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Evaluation of cyclic resistance ratio using in-situ and laboratory-measured shear moduli

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ABSTRACT: There are several limitations with the current liquefaction assessment method based on SPT-N value and shear wave velocity, V_s. Therefore, it is important to conduct laboratory tests using in-situ samples; however, it is known that undisturbed samples collected by conventional tube sampling methods may have quality issues. In this study, undisturbed samples or remolded samples collected from sites where occurrence or non-occurrence of liquefaction was confirmed in the past earthquakes were used to conduct a series of cyclic undrained triaxial tests and V_s measurements to determine cyclic resistance ratio, *CRR*, and small strain shear moduli, G_0. The specimen densities of the undisturbed samples were assumed to be the same as those in situ, and the remolded samples were prepared to have the same density as the in-situ conditions. However, the liquefaction resistance characteristics are influenced not only by soil density but also by soil fabric. Therefore, the *CRR* obtained from the laboratory tests using undisturbed samples with unreliable quality and/or remolded samples only adjusted for density may not accurately reflect the in-situ soil fabric. To address this issue, this study attempted to correct the *CRR* obtained from laboratory tests by using the G_0 obtained from in-situ seismic velocity logging and laboratory tests. As a result, a simplified liquefaction assessment based on the corrected *CRR* was able to explain case of liquefaction or no-liquefaction in the past earthquakes more appropriately than the SPT-N-based JRA method.

KEYWORDS: Liquefaction resistance, soil fabric, shear wave velocity.

1 INTRODUCTION

Simplified liquefaction assessment based on SPT-N values and laboratory tests on undisturbed samples from common sandy soil sampling have pointed out a tendency to underestimate or overestimate cyclic resistance ratio, CRR, due to their accuracy and sample disturbance. In reviewing previous studies on the liquefaction resistance characteristics of saturated sandy soils, the most typical factors include (i) soil type, (ii) density, (iii) soil fabric (inter-locking), (iv) stress history such as previous earthquake, (v) aging effect, and (vi) current stress state (e.g., Seed, 1979; Youd et al., 2001; Dobry and Abdoun, 2015). Of these, for a sandy soil without cementation effects under a given stress condition, the factors affecting on *CRR* can be summarized as 'density' and 'soil fabric' (Kiyota et al., 2009; Kiyota et al., 2016). This is because the influences of the stress history and the aging effect of the sandy soil without cementation effect are essentially included in the soil fabric after all.

Kiyota et al. (2019) summarized the results of a series of cyclic undrained triaxial tests conducted on various sandy soils with different soil fabric for each sample set to the same density. Consequently, as shown in Figure 1, they found that the relationship between the change ratio of shear wave velocity, V_s/V_s^*, and the change ratio of cyclic resistance ratio, CRR/CRR^*, which depend on the soil fabric of sandy soils without plasticity or cementation effects, can be expressed by the following equation:

$$CRR/CRR^* = (V_s/V_s^*)^{5.02} \quad (1)$$

where V_s, *CRR* and V_s^*, CRR^* are combinations of shear wave velocities and cyclic resistance ratios for each specimen set to the same density. By determining CRR^* and V_s^* from laboratory tests and V_s from in-situ seismic velocity logging, it is possible to obtain in-situ *CRR* that could reflect the in-situ soil fabric (Figure 2).

This method attempts to express the influence of 'density' by using a test specimen prepared to have the same density as the in-situ condition, and the influence of 'soil fabric' including stress history and aging effects by using the V_s measured in the laboratory test and the field.

