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# VARIATION OF SHEAR WAVE VELOCITY AND LIQUEFACTION RESISTANCE OF TOYOURA SAND UNDER CONSTANT SPECIMEN DENSITY

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## *Abstract*

In order to investigate variation of shear wave velocity and liquefaction resistance of Toyoura sand specimen with relative density of 50%, which is caused by the different number of cyclic loading histories, first, a series of shear wave velocity measurement were conducted. It was found that the shear wave velocity of the specimen increases with increase in the number of drained cyclic loading history. Second, undrained cyclic triaxial tests were conducted on the above-mentioned specimens. The liquefaction resistance increases with a large number of cyclic loading history, and there is good correlation between shear wave velocity and liquefaction resistance. However, both the shear wave velocity and liquefaction resistance of the specimen with 2000 cyclic loading history and those with 3000 cyclic loading history are similar to each other which indicate an upper limit of shear wave velocity and liquefaction resistance under the given specimen density. Third, in order to obtain a lower limit of shear wave velocity and liquefaction resistance, another series of experiments were performed on a specimen which has several liquefaction histories. The result shows that the smallest values of the shear wave velocity and liquefaction resistance of the specimen were measured at the second stage of liquefaction test. For Toyoura sand specimen with relative density of 50%, the upper limits of shear wave velocity and liquefaction resistance are about 16% and 250% larger than their lower limits respectively.

*Keywords: liquefaction, triaxial test, shear wave velocity*

## 1. Introduction

In general, there is a good correlation between liquefaction resistance and small strain characteristics, including shear wave velocity, of granular soil materials (e.g. Tokimatsu and Uchida, 1990; Zhou and Chen, 2007). Tokimatsu and Hosaka (1986) conducted a series of small strain measurements and liquefaction test on the specimens retrieved by using a conventional tube sampling technique and a high quality freezing sampling technique. They studied the liquefaction resistance, which is affected by natural aging effect, focusing on its possible correlation with small strain characteristics.

In this connection, Kiyota et al. (2009a, b) reported that there are two types of aging effect for natural granular soils, fabric (inter-locking) component and cementation component based on a number of liquefaction tests on high quality undisturbed samples and their reconstituted samples, and suggested that in-situ condition of the less-cemented soil can be reproduced by applying small amplitude of pre-cyclic loading, which is originally suggested by Tokimatsu et al. (1986).

On the other hand, Stokoe et al. (1988) conducted an analytical study on the relationship between liquefaction potential and shear wave velocity. Andrus and Stokoe (2000) summarized previous analytical and laboratory studies for granular soils, and proposed liquefaction potential boundaries based on the obtained relationship between liquefaction resistance and shear wave velocity.

Since the small strain characteristics are considered to reflect the soil fabric as suggested by Santamarina et al. (2001), it is reasonable to use the shear wave velocity for the liquefaction assessment. However, the liquefaction characteristics are affected not only by the soil fabric but also soil density. This study, therefore, investigates the range of liquefaction resistance and shear wave velocity of Toyoura sand with constant relative density.

## 2. Test procedure

A triaxial apparatus was used in this study. The tested sample was Toyoura sand which is fine sand with $e_{max}$= 0.957, $e_{min}$= 0.611 and $\rho_s$= 2.656. The cylindrical specimen, approximately 75 mm in diameter and 150 mm in height, was prepared by pluviating oven-dried particles through air at the relative density of 50 %. As shown in Fig. 1, a trigger and accelerometer system was used for the $V_s$ measurement. An S wave in the form of a single sinusoidal wave at a frequency of 2 kHz was generated by a pair of wave sources attached on the top cap, and they excited simultaneously in the torsional direction. A pair of accelerometers at two different heights, attached on the side surface of the specimen, was employed to measure the arrival time of S wave.

