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EVALUATION OF UNDRAINED CYCLIC SHEAR STRENGTH OF SOILS WITH SHEAR WAVE VELOCITY

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SUMMARY

A method is presented for evaluating liquefaction resistance of cohesionless soils using shear wave velocity. The method includes: shear wave velocity measurements and sand sampling in situ, and liquefaction tests on a specimen reconstituted in the laboratory. The effectiveness of the proposed method was studied at three sites where high quality undisturbed samples were obtained by an in situ freezing technique. Liquefaction tests were made on the in situ frozen samples as well as the reconstituted specimens. The reconstituted specimen was prepared in such a way that its elastic shear modulus becomes equal to the in situ value which can readily be determined based on shear wave velocity measurements. The liquefaction resistance of the reconstituted specimen is compared with that of the in situ frozen samples. There exists a fairly good agreement between the two resistances, indicating that the proposed method using shear wave velocity is an effective means for soil liquefaction evaluations.

INTRODUCTION

There currently exist few reliable methods to evaluate undrained cyclic shear strength (liquefaction resistance) of dense sand and gravel, because of difficulty in obtained good-quality undisturbed samples of these soils and the inability of using penetration type tests at these deposits. The effects of sample disturbance on the undrained cyclic shear strength of these soils are significant and cannot be neglected. Although the in situ freezing technique can secure good-quality undisturbed samples from such deposits, its high cost prevents its use in every practice. There is a strong need, therefore, to develop an alternative method to evaluate liquefaction resistance of these soils. A potential method for this purpose is to use shear wave velocity measurements because of their feasibility in the field. Significant feature of shear wave velocity is that it has a potential to link the lab and field tests since it can be measured in the laboratory as well.

Extensive studies on the shear modulus of sandy soils (e. g., Hardin and Drnevich, 1972) have shown that elastic shear modulus could be a function of such factors as : (1) void ratio or relative density, (2) soil fabric formed during their geological history, (3) effective confining pressures including K_o condition, and (4) soil type. There general effects on elastic shear modulus and liquefaction resistance are summarized in Table 1. Since most of the factors can also affect stress ratio to cause liquefaction, a good correlation would exist

Table 1 Factors Affecting Liquefaction Resistance and Shear Modulus

Factor	Effect on Stress Ratio to Cause Liquefaction	Effect on Shear Modulus
Increased Relative Density	+1)	+
Increased Stability of Soil Fabric	+	+
Increased K_o	+	+
Increased Effective Stress	-2)	+
Factor when different soils are Compared	Plasticity	Void Ratio

1) positive effect, 2) insignificant effect

between liquefaction characteristics and shear modulus if soil and effective confining pressure are specified. In fact, Tokimatsu et al. (1986) showed that: (1) different soils have different relationship between liquefaction resistance and elastic shear modulus, but (2) the liquefaction characteristics could be reasonably well correlated with elastic shear modulus for a given soil under given confining pressures. This means that the reconstituted specimen which has the same shear modulus as that in situ would also retain the in situ liquefaction resistance. Based on this concept, they proposed a method to evaluate liquefaction resistance of saturated cohesionless soils. Although the method is promising, there currently exists limited laboratory verification. The object of this paper is to show the outline of the method using shear wave velocity and to demonstrate its effectiveness in liquefaction evaluations.

OUTLINE OF THE METHOD USING SHEAR WAVE VELOCITY

Fig. 1 shows the proposed procedure for evaluating the in situ liquefaction characteristics of sand and gravel. The procedure shown on the left corresponds to the shear wave velocity measurements in situ. Based on the measured shear wave velocity, V_s, the elastic shear modulus in the field, G_{OF}, can readily be determined.

The procedure on the right involves laboratory tests on a specimen reconstituted from the sample obtained at the site. Before liquefaction test, the shear modulus at small shear strain, G_{OL}, of the specimen is measured, and compared with G_{OF}. If they are equal, the liquefaction test is run on the same specimen. If they are not equal, that usually means that G_{OF} is larger than G_{OL}, cyclic shear stresses are applied to the specimen until the shear modulus reaches the field value; then the liquefaction test is run. The working principle in this procedure is that the liquefaction strength has a good correlation with elastic shear modulus for a given soil under given confining pressures.