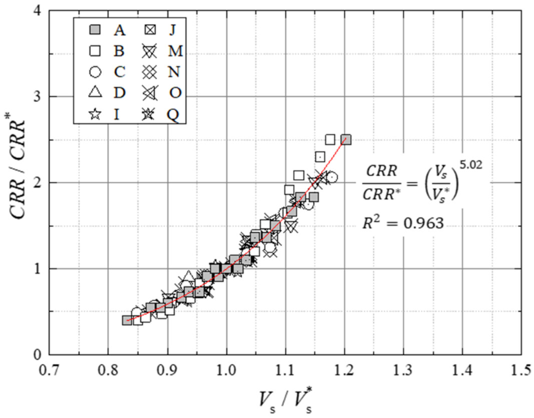

Figure 1. Relationship between V_s/V_s^* and CRR/CRR^* (Kiyota et al., 2019).

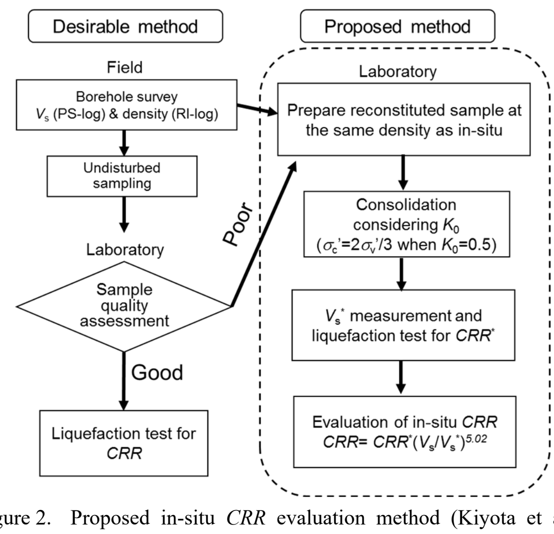

Figure 2. Proposed in-situ *CRR* evaluation method (Kiyota et al., 2019).

In this study, we estimated in-situ *CRR* using the proposed method at survey sites where the occurrence or non-occurrence of liquefaction due to the 2011 Tohoku Earthquake or the 2003 Tokachi-Oki Earthquake was known, and compared the results of liquefaction assessment with the SPT-N based simplified method.

2 SURVEY SITES ANF SPT-N-BASED LIQUEFACTION ASSESSMENT

The survey sites for this study are Urayasu City, Chiba City, Matsudo City in Chiba Prefecture, Kawasaki City in Kanagawa Prefecture, and Bihoro Town in Hokkaido. The soil layers examined for liquefaction resistance are shown in Figure 3, and the results of the simplified liquefaction assessment based on SPT-N using JRA method (Japan Road Association, 2017) are summarized in Table 1. The earthquakes considered for Urayasu City, Chiba City, Matsudo City, and Kawasaki City were the 2011 Tohoku Earthquake, and for Bihoro Town, the 2003 Tokachi-oki Earthquake.

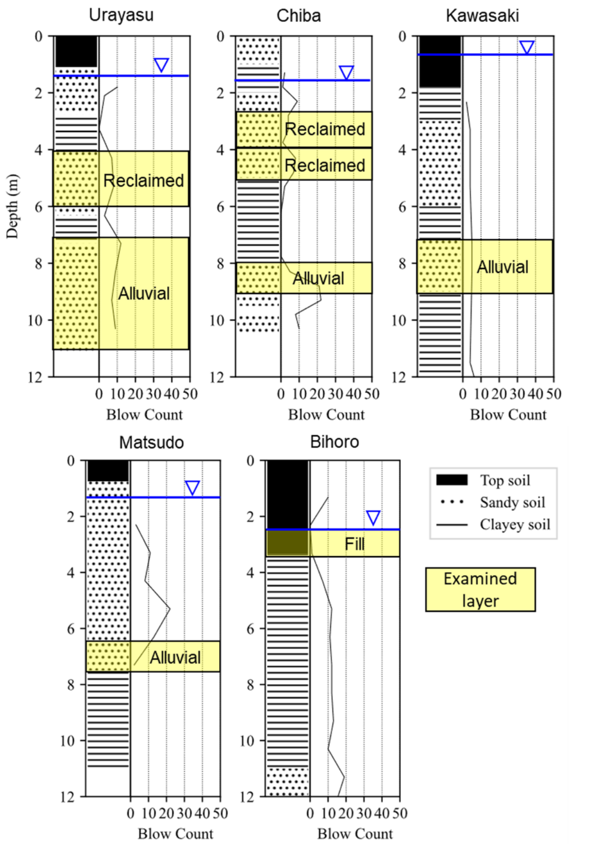

Figure 3. Soil profiles and examined soil layers.

