Correlation between CPT Data and Dynamic Properties of In Situ Frozen Samples

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SYNOPSIS: Correlations between cone penetration resistance and liquefaction resistance of sandy soils are examined, based on high quality undisturbed samples obtained by the in situ freezing method. For this purpose, the CPT tests are conducted at six sites where in situ frozen sands with fines contents up to 30 % were sampled and their dynamic properties were determined in the laboratory. The comparison of the CPT data with the soil properties of the in situ frozen samples has shown that: (1) Robertson's soil classification chart performs well for sandy soils in Japan; (2) the CPT q_t-value shows a good correlation with elastic shear modulus of the in situ frozen samples; and (3) the liquefaction resistance of the in situ frozen samples is uniquely expressed if the cone penetration resistance is normalized in terms of confining pressure and minimum void ratio.

INTRODUCTION

Various empirical correlations have been presented for evaluating the liquefaction resistance of a soil deposit, using index properties of field tests. Among these methods, the standard penetration test (SPT) has been widely used for many years in Japan and North America. However, because of the variability of the SPT results and of the versatility of the cone penetration test (CPT), the CPT has received increasing interest in recent years, and many empirical correlations using CPT data have been presented. Most of these correlations are, however, based on the second correlation between the CPT and the SPT, since there is a limited data base to correlate CPT data with actual field performance or with dynamic properties of high quality undisturbed samples.

Recently, in situ freezing sampling has been invented which can recover high quality undisturbed samples that retain in situ dynamic properties of sands (Yoshimi et al., 1989, Tokimatsu et al., 1990b). The object of this paper is to examine the correlation between the CPT data and the dynamic soil properties, based on the CPT tests performed at site where in situ freezing sampling was made.

IN SITU TEST

CPT Sites and Results

The CPT tests were conducted at six sites: Niigata Station, Showa Bridge, and Meike Elementary School, Niigata Prefecture; a man-made fill; Higashi-Ogishima, Kanagawa Prefecture; and Urayasu, Chiba Prefecture. The liquefaction resistance and the elastic shear modulus of the in situ frozen samples for the first five sites have been published elsewhere (Yoshimi et al., 1989, Tokimatsu et al., 1990b). To increase data base, in situ freezing sampling was made at Urayasu site. The sands at the three sites in Niigata Prefecture and at Urayasu site are fluvial deposits, while the sand at Higashi-Ogishima site had been improved by a vibratory sand compaction pile method.

The electric CPTU tests were conducted at each site with a penetration rate of 2 cm/s, which resulted in continuous records with depth of three components, i.e., cone penetration resistance q_t, sleeve friction f_s, and pore water pressure P_w.

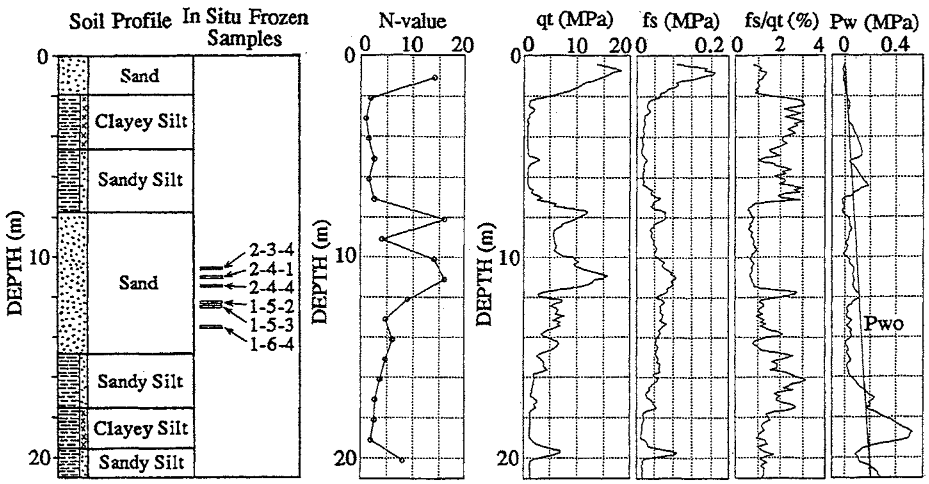
The CPT result for Urayasu site is shown in Fig. 1, along with the SPT result. The CPT result is presented in the form of distributions of the above three components in addition to friction ratio $R_f=f_s/q_t$. The variation of SPT N-value with depth shows a tendency very similar to that of the cone penetration resistance.

Soil Classification

Fig. 2 compares the type of soil in the SPT sampler with that estimated based on Robertson's chart (1990) using cone penetration resistance and friction ratio. The soil type obtained from the two methods agree reasonably well with each other. This indicates that the Robertson's chart is applicable to the soil in Japan.

