ACTA TECHNICA CORVINIENSIS – Bulletin of Engineering
Tome V (Year 2012). FASCICULE 1 [January–March]. ISSN 2067-3809

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ON THE INTEPRETATION OF SHEAR WAVE VELOCITY FROM BENDER ELEMENT TESTS

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ABSTRACT: *Shear wave velocity measurement using bender elements has become more widely adopted in determining the small strain shear modulus (G_o) of soil specimens in recent years. Apart from being a non-destructive and hence easily repeatable test on the same specimen, the adaptability of the bender element transducers for installation in existing test apparatus has also helped popularize the method. With a pair of bender elements, i.e. a transmitter and a receiver, and the assumption of a homogeneous and elastic medium, the shear waves' transmitter-to-receiver travel time is measured, hence giving the shear wave velocity (velocity = transmitter-receiver distance / travel time). Taken in the plane wave propagation context, G_o is conveniently computed as a multiplication of the specimen's bulk density and square of the velocity. Unfortunately simplicity of the test procedure does not extend to the actual characteristics of shear wave propagation through the specimen, which inadvertently affect the received signal for reliable arrival time interpretation. Various factors contribute to distort the received signals and mask the accurate identification of arrival time. These factors were individually examined in this study with unconfined specimens, which were prepared from cement-stabilized artificial kaolin clay. A pair of 80 mm high cylindrical specimens, with 76 mm and 100 mm diameter respectively, was subjected to the shear wave velocity measurements using bender elements. It was found that these influencing factors can be categorized under those of the input frequency, specimen geometry, near-field effects and attenuation of the sent waves. Discussions based on the signals analyzed are presented under each of these categories, and the effects on the shear wave arrival time were assessed. While no best method for identifying the arrival time could be ascertained, a conclusion not dissimilar with reports by other researchers in similar endeavors over the years, these insights can be useful and instructive to minimize uncertainties when using this convenient measuring tool.*
KEYWORDS: *bender elements, shear wave, velocity, stabilized soil*

INTRODUCTION

A bender element test essentially involves sending elastic waves through a specimen to cause transient perturbation to the particles, of which the resistance encountered by the induced vibration is translated as stiffness of the material.

The elastic waves can be compression waves (also known as P-waves), or shear waves (other names include S-waves and transverse waves). The temporary disturbance is observed as being parallel to the direction of the wave movement if a compression wave is transmitted, and perpendicular if it is a shear wave. Logically, a stiffer material would accelerate the wave propagation through the medium. Putting these wave motions in the assumed and simplified context of plane waves passing through a homogeneous, elastic and isotropic medium, the module of stiffness at such small strains can be derived as bulk modulus, $K = \rho v_p^2$, and shear modulus, $G_o = \rho v_s^2$, respectively (ρ = bulk density, v_p = compression wave velocity, v_s = shear wave velocity).

Setup for a bender element test mainly consists of a pair of bender element probes (i.e. a transmitter and a receiver), with the transmitter connected to a function generator, the receiver plugged into an amplifier, and both transducers linked to an oscilloscope, as shown in Fig. 1. Similar setups were used by Leong et al. [1], Hird and Chan [2], Yang et al. [3], Lee and Huang [4], Clayton et al. [5].

