A new tool for the automated travel time analyses of bender element tests

Un nouvel outil pour les analyses automatisées du temps de déplacement des essais « bender element »

Rees S., Le Compte A., Snelling K.
GDS Instruments, UK

ABSTRACT: Whilst bender elements are increasingly used in both academic and commercial laboratory test systems, there still remains a lack of agreement when interpreting the shear wave travel time from these tests. Given such interpretation is often subjective, a software tool was developed to automate the interpretation process using a number of analysis methods recommend in the literature. The tool resulting from this development is accessed through two easy-to-use Microsoft Excel Add-Ins, allowing any digital bender element data to be interpreted. Initial assessment of the tool was provided by a series of tests conducted on a triaxial specimen of Leighton Buzzard sand at a mean effective stress of 100 kPa, with variation of the source element frequency. Travel times estimated from a time-domain cross-correlation showed relatively low scatter, equal to ± 7 µs, across a frequency range of 3.3 kHz to 14.3 kHz, whilst times estimated from a frequency-domain cross-spectrum calculation produced much larger scatter, equal to ± 138 µs. Finally comparisons with subjective observational analyses performed by a geotechnical academic showed good agreement, suggesting the tool can provide accurate, automated interpretation of bender element shear wave travel times.

RÉSUMÉ : Tandis que la technique des *Bender Elements* est de plus en plus utilisée dans les laboratoires commerciaux et de recherche, il subsiste encore une carence dans l'interprétation du temps de parcours des ondes de cisaillement. Pour pallier ce manque, un outil logiciel a été développé pour automatiser le processus en utilisant un certain nombre de méthodes d'analyses recommandées dans la littérature. Cet outil est accessible par la simple utilisation de deux applications Microsoft Excel, permettant d'analyser n'importe quelle donnée issue d'un essai de type *Bender Elements*. Les premiers tests de cet outil ont été effectués sur un échantillon triaxial de sable « Leighton Buzzard » pour une contrainte effective moyenne de 100 kPa, avec une variation des fréquences de l'élément source. Les temps de trajet estimés à partir d'une corrélation temporelle ont montré une dispersion relativement faible égale à +/- 7 µs pour des fréquences de 3,3 kHz à 14,3 kHz, tandis que les temps calculés à partir d'une corrélation spectre-fréquence indiquent une forte dispersion des résultats égale à +/- 138 µs. Enfin, les comparaisons réalisées avec des analyses classiques effectuées par un laboratoire de géotechnique académique ont montré de bonnes similitudes, suggérant que cet outil peut véritablement fournir des résultats précis et automatiques des temps de parcours des ondes de cisaillement.

KEYWORDS: bender elements, shear wave travel time, automated analysis, cross-correlation, cross-spectrum.

1 INTRODUCTION

Bender elements have seen increasing use in laboratory test systems since their initial development in the 1970s (Shirley and Hampton 1978), as they enable the small-strain shear modulus, G_0, of a soil specimen to be estimated using a simple methodology. This is achieved via determination of the shear wave velocity, V_S, estimated from the time required for a shear wave to propagate from one bender element (BE) to another. V_S can then be related to G_0 as shown in Equation 1, wherein ρ = bulk density of the soil, L = shear wave propagation distance, and t = shear wave travel time.

$$G_0 = \rho V_S^2 = \rho (L^2 / t^2) \quad (1)$$

Early studies demonstrated good agreement between G_0 values obtained using bender elements and other small-strain test systems such as the resonant column (Dyvik and Madshus 1986). A number of issues were however subsequently identified that arise when interpreting bender element test results, including the near field effect (Sánchez-Salinero et al. 1986) and subjectivity in determining arrival time of the propagated shear wave (Jovičić et al. 1996). Such issues have meant that despite bender element systems being well-established within academic and commercial testing, there still remains the lack of a satisfactory model or standard for test interpretation (Viana da Fonseca et al. 2009, Alvarado and Coop 2012). Therefore whilst it is understood that potential errors in values of ρ, L, and t may each affect the estimated value of G_0, this paper focuses on a principal issue in interpreting bender element test data – the subjectivity in determining the shear wave travel time, t.