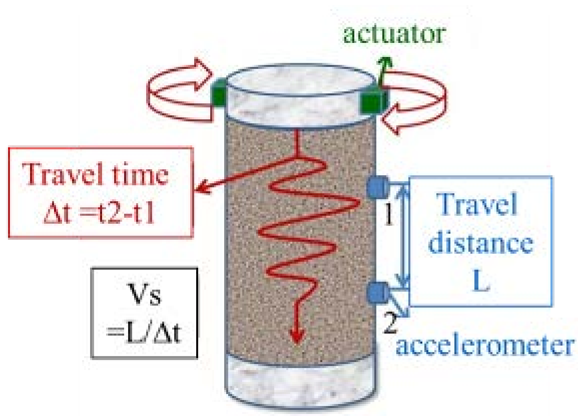


Fig. 1 – Shear wave velocity measurement

The specimens were saturated while keeping a confining pressure of 30 kPa, and then subjected to isotropic consolidation to 100 kPa. The S wave velocity, $V_s$, of each specimen was measured at several stress states during the isotropic consolidation. After the consolidation, undrained cyclic triaxial tests, namely liquefaction tests, were performed with prescribed constant amplitude of deviator stress.

After the consolidation and before liquefaction test, some of the specimens were subjected to 100, 1000, 2000 and 3000 cycles of vertical load with double amplitude strain, $\varepsilon_{v(DA)}$, of 0.1 % under drained condition. This small drained cyclic loading is to enhance the microscopic soil structure of Toyoura sand without significantly changing the specimen density. As is the case of consolidation, the $V_s$ was measured at some interval during the cyclic loading.

In addition, a repeated liquefaction tests were also carried out in this study. The specimen after the first liquefaction test was subjected to isotropic consolidation followed by a sustained loading at the initial stress condition of 100 kPa. After confirming that the volume change due to the re-consolidation was stable and after measuring the $V_s$ of the specimen, the second liquefaction test was carried out and repeated until fourth liquefaction test.

## 3. Test results

### 3.1 Shear wave velocity of specimen

Figure 2 shows the relationship between shear wave velocity, $V_s$, and a stress parameter, $(\sigma_v' \cdot \sigma_h')^{0.5}$, of the tested sample measured during isotropic consolidation. In order to normalize for the effects of change in void ratio on $V_s$, the void ratio function proposed by Hardin and Richart (1963) is applied. The $V_s$ value increased with increase in the effective stress, and the measured values of each specimen demonstrate consistency and repeatability of the experiment.

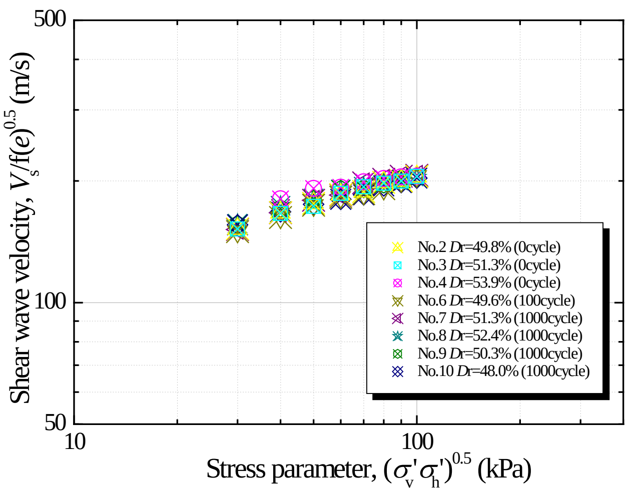


Fig. 2– Shear wave velocity, $V_s/\sqrt{f(e)}$, measured during isotropic consolidation

After the isotropic consolidation, some of the specimen were subjected to small vertical cyclic loading under drained condition. Figure 3 and table 1 show the rate of shear wave velocity increase due to the small cyclic loading. The $V_s/\sqrt{f(e)}$ values measured at 2,000 cycles increased by approximately 1.3 times over the values before the cyclic loading. Since the values of $V_s$ normalized by the void ratio function were increased by the application of the drained cyclic loading, such increment in the $V_s$ could be linked with enhanced structure between the soil particles.

