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 $F_c$ is, the higher the liquefaction resistance $R_L$ becomes under the same penetration resistance $q_t$. However, Kokusho et al. (2012) showed by lab tests on reconstituted samples that the $R_L$-$q_t$ curve is uniquely determined despite the difference in $F_c$. 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 $R_L$-$q_t$ 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 $V_s$ 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 $R_L$ reflecting the aging effect.

In this research, bender-element triaxial tests are carried out to investigate the $R_L$-$V_s$ 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 $R_L$-$V_s$ 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.
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 $\sigma'_c=98$ kPa 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 $H' = \text{BE tip to tip distance (the height of specimen minus 14mm)}$ and $\Delta t = \text{the S-wave travelling time}$. 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 $\varepsilon_{DA}=5\%$ 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 Urayasu sands on the semi-log scale for $\varepsilon_{DA}=5\%$. 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.
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 (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

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 \( C_c = 0 \sim 0.5\% \).

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 \( F_c \).
(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 content $C_c=0$). 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 $\tau_{av}/\sigma'_v$, where $\tau_{av}$=uniform cyclic shear stress with its amplitude and number of cycles equivalent to Mw7.5 earthquakes and $\sigma'_v$=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.
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 Dr ≈ 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 \( \sigma'_c = 98 \text{ kPa} \) 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 \( \varepsilon_{DA}=5\% \). 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.
In Figure 4, the $R_{L10}$-values are directly plotted versus $V_s$ for the Dr=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 $R_{L10}$~$V_s$ 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 $\sigma'_{CE}=98$ 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 ($F_c=45\sim64\%$, $I_p=7$) 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 ($F_c=24\sim36\%$) 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

<table>
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<tr>
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<th>G.L. (m)</th>
<th>Age (year)</th>
<th>$D_r$ (%)</th>
<th>$F_c$ (%)</th>
<th>$\rho_s$ (g/cm$^3$)</th>
<th>$\rho_{d_{max}}$ (g/cm$^3$)</th>
<th>$\rho_{d_{min}}$ (g/cm$^3$)</th>
<th>$w_i$ (%)</th>
<th>$w_p$ (%)</th>
<th>$I_p$ (%)</th>
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Figures 5 (a), (b) show $D_r$ versus $V_s$ plots and $D_r$ versus $R_{L10}$ ($\varepsilon_{DA}=5\%$) 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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References


