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Evaluation of liquefaction resistance of in-situ undisturbed and reconstituted samples with small strain shear moduli

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ABSTRACT

The liquefaction resistance which is one of the most important parameters in the liquefaction assessment would be determined by the laboratory test on undisturbed sample. However, a number of previous studies indicate that the sample by conventional tube sampling technique could be disturbed during the sampling at the field and during the sample preparation in the laboratory. The authors conducted dynamic small strain measurement and undrained cyclic triaxial test on in-situ samples retrieved from the fill and Holocene deposits at the liquefied site of the 2011 Off the Pacific Coast of Tohoku Earthquake. The applicability of the conventional tube sample and reconstituted sample to the liquefaction assessment was discussed, by comparing their small strain shear moduli and liquefaction resistances. The results show that the in-situ soil structure conditions would be reflected in the reconstituted sample of fill and the tube sample of Holocene deposit, and their liquefaction resistance are consistent with the fact observed during the 2011 earthquake.

Introduction

The 2011 Off the Pacific Coast of Tohoku Earthquake, with a *M*w of 9.0, caused significant soil liquefaction over a wide range in the Kanto and Tohoku Regions in Japan (e.g., Towhata et al., 2014). A number of affected cities has conducted liquefaction assessment based on the borehole data and the relevant laboratory tests with undisturbed samples.

However, the soil structure of the sand sample by conventional tube sampling (denoted as TS) method is prone to disturbance during sampling at the field and/or by poor handling during sample preparation in the laboratory (e.g., Seed et al., 1982). Hatanaka et al. (1995) investigated the effects of disturbance of TS sample on liquefaction characteristics by comparing with the sample taken by in-situ frozen sampling (denoted as FS) technique. They reported that the liquefaction resistance of the TS sample was higher than that of the FS samples for loose artificial fill sands, while that of the TS samples was much lower than that of the FS samples for natural medium dense sands, and the difference between them increases with increase in their SPT-N value. In this connection, Tokimatsu and Hosaka (1986) conducted a series of small strain measurements and liquefaction tests on the TS and the FS samples, and reported that the effect of sample disturbance on the liquefaction resistance could be evaluated by comparing the small strain shear moduli measured in the laboratory and in the field by PS logging.

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Tokimatsu et al. (1986) reported that it would be reasonable for the liquefaction assessment 1) to measure the shear moduli in the field, 2) to obtain samples by the TS method, and 3) to pre-stress them to recreate the in-situ shear modulus and density under simulated in-situ stress condition. In addition, Kiyota et al. (2009a and b) conducted a series of liquefaction tests on the FS samples and their reconstituted samples, and found that the application as suggested by Tokimatsu et al. (1986) would be relevant for the less-cemented soils, like recent reclaimed land and Holocene deposit.

In this study, in order to investigate the applicability of tested samples for the liquefaction assessment, a series of dynamic small strain measurements and undrained cyclic triaxial tests was performed on the reconstituted sample of fill and the TS sample of Holocene deposit retrieved from a site in Urayasu City where severe liquefaction occurred by the 2011 earthquake.

Sampling Site

Figure 1 shows spatial distribution of observed boiled sands after the 2011 earthquake in Urayasu City, Chiba Prefecture. Significant liquefaction occurred in the red colored area, while few evidences of liquefaction was reported in the blue colored area (Yasuda et al., 2012). The boundary between those areas overlaps approximately with the old coast line before the middle of the 20th Century. Yasuda et al. (2012) and many others reported that the liquefaction resistance of the surface layer in the old deposit area could be higher than that in the young reclaimed area because of aging effect of soil material.

Figures 2 shows soil profile at the sampling site indicated in Fig. 1. The occurrence of liquefaction at the sampling site was confirmed by the eyewitness account. The Holocene deposit is covered with loose filled soil six meters thick which is thought to be liquefied during the 2011 earthquake. The sample used in this study was retrieved by the TS method by Urayasu City as part of inner working of Technical Committee on Measures against Liquefaction.