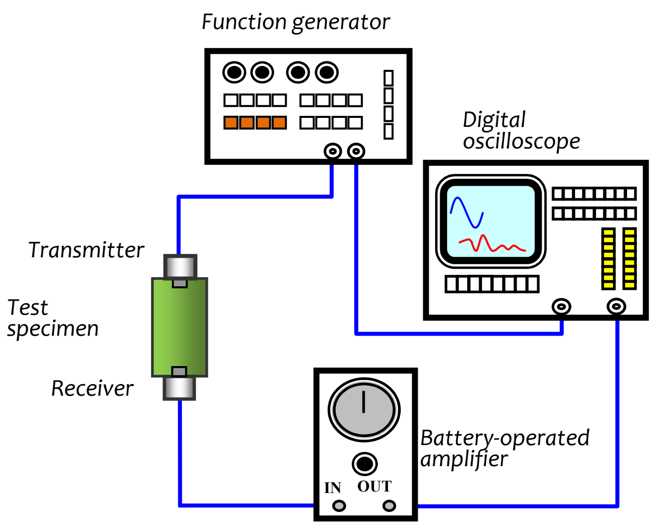

Figure 1. The bender element test setup

Later improvements which replaced the external controllers with specific computer programs and data acquisition cards were demonstrated by researchers like Chan et al. [6] and Boonyatee et al. [7]. Nevertheless the basic principles of shear wave velocity measurement remain the same: the transmitter is powered up by a function generator to vibrate, while the receiver picks up the vibration across the medium on the opposite end and begins to vibrate itself. Bender elements, coming from the family of piezoelectric ceramics, are capable of generating an electrical output when subjected to a mechanical deformation (hence the receiver) and vice *versa (the transmitter). The amplifier used in the original setup mentioned earlier was meant to amplify the received signals as representing the receiver's vibration is significantly smaller compared to the transmitted signal.*

The shear wave arrival time is next determined from both signals captured on a timescale plot, either by direct identification, as with the time domain methods, or with further manipulation in the frequency domain. In recent years, there have been a number of attempts to accurately define the shear wave arrival time in bender element test. For instance, Leong et al. [1], Hird and Chan [2] as well as Lee and Huang [4] have explored shear wave arrival time definitions in the time domain, while Boonyatee et al. [7] and Arroyo et al. [8, 9] experimented in the frequency domain. Some of the work described in the literature also revealed efforts in establishing the configuration effects of bender elements in the resulting signal interpretations. In addition, most of the bender element measurements were incorporated in conventional or specially built test cells and apparatus, as an additional monitoring tool during the primary tests.

This paper discusses the main factors affecting the interpretation of shear wave velocity using bender elements in unconfined specimens, specifically. As bender element test has been widely acclaimed as a quick and simple test to conduct for measure the small strain shear stiffness of a soil material, the use of the transducers without incorporation in an existing apparatus remains relevant. This is particularly so in the quality control of stabilized soils, where bender element tests can be conveniently carried out on unconfined specimens prior to routine compression tests, e.g. Mokhtar and Chan [10], Chan [11] and Mattsson et al. [12].

EXPERIMENTAL WORK

Test Specimens

The test specimens were a pair each of cement-stabilised kaolin cylinders, 76 mm in height, 38 mm (i.e. specimen S1 and S2) and 114 mm (i.e. specimens L1 and L2) in diameter respectively. Pre-mixed in dry forms of kaolin powder and ordinary Portland cement (3 % based on weight of kaolin powder), 50 % of water (also based on weight of kaolin powder) was then added to produce a uniform mix in a food mixer. The mixture paste was next transferred to split mould, compacted using miniature hand tools with combined kneading effect in 3 layers. When extruded from the mould and with the ends trimmed off, the specimens were wrapped in cling film and cured in a moist chamber for the same period of time before tests. A slot 12 mm long x 3 mm wide x 7 mm deep was formed by inserting a Perspex block at each end of the specimen. The slots were later used for insertion of the bender elements, with plasticine used as the coupling agent. This was necessary as curing significantly stiffened the specimen and made it impossible to insert the bender elements without damaging the transducers or the specimen.

Shear Wave Velocity Measurements

The transmitting bender element or transmitter was excited with ±10 V single cycle sine pulses of frequencies ranging between 1-20 kHz using the Thandor TG503 function generator, which was triggered by a separate function generator, Continental Specialities Corporation Type 4001. The received signal, as detected by the receiving bender element or receiver, was amplified through a battery-powered amplifier. This inadvertently reversed the polarization of the signal but was conveniently rectified with the oscilloscope. The transmitted and received signals were both captured on the Tektronix TDS3012B digital phosphor oscilloscope (100 MHz, 1.25 GS/s) and the digitized data were processed in spreadsheets for further analysis described later. The penetration dimensions of the bender element transducers on both ends of the specimen were 12 mm wide and 7 mm long. Two cables were connected to the transducers, a coaxial cable for the electrical connectivity, and an additional cable for earthing purposes. Shielding and earthing were crucial to avoid electromechanical interference, which can distort the received signals and complicate determination of the actual shear wave arrival time [1].

