Performances of saturated sand in liquefaction and re-liquefaction progress under cyclic tri-axial tests with bender elements

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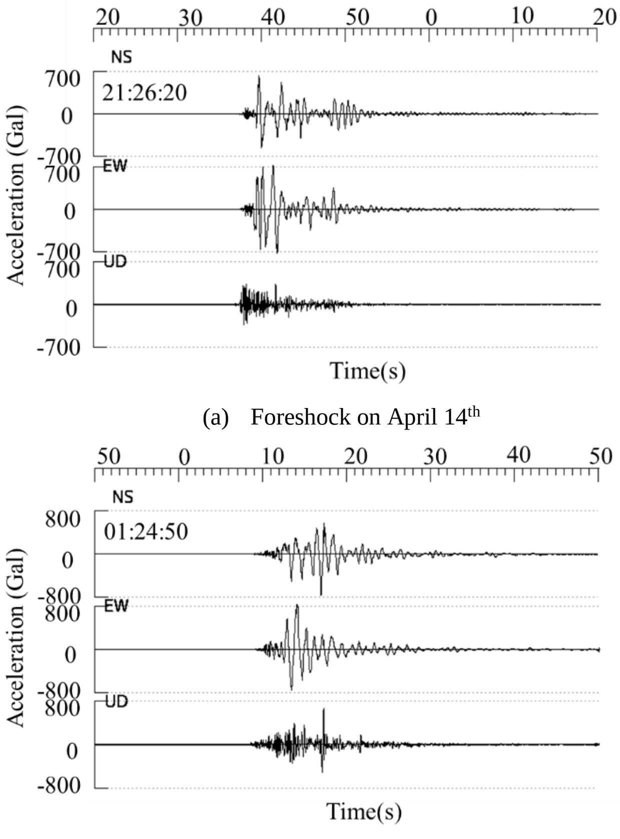
1. Introduction

In the 2016 Kumamoto earthquakes, liquefaction hazards occurred in the wide area in Kumamoto City and vicinities. The great earthquakes included two main shocks, the foreshock attacked there about 28 hours after on April 14th with M6.5 and the main shock attacked there again with M7.3 on April 16th. Fig. 1 exhibited the acceleration histories of the two shocks measured at Mashiki Town, where was the worst site suffered liquefaction disasters in the great earthquakes.



(a) Foreshock on April 14th

(b) Mainshock on April 16th

Fig. 1[2)] Acceleration history measured in Mashiki Town

Based on results of the geologic hazards investigations held by JGS[3)] (Y. Kitazono and N. Yasufuku etc.), they reported that the extreme damages of liquefaction occurred in the local areas suffered from the two main shocks. Besides, some liquefaction hazards occurred in the foreshock and became worse in the mainshock. Thus, it is worth to discuss the liquefaction behaviors of soils by considering the two shocks in this study. Utilizing the cyclic tri-axial tests with bender elements, we discussed the soil performances in liquefaction and re-liquefaction. Bender elements were widely used in situ measurements for investigating the potential risk of liquefaction after earthquakes[1)] (Andrus, R et and Stokoe II, K 2000). The use of velocity of shear wave(Vs), a small strain wave, as a typical index of liquefaction resistance, because both Vs and liquefaction resistance are influence by the similar factors, such as the relative density (void ratio), saturation state, stress history and stress state etc. Utilizing of the propagation characteristic of shear wave in different soil states, this study is expected to find out the variation features of Vs in the liquefying progress, and to discuss the shear modulus G, which is directly related to the velocity of shear wave.

Vs is directly related to small strain shear modulus G by (JGS 0544:2011),

$$G = \frac{\rho_t \cdot V_s^2}{1000} \qquad (1)$$

ρt is density of specimen. For all tests in this study being conducted with saturated and undrain conditions, the volume changes of specimens could be negligible in these tests. Thus, ρsat is instead of ρt to be used on this equation.

2. Cyclic tri-axial test with bender elements

Toyoura sand with different relative densities 58%~68% (Specific gravity Gs=2.644; void ratio emax=0.977 and emin=0.606) were taken as the soil samples in the tests. Sand of these specimens was carefully made up to completely saturated state (B value was greater than 0.95). Table 1 exhibits the conditions of the tests in detail. Before cyclic tri-axial tests, the specimen was consolidated under a cell pressure around 100 kPa for 1 hour in each case. The sand was tested by the cyclic sine loads with 0.1Hz until it was completely liquefied. After that, opened valve, dissipated excess pore water, re-consolidated it again test it again with the same load in first liquefaction test. The duration for the re-consolidation also was controlled within around 1 hour, as same as the time of the first test.

Table 1. Initial conditions of Specimens

	Dr. (%)	ρ_{sat} (g/cm^3)	B value	$\sigma_d/2\sigma'_0$
C-1	60.65	1.938	0.976	0.219
C-2	58.41	1.934	0.954	0.244
C-3	67.91	1.953	0.958	0.244
C-4	65.53	1.948	0.961	0.268

Measurement system of bender elements for Vs was assembled as illustrating in Fig. 2. A set of bender

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elements were installed at both top and bottom sides of the pistons in a standard tri-axial apparatus. The upper cell took charge of sending a shear wave, then the received waves could be recorded both from the lower cell and the amplifier by oscilloscope. The duration for the spreading of shear wave in specimen could be obtained from the delayed time ΔT in the system. And the Vs also could be obtained easily from the equation,

$$Vs = L/\Delta T \qquad (2)$$

L: The distance between the two cells.

