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AGING EFFECT ON SAND LIQUEFACTION OBSERVED DURING THE 2011 EARTHQUAKE AND BASIC LABORATORY STUDIES

Takaji KOKUSHO[1], Yohta NAGAO[2], Fumiki ITO[2] and Takahisa FUKUYAMA[3]

[1] Professor, Department of Civil & Environment Engineering, Chuo University,
Tokyo, Japan, Kokusho@civil.chuo-u.ac.jp
[2] Ex-graduate student, ditto.
[3] Graduate student, ditto.

ABSTRACT: During the 2011 Tohoku Pacific Ocean earthquake (M9.0), liquefaction occurred extensively in reclaimed land in the Kanto plain more than 200 km far from the earthquake fault. The liquefied sand generally contained a lot of non-plastic fines with fines content more than 50% in some places. Almost all sand deposits along the Tokyo bay area reclaimed in 1960’s or later liquefied, while in a good contrast, those older than that did not, though both had almost identical SPT blow counts. In order to study the aging effect on liquefaction strength of sands containing fines, a series of basic laboratory tests combining innovative miniature cone penetration and subsequent cyclic undrained loading were carried out in a modified triaxial apparatus on sand specimens containing fines. A unique curve relating cone resistance q_t and liquefaction strength R_L was obtained for reconstituted specimens, despite the differences in fines content F_c, quite contradictory to the current liquefaction potential evaluation practice. Then a small amount of cement was added to fines in the sand specimens to simulate a geological aging effect in a short time. It was found that the liquefaction strength R_L increases more than the penetration resistance q_t, resulting in higher liquefaction strength under the same cone resistance with increasing F_c. Thus it has been clarified that not the fines content itself but the aging effect by cementation, which becomes more pronounced in sands with higher fines content, can facilitate reasonable basis why liquefaction strength corresponding to the same penetration resistance is raised with increasing fines content. In addition, intact samples recovered from in situ Pleistocene and Holocene deposits with known ages have been tested and confirmed the trends similar to the above results.

Key Words: liquefaction, aging effect, fines content, cone resistance, cementation

INTRODUCTION

During the recent Tohoku Pacific Ocean earthquake (M9.0), liquefaction extensively took place in the Kanto plain, more than 200 km far from the earthquake fault. Almost all sand deposits along the Tokyo bay area reclaimed in 1960’s or later liquefied. In a good contrast, those older than that did not, though both had almost identical SPT blow counts. The liquefied sand generally contained a lot of non-plastic fines, with fines content F_c more than 50% in many places. In addition to this case, recent case studies reveal that aging effect seems to play an important role in seismic liquefaction of sand deposits. Liquefaction mostly occurred in backfills and reclaimed ground of young ages. Also pointed out is that cases are increasing in which sands containing considerable amount of low-plasticity fines liquefied such as in Adapazari, Turkey during 1999 Kocaeli earthquake, in Christchurch during 2010 Darfield earthquake in New Zealand and also in Tokyo Bay area during the recent M9.0 earthquake.

In engineering practice, liquefaction potential is evaluated using penetration resistance in standard penetration tests (SPT) or cone penetration tests (CPT). If sands contain a measurable amount of fines, liquefaction strength is normally raised in accordance to fines content F_c in most liquefaction evaluation methods. This F_c-dependent modification of liquefaction strength may be originated from liquefaction case studies (Tokimatsu and Yoshimi 1983, Seed and De Alba 1984), in which empirical boundary curves, developed in situ, discriminating data points according to liquefaction/non-liquefaction on a chart where seismically induced shear stress was plotted versus SPT N_1-values in many places, were found being strongly dependent on fines content. More directly, Suzuki et al. (1995) carried out CPT tests and soil sampling by in situ freezing technique in the same sand deposits. The study showed that the higher the fines content the greater the liquefaction strength for the same q_t-value.

In contrast to their finding, however, quite a few laboratory tests using reconstituted specimens, having the same relative density D_r (e. g. Kokusho 2007) or the same void ratio (Papadopoulou and Tika 2008), have shown that R_L clearly decreases with increasing fines content of low plasticity fines from F_c=0% to 30%. Thus, a lack of understanding seems to remain in the current practice for liquefaction potential evaluation in the field in relation with laboratory test results for sands containing fines.

The present authors have been carrying out a systematic experimental study in which miniature cone penetrations and subsequent cyclic loading tests were conducted on the same triaxial test specimens (Kokusho et al. 2005). An innovative simple mechanism introduced in a normal cyclic triaxial apparatus by Kokusho et al. (2003) was used enabling a miniature cone to penetrate into the sand specimen at a constant speed. The results from the two sequential tests were compared to develop direct q_t - R_L correlations for sands containing various amounts of fines.

In the first part of the present paper the aging effect by cementation is investigated in a series of laboratory tests using reconstituted specimens containing fines. For the aging effect, a small quantity of cement was added to reconstituted specimens to simulate cementation or chemical bonding for a geological time span in a short time. Penetration resistance q_t and liquefaction strength R_L were measured in the same specimens to investigate the aging effect on the q_t - R_L correlations considering fines content as a key parameter.