Table 1. Soil layers and liquefaction assessment by JRA method.

Site	Acc. cm/s^2	Deposit type	Liquefaction	Ave. SPT-N	*CRR*	FL
Urayasu	200	Reclaimed	Yes	8	0.32	0.77
		Alluvial	Unknown	9	0.24	0.57
Chiba	232	Reclaimed	Yes	4	0.19	0.52
		Reclaimed	Yes	8	0.24	0.57
		Alluvial	Unknown	16	678	1481
Kawasaki	128	Alluvial	No	5	0.22	0.92
Matsudo	262	Alluvial	No	2	0.14	0.33
Bihoro	85	Fill	No	4	0.08	0.78

During the 2011 Tohoku earthquake, a significant liquefaction was observed at the survey sites in Urayasu and Chiba Cities. At the sites in Kawasaki and Matsudo Cities and Bihoro Town, no evidence of liquefaction was identified after the earthquakes. On the other hand, the liquefaction assessment in Table 1 showed FL < 1.0 for all except for the alluvial sand in Chiba, suggesting that the liquefaction resistances of the examined sand layers in Matsudo, Kawasaki and Bihoro may have been underestimated by the SPT-N based JRA method. In addition, in Urayasu, both the *CRR* and FL of the alluvial sand are smaller than those of the reclaimed soil. Many investigation reports on liquefaction in Urayasu City caused by the Tohoku earthquake stated that significant liquefaction occurred in reclaimed land and not in alluvial deposits (e.g., Yasuda et al., 2012; Towhata et al, 2014), however, the assessment results in Table 1 are inconsistent with these reports.

3 SOIL SAMPLE AND LABORATORY TEST RESULTS

At each study site shown in Figure 3, seismic velocity logging was conducted during the borehole surveys. Soil density test using nuclear gauge was also carried out at all sites except for the site in Urayasu. The undisturbed samples (TS: triple tube sample, GP: Gel-push sample) or disturbed samples were collected from the investigated layers.

Remolded specimens using the disturbed sample were prepared with a density equivalent to that obtained from the in-situ density test at each examined depth. For the undisturbed samples from the site in Chiba, it was confirmed that the specimen densities were equivalent to those obtained from the in-situ density test. Note that the in-situ density test was not conducted at the site of Urayasu. Therefore, it is assumed in this study that the specimen density of the undisturbed sample of the alluvial sand in Urayasu is equivalent to the in-situ density. Meanwhile, the density of the remolded specimens of the reclaimed soil was set to the reported value provided by Urayasu City (2012).

The undisturbed specimens or remolded specimens were placed in a triaxial cell and saturated using the double vacuum method. The back pressure of the specimens was increased to 200 kPa, and after confirming that the B-values were 0.95 or higher, the specimens were subjected to isotropic consolidation up to the effective confining pressure at each sampling depth, assuming K_0= 0.5. After the consolidation was completed, shear wave velocity V_{sL} was measured with accelerometer method or bender element method, and then cyclic undrained triaxial test with a constant deviator stress amplitude was carried out.