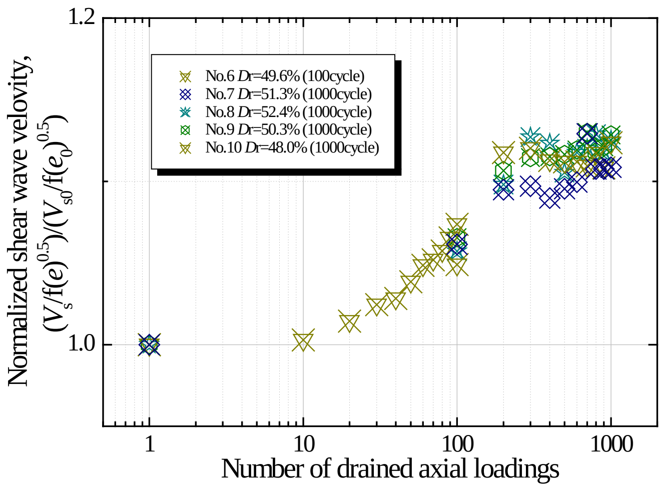


Fig. 3– Relationship between $(V_s/\sqrt{f(e)})$ / $(V_{s0}/\sqrt{f(e_0)})$ and number of drained cyclic loading

Table 1 – Rate of $V_s$ increase due to drained cyclic loading

| No. | Numbers of stress history | $D_r^*$ (%) | Increase ratio of shear wave velocity | |
|---|---|---|---|---|
| | | | $\frac{V_s/\sqrt{f(e)}}{V_{s0}/\sqrt{f(e_0)}}$ (100 cycles) | $\frac{V_s/\sqrt{f(e)}}{V_{s0}/\sqrt{f(e_0)}}$ (1000 cycles) |
| 5 | 100 | 47.6 | - | - |
| 6 | 100 | 49.6 | 1.07 | - |
| 7 | 1000 | 51.3 | 1.06 | 1.10 |
| 8 | 1000 | 52.4 | 1.06 | 1.13 |
| 9 | 1000 | 50.3 | 1.07 | 1.13 |
| 10 | 1000 | 48.0 | 1.05 | 1.12 |
| 11 | 2000 | 47.9 | - | 1.11 |
| 12 | 2000 | 47.8 | - | 1.06 |
| 13 | 2000 | 50.1 | - | 1.09 |
| 14 | 2000 | 50.0 | - | - |
| 15 | 3000 | 56.6 | - | 1.13 |

In this study, the shear wave velocity measurement was also conducted during a series of repeated liquefaction tests. Figure 4 shows the $D_r$ and $V_s$ of the specimen measured before the liquefaction test at each stage. The figure also shows the number of cycle to cause double amplitude of vertical strain of 5 %, $N_c$, as a liquefaction resistance at the each stage. The $D_r$ of the specimen at the second stage was about 52 % which is about 10 % higher than for the first liquefaction stage test. The $V_s$ and $N_c$ value at the second stage, however, decreased as compared to the first stage. This tendency could be inferred that the soil structure represented by the $V_s$ value is independent from the specimen density which may be linked to SPT-N value. Further discussion on the effect of $V_s$ on the liquefaction resistance is given in the next section.