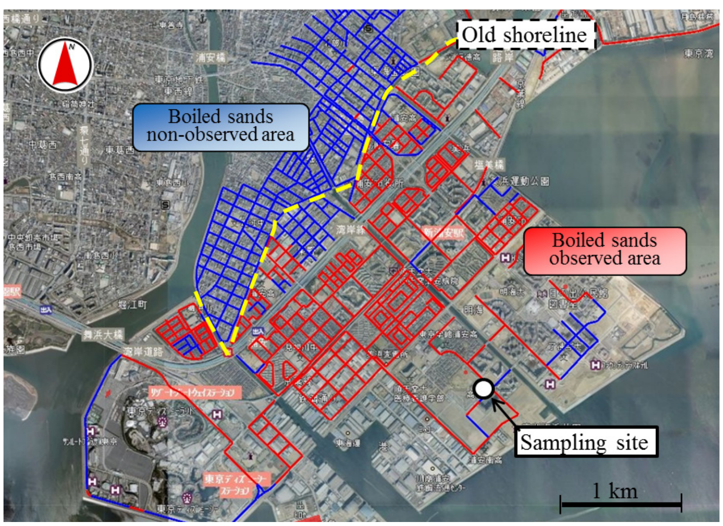

Figure 1. Spatial distribution of observed boiled sands in Urayasu City after the 2011 Off Pacific Coast of Tohoku Earthquake (after Yasuda et al., 2012)

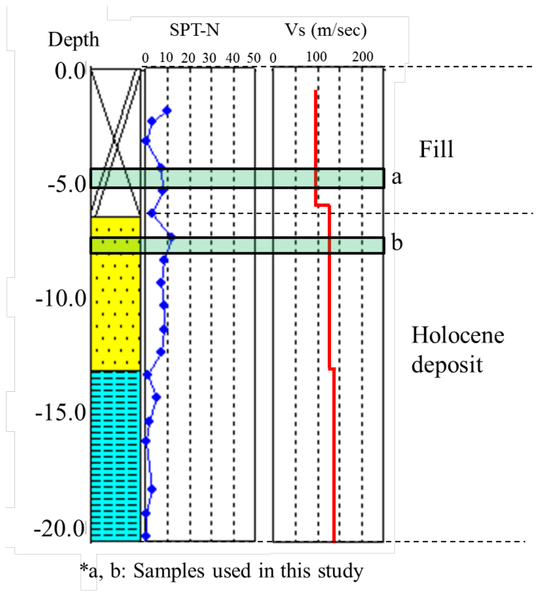

Figure 2. Borehole data, Vs measurement and depths of sampling (after Urayasu City, 2012)

Tested Soil Profiles and Apparatus

Table 1 shows the basic soil properties of the tested samples. It should be noted that the sample of fill is the reconstituted sample which was prepared by pluviating oven-dried particles through air at almost the same dry density levels as the original TS samples that were used in the study of Technical Committee organized by Urayasu City (2012).

A triaxial apparatus shown in Fig. 3 was used. A cylindrical specimen used was approximately 75 mm in diameter and 150 mm in height. A pair of accelerometers was used to measure the S wave velocity, V_s. Refer to Kiyota et al. (2009a and b) for the details of the dynamic measurement of shear moduli. The specimens were saturated at the confining pressure of 30 kPa, and then consolidated to the same isotropic effective stress levels as the in-situ overburden stress at the sampling depth. The small strain shear moduli of each specimen were measured at several stress states during the isotropic consolidation. After the consolidation, undrained cyclic triaxial tests were performed with constant amplitude of cyclic deviator stress.

Table 1. Soil properties of tested samples

Type of soil layer	Depth (GL- m)	Sample condition	SPT-N**	V_s by PS logging (m/sec)	D_{50} (mm)	Fc (%)	e_{max}/e_{min}
Fill	a) 4.45-5.37	Reconstituted*	7-8	95	0.128	28.6	1.823/0.946
Holocene deposit	b) 7.4-7.9	TS	9-12	124	0.186	2.9	1.552/0.912

*: Original TS sample was tested by Urayasu City (Technical Committee on Measures against Liquefaction, 2012).
**: Raw values measured at the site