FACTORS AFFECTING INTEPRETATION OF SHEAR WAVE VELOCITY

Input Frequency

The input frequency (f_{in}) was used to compute the wavelength, $\lambda = v_s/f_{in}$, where v_s is the shear wave velocity determined using the visually picked arrival time. The wavelength (λ) is therefore dependent on the frequency with which the transmitting bender element was excited with during the test, assuming that it was also the dominant frequency in the received signal. Note that this is not always the case. Yamashita et al. [13] compiled results from international parallel bender element tests and concluded that the change in input frequency does not result in corresponding or proportional change in the frequency of the received signal. Therefore the assumption is unlikely to hold true, implying the inherent errors of some shear wave arrival time determination methods (e.g. cross-correlation) which involve matching up the transmitted and received signals.

Lutsch (1959) and Thill and Peng (1969), as reviewed by Leong et al. [14], highlighted the obscuring of the first major deflection in the received signal if the wavelength is equal to the average grain size, taken as

D_{50} (grain diameter with 50 % material passing on the particle size distribution curve). Also, the ratio of λ/D_{50} is recommended to be more than 3 to avoid dispersion in ASTM Standard 2845-95 [15]. The wavelengths in the present tests ranged between 13 - 300 mm for S1 and S2, 14 - 100 mm for L1 and L2 (Table 1).

Table 1. Influence of input frequency on dispersion and attenuation

Specimen S1

fin kHz	to ms	vo ms-1	λ m	L/λ L = 61 mm	L/D	D/λ	Go MPa
1	0.260	235	0.235	0.260	1.605	0.162	94
3	0.250	244	0.081	0.750		0.467	102
5	0.240	254	0.051	1.200		0.748	110
7	0.240	254	0.036	1.680		1.047	110
9	0.240	254	0.028	2.160		1.346	110
12	0.230	265	0.022	2.760		1.719	120
15	0.230	265	0.018	3.450		2.149	120
20	0.230	265	0.013	4.600		2.866	120

Specimen S2

fin kHz	to ms	vo ms-1	λ m	L/λ L = 61 mm	L/D	D/λ	Go MPa
1	0.200	305	0.305	0.200	1.605	0.125	160
3	0.220	277	0.092	0.660		0.411	132
5	0.225	271	0.054	1.125		0.701	126
7	0.225	271	0.039	1.575		0.981	126
9	0.230	265	0.029	2.070		1.290	121
12	0.230	265	0.022	2.760		1.719	121
15	0.220	277	0.018	3.300		2.056	132
20	0.240	254	0.013	4.800		2.990	111

Specimen L1

to ms	vo ms-1	λ m	L/λ L = 63 mm	L/D	D/λ	Go MPa
-	-	-	-		-	-
0.200	315	0.105	0.600	0.553	1.086	166
0.230	274	0.055	1.150		2.081	125
0.230	274	0.039	1.610		2.913	125
0.220	286	0.032	1.980		3.583	137
0.230	274	0.023	2.760		4.994	125
0.230	274	0.018	3.450		6.243	125
0.230	274	0.014	4.600		8.324	125

Specimen L2

to kHz	vo ms	λ ms-1	L/λ L = 63 mm	L/D	D/λ	Go MPa
-	-	-	-		-	-
0.215	288	0.096	0.645	0.544	1.186	139
0.220	282	0.056	1.100		2.023	132
0.220	282	0.040	1.540		2.832	132
0.220	282	0.031	1.980		3.641	132
0.210	295	0.025	2.520		4.634	145
0.200	310	0.021	3.000		5.516	160
0.200	310	0.016	4.000		7.355	160

f_{in}=input frequency (kHz)
t_o=shear wave arrival time (visually picked) (ms)
v_o=shear wave velocity (based on visually picked arrival time) (ms^{-1}); λ=wavelength (m); L=shear wave travel distance (tip-to-tip of bender elements) (m)
D=diameter of specimen (m)

