Determining Arrival Time of Shear Waves in Bender Element Test: Idealized Sine Wave Approach

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ABSTRACT: A novel technique for determining first arrival of shear wave signals based on idealized sine waves is proposed in this study. The four proposed methods are distinguishable by the chosen length of signal for calculating output frequency. Considering the frequency differences that are observed between input and output signals, first arrival times are estimated from peak-to-peak results. This technique is applied to bender element signals measured on compacted residual soil and Singapore Marine Clay. The results show close estimates to actual arrival times while the peak-to-peak often underestimates shear wave velocities. By incorporating signal quality and shape, these methods may contribute reducing uncertainty in applying peak-to peak and allow flexibility in choosing specific arrival times, especially when the first arrival is hindered by signal noise and/or near-field effects. Moreover, the methods are still applicable even without frequency sweep.

RÉSUMÉ: Cette étude propose une nouvelle technique pour déterminer la première arrivée des signaux d'onde de cisaillement basée sur des ondes sinusoïdales idéalisées. Les quatre méthodes proposées sont distinguables par la longueur du signal choisi pour calculer la fréquence de sortie. Compte tenu des différences de fréquence observées entre les signaux d'entrée et de sortie, les temps de première arrivée sont estimés à partir des résultats crête à crête. Cette technique est appliquée sur des signaux de bender éléments mesurés sur du sol résiduel compacté et l'argile marine de Singapour. Les résultats montrent des estimations proches des temps d'arrivée réels alors que le crête à crête sous-estime assez souvent les vitesses d'onde de cisaillement. En incluant la qualité et la forme du signal, ces méthodes peuvent réduire l'incertitude en appliquant la méthode crête à crête et offrent une flexibilité en terme de choix des temps d'arrivée spécifiques, en particulier lorsque la première arrivée est entravée par le bruit du signal et/ou les effets de champ proche. En outre, les méthodes sont toujours applicables même sans balayage de fréquence.

KEYWORDS: Small Strain Stiffness, Bender Elements, Shear Waves, First Arrival, Peak-to-Peak

1 INTRODUCTION

Determining the elastic stiffness parameters is essential to estimate deformation characteristics of geomaterials. Small strain stiffness G_{max} is a representative parameter measured for predicting soil behavior under static and cyclic loading, vibrational impacts and even seismic behavior in earthquake loading (Ku et al. 2013). Most deformation problems in soil structure interaction occur at strain levels below 0.1%, which makes the measurement of G_{max} particularly useful (Jardine et al. 1986). Shirley and Hampton (1978) introduced bender elements consisting of piezoceramic transducers, which generate and receive shear waves, for measuring G_{max} in soils. Dyvik and Madshus (1985) evaluated suitability of bender elements to measure G_{max} via comparison of the results obtained from bender elements and resonant columns.

The measurement of correct travel time is a major challenge in determining shear wave velocity V_s using bender elements. Time domain methods (e.g., first arrival, characteristic peaks or cross correlation) have been applied by researchers to determine correct travel times but their limitations can exceedingly undermine their reliability. By using sine wave as the input signal, first arrival method (first bump or zero crossing) provides reliable results when high quality signals (with low noise) are generated at input frequencies which ensure minimised near field effects (Brignoli et al. 1996; Sanchez-Salinero et al. 1986). Utilizing time difference between characteristic peaks is unreliable if the input and output signals do not have similar frequencies while cross correlation gives promising results only based on input and output signals of similar nature (Jovicic and Coop 1997; Santamarina and Fam 1997). Moreover, undamped signals, especially in stiff soils, result in cross correlation method to overestimate arrival times (Tauta 2011). Based on experimental and numerical analyses, Arulnathan et al. (1998) showed that all these methods might not accurate enough in various conditions.

The objective of this study is to develop a novel technique that utilizes the relationship between characteristic peaks in input and output signals of bender element for predicting first arrival time of shear waves. This technique is applied to shear wave signals collected from compacted residual soil (Leong et al. 2009) as well as on signals obtained by testing Singapore Marine Clay.