In the latter part of the paper, intact specimens sampled from Pleistocene and Holocene deposits were tested in the same test apparatus to know the direct q_t - R_L relationship of natural soils. Then, the same soils, disturbed and then reconstituted to the original density, were tested to compare the results with the intact soils from the viewpoint of aging effect.

TEST APPARUTUS, SOIL MATERIAL & TEST PROCEDURES

In the triaxial apparatus used in this research, the specimen size was 100 mm in diameter and 200 mm in height. In the liquefaction tests, the soil specimen was loaded cyclically by a pneumatic actuator as a stress-controlled test. In order to carry out a cone penetration test in the same specimen prior to the liquefaction tests, a pedestal below the soil specimen was modified as shown in Fig.1, so that a miniature cone can penetrate into the specimen from the bottom. For that goal, the pedestal consists of two parts, a circular base to which the cone rod is fixed and a movable metal cap. Through the center of the cap, the cone rod penetrates in the upward direction into the overlying specimen. The annulus between the two parts is sealed by O-rings, enabling the cap to slide up and down (Kokusho et al. 2003). During the test, the pedestal cap is initially set up at the highest level by filling water in the reservoir, and the specimen is constructed on it. By opening a valve at the start of the cone penetration, the water in the reservoir is squeezed by the cell pressure, resulting in the settlement of a total body of the specimen at the top of the pedestal. Due to the settlement, the cone penetrates into the specimen by 25 mm (from initial length 45 mm to final length 70 mm).

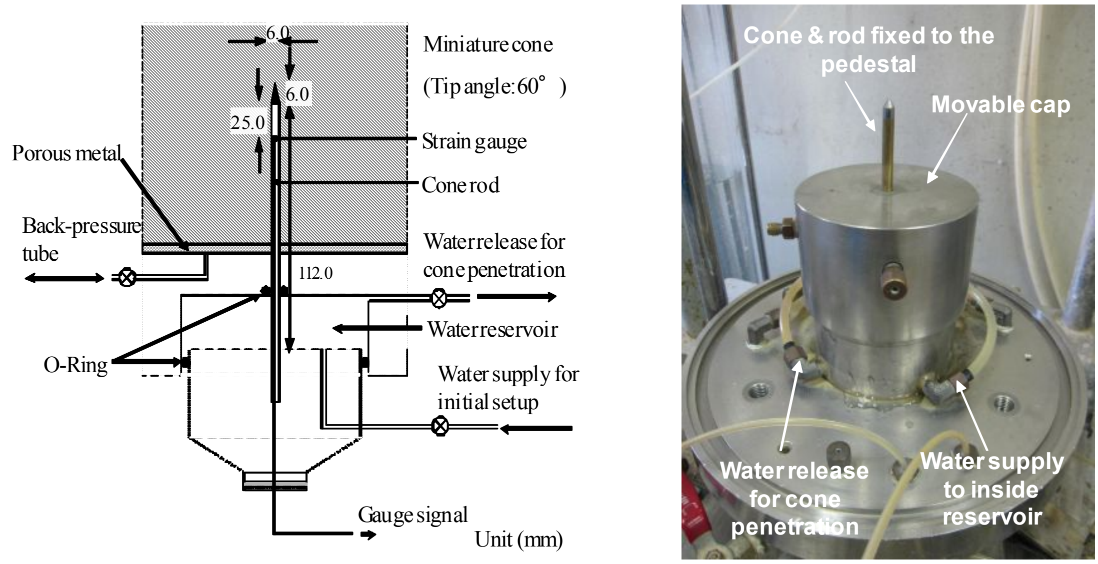

Fig. 1 Cross section (right) and Photograph (left) of the modified pedestal in the lower part of triaxial apparatus

The penetration speed is about 2mm per second, much slower than prototype CPT and is almost constant irrespective of the difference in relative density. The miniature cone is 6 mm diameter and 60 degrees tip angle, about 1/6 smaller in dimension than the prototype cone used in the field. The strain gauges to measure the penetration resistance are glued at the inner wall of the rod tube, 25 mm lower than the foot of the cone.

Beach sand (Futtsu sand) consisting of sub-round particles of hard quality was used for reconstituted specimens. Fines mixed with the sand was silty and clayey soils with low plasticity index of I_p=6 sieved from decomposed granite in reclaimed ground of the Kobe city, Japan. For the test series for cementation, a prescribed quantity of Portland cement was completely mixed with the Masa fine soil to make it with different degree of chemical activity. The cement content C_c, the weight ratio of cement to soil (including fines), varied from 0 to 1.0%, and the fines content F_c including the cement changed from 0 to 30%. This means that the ratio C_c/F_c, a parameter representing chemical activity of fines, varied from 0 to 30%. Then the sand specimen with given F_c was prepared by the wet tamping method to make a given relative density D_r, which was changed in 3 steps, about D_r=30, 50 and 70%. The specimen was then completely saturated with de-aired water, and consolidated under the isotropic effective stress of 98 kPa with the back-pressure of 196 kPa. If cement is added to fines, the consolidation time was controlled exactly 24 hours after wetting, while for tests without cement it was about 2 hours.