1.1 *Current recommendations for determining the shear wave travel time*

Primarily three different approaches have been identified for determining the shear wave travel time, t: observation of the source and received bender element signals, cross correlation of the signals, and a cross-power spectrum calculation of the signals (Yamashita et al. 2009). The two former approaches are typically considered as techniques applied in the time-domain (TD), with the latter viewed as a frequency-domain (FD) method. Recommendations made by the Japanese Geotechnical Society Technical Committee TC-29 suggest use of the two TD methods is generally more appropriate, given the variability in FD travel time estimates obtained from an international parallel test. It is however important to note the suggested observational techniques, which are the 'start-to-start' and 'peak-to-peak' methods, can be performed through visual analysis of the bender element data by a test operator, and thus may produce subjective travel time estimates. It is therefore considered useful to automate the travel time estimation process to decrease the subjectivity in such analyses.

2 DEVELOPMENT OF A MULTI-METHOD AUTOMATED TOOL FOR TRAVEL TIME ANALYSES

A new software tool was developed by GDS Instruments to perform automated analyses of bender element test data. The primary aim of this tool was to allow travel time estimations to be conducted objectively via a simple user interface, providing both visual and numerical representations of the estimated travel times. Implementation of the tool was completed by creating Add-Ins for Microsoft Excel, a decision based on the ubiquitous use of the software.

Based on the recommendations presented in Section 1.1, it was considered important to include a number of analysis methods within the tool, providing flexibility to the user when interpreting the results. Variations of the three primary approaches listed in Section 1.1 were therefore chosen for implementation: observation of points of interest within the received wave signal via software algorithm (TD); cross-correlation of the source and received signals (TD); group travel time calculation obtained from the absolute cross-power spectrum phase diagram (FD). Implementation of these methods is briefly discussed in Section 2.2 and 2.3, whilst the analysis tool is introduced in Section 2.1.

2.1 *GDS Bender Element Analysis Tool user interface*

The GDS Bender Element Analysis Tool (BEAT) is accessed via two Add-Ins for Microsoft Excel (version 2007 or later): the Interactive Analysis tool and the Batch Analysis tool. The Interactive Analysis tool is designed to analyse one BE test at a time, whilst allowing the user some interaction when performing the FD estimation. To use the tool, BE test data is firstly imported into Excel, with relevant test parameters then selected via the window interface displayed in Figure 1. Note this allows data obtained from any BE system to be analysed, assuming the data file can be loaded within Excel. The tool then performs the majority of the analysis before pausing to allow user alteration of the frequency window chosen for the FD estimation.

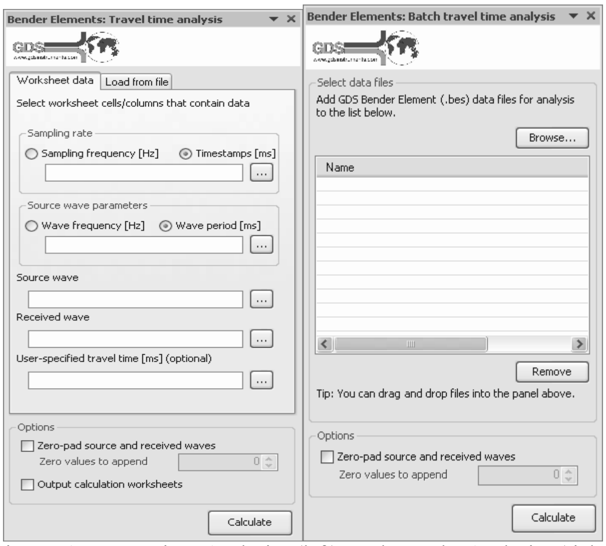

Figure 1. Interactive Analysis (left) and Batch Analysis (right) parameter / data file input windows within Microsoft Excel.

Conversely the Batch Analysis tool is designed to analyse multiple BE tests at a time, assuming the data is organised using the GDS Bender Element System (BES) output format (.bes). The tool is used by simple loading .bes files into the window interface shown in Figure 1 and clicking “Calculate”.

