Variations of velocity of shear wave in sand by utilizing bender elements in cyclic tri-axial tests

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1. Introduction

Soil effective stress and shear stiffness decreases by liquefying progress in cyclic tri-axial tests, and it reduces to zero while soil is completely liquefied. Utilizing of the propagation characteristic of shear wave in different soil states, this study is expected to find out the variation features of velocity of shear wave in the liquefying progress, and also to discuss the relation between shear modulus G, which is directly related to the velocity of shear wave, and effective stress σ’.

Bender elements were widely used in situ measurements for investigating the potential risk of liquefaction after earthquakes (Andrus, R et and Stokoe II, K 2000). The use of Vs (velocity of shear wave, a small strain wave) as a typical index of liquefaction resistance, because both Vs and liquefaction resistance are influenced by the similar factors, such as the relative density (void ratio), saturation state, stress history and stress state etc. Following the research achievements about this point, many researchers performed this measurement in laboratory for small-scaled specimens especially in cyclic tri-axial tests. Thus, bender elements were adopted for measuring the velocities of shear wave for this study.

2. Cyclic tri-axial test with bender elements

Sand with different relative densities was conducted with the other same test conditions in the studies. Toyoura sand (Specific gravity Gs=2.644; void ratio e_{max}=0.977 and e_{min}=0.606) were taken as the soil samples in the tests. Specimens were prepared as two groups (two cases in each group), one group have a greater relative density (Dr.) around 72%, and the other group was made with a lower relative density around 55%. 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 sand in detail. Before cyclic tri-axial tests, the specimen was consolidated under a cell pressure around 100 kPa for one hour in each case. Loading conditions are shown in Table 2.

Measurement system of bender elements was assembled as illustrating in Fig. 1. A set of bender elements with two cells were installed at both top and bottom of the pistons in tri-axial apparatus. The upper cell is taken in charge of sending a shear wave, then both the received wave from the lower cell and the sent wave from the amplifier could be recorded by oscilloscope for further analysis. In addition, the intervals between each two measurements of Vs was set as five load cycles for the C-3 and C-4 with smaller relative density, and set as ten load cycles for C-1 and C-2 with greater relative density.

3. Results and discussion

At first, the velocities were measured after saturation stage and

Table 1. Initial conditions of Specimen

	Dr. (%)	e_0	ρ_{sat} (g/cm^3)	B value
C-1	72.91	0.7065	1.963	0.960
C-2	72.57	0.7078	1.963	0.953
C-3	59.99	0.7545	1.937	0.978
C-4	55.88	0.7697	1.929	0.973