Then, the specimen was fully saturated by using de-aired water in a double negative pressure method so that the B-value larger than 0.95 was measured, and isotropically consolidated with the effective stress of 98 kPa with the back-pressure of 196 kPa. In the test sequence, the penetration test was first carried out under undrained condition after consolidating the specimen. Then, after releasing pore pressure and reconsolidating it under the same confining pressure again, although the volume change by this procedure was almost negligible, the liquefaction test was carried out on the same specimen. The sinusoidal cyclic axial load applied with the frequency of 0.1 Hz was measured with a load cell in the pressure chamber. The cell pressure and the pore-water pressure were measured with electric piezometers and the axial deformation is measured with LVDT of 50 mm maximum capacity. It may well be suspected that, in such a test sequence, the liquefaction strength is possibly influenced by the preceding cone test and subsequent reconsolidation. However, it was already confirmed in previous research (Kokusho et al. 2005) that the cyclic stress ratio for liquefaction was almost unaffected by the cone test and reconsolidation.

RESULTS ON RECONSTITUTED SPECIMENS WITHOUT & WITH CEMENT

In the test, relative density D_r, fines content F_c and cement content C_c of the specimen were parametrically changed to investigate their effects on penetration resistance and undrained cyclic strength. Figs. 2(a)-(e) show cone resistance q_t and associated excess pore-pressure Δu plotted versus the penetration length L in the tests for D_r≈50%, F_c=0, 5, 10, 20, 30% and C_c=0, 0.5, 1.0%. It is clearly observed that q_t for soils without cement (C_c =0) decreases with increasing fines up to F_c =20%. For individual F_c–values, q_t tends to increase more or less with C_c increasing from 0 to 1%. The increase is particularly large for F_c =20% and C_c=1%. The excess pore pressure Δu building up almost linearly with the penetration length L tends to decrease with increasing C_c. In Figs. 3(a), (b), similar

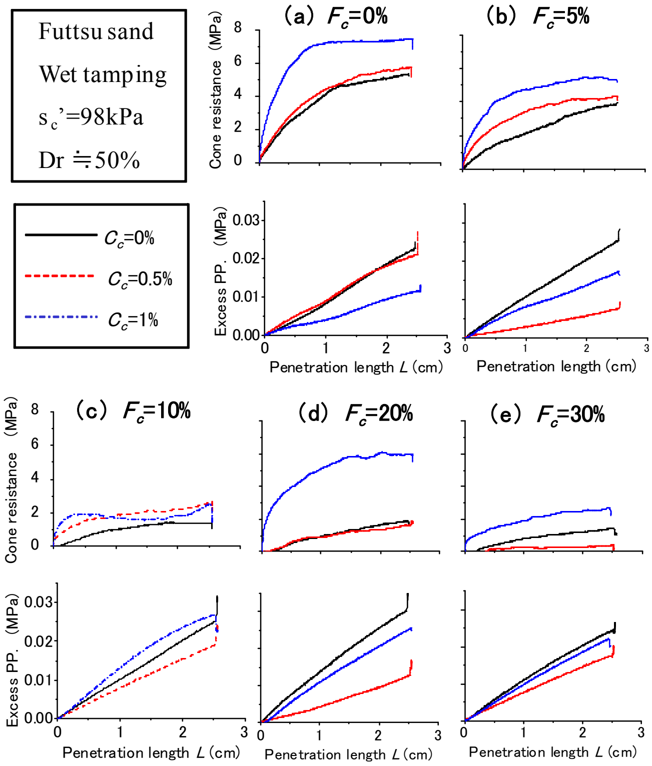

Fig. 2 Cone resistance or excess pore-pressure versus penetration length L for reconstituted specimens of D_r≈ 50% with different fines content.

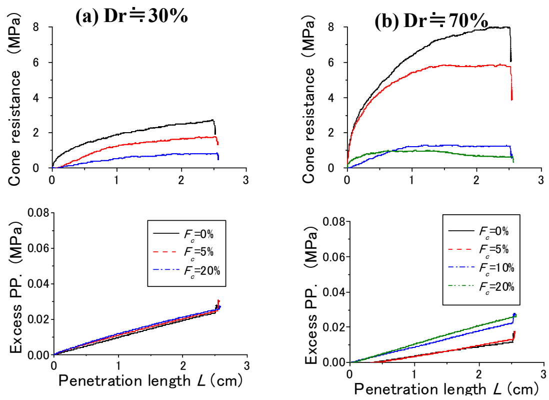

Fig. 3 Cone resistance or excess pore-pressure versus penetration length L for reconstituted specimens of D_r≈ 30% & 70%with different fines content without cement.

penetration test results are shown for sands of Dr≈30% and 70% with varying F_c but no cement. It is observed again that the increase in F_c tends to decrease cone resistance q_t.

