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Correlation between Liquefaction Resistance and Shear Wave Velocity for Volcanic Coarse-grained Soil

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Abstract

According to Geographical Survey Institute of Japan, 11% of the land area is covered by volcanic soil. Since the last few decades, several large earthquakes hit around the area, and have caused severe liquefaction to the subsurface layer. It is highly recommended to understand the characteristic of volcanic soil. On the other hand, the relationship between shear wave velocity (V_s) and cyclic resistance ratio (*CRR*), triggered by the work of Andrus and Stokoe, has been discussed in various studies for several decades. The latest reseach about the V_s -*CRR* relationship indicates that without bonding effect, those trends are consistently similar regardless of soil type, density, fines content and confining pressure. However, there are no studies that discuss how V_s -*CRR* trends change in volcanic coarse-grained soil whose deformation characteritics differ significantly from ordinary soil. In this paper, we conducted series of undrained cyclic tests and mesurement of shear wave velocity (V_s) with a volcanic sample collected in Bihoro-cho, Hokkaido in order to figure out how V_s -*CRR* trend changes.

Keywords: Volcanic Soil, Liquefaction Characteritics, Shear Wave Velocity, in-situ CRR

1. Introduction

Volcanic soil is widely distributed across the land of Japan. Geographical Survey Institute of Japan categorized 11% of the land as covered by sand or mudflow derived from volcanoes [1]. In particular, more than 40% of the Hokkaido island is covered by thick volcanic soil [2]. Such volcanic soils exhibit different deformation characteristics than normal sands, especially during earthquake.

The 1993 Hokkaido Nansei-Oki earthquake (Mw=7.8) caused liquefaction of pyroclastic flow deposits around the foot of Mt. Komagatake, and caused severe damage to port facilities[3, 4]. The 1994 Hokkaido Toho-Oki earthquake (Mw=8.1) hit the east side of the island, which results in the liquefaction of deposited volcanic soil in Nakashibetsu-cho [5], as shown in Fig. 1. Kiyota-ku in Sapporo city was shaken by the 2018 Hokkaido Eastern Iburi earthquake which caused uneven settlement due to liquefaction of shallow volcanic layer [6]. Thus, the disaster risk of volcanic soil during earthquake in recent years is increasing. Therefore it is essential to understand the liquefaction characteristics of volcanic soil.

A large number of researches related to the assessment for liquefaction have been conducted since 1960s. Seed and Idris [7] proposed the simplified procedure to estimate the possibility of liquefaction based on SPT-N value, which is now commonly used for practical work. Andrus and Stokoe [8] deeply examined the relationship between shear wave velocity (V_s) and cyclic resistance ratio (*CRR*), and compute the discriminant of liquifiable or non-liqufiable soil. However, these methods are still insufficient to make a resonably accurate assessment.

In general, the liquefaction resistance of a particular sandy soil is influenced by not only its density, but also the soil fabric, which is affected by the process of soil deposition and environmental changes, such as landform change, seismic history, and age of the deposit. Some previous researches [9, 10] indicates that it is highly necessary to perform laboratory tests while maintaining the quality of in-situ sample because soil fabric are highly affected by the sample quality, however sand samples retrieved by employing existing soil sampling techniques that are considered to yield undisturbed samples (e.g. triple-tube sampler and thin-wall sampler) are actually subject to disturbance, which can result in underestimation or overestimation of the liquefaction resistance. Kiyota et al. [11] and Wu et al. [12] conducted a series of undrained cyclic triaxial tests (denoted as liquefaction tests hereafter) and V_s measurements in order to investigate the respective effects of density and soil fabric on the liquefaction resistance of sandy soil. The results indicated that the V_s –trends of the examined soils are consistently similar regardless of soil type, density, fines content and confining pressure under the condition that the soil particles does not show any bonding effect. They presented that it is possible to estimate in-situ *CRR* based on both in-situ and laboratory-measured V_s.