Figure 4 shows relationship between *CRR* by simplified JRA method and CRR_L by the laboratory test. Note that CRR_L was defined as the cyclic stress ratio to cause $\varepsilon_{v(DA)}$= 5% in 20 cycles. The CRR_L values vary within the range of 0.1 to 0.4 and were not consistent with the *CRR* obtained using the SPT-N-based JRA method. Furthermore, the results shown in Figure 4 have little relationship with the occurrence of liquefaction during earthquakes and the type of deposit (reclaimed or alluvial) shown in Table 1. On the other hand, the values of CRR_L of undisturbed specimens tend to be higher than those of remolded specimens. This may be because the soil fabric is stronger in undisturbed specimens than in remolded specimens. Both undisturbed and remolded specimens had the same density as the in-situ condition in the laboratory test. However, since there is no certainty that either specimen has the same soil fabric as the in-situ condition, it is not reasonable to directly use the CRR_L by the laboratory test for liquefaction assessment.

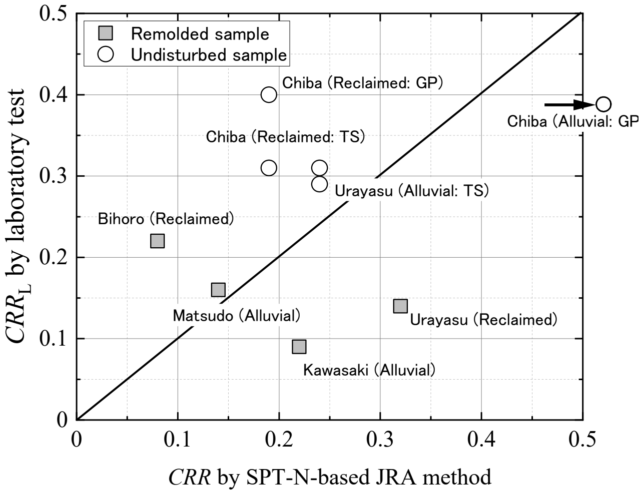

Figure 4. Comparison of *CRR* between laboratory test and JRA method.

4 DISCUSSIONS ON *CRR* EVALUATION BASED ON G_0 MEASURED IN THE FIELD AND LABORATORY TESTS

According to Figures 1 and 2, the in-situ cyclic resistance ratio, *CRR*, of the target soil layer can be evaluated by considering the influence of soil fabric represented by the in-situ and laboratory measured shear wave velocities. However, in this study, considering that shear wave velocity has little physical meaning, the V_s in Figure 1 was replaced with the small strain shear moduli, G_0, as shown in Figure 5, based on the laboratory test data including by Kiyota et al. (2019). We then evaluated the in-situ CRR_F using the following equation.

$$CRR_F = CRR_L\,(G_{0F}/G_{0L})^{n_f} \quad (2)$$

where, G_{0F} is the small strain shear moduli obtained from the in-situ seismic wave logging and soil density test using nuclear gauge or undisturbed specimen, while G_{0L} and CRR_L are the small strain shear moduli and cyclic resistance ratio obtained from laboratory tests on the specimens with the same density as the target soil layer. n_f is the parameter for soil fabric and n_f = 2.5 for typical sandy soils and non-plastic silty sands. The evaluated CRR_F are summarized in Table 2.

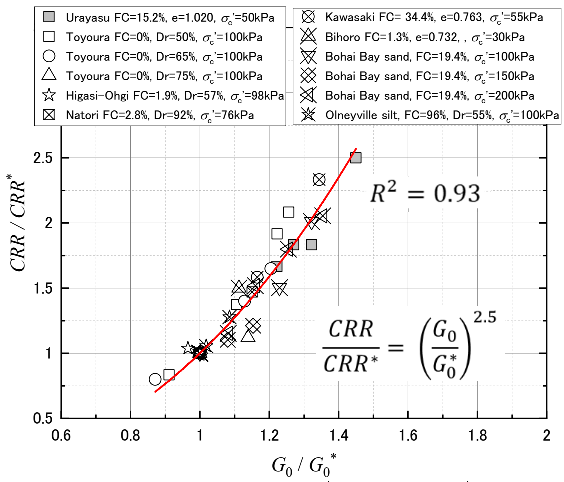

Figure 5. Relationship between G_0/G_0^* and CRR/CRR^* (after Kiyota et al., 2019).

