Evaluation of shear wave travel time in laboratory bender element test

Évaluation du temps de propagation des ondes de cisaillement lors d'essais au laboratoire avec des languettes piézoélectriques

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ABSTRACT: A laboratory investigation of the measurement of shear wave velocity in bender element (BE) test was carried out to examine the effects of wave-form and frequency of input pulse, together with near-field effect (NFE) on the measurement of shear-wave travel time. On the basis of test results of clays, it has been manifested that the travel time of shear wave should be taken as "start-to-start" between two instants at generation and at reception of shear wave. It is suggested to perform BE test with input pulse using various kinds of waveform over a wide range of frequency. It is also preferred to employ incremental loading steps to reach beyond the prescribed consolidation stress. The elastic shear modulus, G of natural clay in laboratory BE test coincided well with comparable G_f from in-situ seismic survey.

RÉSUMÉ: Une étude en laboratoire sur la mesure de la vitesse des ondes de cisaillement aux moyens de capteurs piézoélectriques «bender» a été réalisée. L'influence de la forme et la fréquence du signal d'entrée, ainsi que les effets du champ proche, sur la mesure du temps de vol des ondes de cisaillement ont été examinés. Sur la base des résultats obtenus sur l'argile, il a été montré que le temps de vol d'une onde de cisaillement doit être pris comme le temps écoulé entre l'instant où l'onde est générée et celui où elle est reçue «start-to-start». Il est conseillé de réaliser ces tests avec capteurs piézoélectriques «bender» en utilisant différentes formes de signal d'entrée et en balayant une large gamme de fréquences. Il est également recommandé d'utiliser des paliers de chargement incrémental pour atteindre des valeurs au delà de la contrainte de consolidation prescrite. Le module de cisaillement élastique G de l'argile naturel obtenus en laboratoire à partir des essais avec capteurs «bender» coïncide de manière satisfaisante avec le module G_f obtenus à partir de mesures sismiques *in situ*.

1 INTRODUCTION

A proper understanding of elastic shear modulus at strains of about 0.0001%, G, is of great importance in geotechnical engineering. For instance, the quality of natural soil samples in the laboratory may be assessed by comparing G between field and laboratory measurements (Tokimatsu and Oh-hara, 1990; Toki *et al*, 1994). Bender element (BE) test has become popular over the last decade or so in geotechnical engineering laboratories worldwide, with which G of soils may be readily measured. In spite of the popularity, the determination of 'correct' shear-wave arrival time is still an unsolved issue involved in BE test (Shibuya, 2000). In this paper, an attempt is made to examine correct arrival time of shear wave in laboratory BE test. A series of experiments on clays was carried out by using a fully automated BE recording system developed by the authors.

2 TESTS PERFORMED

The consolidometer quipped with a pair of BEs (Shibuya *et al*, 1997) was employed in the tests. NSF-clay (w_L=55%, I_p=26) reconstituted in the laboratory (Shibuya et al, 1995) using the vertical preconsolidation pressure of 150 kPa was prepared, and disk-shaped specimens with two different heights (*i.e.*, 2cm and 4cm) were provided for the BE test. A high-quality sample of Ariake clay (w_n=137%, w_L=117% and I_p=68) retrieved by Sherbrooke sampler (Tanaka et al, 1996) was also tested. The effective overburden pressure of this Ariake sample was 21 kPa.

In BE test, the shear wave velocity, V_s, is given by

$$V_s = L/\Delta t \tag{1}$$

where L stands for travel distance of shear wave. Note that tip-to-tip distance is appropriate (Dyvic and Madhsus, 1985, Viggiani and Atkinson, 1995), so is adopted when interpreting the test results. Note also that travel time, Δt, is of interest in this research. The G-value is given by

$$G = \rho_t \cdot V_s^{\,2} \tag{2}$$

where ρ_t represents bulk density of soil.