In this paper, several liquefaction tests and V_s measurement on the volcanic sandy soil collected from Bihoro-cho, Hokkaido, Japan. The specimens were subjected to different over-consolidation history to investigate the effect of soil fabric on liquefaction resistance and V_s under the same dansity. Finally, an attempt was made to evaluate in-situ liquefaction resistance based on the experimental results and in-situ measured V_s.

2. Methodology

In this study, a series of liquefaction test was conducted with a strain-controlled triaxial apparatus. The height of specimen is 150 mm and the diameter is 75 mm., while the thickness of the membrane was 0.3 mm. The soil sample was volcanic sand taken in Azahoutoku, Bihoro-cho, Hokkaido as shown in Fig.2. (Specific gravity of soil particle : G_s =2.547 g/cm^3). The soil is geologically classified as Kutcharo pumice flow deposit. The specimens were prepared by dry-tamping method to achieve a dry-density at in-situ condition, ρ_d =1.47 g/cm^3, at the end of consolidation stage. In order to achieve the density, the initial density of the specimen is set slightly lower than the target density. The specimens is subjected to isotropic consolidation, σ'_c=30 kPa with a back pressure of 200 kPa. Some specimens were consolidated to σ'_c of 150 kPa which is equal to *OCR* of 5.0. Afterwards, σ'_c was decreased to 30 kPa. This over-consolidation is intended to change the soil particle structure due to stress history.

A trigger and accelerometer system, originally developed by AnhDan et al. [13], was used to measure V_s transmitted throught specimens. The shear wave, in the form of a single sinusoidal wave with a frequency of 1 kHz, was generated by a pair of wave sources (actuators) attached to the top cap that were simulataneously excited in the torsional direction. A pair of accelerometers was employed to measure the arrival time of the shear wave at two different heights of specimen.

After the measurement of V_s, liquefaction tests were conducted with a constant amplitude of cyclic deviator stress until double amplitude of axial strain $\varepsilon_{a(DA)}$ reached 5%. The specification of all the tests was shown in Table 1.

Fig. 1 Sand ejecta containing Mashu pumice fall deposit (The 1994 Hokkaido Toho-Oki earthquake) [13]

Fig. 2 The site location

Table 1 Specimen conditions and test results

Name	σ'_c (kPa)	*CSR*	*OCR*	B-value	ρ_d (g/cm^3)	V_s (m/s)	N_c ($\varepsilon_{a(DA)}=5\%$)	N_c ($\Delta u/p'_0=95\%$)
TXCUC_Biho_01	30	0.4	5	0.964	1.492	129.2	14.5	13.5
TXCUC_Biho_02		0.25	1	0.976	1.503	N/A	6.5	5.0
TXCUC_Biho_03		0.2	1	0.947	1.450	118.8	59.5*	51.5
TXCUC_Biho_04		0.3	5	0.906	1.465	126.2	39.0	34.5
TXCUC_Biho_05		0.35	5	0.945	1.478	121.4	18.0	14.5

3. Experiment Results

3.1 Effect of over-consolidation history on shear wave velocity

Table 1 shows the values of V_s just before the liquefaction test was performed. Although the number of samples was limited, the shear wave velocity of *OCR* 1 was 118.8 m/s, while the shear wave velocity of *OCR* 5 was 125.6 m/s on average. Kiyota et al. [10] conducted several series of the liquefaction test with the same density and different *OCR*. They used a liquified sand taken in Urayasu, Chiba, Japan. The increment of V_s is from 20 to 25 m/s for *OCR* 4 , from 24 to 30 m/s for *OCR* 6. Verdugo et al. [14] measured V_s by bender element with samples from Sweden (Sand-S) and from Chille (Sand-C) in order to address how *OCR* affects the increment of V_s. It is observed that V_s increased monotonically as *OCR* increased in both samples. However, the increment of V_s reached a plateu for *OCR* higher than 8 in case of Sand-S. The increment of V_s in Sand-C terminated at *OCR* 3. Comparing with those previous result, it can be said that the increment of V_s as for the prepared sample is smaller than that of V_s as for the priviously reported samples.