2 METHODOLOGY

In this study, the proposed technique to determine first arrival time is based on idealized sine waves having different frequencies (see Figure 1). The peak-to-peak method involves time difference between the major peaks in input and output signals, Δt_{pp}, whereas the time difference from signal generation to first zero crossing or first bump of received signal corresponds to first arrival, Δt_{fa}. The difference between these two times can be expressed in terms of their corresponding wavelengths (see Eq. 1 and 2):

$$\Delta t_{pp} - \Delta t_{fa} = \left(\frac{\lambda_{out} - \lambda_{in}}{4}\right) \quad (1)$$

$$\Delta t_{fa} = \Delta t_{pp} - \left(\frac{\lambda_{out} - \lambda_{in}}{4}\right) \quad (2)$$

where, λ_{in} and λ_{out} are the wavelengths with input and output frequencies (f_{in} and f_{out}), respectively. Note that in this study, Δt_{fa} corresponds to the first zero crossing only for simplification. These wavelengths can be found using their respective input and output frequencies, (see Eq. 3 and 4):

$$\lambda_{in} = \left(1/f_{in}\right) \quad (3)$$

$$\lambda_{out} = \left(1/f_{out}\right) \quad (4)$$

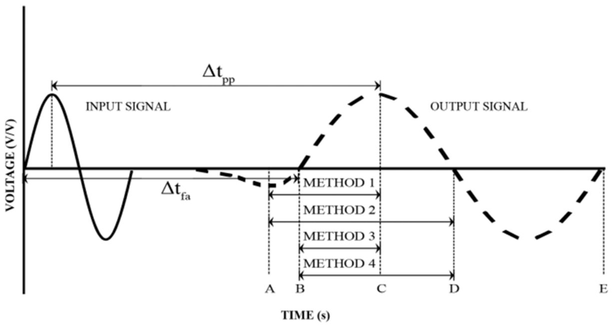

Figure 1. Idealized sine waves-signal lengths for calculating output frequencies in each method.

Any change in the nature of the received signal results from the influence of soil through which it travels but its propagation velocity remains unchanged. Based on such behavior of wave travel, equations 3 and 4 assume that the shear wave signal propagates through soil at a constant velocity from a transmitter to a receiver. The travel time for signal through soil (Δt_{fa}) is utilized to calculate V_s. However, the major challenge in applying this method lies in calculating the correct frequency of the output signal.

Figure 1 illustrates four methods, which are dependent upon the length of the signal chosen for analysis, to calculate the output frequency. It is possible that the remaining half signal (DE) is disturbed by reflections which may distort the output frequency. This can lead to inconsistent estimates using the current technique. Therefore, the maximum extent of signal considered for analysis is point D, which is the first half of the received signal. Each method uses the output frequency calculated either using quarter wavelength (method 1 and 3) or half wavelength (method 2 and 4) of the received signal.

The starting point in methods 1 and 2 for the received signal corresponds to first bump (Point A in Figure 1). In soft soils, the first bump is commonly observed in the received signals, which must be considered for calculating a correct frequency of output signal. The proposed methodology also includes it within the signal length. On the contrary, various soil types may also exhibit output signals initiating at points of first zero crossing (Point B in Figure 1) which have been utilized in methods 3 and 4 for calculating the output frequency. Therefore, all proposed methods cover a range of signal types usually encountered using bender elements for soil testing.

For methods 1 and 3, the output frequency (f_{out}) is calculated (see Eq. 5):

$$f_{out} = (1/4T) \tag{5}$$

where, time period T is length of AC for method 1 and BC for method 3 respectively. Using AD and BD respectively for time period T, methods 2 and 4 have their output frequencies calculated (see Eq. 6):

$$f_{out} = (1/2T) \tag{6}$$

In the current study, all four methods are evaluated for their suitability in determining Δt_{fa} from Δt_{pp} utilizing the output frequencies calculated from equations 5 and 6.

3 RESULTS

The results presented are based on analyses of signals measured from compacted residual soil (data from Leong et al. (2009)) and Singapore Marine Clay.

3.1 Compacted Residual Soil

In the work of Leong et al. (2009), residual soil collected from Bukit Timah Granite was compacted and then subjected to effective isotropic confining stress ranging from 50 kPa to 400 kPa. Shear (S-Waves) wave signals were collected at all confining stresses from Leong et al. (2009). This study presents the results obtained from analysis conducted on sine wave signals with input frequencies that range from 2 kHz to 16 kHz.

Figure 2 compares shear wave velocities obtained using arrival times from each method with the original arrival times specified in Leong et al. (2009) and also using the peak-to-peak method. For each input frequency, the peak-to-peak method generally underestimates V_s while method 1 provides highest values of V_s.