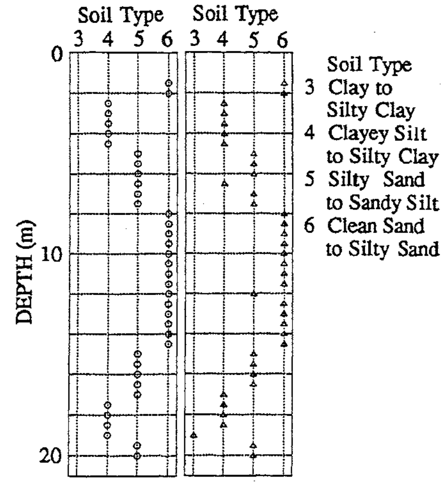
R_f-FC Relationship

Fig. 3 shows the relationship between friction ratio R_f and fines content FC of the samples obtained from the SPT. The friction ratio R_f tends to increase as the fines content FC increases. This suggests a possibility that the fines content FC can be approximately estimated from the friction ratio R_f.



a) Boring Log b) SPT Data c) CPT Data

Fig. 1. Comparison of CPT and SPT results at Urayasu Site



a) Boring Data b) CPT Data

Fig. 2. Soil Classification from Boring Data and CPT Data at Urayasu Site

LABORATORY TEST

Undrained cyclic shear tests were conducted on the samples taken from Urayasu at six different depths as shown in Fig. 1. The samples had dry densities of 1.21 to 1.43 g/cm³, mean grain sizes of 0.13 to 0.27 mm, and fines contents of 1.0 to 30.3 %.

The tests were conducted with an ordinary cyclic triaxial apparatus. Cylindrical specimens 50 mm in diameter and 100 mm high were used. After the specimen had thawed completely and had been consolidated, a non-destructive cyclic loading test was conducted to measure elastic shear modulus at a shear strain amplitude of 10^{-5}, G_o. An undrained cyclic shear test was then performed by applying sinusoidal loading of constant axial load amplitude at a frequency of 0.1 Hz.

Fig. 4 shows the relationship between cyclic stress ratio $\sigma_d/2\sigma_o'$ required to cause a double amplitude axial strain DA of 5 % and the number of cycles N_c. The cyclic stress ratios for DA=5% and N_c=15 cycles for the sands, hereby called liquefaction resistance, vary from 0.21 to 0.36.

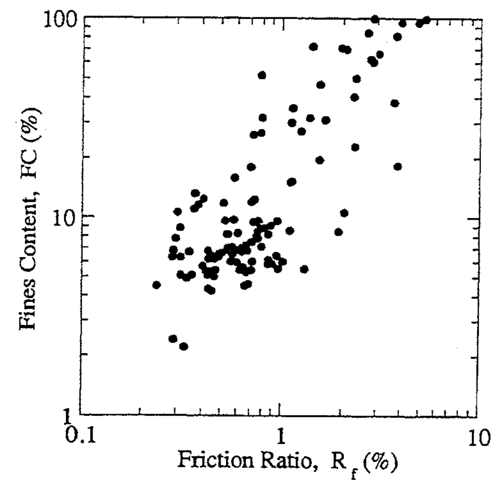


Fig. 3. Correlation between Fines Content and Friction Ratio

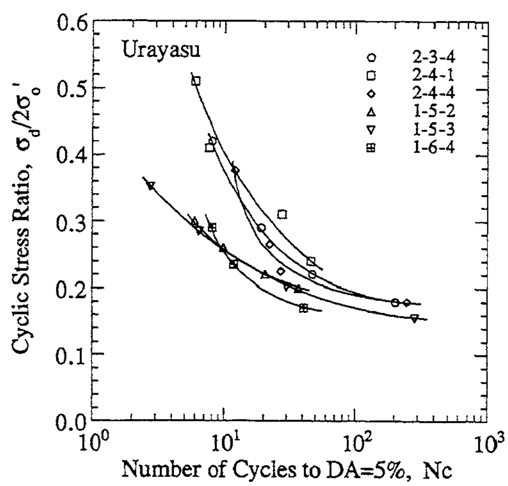


Fig. 4. Cyclic Stress Ratio Required to Cause Double Amplitude Axial Strain of 5%

CORRELATION BETWEEN IN SITU AND LABORATORY TESTS

Fig. 5 shows the correlation between modified cone penetration resistance q_{t1} and liquefaction resistance obtained from the in situ frozen samples, in terms of fines content. The q_{t1} corrected for an effective overburden pressure of 1 kgf/cm² (98 kPa) are defined as;

$$q_{t1}=q_t/\sigma_v'^{0.5} \tag{1}$$

where σ_v' is effective overburden pressure (kgf/cm²). As expected the liquefaction resistance increases with increasing the q_{t1}-value, and the higher the fines content, the higher the liquefaction resistance for the same q_{t1}-value. The liquefaction resistance, therefore, varies considerably when the q_{t1}-value exceed 15 MPa, depending on the variation in fines content. Considering the good correlation between FC and R_f in Fig. 3, the effects of fines content on liquefaction resistance may be estimated with use of R_f even though soil samples cannot be obtained.