3.2 Liquefaction characteristics of specimens with the same density

Fig. 3 shows the stress-strain relationship and the effective stress path of TXCUC_Biho_01 (*OCR* 5) and TXCUC_Biho_02 (*OCR* 1). Fig. 4 shows the relationship between the normalized number of cycle, $N_c/N_{c(\varepsilon a(DA)=5\%)}$ and $\varepsilon_{a(DA)}$. Fig. 5 shows the relationship between the normalized N_c and excess pore water pressure, Δu. In Fig. 4 and Fig. 5, N_c is normalized by number of cycle when $\varepsilon_{a(DA)}$ reaches 5%.

As shown in Fig. 3, positive excess pore pressure is generated in the *OCR* 1 specimen immediately after the loading of the first cycle. Subsequentyly, gradual accumulation of excess pore pressure is observed in each cycle. On the other hand, after loading the first wave, the *OCR* 5 specimen does not show the significant change of excess pore water pressure even the same density as *OCR* 1.

The typical increasing tendency of the double amplitude vertical strain, $\varepsilon_{a(DA)}$ is shown in Fig.4, and the excess pore water pressure, Δu, during the liquefaction tests is shown in Fig. 5. The specimens have the same D_r, while the V_s and *OCR* are different. In terms of the increasing tendency of $\varepsilon_{a(DA)}$, there is no significant difference between *OCR* 1 and *OCR* 5. When $N_c/N_{c(DA=5\%)}$ becomes from 0.7 to 0.8, a sharp increase in $\varepsilon_{a(DA)}$ is observed, as shown in Fig. 5. In addition to $\varepsilon_{a(DA)}$, OCR 1 and *OCR* 5 specimens has the same tendency from the perspective of accumulation of Δu. Before the value of $N_c/N_{c(DA=5\%)}$ reaches 0.9, the Δu gradually increases while drawing a downward convex function. Thus, it can be said that although a change in soil fabric due to over-consolidation leads to an increase in liquefaction strength, the change does not have significant effect on the deformation characterisitcs before the occurrence of liquefaction.

3.3 Correlation between liquefaction resistance and shear wave velocity

Fig. 6 shows the relation between cylic shear stress ratio (*CSR*) and N_c with the curve of liquefaction resistance. The N_c in this paper is defined as the number of cycle when $\varepsilon_{a(DA)}$ becomes equal to 5%. The liquefaction strength is defined by *CSR* such that N_c is equal to 20. As the *OCR* increases, the liquefaction strength curve moves upward on the figure. The liquefaction resistance for *OCR* 1 was 0.22 and that for *OCR* 5 was 0.33.