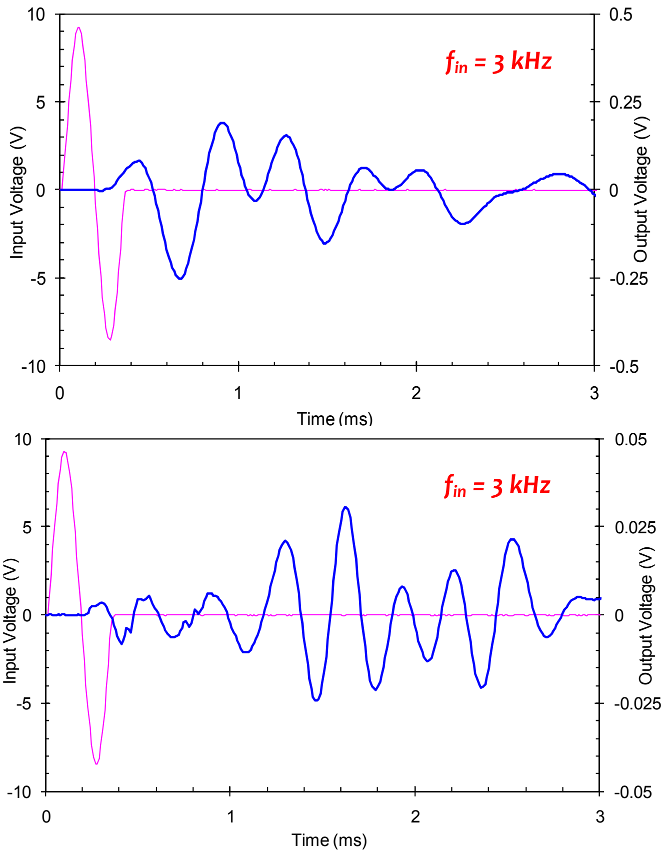

Figure 2a. Transmitted and received shear waves for specimens S1 (up) and L1 (down)

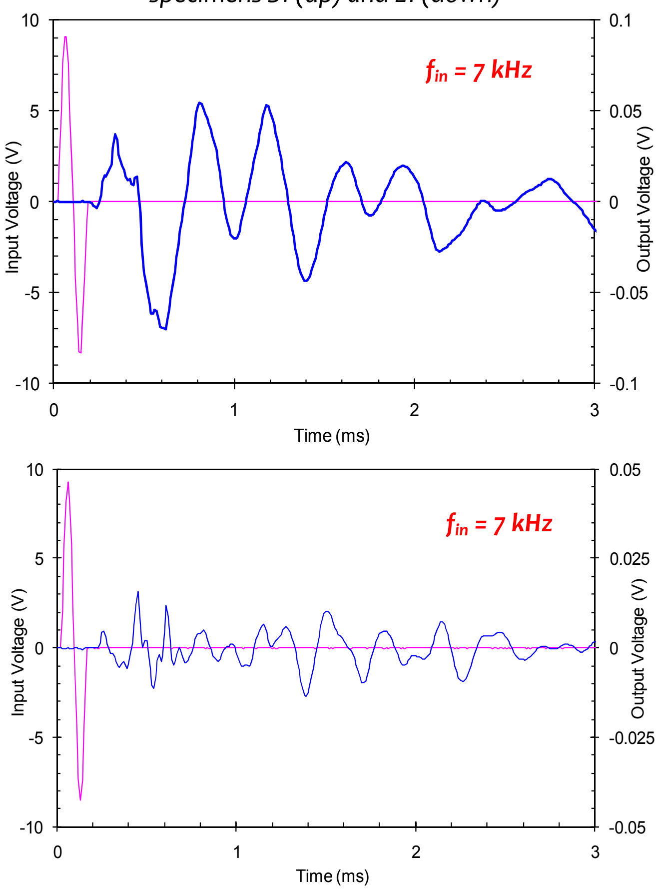

Figure 2b. Transmitted and received shear waves for specimens S1 (up) and L1 (down)

