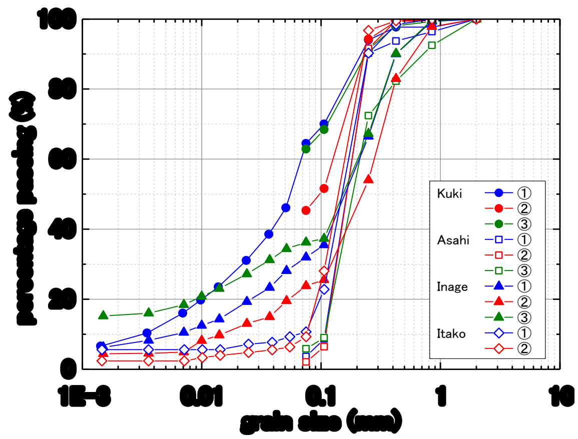


Figure 8. Grain size accumulation curve

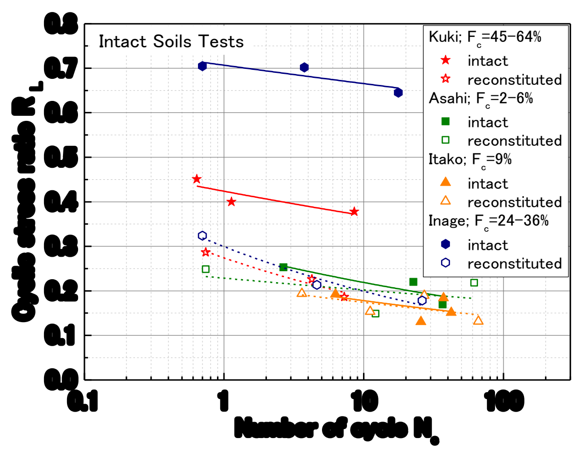


Figure 9. Relationship between N_c and R_L

4 INTACT SOIL TESTS (STEP3 & STEP4)

4.1 Intact Soil Samples

Intact samples taken from four different sites near Tokyo, Kuki, Asahi, Inage, and Itako, were tested and compared with the same soils reconstituted subsequently to have the similar relative densities D_r. All the tests were conducted in the same way previously mentioned under the isotropic effective confining stress of σ'_c =98 kPa. Table 1 and Figure 8 show physical properties and grain size accumulation curves of the four intact soils. Kuki sandy soil about 2000 years old was taken out by block sampling in a trench at the depth of about 6 m. It contained the largest amount of fines (F_c=45 to 64%, I_p=7) among the four sands. Asahi sand of 4000 to 5000 years old sampled by a triple tube sampler from the depth of 6 m had the smallest amount of fines of non-plasticity. Inage sand with tens of thousands years old (Pleistocene age) containing a plenty of fines (F_c=32 to 36%) with I_p=9 was sampled by Gel-Push (GP)-S type sampler by Kiso-Jiban Consultants Co. Ltd. Itako sand of 710 to 770 years old with F_c=9% was sampled in block from natural Holocene deposits. Geological age of Itako was investigated with active carbon dating method, that of the others were investigated by some documents.

4.2 Test results

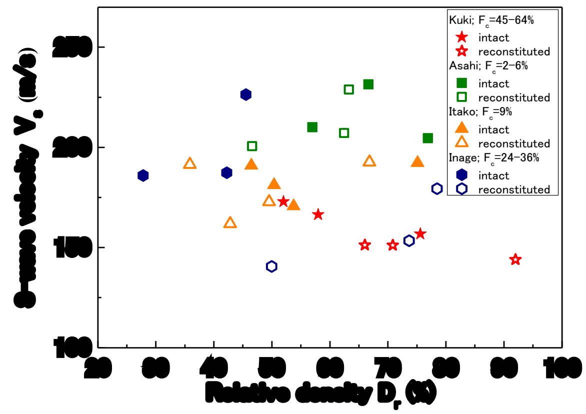
Figure 9 show relationship between N_c and R_L. For Kuki and Inage, R_L-values of intact samples are larger than that of reconstituted ones. On the other hand, for Asahi and Itako, R_L-values of intact samples are similar to those of reconstituted ones. Figures 10 (a) and (b) show D_r versus V_s plots 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. Herein, D_r is calculated with Equation 1 from the dry densities ρ_d of samples. The maximum and minimum dry densities, ρ_{dmax} and ρ_{dmin}, are determined by the tests standardized by the Japanese Geotechnical Society. It is assumed here that the relative density defined in Equation 1 is still applicable to sands with high fines content.

$$D_r = \{\rho_{dmax}(\rho_d - \rho_{dmin})\} / \{\rho_d(\rho_{dmax} - \rho_{dmin})\} \qquad [1]$$

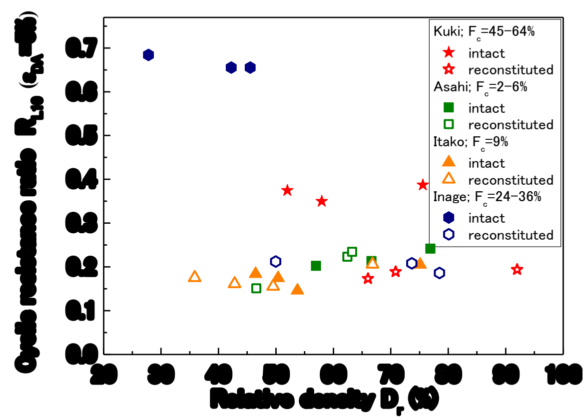
Though the D_r-values in the reconstituted soils were not successfully controlled to be identical to the intact ones, it is remarkable that, in Kuki and Inage sands, R_{L10} and V_s are obviously higher for the intact specimens than for the reconstituted specimens unlike Asahi and Itako sands, and their differences are particularly large in R_{L10} compared to V_s.