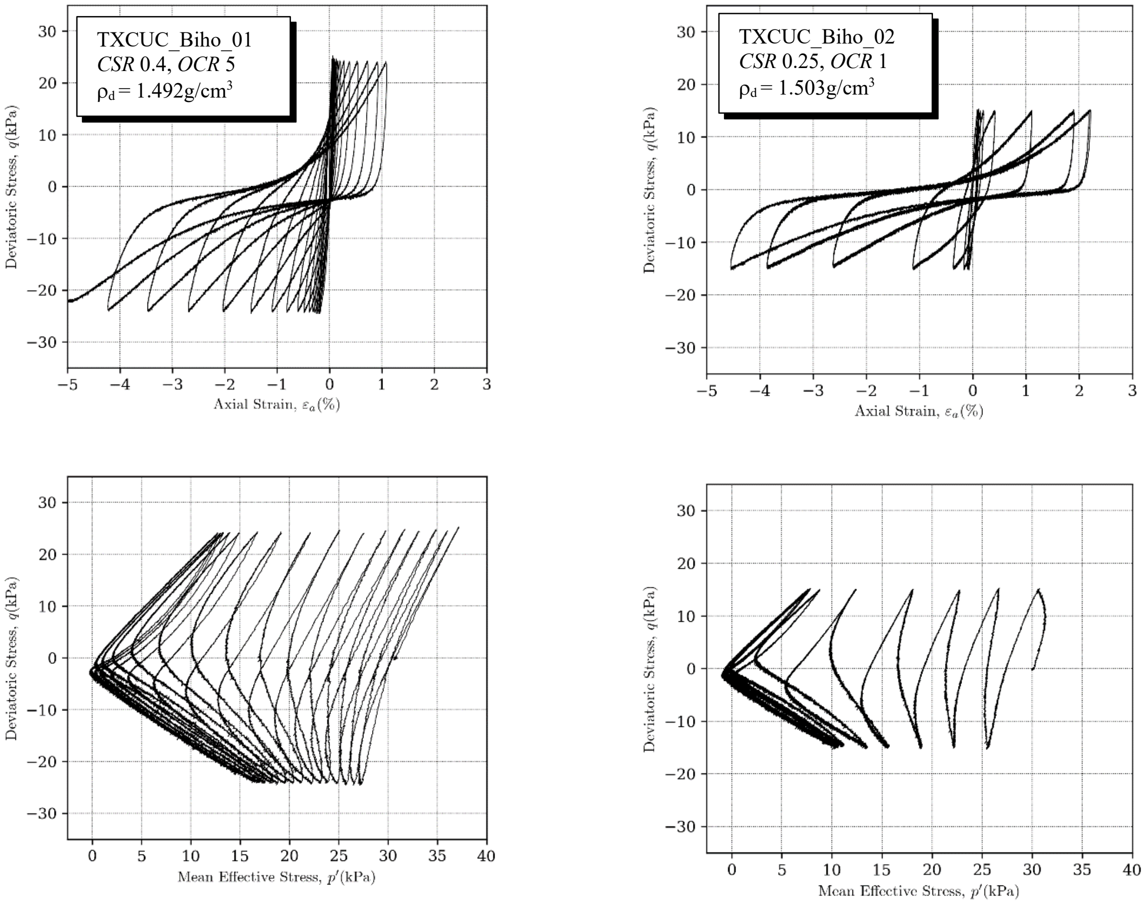

Fig. 3 The test result of TXCUC_Biho_01 (left) and TXCUC_Biho_02 (right)