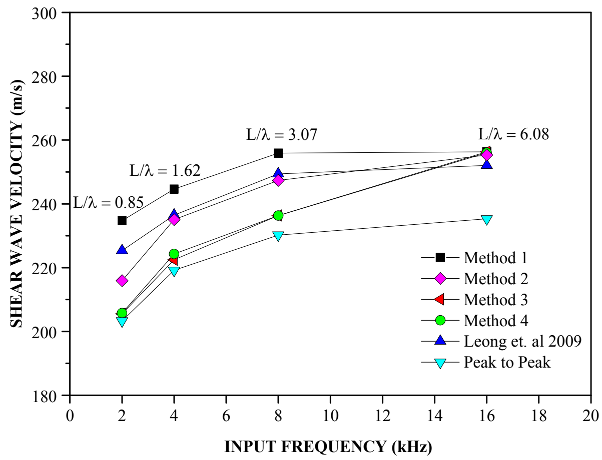

Figure 2. Comparison of V_s obtained using methods 1 to 4 with actual arrival times for confining stress = 50 kPa on compacted residual soil.

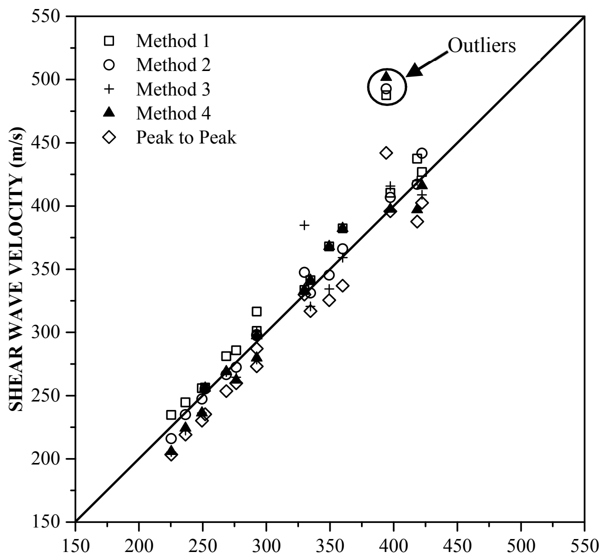

Figure 3. Comparison of predicted V_s obtained using methods 1 to 4 with actual arrival times for all confining stresses on residual soil.

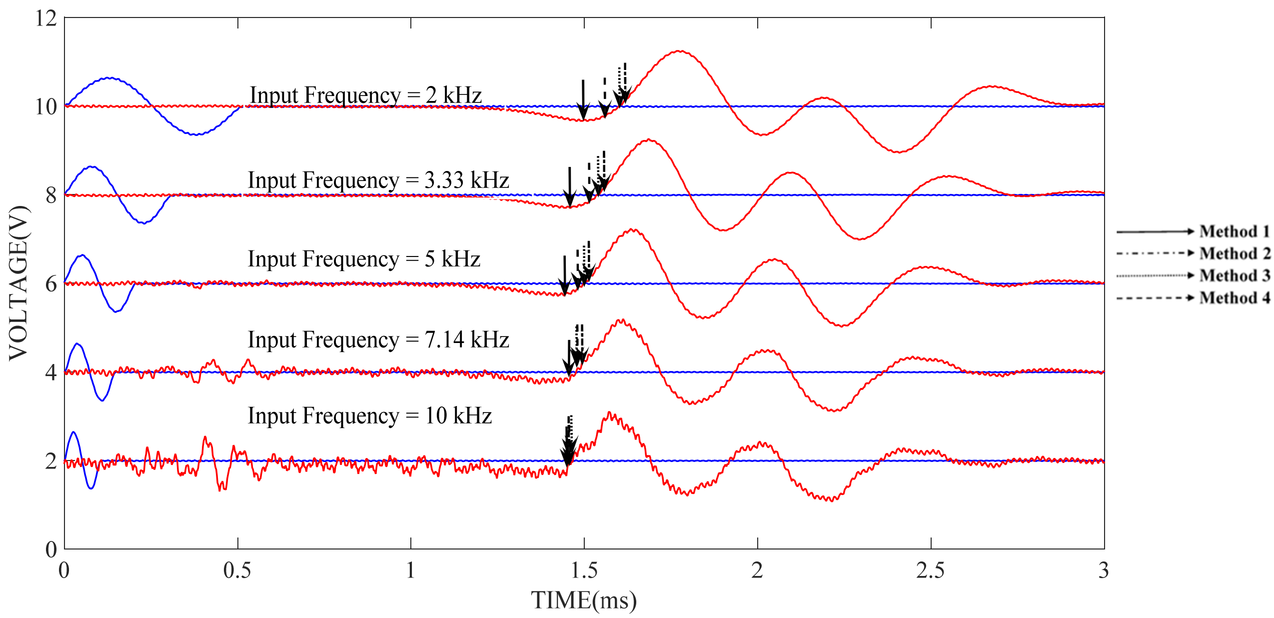

Figure 4. Shear wave signals for Singapore marine clay at confining stress of 10 kPa.

