AGING EFFECT ON RELATIONSHIP BETWEEN LIQUEFACTION STRENGTH AND CONE RESISTANCE OF SAND CONTAINING NON-PLASTIC FINES

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ABSTRACT

Miniature cone penetration tests (CPT) and cyclic loading tests are carried out in a triaxial test specimen. An innovative simple mechanism is introduced in a normal cyclic triaxial apparatus enabling a miniature cone to penetrate into the specimen with a constant speed. The two test results are compared to yield direct correlations between penetration resistance ($q_t$) and liquefaction strength ($R_L$) for sands of different relative density containing various amount of fines and cement. An unique line relating cone resistance and liquefaction strength has been found for soils without cement irrespective of relative density and fines content. This indicates that liquefaction strength corresponding to a given cone resistance can be uniquely determined despite the difference in relative density, fines content etc. In order to simulate aging effect on the relationship between penetration resistance and liquefaction strength, sand samples mixed with cement are consolidated for a day to make an accelerated test. The results on the cement-mixed specimens show that the $R_L$ ~ $q_t$ relationship shifts upward with increasing cement content, indicating that the aging effect tends to considerably increase the liquefaction strength for the same CPT resistance $q_t$.

Keywords: liquefaction, cone penetration test, aging effect, fines content

INTRODUCTION

Recently liquefaction strength is evaluated using not only standard penetration tests but also by cone penetration tests (CPT) in engineering practice. If sand contains a measurable amount of fines, liquefaction strength is normally raised in accordance to fines content in most of liquefaction potential evaluation methods. As one of its experimental basis, Suzuki et al. (1995) carried out in situ penetration tests and soil sampling by in situ freezing technique from the same soil deposit and compared the tip resistance $q_t$-value and liquefaction strength $R_L$ of the undisturbed samples. The result showed that the higher fines content tends to increase the liquefaction strength for the same penetration resistance. In contrast to their finding, however, quite a few laboratory tests show that liquefaction strength clearly decreases with increasing content of low plasticity fines having the same relative density (e.g. Sato et al. 1997; Kokusho and Komiyama 2001, Hara et al. 2005, Kokusho et al. 2007). Thus, a wide gap seems to remain between the current practice for liquefaction potential evaluation and the laboratory experiment on the modification of the liquefaction strength in sands containing fines despite its importance in engineering design.

In order to establish direct correlations between cone resistance and liquefaction strength considering the effect of fines, a systematic experimental study was undertaken, in which cone

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penetration test and subsequent cyclic loading test were carried out on the same triaxial test specimen with parametrically changing relative density and fines content (Kokusho et al. 2005). An innovative simple mechanism originally introduced by Kokusho et al. (2003) was used enabling a miniature cone to penetrate the sand specimen.

In this paper, in addition to the previous tests (Kokusho et al. 2005), a new series of test are undertaken using the same triaxial apparatus for sand specimens containing various amount of fines mixed with cement. In the accelerated tests where the aging effect of natural sand deposits in a long geological period is simulated in a short time, penetration resistance and liquefaction strength are measured in the same specimen and compared to develop direct correlations between them.

TEST APPARATUS AND TEST PROCEDURES

In the triaxial apparatus used in this research, the specimen size is 100 mm in diameter and 200 mm high. In liquefaction tests, the soil specimen is 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 undrained cyclic loading, a metal pedestal below the soil specimen was modified as shown in Fig.1, so that a miniature cone can penetrate into the specimen from below. For that goal, the pedestal consists of two parts, a fixed circular base to which the cone rod is fixed and a movable metal cap, through the center of which 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 by water pressure supplied into a water reservoir in between the two parts (Kokusho et al. 2003). During the test, the pedestal cap is initially set up at the highest level by supplying water inside, and specimen is constructed on it. By opening a valve at the start of the cone penetration, the water in the reservoir is drained by the cell pressure, resulting in the settlement of a total body of the specimen at the top of the pedestal, realizing the relative upward penetration of the cone by 25 mm. The penetration rate 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 1/35 smaller in the cross-sectional area than the 10 cm$^2$ prototype cone normally used in the field. The strain gauges 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 in this test. Fines mixed with the sand is silty and clayey soils with low plasticity index of Ip<6 sieved from decomposed granite in reclaimed ground of the Kobe city, Japan. The grain size distribution curve is shown in Fig.2 and physical properties of sand, fines and cement are shown Table 1 and Table 2.

![Fig. 1 cross section (right) and Photograph (left) of the modified pedestal in the lower part of triaxial apparatus](image-url)
A prescribed quantity of Portland cement was completely mixed with the Masa soil to make the fines 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 values of $F_c$ 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 the fines, the consolidation time was controlled exactly 24 hours after wetting, while for tests without cement it was about 2 hours.

The specimen was fully saturated by using de-aired water in a double negative pressure method so that the Skempton’s 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. Modification of the cone resistance was implemented because the pore-pressure change during the undrained cone-penetration had some effect on the reading of the strain-gauge attached on the cone.

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 same specimen was cyclically loaded in undrained condition. 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 outside the pressure chamber. 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 is already confirmed in previous research (Kokusho et al. 2005) that the cyclic stress ratio for liquefaction is almost unaffected by the existence of cone rod and previous reconsolidation.