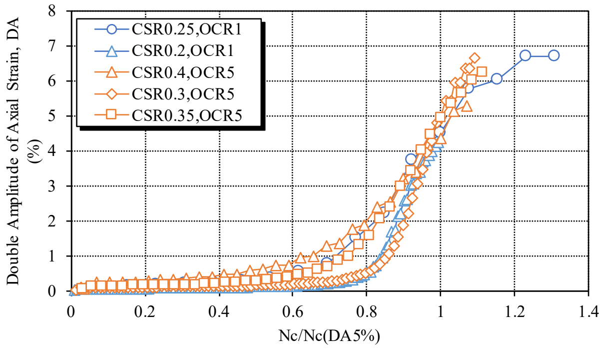

Fig. 4 Relations between N_c/ $N_{c(DA=5\%)}$ and $\varepsilon_{a(DA)}$

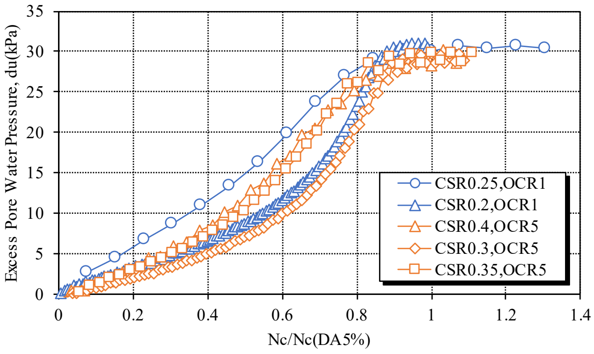

Fig. 5 Relations between N_c/ $N_{c(DA=5\%)}$ and Δu

Fig. 7 shows the particle size distribution curve before and after the test. The curve does not change significantly while that of *OCR* 5 is slightly shifted to the finer side rather than that of *OCR* 1. In *OCR* 5 specimen, U_c slightly increases by 2.5 and F_c increases by 10.5%, although the parameters such as D_{50} and C_g does not have so large changes. Miura et al. [15] has reported that F_c increases by 15% at most due to the liquefaction tests with volcanic soil taken in Hokkaido, which is consistent with the result of the prepared sample. Koester et al. [16] discribed that as fine contents of specimen increased from 5% to 12.5%, *CRR* dropped by approximately 40%. Miura et al. [17] have shown that further addition of fines to specimens with F_c as low as 0 to 10% reduces liquefaction resistance. These studies are incositent with the result with the prepared sample, which infers that the effect on the liquefaction resistance is more pronounced in the strengthening of soil fabric due to the increase of *OCR* than in the increase of F_c due to the particle crushing.

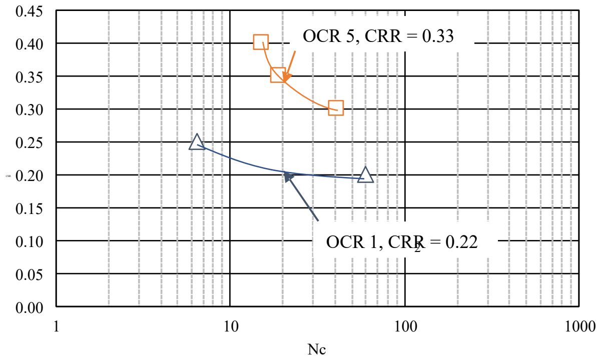

Fig. 6 Relation between N_c and CSR

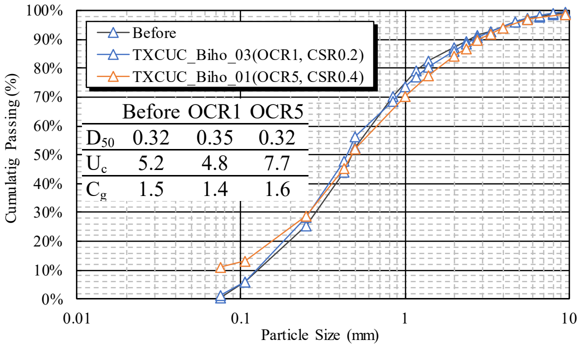

Fig. 7 Particle size distribution curve before and after testing

Fig. 8 combines the series of the test and the results reported by Kiyota et al [11]. Kiyota et al. shows the relationship between V_s/V_s* and *CRR*/*CRR**, where V_s* and *CRR** are V_s and the *CRR* of the MT(Moist Tamping) and PA(Air Pluviation) specimens for Urayasu sand and Toyoura sand for each D_r group. They found that a good correlation was obtained between V_s/V_s * and *CRR*/*CRR**, regardless of the type of sample, difference in confining pressure and specimen density. In order to confirm whether the relationship can be applicable to this volcanic sample, the average value of V_s was calculated for the specimens with the same *OCR*. Consequently, V_s in *OCR* 5 is 1.06 times and *CRR* is 1.5 times, comparing with *OCR* 1 specimen. These plots are consistent with the other samples which were reported in the previous study.

3.4 Practical application for updating the current liquefaction estimation method

In general, in-situ shear wave velocity can be obtained using a method such as PS logging. On the other hand, the in-situ *CRR* can be computed from the *CRR** and V_s* which are measured in the laboratory test with the power function proposed by Kiyota et al. [11].

Fig. 9 shows the results of a standard penetration test on JIS A1219 performed in parallel with sampling. It is found that the layer up to 5 m depth is composed of relatively weak reclamed volcanic soil, and the layer at more than 5 m depth is composed of naturally deposited volcanic soil.

The result of liquefaction assessment based on Recommendations for Specification for Highway Bridges of Japan, is shown on the right side of Fig. 11. The input ground motion was 86.5 gal observed at the site in the 2003 Tokachi-oki earthquake. Liquefaction was not confirmed at this location during the Tokachi-oki earthquake, but the Factor of Liquefaction (F_L) was less than 1 at a depth of 3.3 m, which indicates that liquefaction was expected to occur. It is reported that such underestimation of liquefaction resistance was found at more than 100 sites during the 2011 off the Pacific coast of Tohoku earthquake [18].