2.2 *Observation of received wave signal via algorithm*

Figure 2 displays an idealised received shear wave signal containing the near field effect, with four points of interest noted: first deflection (A); first bump maximum (B); zero after first bump (C); major first peak (D) (Lee and Santamarina 2005). To observe the time at which each point occurs, relative to initial triggering of the source signal (time zero), an algorithm was included within BEAT to implement the following procedure:

- The major first peak (D) is located by scanning the signal and determining the maximum (i.e. most positive) output. The time signature corresponding to this maximum thus defines point D.
- Point B is determined next by scanning the signal from time zero up to point D and locating the minimum (i.e. most negative) output. The corresponding time signature defines point B.
- Point C is then found by scanning the signal between point B and point D to locate the output closest to zero. The corresponding time signature defines point C.
- Point A is located via an iterative process: beginning at time zero, the mean and standard deviation of 10 consecutive outputs (e.g. $n_1 - n_{10}$) are calculated, with the subsequent five outputs ($n_{11} - n_{15}$) then assessed to determine whether all are at least three standard deviations more negative than the calculated mean. If ‘true’, the time signature of the first of the five subsequent outputs (i.e. n_{11}) is used to define point A; if ‘false’, the iteration proceeds by determining the mean and standard deviation of the next set of 10 consecutive outputs (i.e. $n_2 - n_{11}$) until a ‘true’ condition is reached.

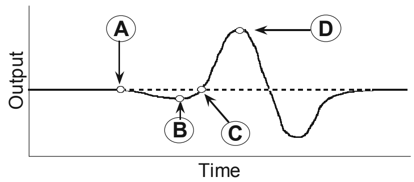

Figure 2. Idealised received shear wave signal containing the near field effect (reproduced from Lee and Santamarina 2005).

2.3 *Cross-power spectrum and cross-correlation of source and received wave signals*

Use of the cross-power spectrum and cross-correlation functions to provide travel time estimations has been extensively covered in the literature (Viggiani and Atkinson 1995, Leong et al. 2005), and as such only the two primary equations relating to each method used within BEAT are presented here. Equation 2 firstly displays the group travel time, t_g, where $d\varphi/df$ corresponds to the slope of the absolute cross-power spectrum phase diagram across a user-defined frequency range. Equation 3 provides the discrete cross-correlation function, CC_{xy}, with respect to source signal time shift, t_s, where T corresponds to the signal time record and $Y(T)$ and $X(T)$ correspond to the source and received signal outputs respectively.

$$t_g = \frac{1}{2\pi}\frac{d\varphi}{df} \tag{2}$$

$$CC_{xy}(t_s) = \frac{1}{T}\sum_{T=0}^{T-1} X(T)Y(T+t_s) \tag{3}$$

The time shift corresponding to the maximum value of CC_{xy} is used for the travel time estimate obtained from the TD analysis (i.e. $t = t_s$ when CC_{xy} = maximum), whilst a frequency window running from 0.8 to 1.2 times the source signal frequency is used to determine the group travel time $t_g = t$

(unless the user alters this frequency window when using the Interactive Analysis tool).

2.4 *GDS Bender Element Analysis Tool output*

Following the analysis process, BEAT produces two output tabs within Excel: these are Travel Time Report and Graphs. The Travel Time Report lists all relevant data numerically, including the data filenames, travel time estimates obtained from the TD and FD analysis methods, and various analysis metrics. The Graphs tab displays a number of plots for each data file, including the source and received wave signals with travel time estimates shown, frequency spectrums for each signal, the unwrapped phase angle, and values of the cross-correlation function. These outputs allow the user to further assess the validity of the analysis, and to use the travel time estimates in V_S and G_0 calculations.

3 BENDER ELEMENT TESTS ON LEIGHTON BUZZARD SAND TRIAXIAL SPECIMEN

To initially assess the performance of BEAT, a series of bender element tests were performed on a triaxial specimen of Leighton Buzzard sand Fraction D. The triaxial apparatus used was a GDS Dynamic Triaxial Testing System (DYNTTS), with bender element tests conducted via a GDS BES. The specimen, nominally 70 mm diameter by 144 mm in height, was prepared using a moist-tamping method similar to that previously employed by the authors (Rees 2010). Following saturation (B value ≥ 0.95), the specimen was isotropically consolidated to four mean effective stresses, p', with bender element tests being conducted at each stress level. The data presented herein focuses exclusively on the tests performed at p' = 100 kPa using a single sine-wave source.