Figs. 4 (a)-(e) show relationships between the cyclic stress ratios R ($\sigma_d/2\sigma'_c$: σ_d =cyclic stress amplitude, σ'_c = effective isotropic confining stress) versus the number of loading cycles N_c for the double amplitude axial strain ε_{DA}=5% obtained by undrained cyclic loading tests on sand specimens having D_r≈50%, F_c=0, 5, 10, 20, 30%, and C_c=0, 0.5, 1.0%. Obviously, the increase in fines content tends to reduce stress ratio R in specimens without cement as already demonstrated by previous researches (e.g. Kokusho 2007). Also indicated in the figure is that the R-value increases with increas-

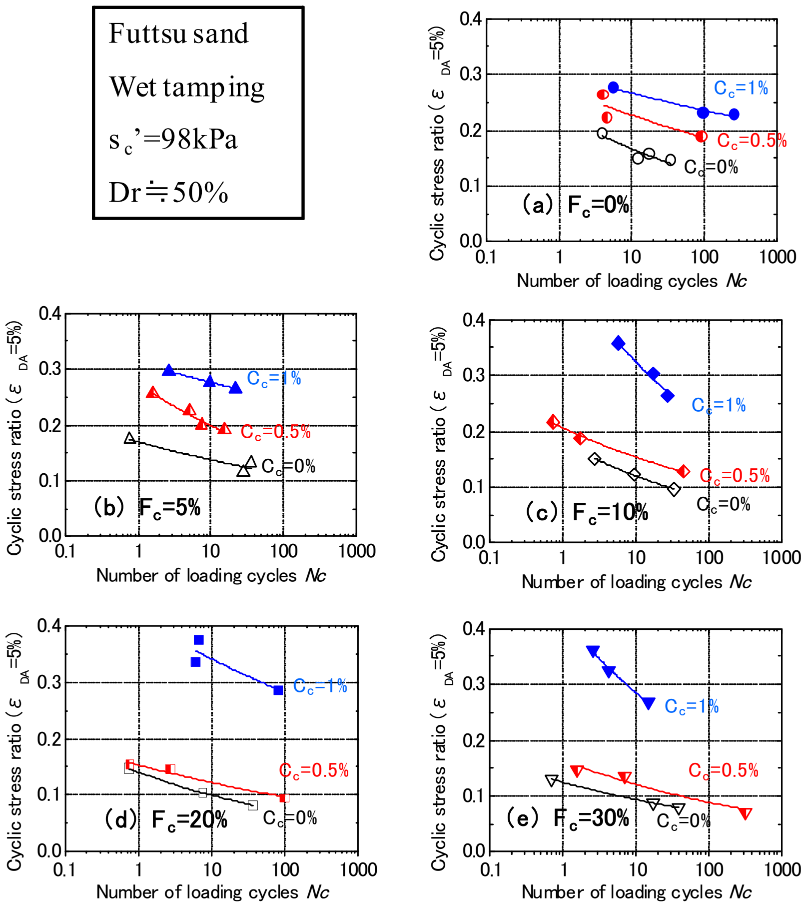

Fig. 4 Stress ratios R versus number of loading cycles N_c for reconstituted specimens of D_r≈50% with different fines content.

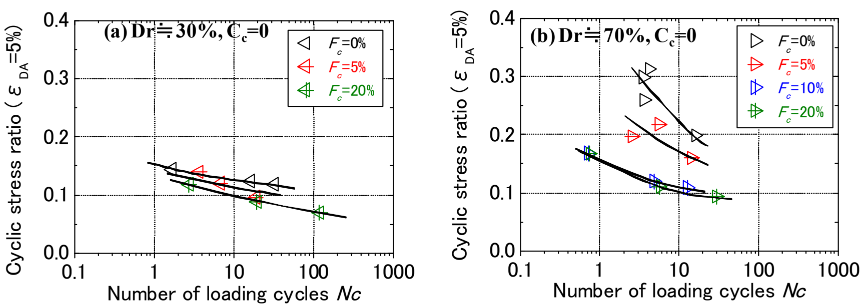

Fig. 5 Stress ratios R versus number of loading cycles N_c for reconstituted specimens of D_r≈30% & 70% with different fines content without cement.

ing cement content for all the fines content F_c and the increment is larger for C_c=1% and F_c =10 -30%. In Fig. 5(a), (b), the similar liquefaction strength results are shown for specimens with D_r≈30%, 70% with varying F_c but no cement. Again, the increase in F_c obviously decrease the stress ratio R for dense sand of D_r≈70% in particular.

In Fig. 6, test results for different values of D_r, F_c and C_c are shown on the $R_L \sim q_t$ diagram with different symbols. The liquefaction strength R_L in the vertical axis is defined as the stress ratio $\sigma_d/2\sigma'_c$ for ε_{DA}=5% and N_c=20. The penetration resistance q_t in the horizontal axis is determined as the maximum value of the cone resistance during penetration from the $q_t \sim L$ curves shown in Figs. 2 and 3. The open symbols in Fig. 6 along the thick dashed line which correspond to the specimens without cement are located along the thick dashed line in the chart despite wide differences in D_r (30~70%) and F_c (0~30%) as already pointed out in the previous research (Kokusho et al. 2005, 2009), indicating that the liquefaction strength R_L is uniquely correlated to q_t irrespective of F_c. This finding is contradictory with the current liquefaction potential evaluation practice, where R_L is raised accord-