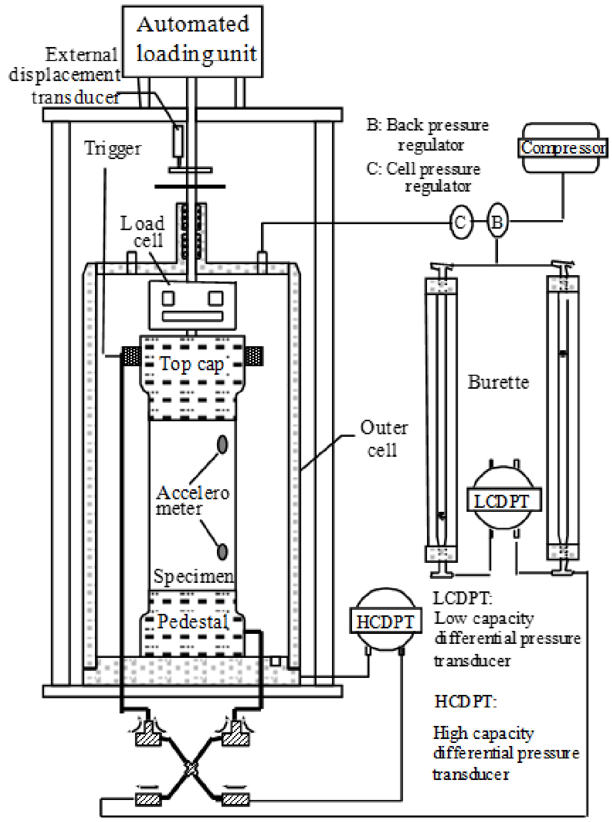

Figure 3. Triaxial apparatus and measurements (Kiyota et al., 2009)

Dynamically Measured Small Strain Shear Moduli

Figure 4 shows the relationship between small strain shear moduli, G_d, and effective stress parameter, $(\sigma_v'\sigma_h')^{0.5}$ of the reconstituted sample of fill. Note again that the initial density of the reconstituted samples in this study was adjusted to that of the original TS samples, which was provided by Urayasu City (2012). The values of G_d increased with increase in $(\sigma_v'\sigma_h')^{0.5}$ during an isotropic consolidation. The results of G_d obtained by in-situ PS logging, which saturated soil density was assumed to be the average value of the TS samples, are also plotted in Fig. 4 with a black square symbol assuming K_0= 0.5. The G_d values of the reconstituted samples were comparable to the result of in-situ PS logging. Unfortunately, the small strain measurement was not carried out on the original TS sample. However, the result in this study indicated that the in-situ soil condition was successfully reproduced in the reconstituted sample in terms of the small strain characteristics (Tokimatsu et al, 1986; Kiyota et al., 2009a).

Figure 5 shows the G_d values of the TS samples of Holocene deposit. The G_d values of Holocene deposit were larger than those of fill soil shown in Fig. 4. This trend is naturally accepted by considering the SPT-N value for each sample shown in Table1. The average value of G_d of the TS samples of Holocene deposit was nearly identical to the result of PS logging, which implies that the sample disturbance could be relatively small.

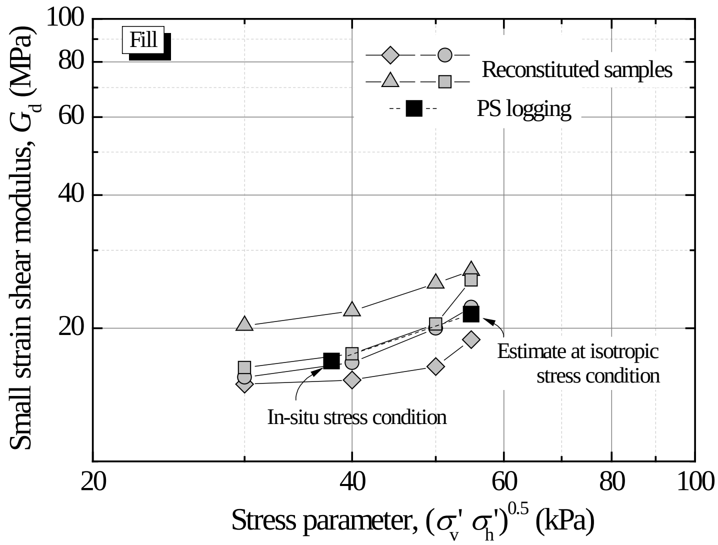

Figure 4. Relationship between small strain shear moduli, G_d, and $(\sigma_v'\sigma_h')^{0.5}$ of reconstituted sample (Fill)