Properties of the specimen are presented in Table 1, including void ratio, e, and relative density, D_r. Note values of the maximum and minimum void ratios used to estimate D_r were 1.01 and 0.72 respectively (Klotz 2000), with L equal to the element tip-to-tip distance.

Table 1. Properties of the Leighton Buzzard sand triaxial test specimen.

p' (kPa)	e	D_r (%)	ρ (t/m^3)	L (mm)
100	0.88 ± 0.03	43 ± 10	1.88 ± 0.02	139.1

The bender element tests were conducted by systematically varying the source wave frequency, as recommended by TC-29, from the chosen values of 14.3 kHz to 1.0 kHz. For each test frequency five separate source element triggers were applied to the specimen, with the received signal output then stacked in the time domain to remove random signal noise. Three examples of source and received signals obtained during these tests are presented in Figure 3.

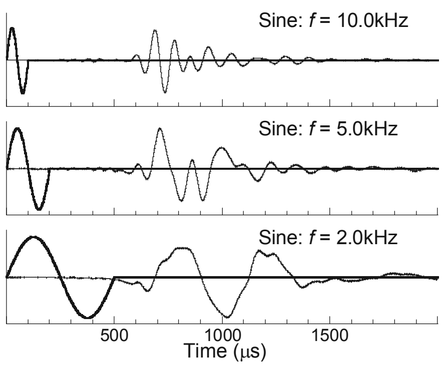

Figure 3. Source and received bender element signals obtained from the test specimen at p' = 100 kPa.

After completion of the bender element tests, the Batch Analysis Add-In tool was used to automate the data analysis and report the estimated travel times. Note the analysis was completed after approximately 45 seconds using a desktop PC running Windows XP SP3 with a 2.93 GHz Intel Core 2 Duo CPU and 2.00 GB RAM. Travel time estimates obtained from this process are presented in Table 2.

Table 2. Travel time estimates from the Batch Analysis tool.

Source f (kHz)	**Shear wave travel time estimates, t (μs)**					
	Observation of Received Signal (TD)				Cross-correlation (TD)	Cross-spectrum (FD)
	Point A	Point B	Point C	Point D		
14.3	221	635	651	675	662	620
12.5	224	637	655	681	663	703
11.1	224	641	658	685	663	663
10.0	225	643	662	689	662	641
8.3	227	646	667	698	662	697
6.7	226	652	671	706	661	678
5.9	278	650	671	712	662	613
5.0	497	650	672	713	662	495
3.3	227	653	676	719	674	771
2.5	229	654	682	784	669	735
2.0	488	655	690	828	657	767
1.7	450	657	696	846	645	642
1.4	404	658	700	855	640	633
1.3	398	659	707	858	632	515
1.1	442	658	716	862	632	325
1.0	443	659	744	868	640	235
Scatter for f ≥ 3.3kHz :	± 138	± 9	± 13	± 22	± 7	± 138

To compare the performance of BEAT with subjective analyses, a geotechnical academic at Warsaw University (WU) with previous bender element signal analysis experience was sent the test data (from 12.5 kHz – 1.0 kHz) and asked to provide travel time estimates using any observational, non-automated analysis methods they considered appropriate. This resulted in travel times being estimated with five separate methods, including the first arrival or start-to-start method (specified as point C in Figure 2) and the peak-to-peak technique. Travel time estimates produced by BEAT and the subjective analyses from WU were subsequently used to calculate V_S and G_0 values, which are presented in Figure 4. It should be noted a system delay of 42 μs was subtracted from all travel time estimates when calculating V_S, and that G_0 values are approximate (± 2 MPa) due to axis scaling when plotting both parameters in Figure 4.