In order to eliminate such underestimation, in this paper, a simple evaluation update of *CRR* using in-situ and laboratory V_s is performed. Given 124.4 m/s as in-situ V_s , 118.8 m/s as laboratory V_s and 0.22 as *CRR** The revised *CRR* can be computed by the following formula, which was proposed in Kiyota et al.[11].

$$CRR = 0.22\left(\frac{124.4}{118.8}\right)^{5.02} = 0.277 \tag{1}$$

As a result F_L increased from 0.96 to 2.42 when the in-situ *CRR* increases from 0.097 to 0.277. Thus, although this method seems to be simple and doesn't consider other factors, it can reproduces the actual phenomenon of liquefaction occurrence.

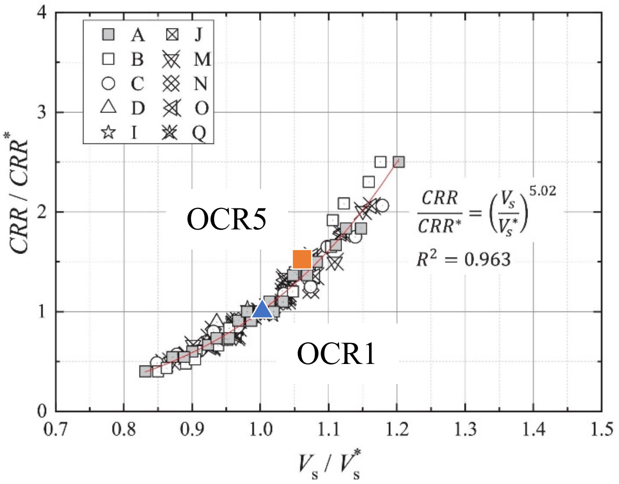

Fig. 8 Relation between *CRR* and V_s with the result by Kiyota et. al [10]

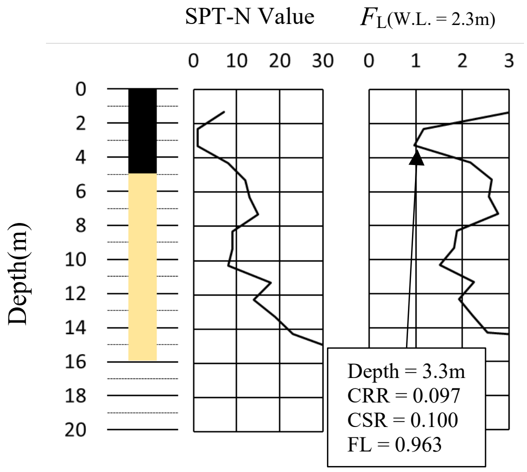

Fig. 9 Pit log, blow counts of SPT and F_L obtained the borehole surbey.

4. Conclusion

In this paper, a series of liquefaction tests was conducted to understand the deformation characteritics of volcanic soil in Bihoro-cho, Hokkaido, and to examine the applicability of the simple method to evaluate in-situ liquefaction resistance by using V_s. The deformation characteristics were investigated by adding over-consolidation history to some specimens for the purpose of changing soil fabric beofore conducting a liquefaction test. The following summarizes the conclusions of this study.

(1) V_s increased by 2.5 to 8.5 % due to over-consolidation, and *CRR* increased by 1.5 times, although there was no significant difference in the development trend of strain and pore water pressure during liquefaction.

(2) The result of the increment of F_c and changes in *CRR* are incositent with the result of the prepared sample, which infers that the effect on the liquefaction resistance is more pronounced in the strengthening of soil fabric due to the increase of *OCR* than in the increase of F_c due to the particle crushing.

(3) With the use of the relationship between V_s and *CRR* proposed in the previous research, the F_L value was re-examined, and the presence or absence of liquefaction could be correctly determined.

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