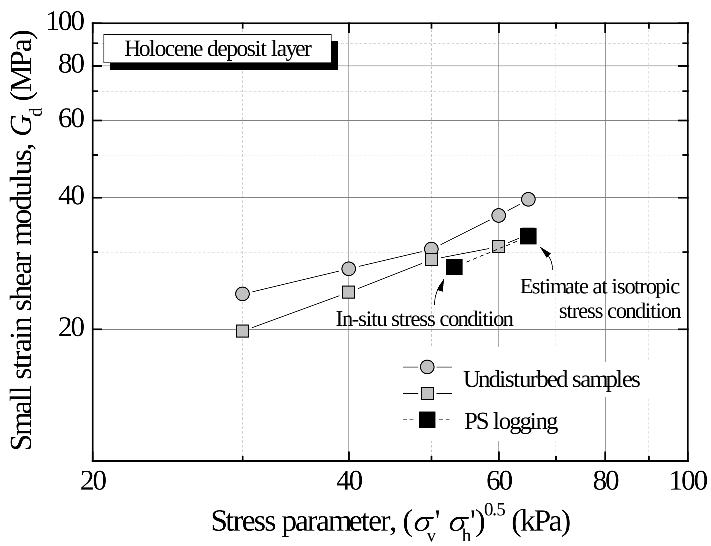

Figure 5. Relationship between small strain shear moduli, G_d, and $(\sigma_v'\sigma_h')^{0.5}$ of TS sample (Holocene deposit)

Liquefaction Tests

Figures 6 and 7 show the typical results of the undrained cyclic triaxial test on the reconstituted sample of the fill and the TS sample of the Holocene deposit, respectively. The liquefaction process of both samples were different from each other in spite of the same cyclic stress ratios applied, $\sigma_d/2\sigma'_c = 0.3$, where σ_d and σ'_c denote single amplitude of the cyclic vertical stress and the effective confining pressure at the end of isotropic consolidation, respectively.

Figure 8 shows the relationships between the $\sigma_d/2\sigma'_c$ and the number of cycles, N_c, required to cause double amplitude of vertical strain, $\varepsilon_{v(DA)}$= 5% for the reconstituted sample of fill and the TS sample of Holocene deposit. The results of original TS samples by Urayasu City (2012) are also shown in Fig. 8. The liquefaction resistance, R_{L20}, of the TS sample of fill was about 30 % higher than that of Holocene deposit, which is inconsistent with the fact that severe liquefaction occurred in the fill area rather than the natural deposit area. In the previous section, since we have verified that the disturbance of the TS sample of Holocene deposit was relatively small, it is likely that the TS sample of fill would had disturbance strengthening the specimen against liquefaction. On the other hand, the R_{L20} of the reconstituted sample of fill was about 50 % lower than that of Holocene deposit, which is consistent with the field survey results in Urayasu City shown in Fig. 1.

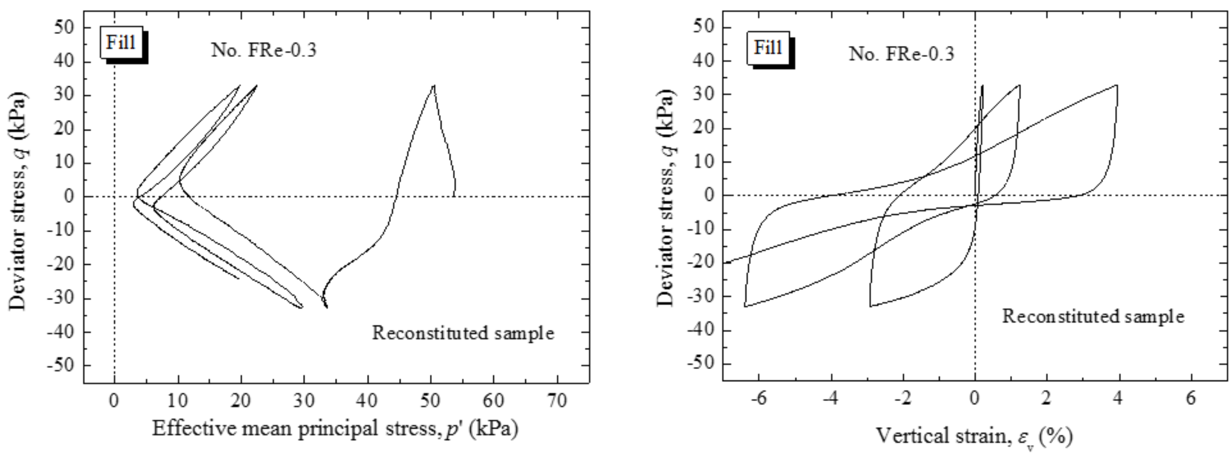

Figure 6. Stress path and stress-strain relation during liquefaction test of reconstituted sample (Fill)