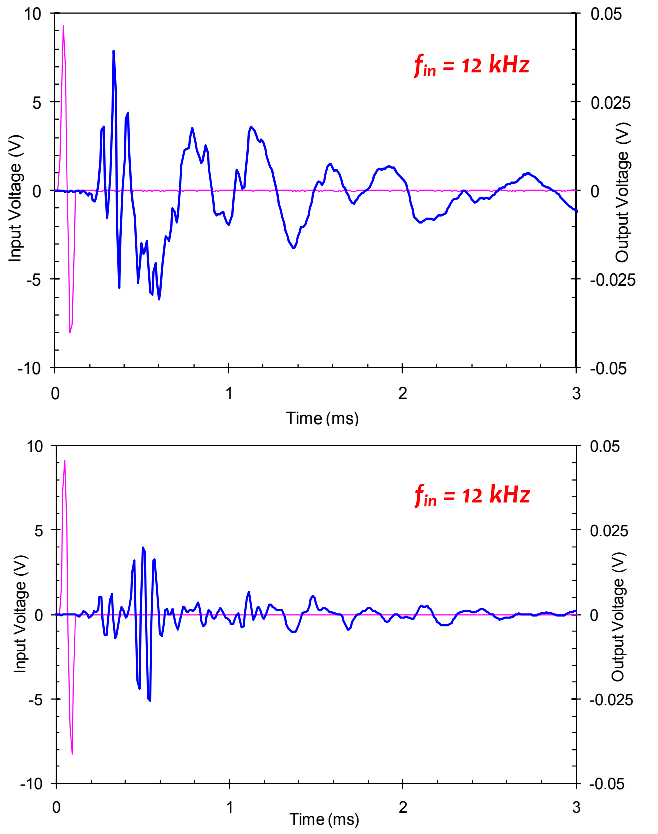

Figure 2c. Transmitted and received shear waves for specimens S1 (up) and L1 (down)

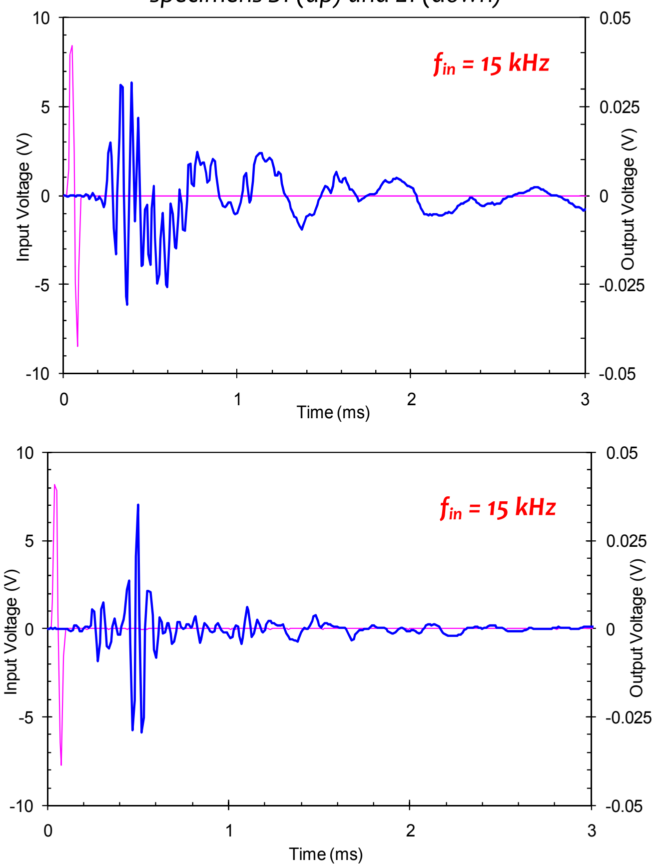

Figure 2b. Transmitted and received shear waves for specimens S1 (up) and L1 (down)

Considering that the specimens were essentially composed of clay particles with small quantities of cement, D_{50} could be assumed to be sufficiently low, satisfying the criteria recommended in both sets of test specimens. This contributes to the clearly discernible shear wave arrival time on the received traces for both pairs of the specimens, Figure 2.

It is also apparent from Figure 2 that higher input frequencies (f_{in}) tend to introduce interference to the received signal prior to the first positive major deflection. In some cases, a minor negative deflection can be observed to precede the positive departure (e.g. specimen S1, f_{in} = 7 kHz). Strength of the received signals also diminished with increased f_{in}. These behaviors are further discussed and explained in the following sections.