3 DISCUSSION ON DETERMINATION OF SHEAR-WAVE TRAVEL TIME (Δt)

3.1 *Effects of wave-form and frequency of input pulse*

Fig.1 shows the record of voltage with time at reception when using a single sinusoidal wave of 1, 2, 4 and 8 Hertz as well as a rectangular wave of 100 Hertz. In this test, the measurements were made using a NSF clay specimen at σ_{vc}=400 kPa.

Note that neither the waveform nor the frequency of input pulse influenced the instants corresponding to the first and second peaks of the received waves. In addition, these peaks were more clearly identified when the rectangular waveform was employed. Indeed, the peaks were not clearly identified when a single sinusoidal wave of 1Hertz was employed as the input pulse. It may be inferred that the amplitude of the peaks at reception depends greatly on the initial movement velocity of the triggered bender. Since the peaks at reception were observed at similar instants in this test using different frequencies, it may be said that the shear wave at reception was generated at the very beginning of input pulse.

Considering the test results, the previous definition that the travel time corresponds to peak-to-peak between input and output pulses as suggested by Viggiani and Atkinson (1995) and Lohani et al (1999) could essentially be incorrect. This definition may be practically acceptable only when the frequency of shear wave is high enough, but is unacceptable in tests using a low frequency of input pulse. As a matter of fact, according to the

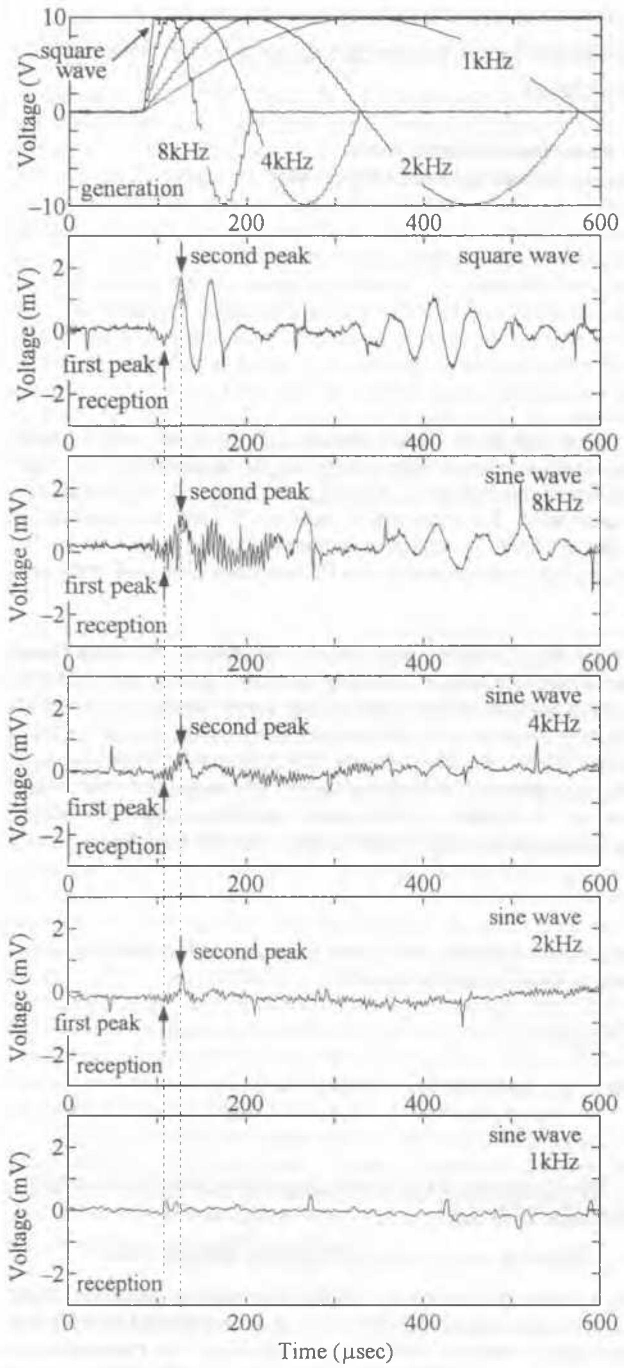

Figure 1. Effects of form and frequency of input pulse at reception (NSF clay).