In order to compare the liquefaction resistance vs. q_{t1} relations of the in situ frozen samples with those based on field performance data during earthquakes, the liquefaction resistance $\sigma_d/2\sigma_o'$ in Fig. 5 is converted to the in situ liquefaction resistance τ_l/σ_v' by the following relationship (e.g. Seed, 1979).

$$\left(\frac{\tau_l}{\sigma_v'}\right)_{field} = 0.9\,\frac{1+2K_o}{3}\left(\frac{\sigma_d}{2\sigma_o'}\right)_{triaxial} \qquad (2)$$

in which 0.9 is a factor to correct for the effects of multidirectional shear, and K_o is the coefficient of earth pressure at rest. Because it is quite difficult to evaluate K_o in situ, K_o is assumed to be between 0.5 and 1.0.

Fig. 6 shows the correlation between in situ liquefaction resistance of the in situ frozen samples and q_{t1}. Also shown in the figure are the correlation by Shibata et al. (1988), and a correlation converted from the SPT-based correlation by Tokimatsu et al. (1983), using $q_{t1}=7N_1$. The frozen samples show a slightly lower liquefaction resistance than that suggested by Shibata et al. (1988) in the q_{t1} range from 15 to 20 MPa, particularly for clean sands with FC<1.0(%). These clean sands, however, show a fairly good agreement with the curve converted from $q_{t1}=7N_1$.

CPT-BASED LIQUEFACTION EVALUATION

Fig. 7 shows the correlation between cone penetration resistance q_t and elastic shear modulus G_o of the in situ frozen samples. There is a unique correlation between the two.

Tokimatsu et al. (1990a), pointed out that, regardless of soil type, the liquefaction resistance is uniquely defined by normalized shear modulus defined as;

$$G_N = G_o/\{f(e_{min})\sigma_m'^{0.5}\} \qquad (3)$$

where $f(e)=(2.17-e)^2/(1+e)$, e_{min} is minimum void ratio and σ_m' is mean effective pressure (kgf/cm²). It is considered in Eq. (3) that both the effects of confining pressure and soil type are normalized by the terms $\sigma_m'^{0.5}$ and $f(e_{min})$. Considering the good correlations between G_N and liquefaction resistance and between q_t and G_o, it is expected that the liquefaction resistance vs. q_t relation is also influenced by confining pressure as well as soil type, e.g., $f(e_{min})$. To examine this, the correlation between modified cone penetration resistance q_{t1} and liquefaction resistance $\sigma_d/2\sigma_o'$ is shown in Fig. 8 in terms of minimum void ratio e_{min}. As expected, the liquefaction resistance tends to

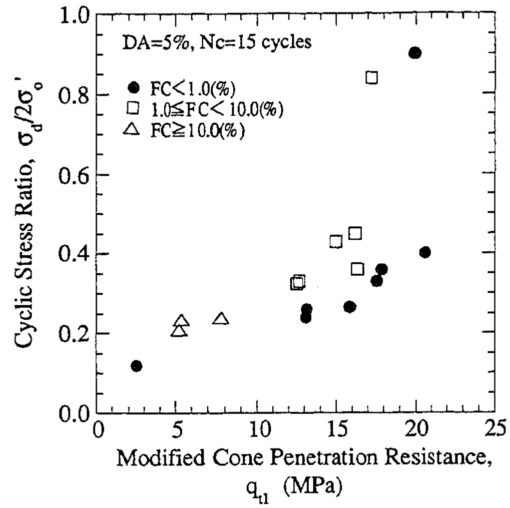


Fig. 5. Correlation between Cyclic Stress Ratio and Modified Cone Penetration Resistance

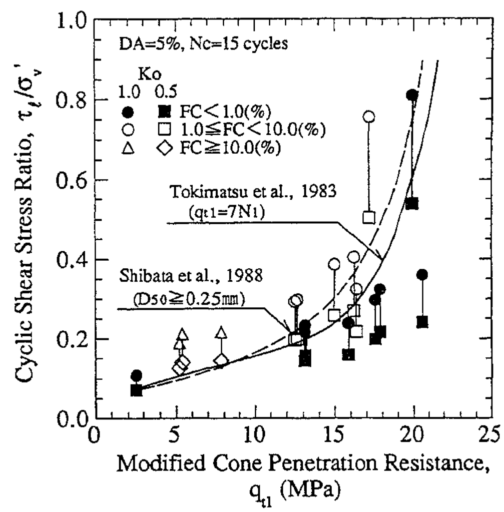


Fig. 6. Correlation between Cyclic Shear Stress Ratio and Modified Cone Penetration Resistance