**TEST RESULT**

In the test, relative density $D_r$, fines content $F_c$ and cement content $C_c$ of the specimens were parametrically changed to investigate their effects on penetration resistance and undrained cyclic strength. Fig.3 shows cone resistance $q_t$ and excess pore-pressure $\Delta u$, respectively, plotted versus the penetration length for test results for $D_r=50\%$ with fines content, $F_c=0$, 5, 10 and 20% and cement content $C_c=0$, 0.5, 1.0%, respectively. It is clearly observed that $q_t$ increases with increasing $C_c$ under the same fines content $F_c$.

Fig.4 shows a relationship between stress ratios $R_s$ and number of loading cycles $N_c$, for the
double amplitude axial strain $\varepsilon_{DA}=5\%$ obtained by the series of undrained cyclic loading tests on sand specimens having $D_r \approx 50\%$ with fines content, $F_c = 0, 5, 10$ and $20\%$, and cement content $C_c = 0, 0.5$ and $1.0\%$ respectively. Obviously, the increase in fines content tends to reduce liquefaction strength $R_L$ in specimens without cement as already demonstrated by previous researches (Sato et al. 1997, Kokusho and Komiyama 2001, Hara et al. 2005, Kokusho 2007). Also indicated in the figure is that the $R_L$-value increases with increasing cement content for all the fines content $F_c$ and the increment is particular large for $F_c = 20\%$.

In Fig. 5, test results for different values of $D_r$, $F_c$ and $C_c$ are shown on the $R_L$- versus number of loading cycles $N_c$ diagram with different symbols. The open symbols (expect the star symbols) corresponding to the reference test for samples without cement are located along the solid straight line in the chart despite the differences in $D_r$ and $F_c$ as already found in the previous research (Kokusho et al. 2005).

The half-close and close symbols except the stars are all for samples with cement. Among them, the triangles for instance represent the case $F_c = 5\%$, and they move up from the open symbols ($C_c = 0$) to the half-close ($C_c = 0.5\%$) further to the full-close ones ($C_c = 1.0\%$) as $C_c/F_c$ changes from 0 to 20% for the same value of $F_c = 5\%$. In the similar manner, the diamonds and the squares move up with increasing $C_c$ or $C_c/F_c$ for the same fines content of $F_c = 10\%$ and $F_c = 20\%$. 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 aging effect tends to push up the data points on the $R_L$- diagram from the line of the reference tests without cement and gives higher liquefaction strength under the same cone resistance.

The star symbols in the same figure indicates the $R_L$- $q_i$ plots based on field investigations by Suzuki et al. (1995) combining prototype cone tests in situ and undrained cyclic triaxial tests on intact samples recovered from the same soil deposits by in situ freezing technique. It demonstrates a clear difference in the $R_L$- $q_i$ relationships due to different fines contents of $F_c < 1.0\%$, $F_c = 1.0-10\%$ and $F_c > 10\%$. Also noted is that two research results are in a good coincidence not only qualitatively but also quantitatively, particularly for the case without cement, despite a large difference in the procedure and the size of the CPT test.

On the other hand, if the data points with the same $C_c/F_c$-value of 5% or 10% are concerned, they can be recognized to shift upward from the reference line with increasing fines content. This
indicates that, under the same geological age, the higher fines content results in higher liquefaction strength for the same cone resistance. The present research results by the accelerated test clearly indicate that not the fines content itself but the chemical bonding effect by aging is responsible for the higher liquefaction strength for larger \( F_c \) under the same cone resistance.

Based on the data shown in Fig. 5, a relationship between the rate of increase in the cyclic stress ratio \( R_L \) or in the cone resistance \( q_t \) and the \( C_c/F_c \)-value with the fines content \( F_c \) as a parameter is shown in Fig. 6. It clearly indicates that the \( R_L \)-value increases more than the \( q_t \)-value with increasing chemical activity. This is probably because the liquefaction strength tends to be very sensitive to chemical bonding between sand particles, whereas the cone penetration tends to break it easily without much increase in the penetration resistance. Also noted in Fig. 6 is that not only the \( C_c/F_c \)-value but also the fines content \( F_c \) tends to considerably increase the rate of liquefaction strength in particular even under the same cement content as shown with the circles for \( C_c=1.0\% \) in the figure. It is probably because that higher fines content means larger soil surface area on which greater chemical reaction can occur. For the cone resistance, the effect of \( F_c \) are considerably large for the case of \( F_c=20\% \) and \( C_c/F_c=5\% \) in which some unknown effect may be responsible for the drastic increase in \( q_t \). In all other cases, the effect of \( F_c \) on cone resistance is evidently smaller than on liquefaction strength.
CONCLUSIONS

A series of experimental study by miniature cone penetration tests and subsequent cyclic loading tests are carried out in the same triaxial test specimen with parametrically changing fines content $F_c$ and cement content $C_c$ yielded the following major findings;

・ For reconstituted soils 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 relative soil density $D_r$ and fines content $F_c$.

・ 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 aging effect tends to raise the $R_L \sim q_t$ line from that for soils without cement.

・ For the same $C_c/F_c$-value (simulating the same geological age), higher fines content results in higher liquefaction strength for the same cone resistance, which is consistent with the trend found in the field investigations.

・ The liquefaction strength $R_L$ increases more than the $q_t$-value due to chemical bonding between sand particles and this effect is more pronounced for higher fines content. This is why the $R_L \sim q_t$ curves tend to shift upward due to the increase of fines content in the field, which is not observed for reconstitute soils in the laboratory.

Thus, it is revealed that the reason why higher fines content leads to higher liquefaction strength does not depend on fines content itself but bonding effect by aging, which tends to be pronounced as fines increase.

REFERENCES