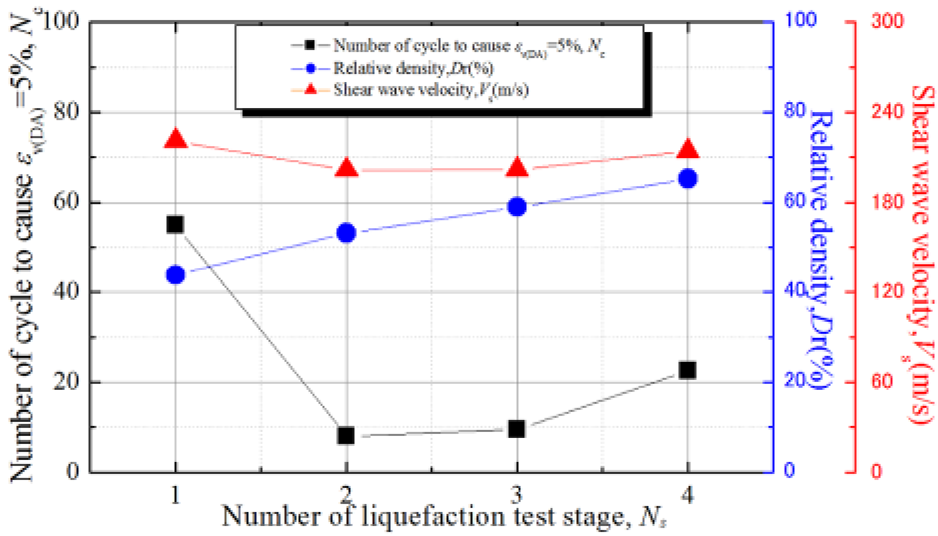


Fig. 4– $D_r$, $V_s$ and $N_c$ of the specimen during repeated liquefaction test

## 3.2 Liquefaction test

As the results of typical liquefaction tests, Fig. 5 shows effective stress paths of the specimen with/without drained/undrained cyclic loading history. As shown in the figure, the respective cyclic stress ratio applied and the $D_r$ value of the specimens were the same, however, different tendency to develop excess pore water pressure was observed. The effective stress of the original specimen was moderately decreased at the first several cycles (Fig. 5 (a)), whereas that of the specimen with 1,000 cyclic loading history was decreased slowly with the increase in the number of cycles as shown in Fig. 5 (b). Meanwhile, the decrease in the effective stress was significant for the specimen at the second stage of the repeated liquefaction test (Fig. 5 (c)).

It could be inferred that the different resistance against development of excess pore water pressure of the specimen in Figs. 5 (b) and (c) as compared to the original specimen in Fig. 5 (a) was caused by the enhancement or degradation of structure between the soil particles due to the application of drained or undrained cyclic loading before the liquefaction test. In this study, the values of liquefaction resistance and $V_s$ of the specimen at the second stage of repeated liquefaction test is considered as a lower limit value that Toyoura sand under the given density might have had.