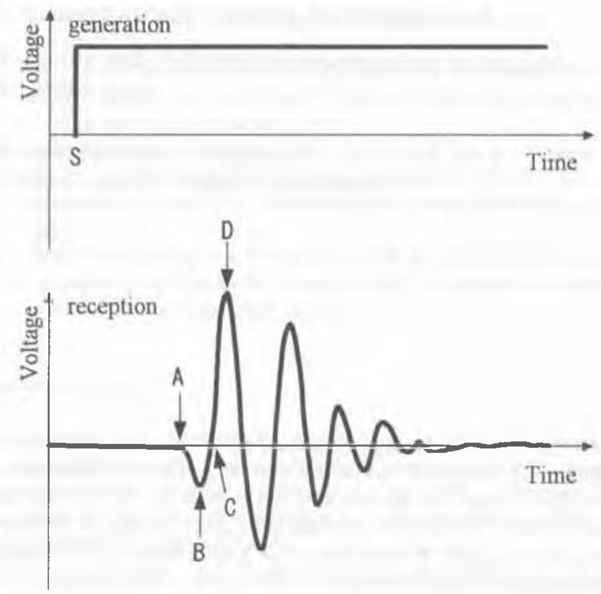

Figure 2. A schematic diagram showing voltage variation with time at reception.

		S-A	S-B	S-C	S-D
○	t (μsec)	13.8	25.6	35.4	43.3
	G (MPa)	414.3	120.4	62.9	42.1
□	t (μsec)	116.3	130.0	151.1	163.3
	G (MPa)	102.6	82.1	60.8	52.0

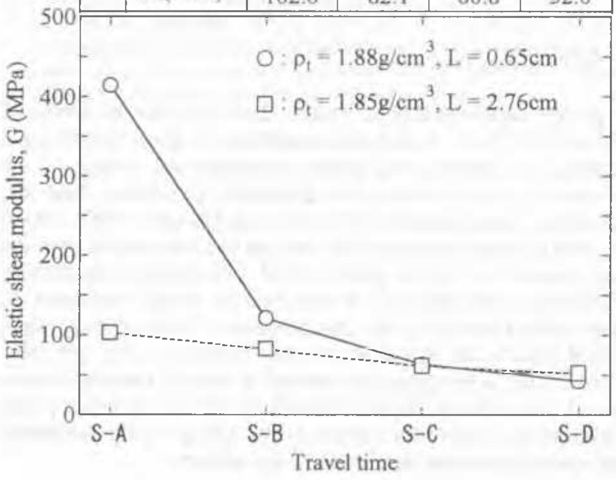

Figure 3. A comparison of G in two comparable tests using different specimen heights (NSF clay).

peak-to-peak definition, Δt becomes negative over the frequency range of input pulse less than 4 kHz (see Fig.1). Therefore, an alternative definition of "start-to-start" between input and output pulses may be adequate.

3.2 *Examination using specimens of different heights*

Fig.2 shows a sketch representing time history of output voltage at reception. In defining Δt, the generation of shear waves at t=0 was considered at starting instant of input pulse (*i.e.*, point S).

Fig.3 shows the results of comparative two BE tests on NSF clay specimens of different heights of 0.65cm and 2.76cm. In this figure, the G-value was calculated by using four different definitions of Δt equal to S-A, S-B, S-C and S-D. Note that the G-values of these two tests coincided most closely to each other in case of Δt of S-C. Moreover, it should be mentioned that the G-value of 61-63 kPa is close to the G-value of 54 MPa from undrained Young's modulus (E_u=162 kPa) in triaxial test at very small strains (Kawaguchi *et al*, 1999). Therefore, the 'correct' arrival time of shear wave could be in between two instants of S-C and S-D. At least, we definitely say that the choice of S-A is utterly inappropriate.