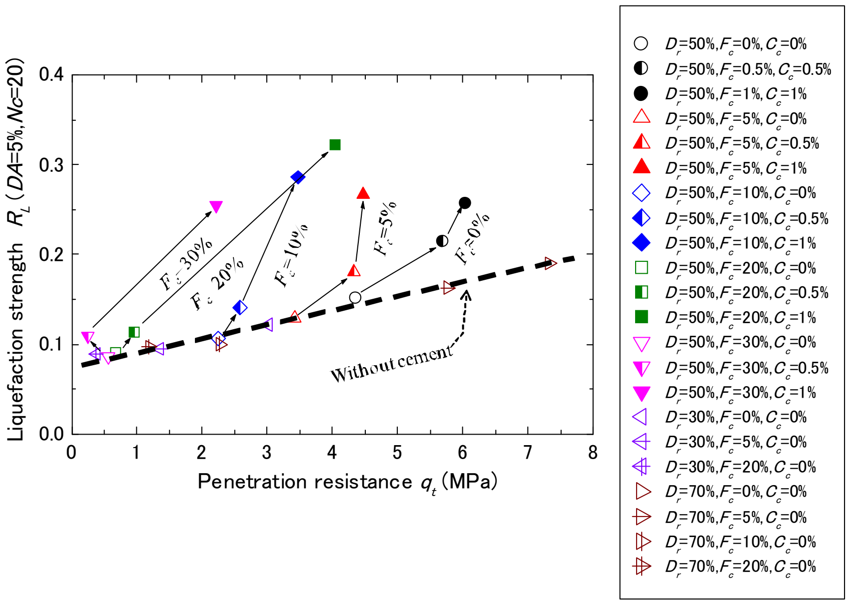

Fig. 6 Liquefaction strength R_L versus penetration resistance q_t diagram for different values of D_r, F_c and C_c.

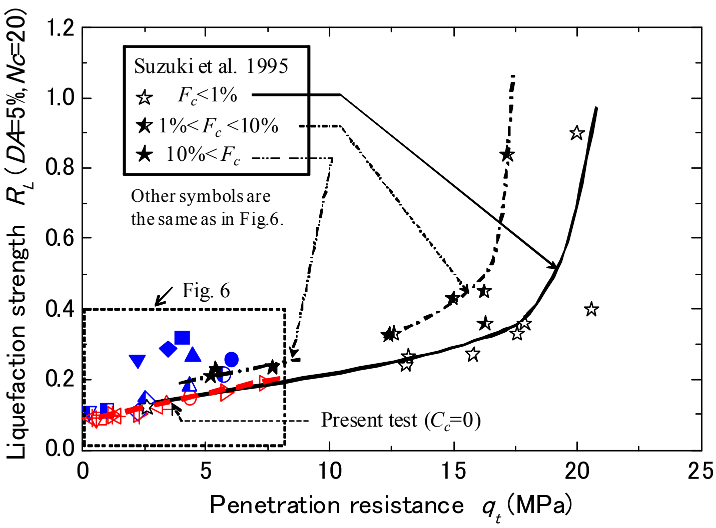

Fig. 7 Liquefaction strength R_L versus penetration resistance q_t compared with field investigations combining prototype CPT and triaxial tests on intact samples.

ing to F_c.

The half-close and close symbols in Fig. 6 are from the accelerated tests on specimens containing cement. Among them, upward triangles, for instance, represent the case F_c=5%, and they move up from the open (C_c =0) to the half-close (C_c =0.5%) further to the full-close symbols (C_c =1.0%) as C_c / F_c changes from 0 to 20% for the same value of F_c =5% as indicated by thin arrows in the diagram. In the similar manner, other symbols move up with increasing C_c or C_c / F_c for the same fines content of F_c =10%, 20% and 30%. Samples with higher value of C_c / F_c may be considered as of longer geological age because higher chemical activity is exerted in the same soil in the accelerated test. This indicates that the cementation effect tends to push up the data points on the $R_L \sim q_t$ diagram from the unique line of no cement and gives higher liquefaction strength under the same cone resistance.

In Fig. 7, the same data points as in Fig. 6 are plotted again together with star symbols representing in situ soil data by Suzuki et al. (1995). In their research, prototype cone tests in situ and laboratory undrained cyclic triaxial tests on intact samples recovered from the same soil deposits by in situ freezing technique were combined. It demonstrates a clear difference in the $R_L \sim q_t$ relationships due to different fines contents of F_c <1.0%, F_c =1.0-10% and F_c >10%. Also noted is that the two research results are in a good coincidence not only qualitatively but also quantitatively, particularly in the case without cement, despite a large difference in the cone size and CPT test procedures.

Based on the data shown in Fig. 6, the ratio of increase in R_L or q_t with respect to those without cement is shown versus the C_c/F_c -value with the fines content F_c as a parameter in Fig. 8. With increasing chemical activity C_c/F_c, the R_L-value increases more than the q_t-value for $F_c \leq 10\%$, but it is reverse for $F_c \geq 20\%$. Also noted in Fig. 8 is that not only the C_c/F_c -value but also the fines content F_c increasing up to F_c=20% tends to considerably increase R_L and q_t even under the same cement con-