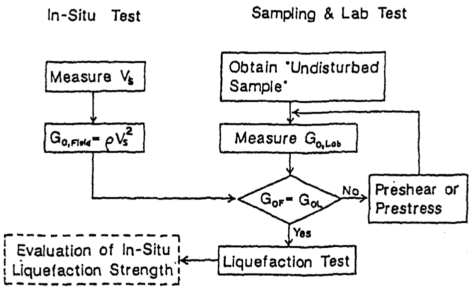

Fig. 1 Outline of the Proposed Method

SITE CHARACTERISTICS AND IN SITU SAMPLING

To investigate the effectiveness of the method, in situ sampling and shear wave velocity measurements, and laboratory tests were performed for a saturated sand fill and natural soil deposits at two sites in Niigata, Japan. The soil profile of the fill is shown in Fig. 2, and those at two sites in Niigata in Figs. 3 and 4. The sand shown in Fig. 2 was filled in a large bin by pouring saturated sand underwater about 7 days before sampling. Thus it is an extremely young deposit. The sand shows in Fig. 3 is an alluvial stratum with a relative density of 55%. The sands in Fig. 4 is a dense alluvial stratum with a relative density of 87%.

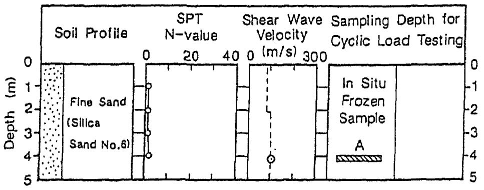

Fig. 2 Soil Profile of Man-Made Fill

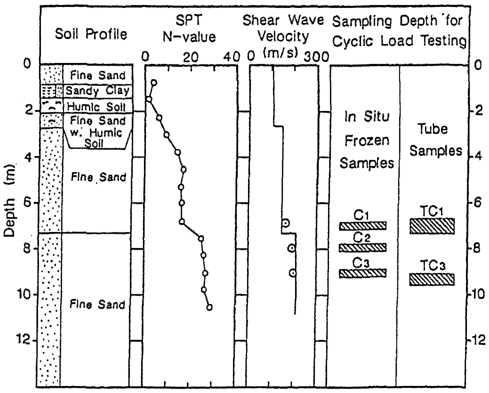

Fig. 3 Soil Profile at Sampling Site at Meike Elementary School

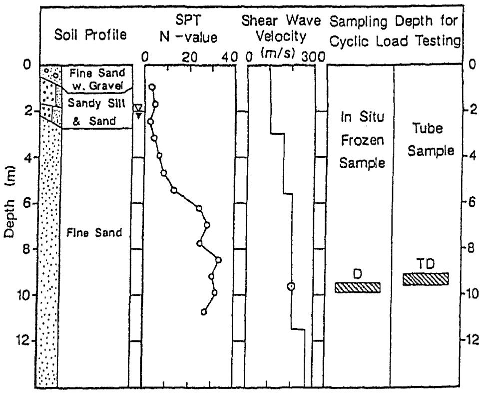

Fig. 4 Soil Profile at Sampling Site near Niigata Station

At each site, samples were obtained by in situ freezing method which is considered to recover high-quality undisturbed samples. Detailed procedures of the sampling are described elsewhere (Yoshimi et al., 1984). A conventional tube sampling was also made at the two sites in Niigata. After draining pore water, the tube samples were frozen to prevent disturbance during transportation. Physical properties of the sand used in this study are summarized in Table 1, and sampling depths are shown in Figs. 2 to 4. The in situ frozen samples from these sites are designated as Sample A, Sample C_1, and Sample D, respectively. The normalized N-values, N_1, for the effective vertical stress of 1 kgf/cm^2 for these samples are 2 for Sample A, 18 for Sample C_1, and 30 for Sample D. Table 1 indicates that the N_1-values of Sample A and Sample C_1

Table 2 Field Conditions and Physical Properties of In Situ Frozen Samples

Sample	A	C_1	D
N-value	1	16	32
σ_v' (kgf/cm^2)	0.37	0.80	1.08
N_1-value	2	18	30
G_s	2.68	2.74	2.69
ρ_{max} (g/cm^3)	1.55	1.64	1.52
ρ_{min} (g/cm^3)	1.23	1.33	1.22
D_{50} (mm)	0.26	0.23	0.29
D_{10} (mm)	0.16	0.16	0.18
U_c	1.8	1.6	1.8
ρ_d (g/cm^3)	1.39	1.48	1.47
D_r(%)	56	54	87
G_r(kgf/cm^2)	275	580	800

differ considerably although their relative densities are about equal.

LABORATORY TESTS ON SAMPLES OBTAINED BY IN SITU SAMPLING

Undrained cyclic triaxial tests were conducted using the in situ frozen samples to provide probable in situ liquefaction characteristics which are used as references in studying the effectiveness of the proposed method. The tests were also made using tube samples to examine the effects of sample disturbance during conventional sampling.