3.3 *Near-field effects (NFE)*

Near-field effects are known to affect the determination of arrival time of shear wave, especially when the travel distance of shear wave is short (Salinero et al, 1986).

Fig.4 shows the results of BE measurement of a single NSF clay specimen subjected to different consolidation pressures. Despite that G increases with consolidation pressure, the arrival time of first peak indicated by the symbol A was unchanged with

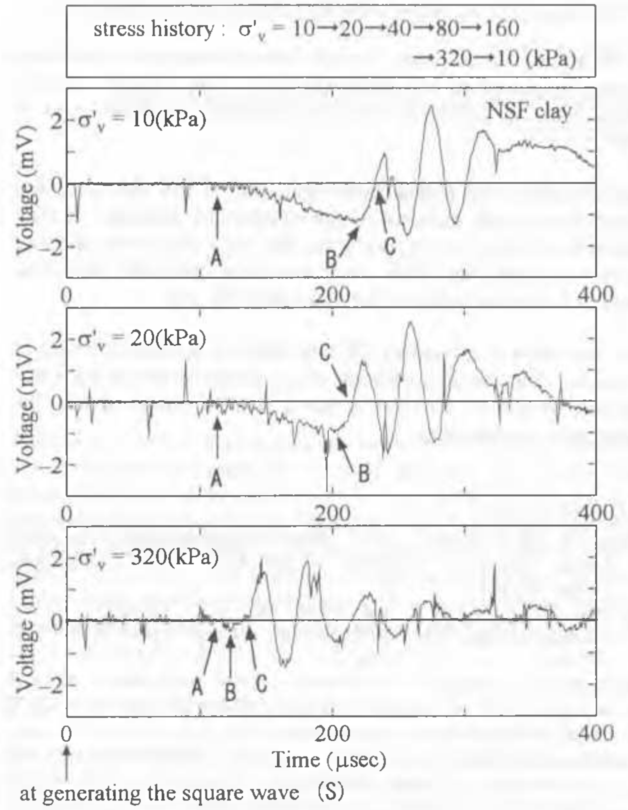

Figure 4. Near field effect (NFE) depending on pressure level.

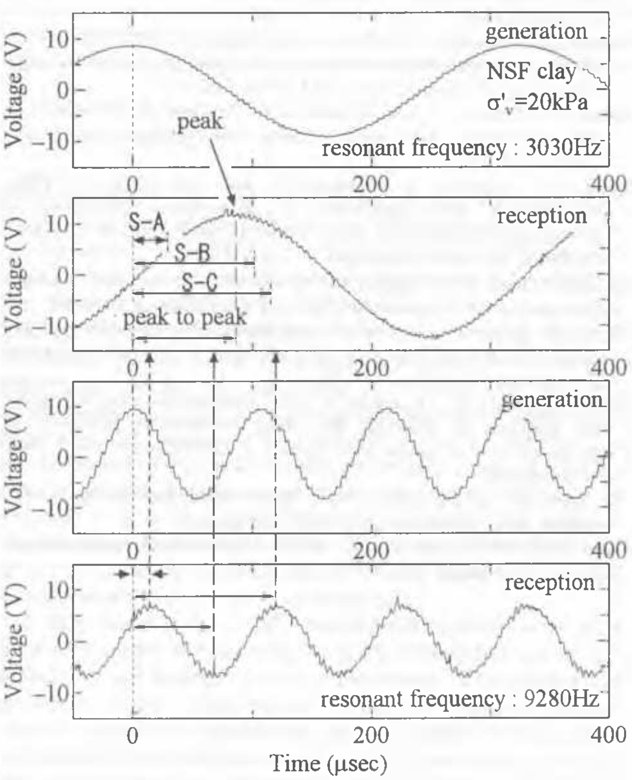

Figure 5. Examination of shear-wave travel time at resonant condition.