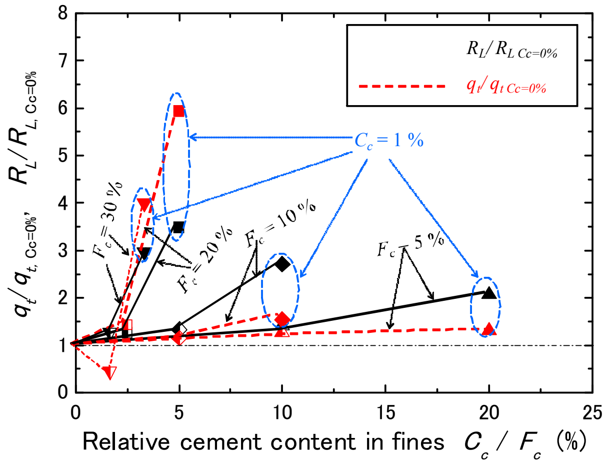

Fig. 8 $q_t/q_{t,\,Cc=0\%}$ or $R_L/R_{L,\,Cc=0\%}$ versus C_c/F_c

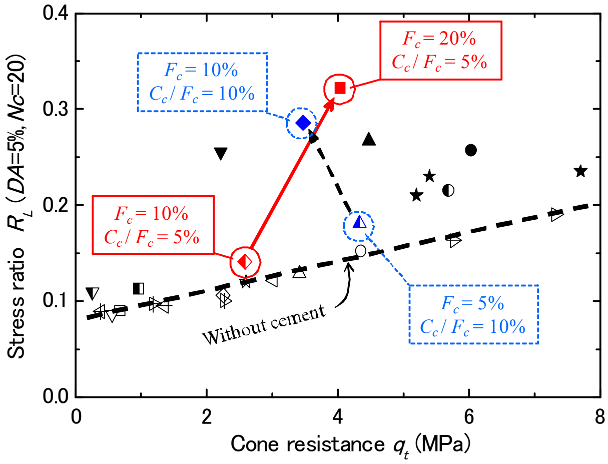

Fig. 9 Close-up of Fig. 6 showing the effect of fines content F_c for the same C_c/F_c.

tent of C_c =1.0% as demonstrated by the encircled plots but the trend seems to change at F_c=30%. Thus, there seems to be a kind of transition between F_c=20% and 30%, where the increasing trend in R_L or q_t with increasing C_c/F_c -value changes. This may possibly have something to do with the change in soil fabric from grain-supporting to matrix-supporting structure.

In Fig. 9, where the same data as in Fig. 6 are plotted again, it is recognized that the plot for C_c/F_c –value, 5% or 10% shifts upward as F_c increases from the unique line of no cement as indicated by the thick arrows in the graph. This indicates that, for the same C_c/F_c –value (simulating the same geological age), higher F_c-value results in higher liquefaction strength for the same cone resistance. This trend is compatible with the liquefaction potential evaluation practice currently employed. Thus, the present research results by the accelerated test clearly indicate that not the fines content itself but the cementation effect is responsible for the higher liquefaction strength for larger F_c under the same cone resistance.

TEST RESULTS ON IN SITU INTACT SPECIMENS

In order to know the direct $R_L \sim q_t$ relationship of natural soils and compare them with the accelerated test results on reconstituted soils using small amount of cement mentioned above, intact soils have been sampled from in situ soil deposits. They have been tested in the same way to measure mini-cone penetration resistance and undrained cyclic strength for the same specimens. Pleistocene sands and Holocene sands have been recovered from two sites in the Kanto area near Tokyo by block sampling using PVC tubes as shown in Fig.10. The size of the PVC tube was 120 mm in inner diameter and 200 mm in height, and a circular metal cutting edge was attached to the tube to penetrate it slowly into sampled soil.

Pleistocene soil was taken from two sand deposits A and B inter-bedded in a river terrace near Narita-city in Chiba Prefecture. Their ages were estimated about 100×10^3 and 150×10^3 years old, respectively (Mitani 2006). The overburden depth was about 5 m and 11 m for the two soils, A and B, respectively. The relative density and fines content of A are D_r=101-107% and F_c=6.1-8.5%, and those of layer B are D_r =75-81% and F_c =12-19%, respectively. Samples taken out in PVC tubes were frozen in the laboratory and then trimmed into the specimen of 100 mm in diameter and 200 mm in height, because it was difficult to handle them without freezing.

Holocene soil with D_r =35-81% and F_c=13-25% was taken from a river terrace sand layer in Tateyama-city in Chiba Prefecture by using the same PVC tubes. Its age was estimated $2\text{-}4 \times 10^3$ years old (Shishikura 2005). The overburden depth for the soil was about 5m. For this soil, it was possible to trim the sample into the specimen size without freezing.

Fig. 10 Photographs of block sampling using a PVC tube with metal edge at the tip
(Left: Pleistocene sand, Right: Holocene sand)

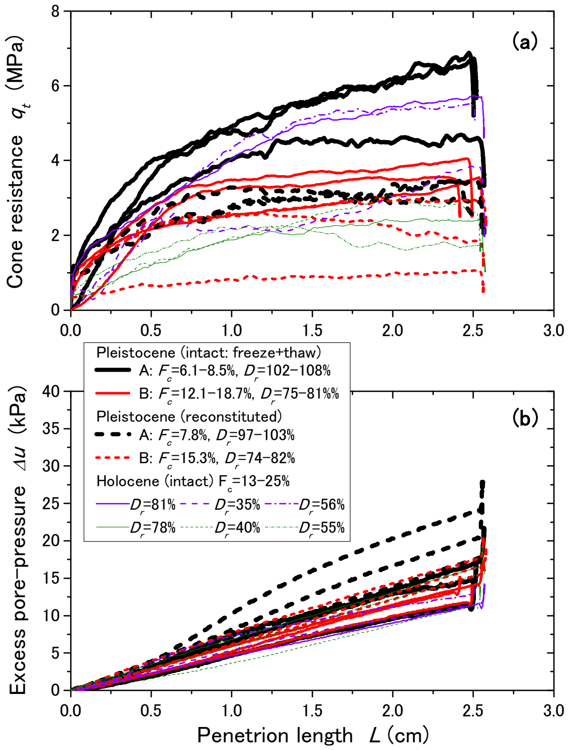

Fig. 11 Cone resistance (a) or excess pore- pressure (b) versus penetration length L for intact and reconstituted Pleistocene/Holocene sands.