Cylindrical specimens, 50 mm in diameter and 125 mm high or 75 mm diameter and 150 mm high, were cut out from frozen sand with a power saw and a steel straight edge. The specimen was then thawed and consolidated under an isotropic confining pressure which was the vertical or mean effective stress of the sample in situ. After the specimen had been consolidated for about two hours, a non-destructive cyclic loading test was conducted to measure elastic shear modulus at shear strain amplitude of 10^{-5}, G_r. Further details of the procedure and interpretation of the test results were described elsewhere (Tokimatsu et al., 1986). An undrained cyclic triaxial test was then performed by applying sinusoidal loading of constant axial load amplitude at a frequency of 0.1 Hz.

The liquefaction characteristics of the samples are shown in Figs. 5 to 7 in which the shear stress ratios are plotted against the number of cycles to cause a double amplitude axial strain of 5%. The circles are for high-quality undisturbed samples obtained by in situ freezing, and the triangles are for so-called "undisturbed" samples obtained by a conventional tube sampling method. It can be seen that the strengths of the tube samples are significantly lower in shear modulus and strength than the in situ frozen samples, and that the shear moduli of the in situ frozen samples are consistent with the shear wave velocities in situ as shown in Figs. 2 to 4. The good agreement implies that high quality

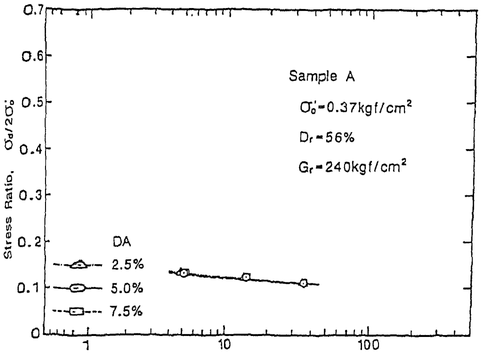

Fig. 5 Liquefaction Characteristics of Sample A

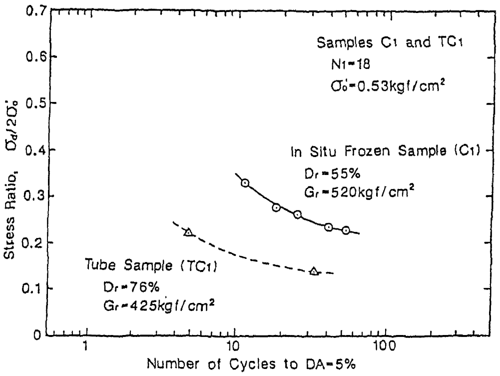

Fig. 6 Liquefaction Characteristics of Sample C_1

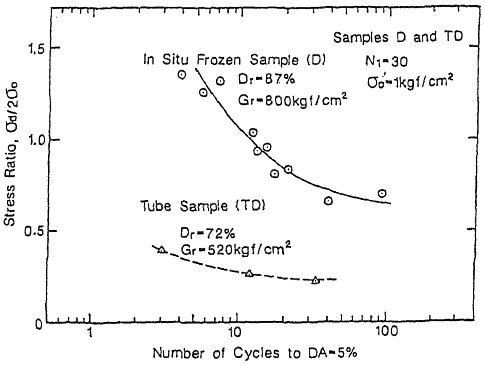

Fig. 7 Liquefaction Characteristics of Sample D

undisturbed samples have been secured by the in situ freezing, while the tube samples were disturbed during sampling. Liquefaction strength of tube samples is about 50 % that of the high quality undisturbed sample in Fig. 6 and only 30% in Fig. 7. This indicates that the effects of sample disturbance becomes pronounced as the soil gets denser.

Concerning the in situ frozen samples, Sample C_1 has a considerably higher liquefaction resistance than dose Sample A, despite their similar relative density. It is conceivable that the difference in liquefaction resistance is due to the difference in soil fabric between the two samples.

LIQUEFACTION CHARACTERISTICS OF SAMPLES PRESHEARED IN THE LABORATORY

Another series of liquefaction tests was run to investigate the effectiveness of the proposed method. According to the proposed procedure shown in Fig. 1, specimens were reconstituted from either tube samples or the remainder of the in situ frozen samples so that their shear moduli became equal to that in situ. Concerning the young deposited sand shown in Fig. 2, such specimen was able to be prepared by pluviating dry sand without any application of shear stress. The specimen corresponding to Sample C_1 in Fig. 3 was first prepared by pluviating dry sand, and then subjected to cyclic shear strain to increase their elastic shear moduli to the in situ values. The specimen corresponding to Sample D in Fig. 4 was the tube sample subjected to cyclic shear strain history in the laboratory. The application of cyclic shear strain history increased its elastic shear modulus from 520 kgf/cm^2 to 800 kgf/cm^2.