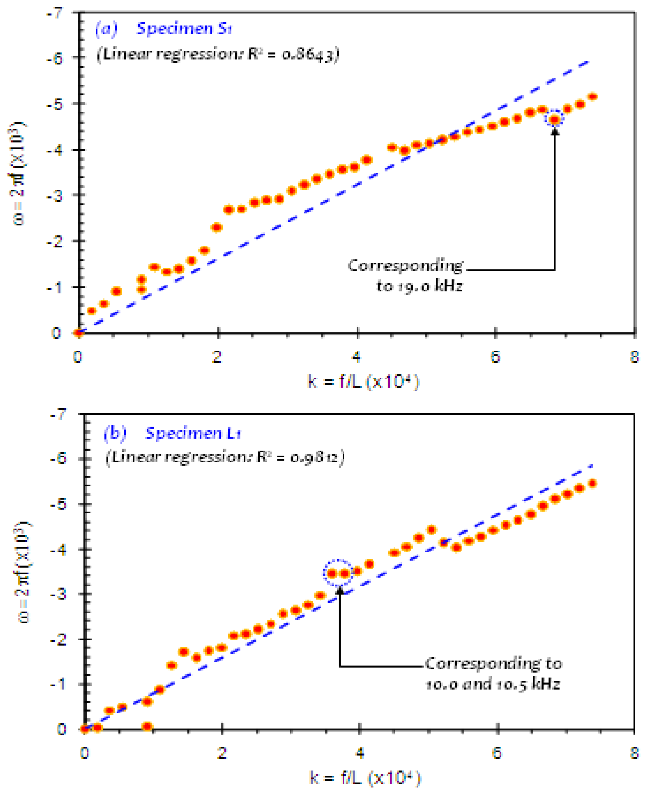

Figure 3. Dispersion plots for specimens (a) S1 and (b) L1; f_{in} = 7 kHz

Specimen Geometry

As soil is an attenuating medium, an excessive travel distance for a low energy shear wave would significantly reduce its amplitude and mask the time of arrival at the receiver. Therefore attenuation ultimately limits the length or height of test specimens. However, the length of the specimens in the p resent test series was fixed at 76 mm, hence leaving the diameter, D, as the variable in terms of specimen geometry. The shear wave travel distance, L, was taken from tip to tip of the bender elements, as proposed by pioneers like Dyvik and Madshus [16] and Viggiani and Atkinson [17].

The ASTM Standard 2845-95 (2000) recommends the minimum specimen length or height to be at least 10 times D_{50} to accurately define the average propagation velocity. Referring to the discussions in the previous section, it can be seen that this criterion was readily satisfied in the present work.

Distortion of a signal (dispersion) can occur due to interference of reflected waves from the medium boundaries, resulting in a composite wave with various frequency components. Such an occurrence could easily obscure the arrival of the transmitted shear wave. According to Wasley [18], and as mentioned in the ASTM Standard 2845-95 [15], the lateral dimension, i.e. D, should exceed the wavelength, λ, by at least 5 times (D/λ ≥ 5) in order to avoid such dispersion.

From Table 1, it is shown that S1 and S2 barely meet the requirements even with high frequencies, whereas L1 and L2 do, but only at frequencies higher than 12 kHz. In the corresponding dispersion plots, Fig. 3, the linearity of the plots improves at higher frequencies, indicating a reduction of dispersion effects. However, with closer inspection, it can be seen that Fig. 3(a) depicts a non-linear trend, indicating varying group and phase velocities with frequency, while Fig. 3(b) shows better linearity and hence less dispersion.

Based on the analysis and discussion above, it is clear that lateral boundaries have a significant effect on how well the received signal represents the transmitted signal, in terms of frequency content. When the diameter of a cylindrical specimen is restricting the free propagation of waves through the specimen, a phenomenon that is comparable to 'waveguide effect' is observed. The further the distance of the boundaries is in the direction of polarization (perpendicular to the direction of propagation) of the shear wave, the less prominent is the effect of lateral rebounds and distortion of the propagating wave. That explains why dispersion plots from the larger specimens display better linearity than those from the smaller specimens.