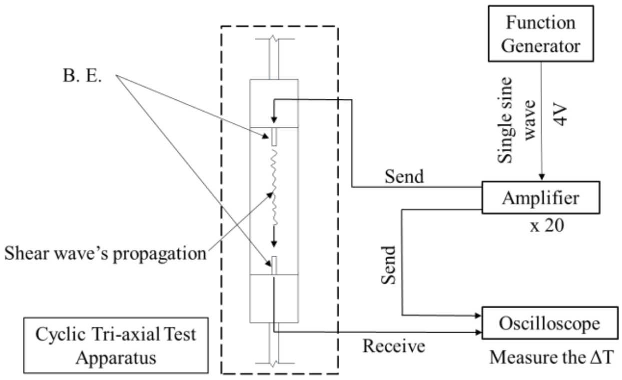

Fig. 2. Illustration of test apparatus

3. Results

At first, the Vs were measured with B-value measurement tests. The Vs arranged in Fig. 3 and exhibited the similar values before and after confining pressure's applications in four cases. Before the applying the confining pressures, the velocities were around 130 m/s; after the applications and opened the valves for the dissipating of excess pore pressures, the Vs raised to around 200 m/s. It could be fund that the Vs, which were measured after confining pressures' applications however before the valves' openings, showed the similar values as the Vs measured before confining pressures' applications. The contact force between particles didn't change because that the water defensed the all applied confining pressures in fully saturated sand. It also may prove the Vs may be only affected by the contact forces (or effective stress) in these tests.

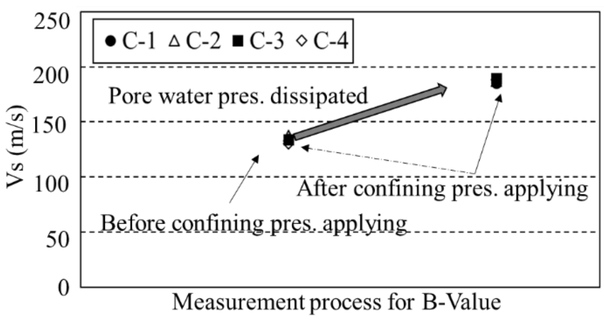

Fig. 3. Measurement of Vs with B value tests

According to the Fig. 4 and Fig.5, the liquefaction strength and initial stiffness in two liquefaction progresses. The relative densities increased around 5%~7% in all cases before second cyclic load tests. It is because that the volume of specimens decreased with the pore water running out from the specimens while the pore pressures were dissipating after the first liquefaction progresses.

Fig. 6 indicates a relation between initial shear modulus G and the liquefaction strength in each case. Nc is the total number of load cycles until the soil was liquefied in the tri-axial test. The greater value means the greater liquefaction strength owned by the specimens. The G didn't change great in all case(70~75MN/m^2) in the initial states before two cyclic load tests. Except C-3, the initial G increased in different degrees after re-consolidation in the other cases. On the contrary, the liquefaction strength (Nc) of the sand in second liquefaction progress decreased much great by comparing with it in first liquefaction progress.

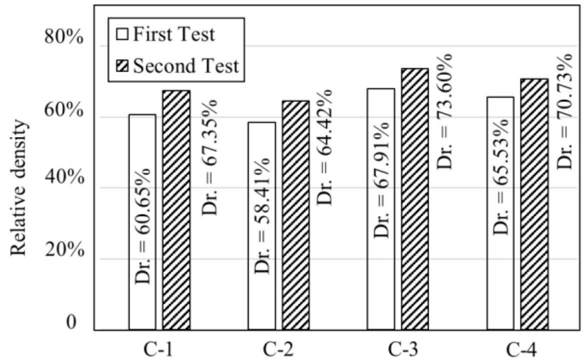

Fig. 4. Comparisons of relative density before first and second cyclic load tests

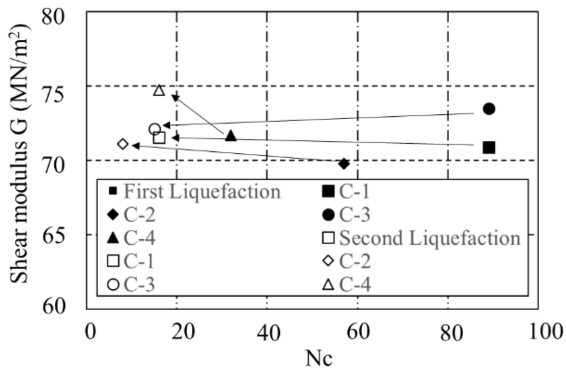

Fig. 5. Relations of Nc-G between liquefaction and re-liquefaction

4. Summaries

Utilizing the cyclic tri-axial tests with bender elements, the performances of saturated sand were discussed in the liquefaction progress and the re-liquefaction progress.

1. The velocity of shear wave Vs in sand may be only affected by the effective stress in the cyclic tri-axial tests.
2. In the re-liquefaction progress, the liquefaction strength lost very fast than it in the first liquefaction progress, even if the relative densities and shear modulus G increased after the re-consolidations.

References

1) Andrus, R et and Stokoe II, K (2000): Liquefaction resistance of soil from shear-wave velocity, *Journal of geotechnical and geoenvironmental engineering*, 1015-1025.
2) Japan Meteorological Agency. (In Japanese) *http://www.data.jma.go.jp/svd/eqev/data/higai/higai1996-new.html*
3) JGS: Reports of H28 Geologic Hazard Investigation (2017) (in Japanese)