Table 2. load conditions in test

Function	Frequency	Deviator stress	σ_d(kPa)
Sin	0.1 Hz	≈48.9kPa	≈46.5

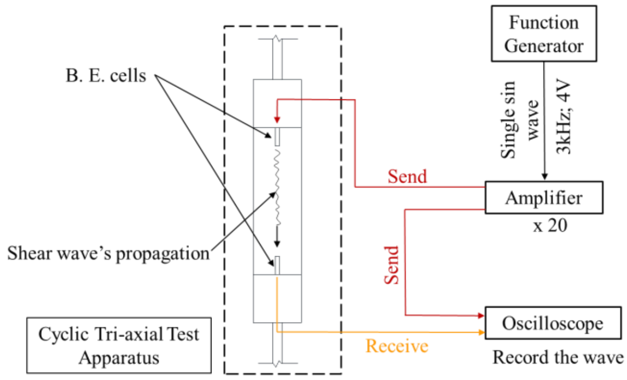

Fig. 1. Illustration of test apparatus

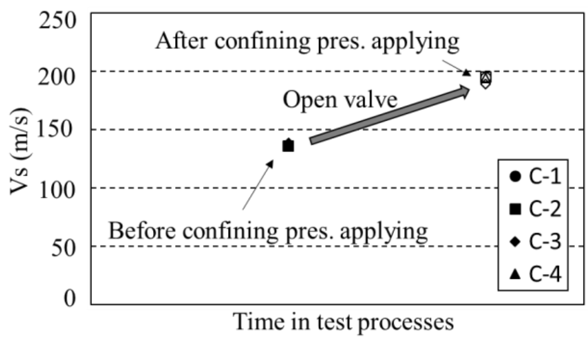

Fig. 2. Measurement of Vs with B value tests

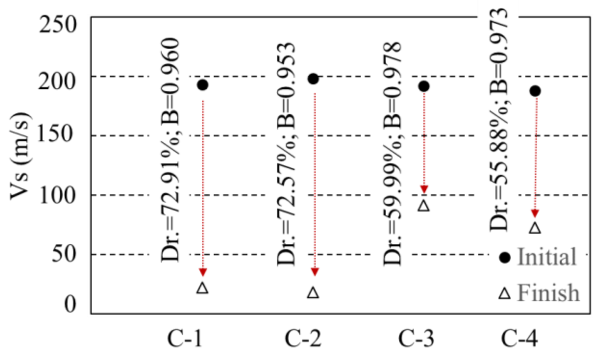

Fig. 3. Variations of Vs between initial and finish states

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before confining pressure applying for detecting the relation between Vs and B values. Then, switched on the valve to dissipate the excess pore water pressure away from specimen, and measured the velocities again. The arranged outcomes are plotted in Fig. 2. Velocities in four cases exhibited the approximate results. Before B value testing, all of them are around 130 m/s; and then they raised to near 200 m/s while excess pore water dissipated (the phase at this point is considered as consolidation starting).

Comparing with the velocities in initial state of specimens shown in Fig. 3, these velocities did not change great until consolidation finished. Four cases were made with different relative densities, but they owned almost the same velocity at initial. The same cell pressure of 100 kPa in each case perhaps resulted in this kind of presents. On the contrary, velocities at liquefied state present the very different outcomes. For ensuring the facticity of test results, the velocities, marked as "Finish" in Fig. 3, were measured immediately while liquefaction occurred in these specimens. The results showed that the velocities dropped to less than 100 m/s when the specimens liquefied with the original shear strength losing in cyclic tri-axial tests. Moreover, the velocities were further reduced to less than 50 m/s in C-1 and C-2 with greater relative density.

Fig. 4 describes the variation history of Vs during the tests. It exhibits about the variation of velocities: it reduced rapidly at first few sample points, then the curves become gentle and trend to near linear changes. This stage was the longest period in whole test. Approaching to liquefaction, the velocities dropped very fast and tests finished with only four or five sample points. The velocity in C-4 dropped in a very short time with only twenty cycles. However, it is still present a same variation tendency with others.

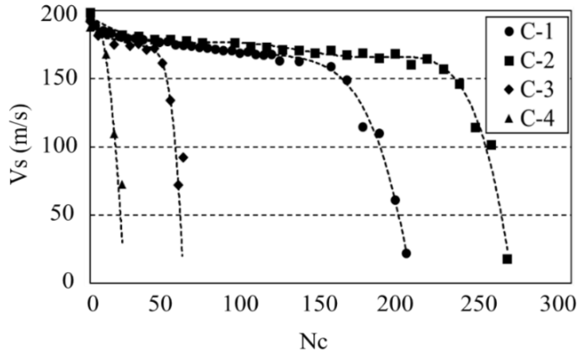

Fig. 4. Variations of Vs with Nc

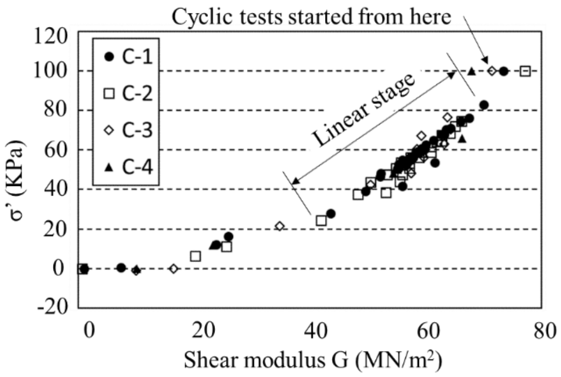

Fig. 5. Relation between shear modulus G and effective stress σ'

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

$$G = \frac{\rho_t \cdot V_s^2}{1000} \tag{1}$$

ρ_t 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, ρ_{sat} is instead of ρ_t to be used on this equation.

Relations between shear modulus G and effective stress σ' of four cases were plotted in Fig. 5. The variation of effective stress with shear modulus could be divided to three phases, 1) Effective stress decreased faster than shear modulus during the interval of first or second sample point; 2) After a short time in initial, the variation of effective stress shows a approximate linear relation with shear modulus and more than 90% of sample points gathers in this phase; 3) In final phase, shear modulus decreased very faster with the decreasing of effective stress.

4. Summaries

Utilizing the cyclic tri-axial tests with bender elements, the performance of velocities of shear wave in Toyoura sand were discussed. Some results are summarized mainly:

1) Similar velocities of shear wave around 200 m/s in initial states of specimens with different relative densities. And velocities of shear wave in final reduced less 100 m/s in all cases. In the two cases with greater relative density, the velocities reduced further to 50 m/s in each specimen;
2) Velocities of shear wave decreased rapidly in the initial and approached liquefied stages. Most of the sample points reduced very slowly closed to linear changes with Nc;
3) Effective stress decreased faster than shear modulus in a very short period after test start, on the contrary, shear modulus decreased very faster than effective stress in a short period before liquefaction. Much of this progress is showed a linear relation in middle stage.

References

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