According to the accelerated test results by adding a small amount of cement as previously shown in Figures 6 (a) and (b), the cementation under the identical cement content C_c=0.5 or 1.0% 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 than in the Asahi and Itako sands. This further indicates that not only the geological age but also the fines content makes the difference in the liquefaction resistance R_L by the aging effect.

In Figure 11, 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



(a) D_r versus V_s relationship



(b) D_r versus R_{L10} relationship

Figure 10. Relationships between F_c and V_s or R_{L10}

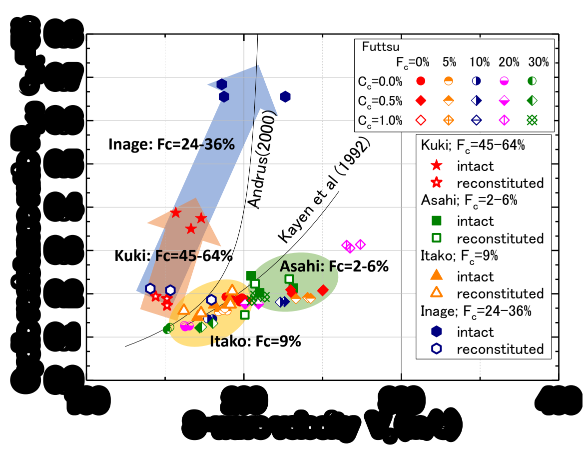


Figure 11. V_s versus R_{L10} relationship

Table 2. Minerals involved in Kuki or Asahi sand

sample	mineral	
Kuki	quartz	SiO_2
	cristobalite	
	opal	$SiO_2 \cdot nH_2O$
	kaolinite	$Al_4SiO_4O_{10}(OH)_8$
	plagioclase	$NaAlSi_3O_8$, $CaAl_2Si_2O_8$
Asahi	quartz	SiO_2
	plagioclase	$NaAlSi_3O_8$, $CaAl_2Si_2O_8$
	amphibole	$NaCa_2(Mg,Fe,Al)_5(Si,Al)_8O_{22}(OH)_2$
	mica	$KMg_3(Si_3Al)O_{10}(OH)_2$
	chabazite	$(Ca_{0.5},Na,K)_4[Al_4Si_8O_{24}] \cdot 12H_2O$

recovered from in situ are superposed on the accelerated test results previously mentioned. Regarding to relatively clean Asahi and Itako sands, the plots of both intact and reconstituted samples are located close to those of the reconstituted Futtsu sand with/without cement previously explained. Both V_s and R_{L10} of these two intact soils are not so much different from those reconstituted from the same soils, indicating negligible aging effects probably because the F_c-values are low (F_c=3 to 9%) and the geological ages are relatively young. On the other hand, in Kuki and Inage sands, the R_{L10} versus V_s plots are located quite differently, and the intact values are distinctively higher than the reconstituted values for the same soils. And more, this trend is differrent from ones of Futtsu with artificial aging. This is presumably because these soils contained much more fines (F_c=24 to 64%) with plasticity of I_p=7 to 9, leading to a clear difference in the manifestation of the aging effect.

5 CHEMICAL ANALYSIS WITH X-RAY

It has been indicated in the accelerated and intact soil tests that physical properties is important factor for the aging effect to appear. Hence, a chemical analysis with X-ray was conducted to investigate the relationship between the mineral content of fines and the manifestation of aging effect. Table 2 shows minerals involved in the soils at Kuki and Asahi where the aging was highly and marginally manifested, respectively. It should be specially mentioned that cristobalite, opal and kaolinite were identified in Kuki but not in Asahi. These minerals are not normally involved in sands. Cristobalite and opal exist as an amorphous structure of silica *Si* in nature. It was also found that Inage sand had the similar component as Kuki sand by fluorescence X-ray analysis (Sasaoka 2015). It is thus estimated that the aging effects of Kuki and Inage sands were caused by alkali-silica reaction of cristobalite or opal. Hydrates generated by the alkali-silica reaction may have made the soil particles cemented, partially contributing to the significantly large liquefaction resistances in the intact samples compared to the reconstituted samples.

6 CONCLUSIONS

Liquefaction resistance R_L versus shear-wave velocity V_s relationships of various sandy soils have been investigated by conducting cyclic triaxial tests combined with bender element tests to develop R_L-V_s relationships focusing the aging effect, yielding the following major findings.

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 20-30%. 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 two different previous research results based on liquefaction case histories very accidentally. The present lab test demonstrates that the R_{L10} versus V_s relationship is sand-specific, not applicable to any sands in general but only to specific sands individually.
4) The accelerated tests by adding a small amount of cement to simulate long-term aging effect 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 the manifestation of aging effect on the liquefaction resistance.
5) The results of intact soil tests are grouped into two types; One is that both V_s and R_{L10} in intact samples are much larger than in reconstituted samples and the other is that they are not so much different from reconstituted samples.
6) 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 the difference in the aging effect, as also implied by the accelerated tests of sands with a small amount of cement.

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