On the other hand, Chan et al. [6] experimented with isotropically consolidated Kasaoka clay specimens of different diameters (i.e. 33, 40 and 50mm) but with a constant height/diameter ratio of 2, and found that there was no difference in the shear wave velocity measured in all the specimens (f_{in} = 5 kHz, L/λ > 2). Lateral rebound and waveguide effects were apparently absent in their studies, though the diameter difference was arguably much smaller compared to those of the present study. This could be a factor of the negligible differences reported.

Near-field Effects

Most of the traces showed the presence of near-field effects in varying degrees, where the first deflection of the received signal is reversed, Fig. 2. This is primarily attributed to a shear wave component traveling at the velocity of compression wave, with an early arrival prior to the actual shear wave. Sánchez-Salinero et al. [19] suggested keeping the ratio of L/λ between 2 and 4, where the lower limit was meant to avoid near-field effects, and the upper limit was to cater for attenuation via damping (discussed in later section). More recently Leong et al. [1] recommended an increase of the lower limit to 3.33.

The L/λ values for both sets of specimens only fall within between 2 and 4 when frequencies are higher than 9 kHz (Table 1), with corresponding diminished the near-field effects. To meet the criteria of Leong et al. [1], however, f_{in} must be higher than 15 kHz (Table 1). Jovičić et al. [20] recommended mechanical remediation which involved manipulating the shape and frequency of the input shear wave. However it was thought that such manipulations could not only be inconveniently time-consuming, but could also adversely increase the subjectivity of the interpretation method.

Looking at the discussions so far, since D/λ ≥ 5 is necessary to avoid lateral rebound and waveguide effects, and L/λ > 2 is satisfied to keep off near-field effect, then logic follows that the lower limit for λ ought to be ≥ 5D. Most test specimens have aspect ratios (height to diameter) of at least 2, but these may not be wide enough to avoid lateral interference. Combining both criteria results in D/L ≥ 2.5, a ratio which is perhaps more readily met by, for instance, oedometer or Rowe cell specimens.

Attenuation

Although higher frequencies are sometimes preferred to avoid near-field effects, the guideline recommended by Sánchez-Salinero et al. [19], as discussed in the previous section, ought to be used with caution. At higher frequencies the energy-absorbing nature of soil makes it ineffective in sustaining prolonged and effective dynamic interaction between the bender element and the soil, hence resulting in attenuation. Leong et al. [1] also cautioned against high frequency input waves as the damping properties and soil-bender element interaction can cause lower frequencies in the received signals.

According to Brignoli et al. [21], input waves with f_{in} ≥ 5 kHz tend to generate received signals of considerably lower frequencies than the sent ones. This was however not observed in the present work. Frequency decomposition of both the input and output signals (via Fast Fourier transform, FFT) showed that the dominant frequency component in the output signal strongly represented that of the input signal. Cho and Finno [22] used 2-10 kHz shear waves in glacial clay specimens and reported no discordance between f_{in} and f_{out} too. Nevertheless in the present study, the amplitude of the output signal was observed to reduce with increased input frequency, which obviously indicated the effect of attenuation.

CONCLUSIONS

Various factors were found to affect the measurement of shear wave velocity, with the main ones being input frequency, specimen geometry, near-field effects and attenuation. The quality of the received signals was found to be satisfactory when the input frequency was kept high enough to achieve $\lambda/D_{50} > 3$. In terms of the specimen geometry, less dispersion was found when fulfilling the criterion $D/\lambda \geq 5$. Also, keeping the specimen height at least 10 times D_{50} helps ensures accurate definition of the average shear wave velocity propagating through the soil specimens. Near-field effects and attenuation were found to be reduced when the ratio L/λ was kept between 2 and 4. High frequency input waves, while giving the necessary wavelength for avoiding near-field effects and attenuation, should be used with caution against damping and frequency-incompatibility of the received waves.

ACKNOWLEDGMENT

The experimental work in this study was carried out at the Geotechnical Engineering Laboratory of Sheffield University, with the invaluable guidance of Dr. C. C. Hird and support of the technical staff. Funding was provided by the Ministry of Science, Technology and Innovation, Malaysia in the form of the Author's doctoral study scholarship.

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ACTA TECHNICA CORVINIENSIS – BULLETIN of ENGINEERING

ISSN: 2067-3809 [CD-Rom, online]