Table 2. Liquefaction assessment results using proposed method.

Site	Deposit type	Sample	G_{0L} (MPa)	CRR_L	G_{0F} (MPa)	CRR_F	FL
Urayasu	Reclaimed	Remolded	99	0.14	98	0.13	0.32
	Alluvial	TS	128	0.29	124	0.25	0.58
Chiba	Reclaimed	TS	110	0.31	89	0.11	0.30
		GP	117	0.40		0.10	0.27
	Reclaimed	TS	135	0.31	129	0.25	0.60
	Alluvial	GP	151	0.39	148	0.35	0.76
Kawasaki	Alluvial	Remolded	104	0.09	179	1.07	4.52
Matsudo	Alluvial	Remolded	128	0.16	155	0.42	1.02
Bihoro	Reclaimed	Remolded	119	0.22	124	0.28	2.42

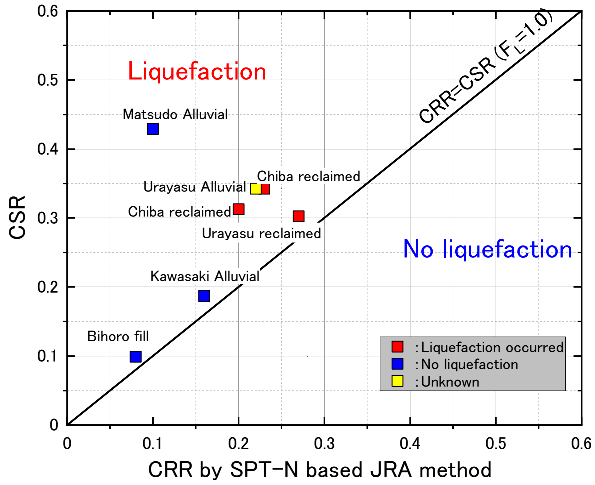

Figure 6. Liquefaction assessment results by SPT-N based JRA method.

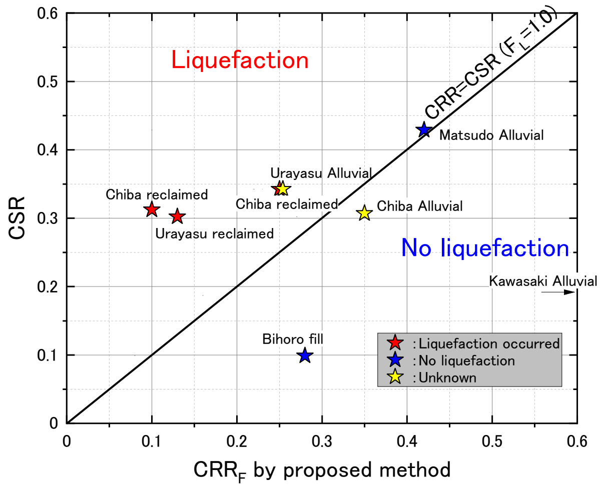

Figure 7. Liquefaction assessment results by proposed method.

For the Urayasu reclaimed and alluvial sandy soils, the differences between in-situ G_{0F} and laboratory-measured G_{0L} were small. It can therefore be inferred that the quality of the undisturbed sample from the alluvial sand was relatively high. As a result, the evaluated in-situ CRR_F were similar to the laboratory-measured CRR_L. The CRR_F of the reclaimed layer was smaller than those by the SPT-N based method as shown in Figures 6 and 7, reflecting the fact that significant liquefaction occurred in the reclaimed layer during the 2011

Tohoku earthquake. As shown in Table 2 and Figure 7, the CRR_F and FL of the alluvial sand are higher than that of the reclaimed layer. It is not known whether this alluvial sand actually liquefied during the 2011 Tohoku earthquake, however, it is inferred that even if it liquefied, the severity was less than that of the reclaimed layer.