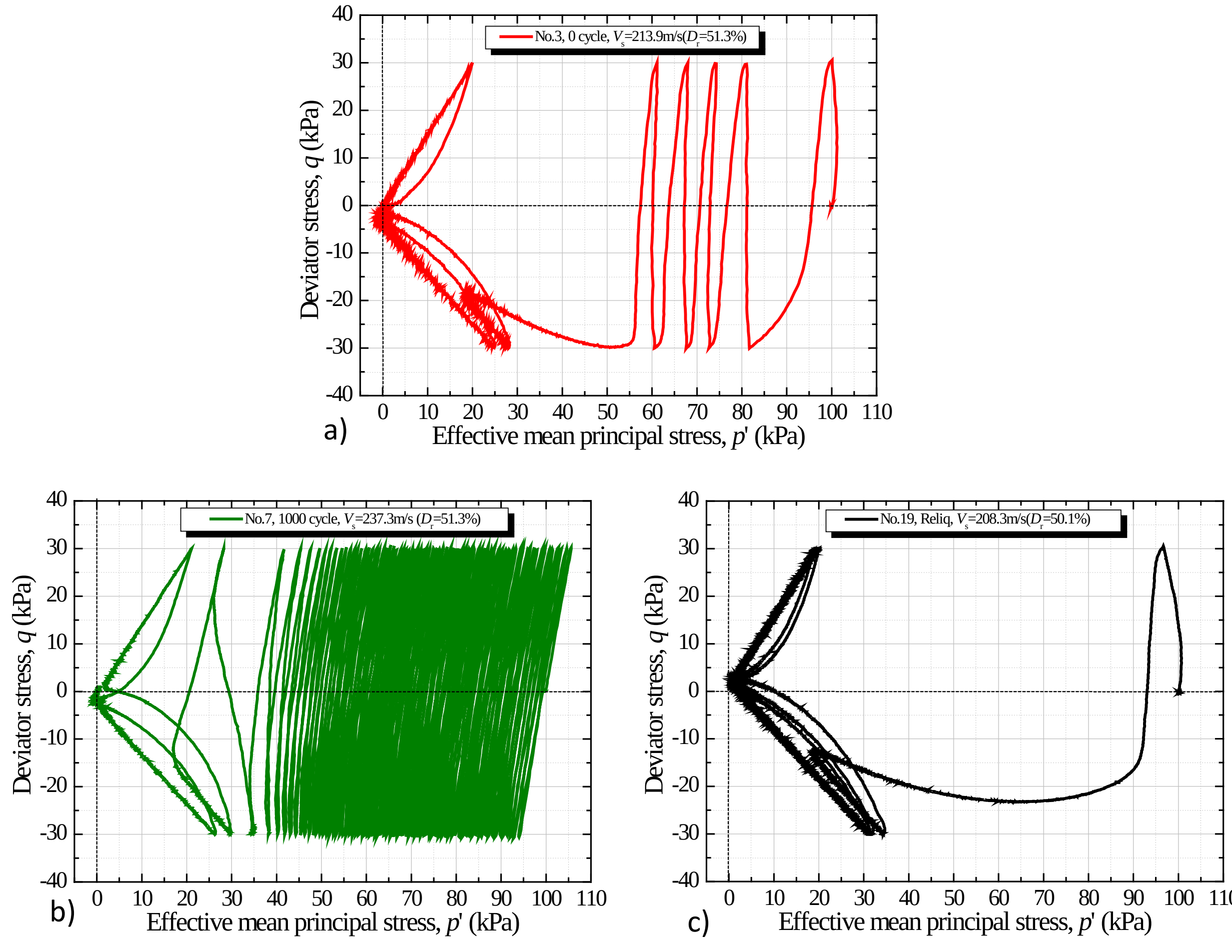


Fig. 5– Effective stress paths of a) original specimen, b) specimen with 1,000 drained cyclic loading history and c) specimen with liquefaction history

## 4. Discussion

The test results in this study clearly indicate that the liquefaction resistance of the specimen with different loading histories is not dependent only on the specimen density. Figure 6 shows liquefaction resistance curves obtained from the specimens with different loading histories. The liquefaction resistance defined as the cyclic stress ratio to cause double amplitude vertical strain, $\varepsilon_{v(DA)}$= 5%, in 20 cycles, $R_{L20}$, was 0.12 for the original specimen, and were 0.16, 0.23 and 0.25 for the specimens with 100, 1,000 and 2,000 drained cyclic loading histories, respectively. In addition, that of specimen with liquefaction history was 0.1.

Figure 7 shows the relationship between $R_{L20}$ and $V_s$ measured immediately before the liquefaction test. The figure indicates that the $R_{L20}$ is correlated with the $V_s$. Note again that the average value of $D_r$ of the specimens are almost the same (approximately 50 %), however, the maximum values of shear wave velocity and liquefaction resistance are about 16% and 250% larger than their lowest values, respectively.

Meanwhile, the liquefaction resistance and $V_s$ of the specimen with 3,000 drained cyclic loading history was almost equal to those with 2,000 cyclic loading history. This study, therefore, consider the values of $R_{L20}$ and $V_s$ of the specimen with 2,000 drained cyclic loading history as upper limit values that Toyoura sand under the given density and stress condition might have had. There are several research on the effects of different specimen preparation method and consolidation method on the liquefaction resistance by using Toyoura sand having similar $D_r$ to this study. Tatsuoka et al. (1986) reported that the $R_{L20}$ of Toyoura sand specimen prepared by different method varied from 0.11 to 0.14, while Tatsuoka et al. (1988) showed the $R_{L20}$ changed in a range of 0.12 to 0.15 due to change in the consolidation period. These values of $R_{L20}$ fall within the variation range obtained in this study.