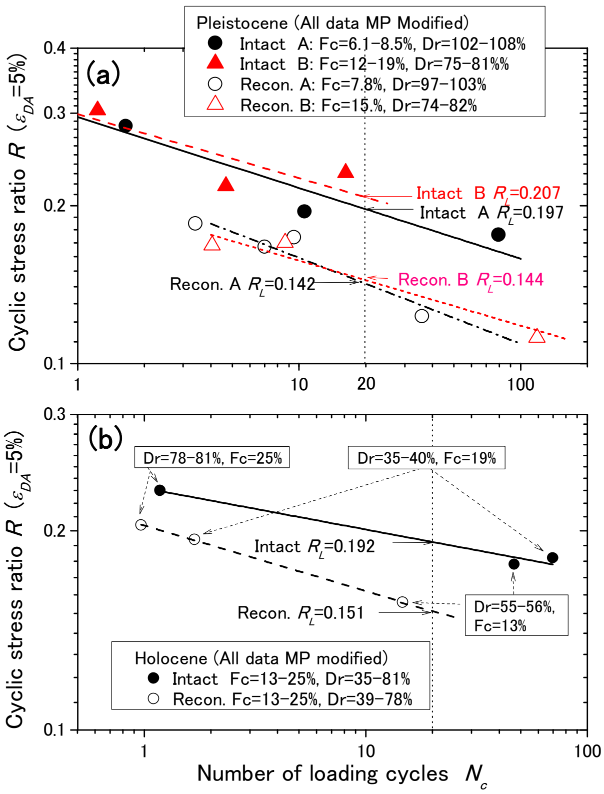

Fig. 12 Stress ratios R for ε_{DA} = 5% versus number of loading cycles N_c for intact specimens from Pleistocene sands.

A hole for the mini-cone was drilled in advance at the center of the specimen bottom with a drill bit, 6 mm in diameter and 43 mm in depth (2mm shorter than the cone length). It was then set on the pedestal of the modified triaxial apparatus. The specimen was fully saturated with de-aired water to secure the B-value larger than 95%, consolidated by isotropic pressure of p'_0=98 kPa for all the intact samples. Then, the mini-cone penetration test was conducted in undrained condition. After that, the specimen was reconsolidated by p'_0=98 kPa and undrained cyclic test was carried out in the same manner as in the reconstituted specimens mentioned before.

Fig. 11 shows cone resistance q_t and associated excess pore-pressure Δu plotted versus the penetration length for intact Pleistocene soils A and B with thick curves. The corresponding data are also shown with dashed curves for reconstituted specimens, which were once disturbed and compacted in a mold by moist-tamping method to reproduce the same in situ density. Despite some data dispersions, the cone resistance q_t for intact soils is generally larger than that for reconstituted soils. The mini-cone data for Holocene soils are superposed in Fig. 11 with thin curves. The difference in q_t between intact and reconstituted specimens is again obvious despite wide variation in D_r among the specimens.

In Fig. 12, the cyclic stress ratios $R=\sigma_d/2\sigma'_c$ for axial strain $\varepsilon_{DA}=5\%$ are plotted versus the number of load cycles obtained from cyclic loading tests conducted for the same intact or reconstituted specimens of Pleistocene and Holocene soils after the mini-cone penetration tests. For intact specimens, the R-values have been modified considering the effect of rubber membrane penetration because of their rugged side face. Even for the reconstituted specimens, the MP correction has been found necessary and implemented, in contrast to Futtsu beach sand, previously mentioned, in which the MP effect was negligible. For the Pleistocene soils shown in (a), R-values of intact specimens are evidently larger than those of reconstituted soils in spite of the data dispersions. For the Holocene intact soils in (b), the data points on the $R-N_c$ chart seem to be consistently plotted not only for intact but also for reconstituted specimens, despite the big difference in D_r as indicated in the chart. The R-values of intact specimens are again evidently larger than those reconstituted. From Fig 12, the liquefaction strength (cyclic resistance ratio) R_L defined as R for $\varepsilon_{DA}=5\%$ and N_c=20 was read off as in dedicated in the chart for intact or reconstituted specimens of each soil.

In Fig. 13, the liquefaction strength R_L and penetration resistance q_t for Pleistocene and Holocene soils are directly compared on the $R_L \sim q_t$ diagram using different symbols. The liquefaction strength R_L in the vertical axis is defined as the stress ratio R for ε_{DA}=5% and N_c=20 as indicated in Fig. 12. The penetration resistance q_t is determined as the maximum value of the cone resistance during penetration from the $q_t \sim L$ curves shown in Fig.11. The q_t–value in the horizontal axis of Fig. 13 is the average for 3 to 4 penetration tests on the same soil.