the pressure level, implying that the portion A–B was induced as a result of NFE. The apparent peak due to NFE exhibited a trend to disappear with increase of the pressure. The NFE was more significant over a low-pressure range, resulting that the second peak was pushed downwards (see uppermost record in Fig.4). When the NFE is evident, Δt is underestimated, hence G is over-

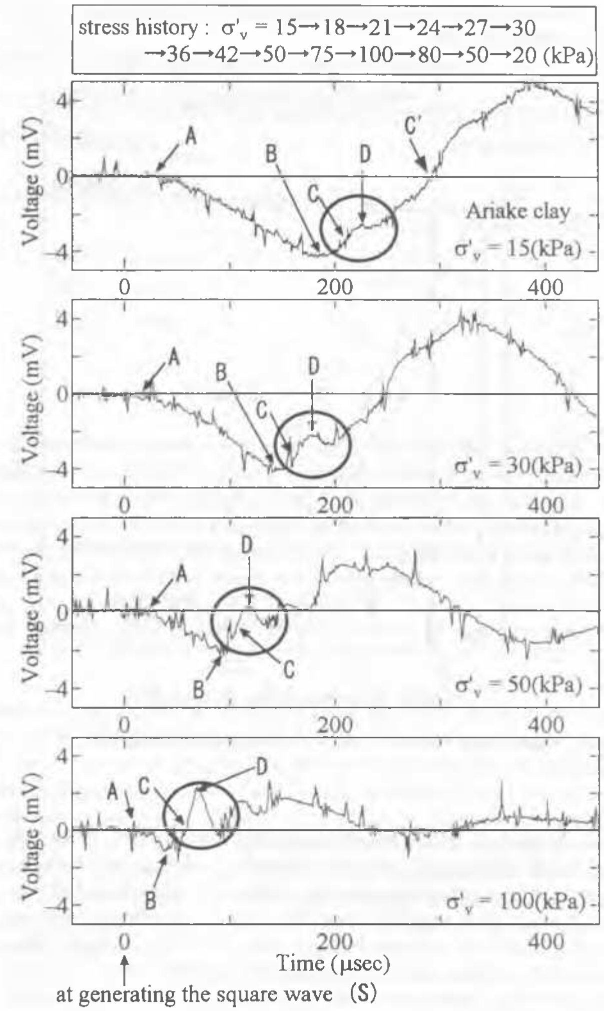

Figure 6. Result of BE test on natural sample of Ariake clay.

estimated conversely (see Eqs.1 and 2). It may thus be suggested to perform a BE test over a wide pressure range so as to identify the NFE.

3.4 *Resonant frequency*

When input pulse is continuously generated using, for example, sinusoidal wave, the resonance conditions are observed at some frequencies. The arrival time, Δt is often determined as the time lag corresponding to peak-to-peak at resonance (Jovičić et al, 1996, Lohani et al, 1999). An example of the BE measurement at resonance is shown in Fig.5, in which the time records of resonance conditions at two different frequencies are shown, together with indication of possible definition of Δt of S–A, S–B and S–C. Note that none of these three definitions is satisfactory in providing the same Δt between two conditions of resonance. Therefore, we dare say that the definition of Δt to make use of resonance conditions seems inappropriate, too.