In Chiba, undisturbed samples (TS, GP) were studied in the reclaimed soils, with CRR_L values of 0.3 and 0.4, which are too large for a significantly liquefied soil. Although the specimen density of the undisturbed samples was generally consistent with the in-situ density test results, it is possible that the soil fabric was strengthened during the sampling process as they were very loose sandy soils. However, the correction using G_{0F} resulted in CRR_F= 0.1 for upper reclaimed layer, and the FL was also much lower than that from the SPT-N based JRA method as shown in Table 2. It is interesting to note that the specimens collected by two different undisturbed sampling methods, TS and GP, were examined for upper reclaimed layer, and although the CRR_L was different for each, the correction by G_{0F} resulted in comparable CRR_F. This suggests that regardless of how the sample is disturbed during the sampling, the proposed method can appropriately correct the CRR_F as long as the specimen density is equivalent to the in-situ density. For the alluvial sand layer, the SPT-N based JRA method resulted in a very large *CRR* due to the correction for fines content, while the proposed method yielded CRR_F= 0.35 and FL greater than 1.

In Kawasaki and Matsudo, the studied soil layers were alluvial deposits, and no evidence of liquefaction was observed during the 2011 Tohoku earthquake. In both cases, remolded specimens were prepared using disturbed samples and their densities were adjusted to the results of the in-situ density test. Table 2 shoes that the CRR_L values obtained in the laboratory were 0.09 and 0.16 for Kawasaki and Matsudo, respectively, which are relatively low. This may be due to the loss of aging effect in the remolded specimens, which cannot reproduce the liquefaction characteristics of the in-situ deposits. However, in both Kawasaki and Matsudo, the in-situ G_{0F} is higher than the laboratory-measured G_{0L}, and the in-situ CRR_F values evaluated using G_{0F}/G_{0L} are sufficiently large to reflect the degree of soil fabric (aging effect) in the in-situ conditions. As a result, as shown in Figure 7, the FL values obtained using the CRR_F are consistent with the fact that liquefaction did not occur during the 2011 Tohoku earthquake in these areas.

The target layer in Bihoro was the surface fill soil. The estimated *CRR* using the JRA method was very small (*CRR*= 0.08) as shown in Table 2, however, the CRR_L obtained from laboratory tests was 0.22, and even after correction using G_{0F}, the CRR_F was 0.28. As a result, the FL value is consistent with the fact that liquefaction did not occur during the 2003 Tokachi-oki earthquake, as shown in Figure 7.

5 CONCLUSION

This study presented a new method of evaluating in-situ *CRR* using small strain shear moduli obtained by in-situ seismic wave logging and laboratory test. A liquefaction assessment using the method was carried out for sites where liquefaction occurred or not due to the 2011 Tohoku earthquake or the 2003 Tokachi-oki earthquake, and the results were compared with the SPT-N based simplified method (JRA method).

The accuracy of the SPT-N based JRA method, which was carried out for the examined sites in this study, was not very good, with relatively large *CRR* even for the reclaimed soils where significant liquefaction occurred (Urayasu and Chiba), and FL< 1.0 for the sites where no liquefaction was confirmed (Kawasaki, Matsudo and Bihoro). In addition, undisturbed samples using tube sampling methods at Chiba where significant liquefaction occurred showed very large CRR_L due to disturbance of the soil fabric of the specimen, even though the specimen density was equivalent to that of the in-situ condition. Furthermore, in liquefaction tests using disturbed samples from Kawasaki, Matsudo and Bihoro sites where liquefaction did not occur, relatively low CRR_L were obtained. On the other hand, the proposed method showed that the FL values based on the in-situ CRR_F corrected by using in-situ and laboratory measured G_0 were generally consistent with the fact that occurrence or non-occurrence of liquefaction due to the 2011 Tohoku earthquake and the 2003 Tokachi-oki Earthquake.

6 ACKNOWLEDGEMENTS

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