Interestingly, method 2 and arrival times specified by Leong et al. (2009) closely agree with each other, especially at input frequencies greater than 2 kHz. In addition, higher wave path to wavelength (L/λ) ratios result in closer agreement between all the four methods and the original arrival times. At higher L/λ ratios, initial bumps within output signals diminish and the estimated initial point for each method intersects with each other. Consequently, similar output frequencies chosen by each method result in closer arrival time values.

For all confining stresses, a comparison of shear wave velocities obtained by applying methods 1 to 4 is plotted against those specified by Leong et al. (2009) (see Figure 3). It proves that most predicted values using proposed methods match well with the V_s values obtained from the original first arrival with exception of some outliers (encircled in Figure 3) that are attributed to poor signal quality at low input frequencies.

3.2 *Singapore Marine Clay*

Upper Singapore Marine Clay was remolded and consolidated in a consolidometer with a diameter of 50mm under an overburden stress of 75 kPa. After achieving complete consolidation, the sample was setup in a triaxial cell with bender elements embedded in the base and top caps followed by saturation (B value = 0.98) at back pressure of 100 kPa. The soil was then subjected to confining stresses ranging from 10 kPa to 150 kPa with shear wave signals being collected at various intervals. Sine wave input signals were applied with frequency range of 2 kHz to 10 kHz.

Figure 4 illustrates input and output signals collected at various input frequencies for an effective confining stress of 10 kPa. Arrows along the output signals correspond to first arrival times obtained using all methods. The difference between the arrival times reduces with increase in input frequency. At higher input frequencies, initial bumps in output signals diminish which results in closer agreement between each method. The observed trend is similar to that of compacted residual soil described in previous section.

In figure 5, the results obtained using the four proposed methods are compared against first arrival (zero crossing) and peak-to-peak with their L/λ ratios given as well. These L/λ ratios were calculated using arrival times obtained using first arrival (zero crossing). It is observed that peak-to-peak and first arrival (zero crossing) overall provide relatively low V_s. Method 1 results in giving highest V_s values while methods 2 to 4 closely agree with each other at all input frequencies Therefore, these results indicate that the proposed methodology produces reasonable estimates of arrival times that located between initial bump and first zero crossing for most signals.

4 SUMMARY AND CONCLUSION

This study proposes four methods for improved estimation of arrival times by using peak-to-peak results. Each method is dependent upon varying lengths of output signals to calculate arrival times. Conventional methods such as the peak-to-peak and the first arrival are often not accurate as they have inherent limitations, associated with input signal quality and similarity of input and output signals, in their application.

To verify the applicability, V_s values obtained using the four proposed methods are compared against the peak-to-peak and first arrival methods for compacted residual soil and Singapore Marine Clay. The following conclusions are made from the results of this study:

- Method 1 generally estimates largest V_s values as it produces smallest frequencies of output signals compared to other methods.

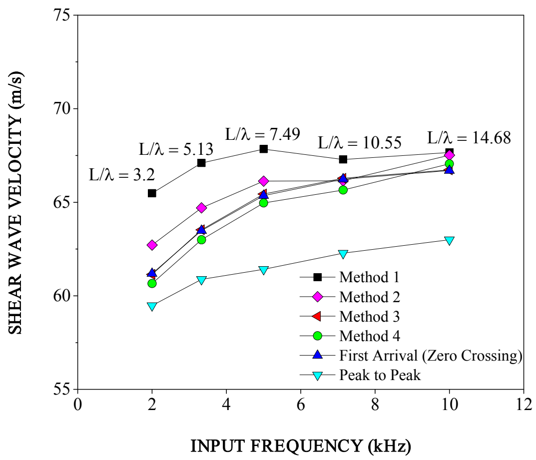

Figure 5. Comparison of V_s obtained using methods 1 to 4 with first zero crossing times for 10 kPa on Singapore marine clay.

- V_s results obtained using methods 2,3 and 4 closely agree with each other rather than those obtained by applying first arrival techniques such as first bump or first zero crossing.
- The peak-to-peak method consistently underestimates V_s in comparison to the proposed methods as well as first arrival.
- All proposed methods give closely agreeing values at higher L/λ ratios due to reduction of bump size in the output signal.

In comparison to conventional methods, the major feature of the proposed methods is that they can provide more reliable results by adjusting uncertainty (e.g., signal shape and frequency difference) in a systematic manner. To incorporate signal shape and quality in the analysis, illustrative points such as bump or zero crossing are taken into account, thereby leading to robust estimates of arrival times. Hence, the proposed methods can provide relatively consistent results regardless of the procedure of frequency sweeping required to match input and output signals.

5 ACKNOWLEDGEMENT

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