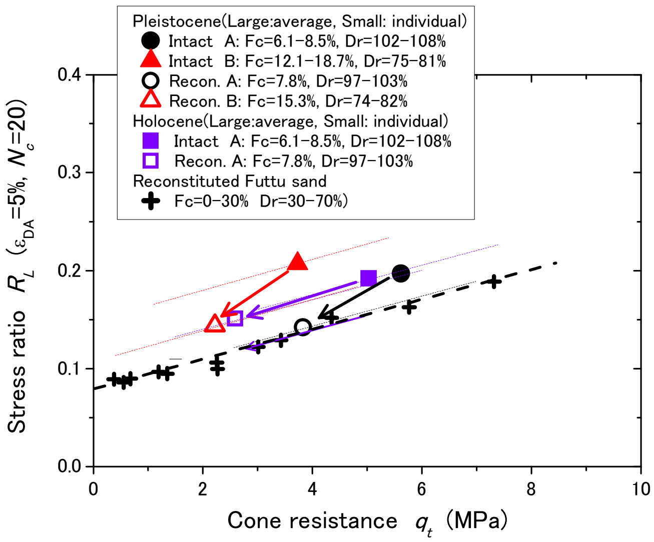

Fig. 13 Stress ratios R_L versus cone resistance q_t of intact Pleistocene and Holocene soils compared with reconstituted specimens.

The cross symbols in Fig. 13 indicate the $R_L \sim q_t$ plots obtained for Futtsu beach sand with varying F_c, which are exactly the same data points without cement in Fig. 6. As already explained, they are located along the thick dashed line irrespective of differences in D_r and F_c. Obviously, the plots of intact soils (the solid symbols) are located higher than the thick dashed line. The reconstituted specimens of in situ soils are not completely coincident with the thick dashed line but slightly higher than that. However, the plots for intact soils (the solid circle and triangle) are found still higher than those of the reconstituted soils if the lines parallel with the thick dashed line passing through them are compared. The difference in the parallel lines between intact and reconstituted is larger for Pleistocene than for Holocene, seemingly reflecting the difference in ages. More test data on in situ soils are needed to know exactly the aging effect on the plots considering the effect of fines content of F_c.

CONCLUSIONS

During the 2011 Tohoku Pacific Ocean earthquake (M9.0), liquefaction occurred extensively in reclaimed land in Kanto area more than 200 km far from the earthquake fault. The liquefied sand generally contained a lot of non-plastic fines with fines content more than 50% in some places. Almost all sand deposits along the Tokyo bay area reclaimed in 1960's or later liquefied, while in a good contrast, those older than that did not, though both had almost identical SPT blow counts. The first part of the paper contributes to basically understand the aging mechanism for liquefaction by conducting a series of experimental study by miniature cone penetration tests and subsequent cyclic loading tests in the same triaxial test specimen with fines content F_c as a key parameter. Accelerated tests on the cementation effect using Futtsu beach sand without or with a small quantity of cement yielded the following major findings;

- For reconstituted sands without cement, the liquefaction strength R_L is uniquely related to the cone penetration resistance q_t, forming a single $R_L \sim q_t$ line, irrespective of fines content F_c, quite contradictory to the current liquefaction potential evaluation practice where R_L is modified according to F_c.
- This laboratory test result coincides with in situ $R_L \sim q_t$ relation by Suzuki et al.(1995) quantitatively despite clear difference in the test procedures and cone size.
- Specimens with higher value of C_c/F_c (simulating longer geological age) results in higher liquefaction strength under the same cone resistance, indicating that the cementation effect tends to raise the $R_L \sim q_t$ line from that for soils without cement (without aging effect).
- For the same C_c/F_c-value (simulating the same geological age), higher fines content results in higher liquefaction strength R_L under the same cone resistance q_t, which is consistent with the trend found in the field investigations.

In order to examine that the above test results are consistent with natural deposits of long geological ages, intact specimens sampled from Pleistocene deposits (100-150×10^3 old) and Holocene deposits (2-4×10^3 old) were tested in the same way to know the direct R_L - q_t relationship of natural soils and compared with reconstituted soils, yielding the following;

- Differences are clear in both penetration resistance q_t and liquefaction strength R_L between intact and reconstituted specimens of Pleistocene or Holocene deposits.
- Direct relationship between R_L and q_t is found compatible with that of the accelerated tests using cement, so that the R_L - q_t line of intact specimens is located higher than that of reconstituted specimen. The difference between the lines seems to be larger with geological ages.

Consequently, the series of tests on reconstituted and intact natural sands revealed that the reason why higher fines content leads to higher liquefaction strength does not depend on fines content itself but cementation effect, which tends to be pronounced as fines increase. This further indicates that the current practice on liquefaction resistance modification by fines content may lead to dangerous results if it is applied to very young deposits. In this vein, the ages of reclaimed lands, which generally contained a plenty of non-plastic fines, may have made differences during the Tohoku Pacific Ocean earthquake in liquefaction susceptibility of reclaimed lands despite their similar soil conditions.

Needless to say, more tests on in situ soils are needed in order to quantitatively propose an empirical formula for revising current liquefaction potential evaluation methods considering the aging effect in conjunction with the effect of fines content.

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