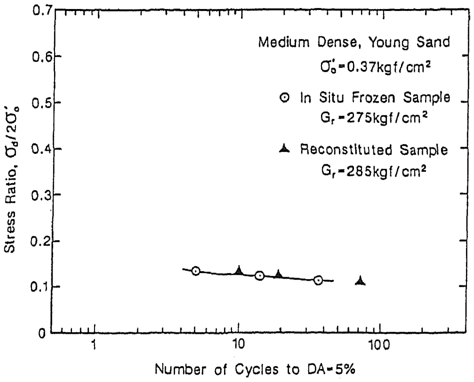

Fig. 8 Comparison of Liquefaction Resistances between Sample A and Reconstituted Sample

The test results are shown in Figs. 8 to 10 together with the strength curves of the samples obtained by in situ freezing. The solid symbols in the figures represent the test results of the reconstituted specimen. The liquefaction resistance of the reconstituted specimens agrees reasonably well with those of the in situ frozen samples. The good agreement in resistance between the two

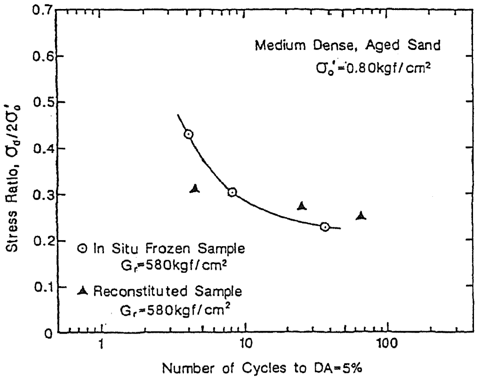

Fig. 9 Comparison of Liquefaction Resistances between Sample C_1 and Reconstituted Sample

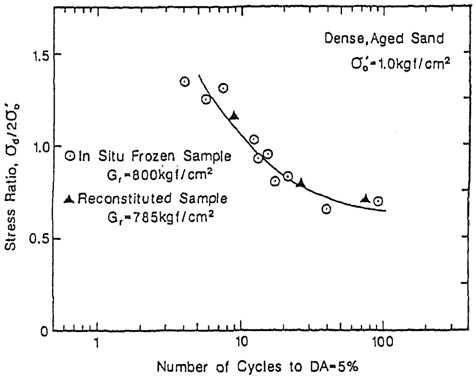

Fig. 10 Comparison of Liquefaction Resistance between Sample D and Reconstituted Sample

specimens seems to show that the proposed method is effective for liquefaction evaluations. Thus the elastic shear modulus can be an effective indicator for reproducing an equivalent soil fabric likely to be developed in the field and hence for assessing liquefaction characteristics with a reasonable degree of accuracy.

CONCLUSIONS

A method is presented for evaluating liquefaction resistance of cohesionless soils based on the comparison of shear wave velocities measured in the field and the laboratory. The undrained cyclic triaxial tests were conducted on undisturbed samples as well as reconstituted samples to investigate the effectiveness of the proposed method. The test results indicate that: (1) the sand obtained by tube sampling yields significantly lower undrained cyclic shear strength and modulus than those of the in situ frozen samples, but (2) a reconstituted specimen which was prepared to have the shear modulus equal to that in situ, provides liquefaction characteristics similar to those of the in situ frozen samples. Hence, the method based on measuring shear wave velocities in the field, obtaining samples by a conventional method, and reconstituting them to recreate the in situ shear modulus under simulated in situ stress conditions, would be a promising means for reasonably assessing liquefaction characteristics on the basis of laboratory tests. This procedure can be particularly attractive for relatively dense sands and for gravels where SPT and CPT measurements cannot be operated or their results are unreliable.

In order to make the proposed method more reliable, it is required to improve the accuracy of shear wave velocity measurements because the error in the shear wave velocity is doubled when computing the shear modulus. Another item for future improvement is the estimation of the earth pressure at rest, K_o, for simulating the in situ confining stress in the laboratory. Never-the-less, it is believed that the proposed method provides a practical means for evaluating the in situ liquefaction characteristics of sand and gravel.

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