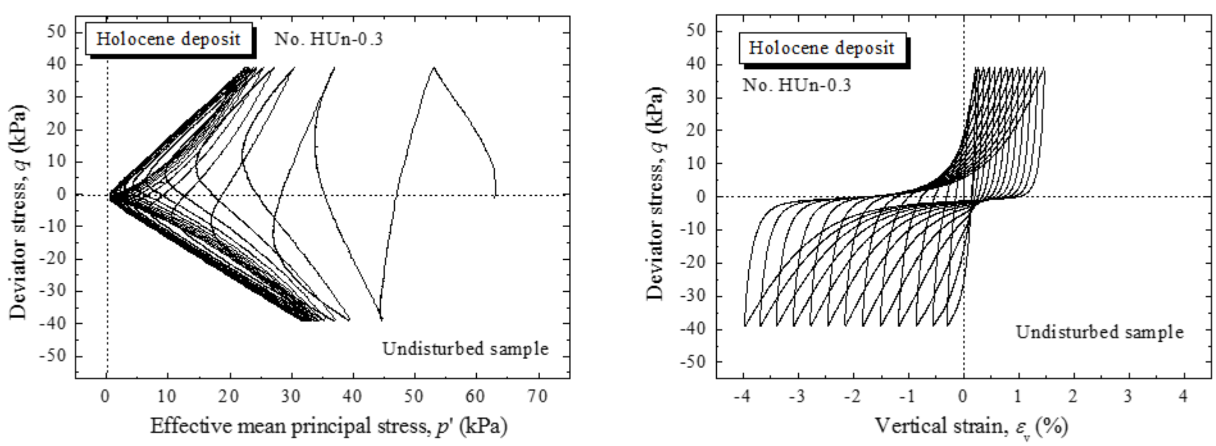

Figure 7. Stress path and stress-strain relation during liquefaction test of TS sample (Holocene deposit)

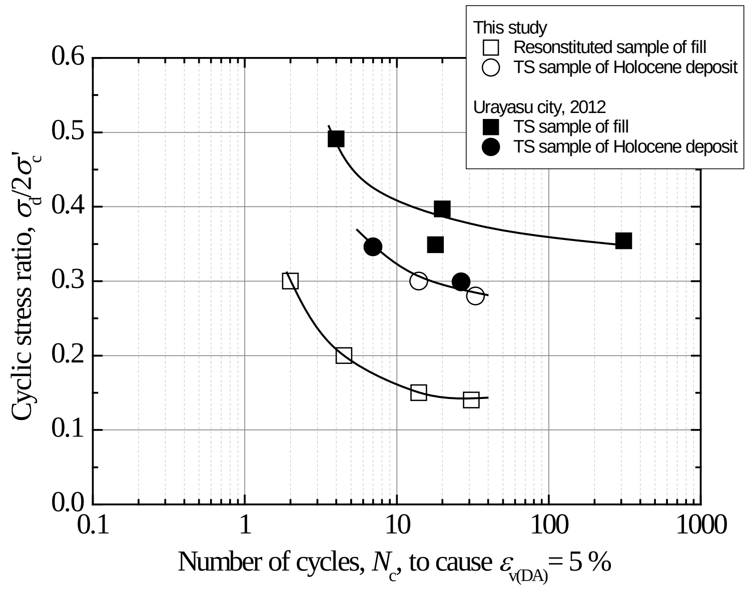

Figure 8. Liquefaction resistance curves of fill and Holocene deposit

Conclusions

In order to investigate the applicability of sample taken by conventional tube sampling (TS) technique and reconstituted sample to liquefaction assessment, a series of dynamic small strain measurement and undrained cyclic triaxial test was conducted on in-situ samples retrieved at the liquefaction site of the 2011 Off the Pacific Coast of Tohoku Earthquake. By comparing the small strain shear moduli of the tested samples with that measured by in-situ PS logging, we confirmed that in-situ soil structure conditions in terms of the small strain characteristics would be reflected in the reconstituted sample of fill and the TS sample of Holocene deposit. The liquefaction resistance defined as the cyclic stress ratio to cause $\varepsilon_{v(DA)}$= 5% in 20 cycles of the reconstituted sample of fill was about 50 % lower than that of Holocene deposit. That trend is consistent with the fact observed during the 2011 earthquake. However, it is likely that the TS sample of fill could have been disturbed leading overestimation of actual liquefaction resistance.

Acknowledgments

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