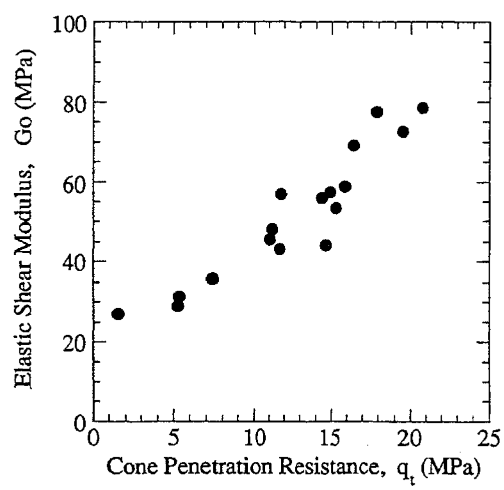


Fig. 7. Correlation between elastic Shear Modulus from In Situ Frozen Samples and Cone Penetration Resistance

increase with increasing minimum void ratio for the same q_{t1} value. It is therefore considered that the effects of soil type on liquefaction resistance may be estimated with the minimum void ratio as well as with fines content.

Thus, according to Eq. (3), the cone penetration resistance is normalized in terms of minimum void ratio and confining pressure as;

$$q_{tN}=q_{t1}/f(e_{min})=q_t/\{f(e_{min})\sigma_v'^{0.5}\} \quad (4)$$

Fig. 9 shows the correlation between the normalized cone penetration resistance q_{tN} and liquefaction resistance of the in situ frozen samples. The data come to fall within a narrower band, compared with those in Fig. 8, and appear to be independent of minimum void ratio. This suggests that e_{min} is a good index to normalize CPT resistance in terms of soil type. The minimum void ratio is nevertheless a value which cannot be measured directly from the CPT. In the future, a method for evaluating the minimum void ratio or an alternative index from the CPT results should be sought.

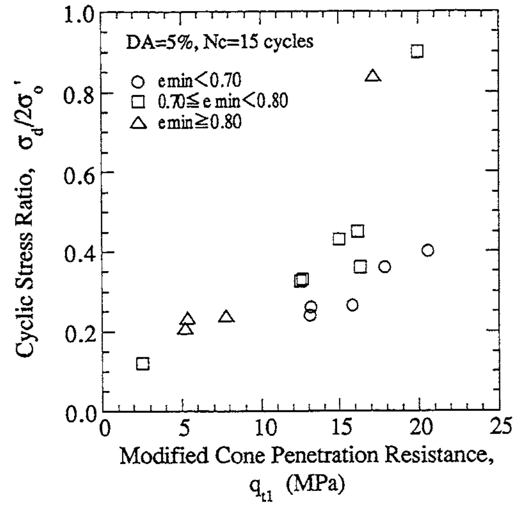


Fig. 8. Correlation between Cyclic Stress Ratio and Modified Cone Penetration Resistance

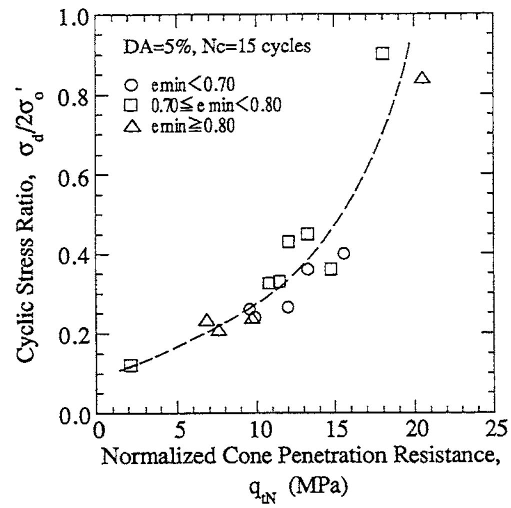


Fig. 9. Correlation between Cyclic Stress Ratio and Normalized Cone Penetration Resistance

CONCLUSIONS

Cone penetration tests were conducted at six sites where the dynamic characteristics of sandy soil had already been determined from in situ frozen samples. The CPT results were compared with the liquefaction resistance and the elastic shear modulus of the samples with fines contents up to 30 %. Based on the above, the following conclusions may be made:

(1) The soil classification chart by Robertson may be successfully applicable for evaluating soil type in Japan.

(2) The liquefaction resistance of sandy soils can be predicted using modified cone penetration resistance q_{t1} and fines content FC. Fines content FC can be approximately estimated from friction ratio R_f.

(3) There is a unique correlation between cone penetration resistance q_t and elastic shear modulus G_o of in situ frozen samples, irrespective of fines content.

(4) There is a unique correlation between normalized cone penetration resistance q_{tN} and liquefaction resistance, irrespective of minimum void ratio.

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