4 VALIDATION USING NATURAL SAMPLE OF ARIAKE CLAY

Fig.6 shows the results of BE test, in which a natural sample of Ariake clay was consolidated using incremental loading up to five times in-situ effective overburden pressure. In this test, the instant of t=0 refers to the start of input pulse with rectangular waveform. Similar to the result shown in Fig.4, the arrival of first shear wave seems as if point A. However, it is clear that the

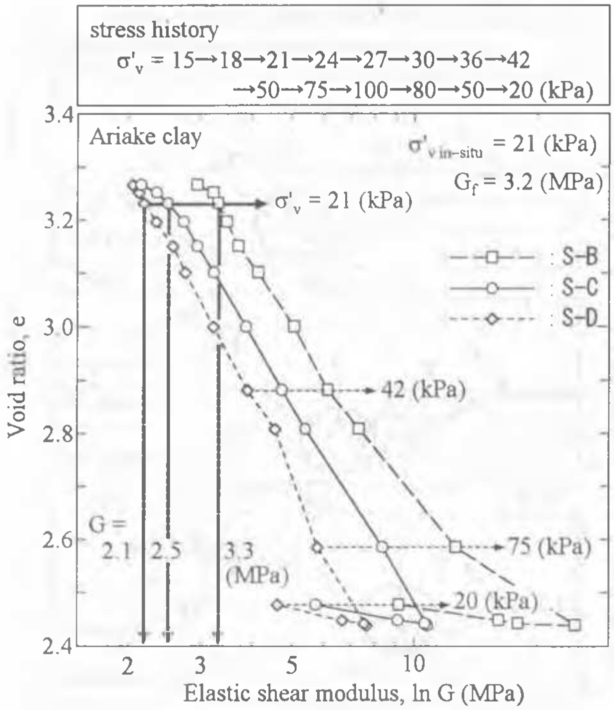

Figure 7. Relationship between e and G in test on natural sample of Ariake clay.

portion from A to B was merely apparent due to NFE, since the point A was unchanged, and also the portion diminished with increase of the overburden pressure (refer to subsection 3.3). In addition, one may consider that the point C' in the uppermost picture seems to be corresponding to point C in Fig.2. Again, this is obviously a misjudgment because the genuine peak of shear wave gradually turned out as the pressure increased (see circled portion in Fig.6).

Accordingly, it was considered that the supposed peak in the circled portion refers to the second peak; *i.e.*, the point D in Fig.6, and that the point of deflection between B and D corresponds to point C in Fig.6. Fig.7 shows the relationship between void ratio, e, and G by using different definitions of Δt equal to S–B, S–C and S–D. Note that the linearity between e and G in their semi-logarithmic representation is attained when the time lag between S and C is taken as Δt. The validity of employing S–C as Δt can be corroborated when considering the fact that the linearity is commonly seen for the e-$\log G$ relationship of reconstituted clays over the state of normally consolidation (Kawaguchi et al, 1999; Shibuya et al, 2000). It should also be mentioned that the G-value of 2.5 MPa is close to the corresponding measurement of G_f=3.2 MPa from in-situ seismic survey.

In situations where the NFE is too significant to identify point C, we may be allowed to derive of Δt by taking the averaged time of two instants at points B and D. The authors strongly insist the need to measure G over a wide range of stress in situations where the NFE is evident in the measurement. To achieve this, automatic recording system is indispensable in the laboratory BE test.

The results shown in Figs.6 and 7 suggest that the value of laboratory BE test is seen on its measurement of G under clear stress conditions. Also, interpretation of the comparable results of field measurement will be enhanced with the laboratory measurement.

5 CONCLUSIONS

i) The 'correct' travel time of shear wave in BE test is described as "start-to-start" between two instants at generation and at reception of shear wave (*i.e.*, the time lag from S to C in Fig.2).

ii) The previous definition to make use of resonance conditions seems inappropriate in describing the 'correct' travel time of shear wave, in particular when the frequency of shear wave is low.

iii) The NFE was found more significant at low pressure, and disappeared with increase of the overburden pressure. It may therefore be suggested to perform a BE test over a wide pressure range to identify the NFE. To achieve this, automatic recording system is indispensable in the laboratory BE test.

iv) The value of laboratory BE test refers to the measurement of G under clear stress conditions. Also, interpretation of the comparable results of field measurement will be enhanced with the laboratory measurement.

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