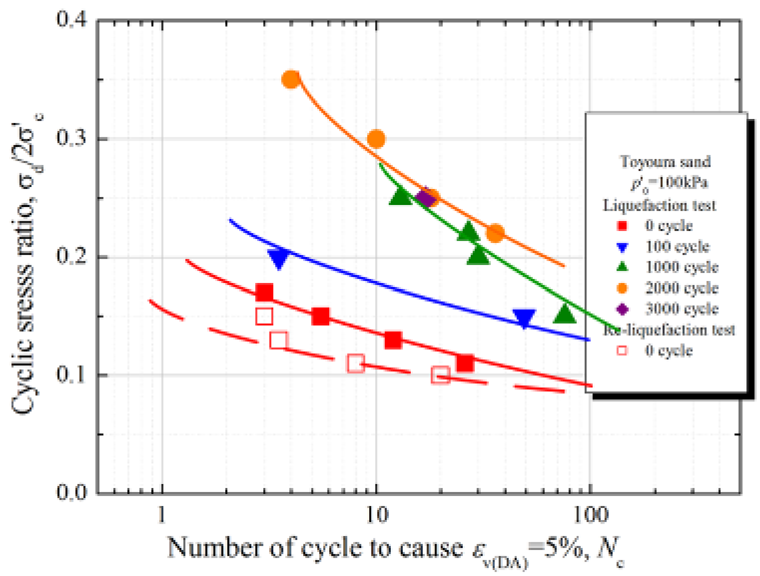


Fig. 6– Liquefaction resistance curves of specimens with different loading histories

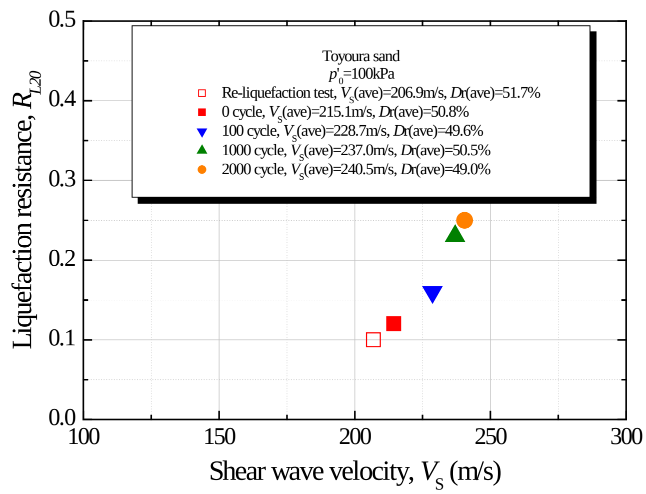


Fig. 7– Relationship between $R_{L20}$ and $V_s$ of the tested specimens

## 5. Conclusion

This study investigated a variation of shear wave velocity and liquefaction resistance of Toyoura sand specimen with relative density of 50%, which is caused by the different loading histories. The shear wave velocity of the specimen was measured by using a trigger and accelerometer system, while the liquefaction test was carried out with triaxial apparatus. The results showed that both the shear wave velocity and liquefaction resistance increased with increase in the number of drained cyclic loading. Meanwhile, they decreased significantly due to the liquefaction history. It could be inferred that the above features were caused by the enhancement or degradation of structure between the soil particles due to the application of drained or undrained cyclic loading history. It was also found that the upper and lower limit values of shear wave velocity and liquefaction resistance that Toyoura sand under the given density and stress condition might have had. For Toyoura sand specimen with relative density of 50%, the upper limit values of shear wave velocity and liquefaction resistance are about 16% and 250% larger than their lower limit values, respectively.

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