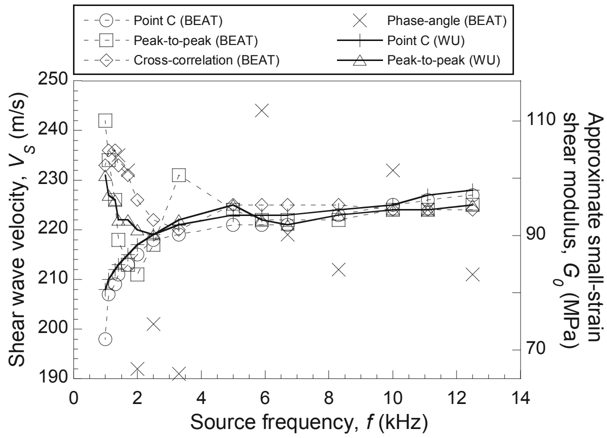

Figure 4. Shear wave velocity and approximate small-strain shear modulus values calculated from estimated travel times.

4 DISCUSSION

Table 2 lists the scatter in travel time estimates for source frequencies from 14.3 kHz to 3.3 kHz, as this provides an indication of the robustness of each analysis method. Note the lower limit of 3.3 kHz was chosen as this value corresponds to an approximate propagation distance-to-wavelength ratio equal to two, avoiding data which may include near field effects (Sánchez-Salinero et al. 1986). The values in Table 2 indicate significant variation in estimates obtained using the cross-spectrum calculation and first deflection observational algorithm (both ± 138 µs), suggesting estimates taken from either method may be unreliable if not validated by other data. In particular the scatter observed from cross-spectrum analyses has been previously been reported following other studies (Yamashita et al. 2009), with the sensitivity of estimates to the frequency window used within the analysis method also being highlighted (Viana da Fonseca et al. 2009). As such it is recommended the cross-spectrum method be used with caution, and it is recognized that a more advanced technique for determining the frequency window may be required for implementation within the Batch Analysis tool.

Conversely the scatter in estimates obtained from the cross-correlation function (± 7 µs) and first bump maximum observation (± 9 µs) were relatively minimal. These values suggest each method is relatively robust, an observation also made for the cross-correlation function after reviewing recent studies comparing analysis methods (Styler and Howie 2012).

Whilst the V_S and G_0 values presented in Figure 4 demonstrate the carry-on effect of scattered travel time estimates produced by the cross-spectrum calculation, they also display good comparison between values obtained via BEAT and the subjective WU observational analyses. It can specifically be seen that travel times based on a determination of point C (i.e. the start-to-start method) lead to V_S values generally within 2 m/s of each other, whilst the peak-to-peak estimates follow the same trend with variation in source frequency (e.g. increased V_S and G_0 values when $f < 3.3$ kHz). Such preliminary results suggest the use of BEAT may decrease subjectivity when interpreting travel times using standard observational techniques, whilst still allowing accurate estimates of the shear wave velocity and small-strain shear modulus to be calculated.

5 CONCLUSIONS

The subjectivity and lack of a satisfactory model for interpreting shear wave travel times from bender element test data has led GDS Instruments to develop BEAT, a tool designed to automate the interpretation process using a number of recommended analysis methods in both the time and frequency domains. The tool is accessed via two easy-to-use Microsoft Excel Add-Ins, allowing data derived from almost any bender element system to be analysed, either one test at a time, or in batches when organised using the GDS .bes file format. Outputs from the tool include numerical values of the travel time estimates and analysis metrics, as well as visual representations of the source and received bender element signals to assist with rapid data validation by the user.

An initial assessment of BEAT was made by conducting bender element tests on a saturated, isotropically consolidated triaxial specimen of Leighton Buzzard sand. During these tests the single sine-wave source frequency was systematically varied from 14.3 kHz to 1.0 kHz, allowing the robustness of each analysis method to be investigated. Results from BEAT when $f \geq 3.3$ kHz showed significant scatter in travel time estimates obtained from a cross-spectrum calculation (± 138 µs), whilst the cross-correlation function produced relatively consistent estimates (± 7 µs) with variation in the source frequency. Observational analyses of the received bender element signals conducted by BEAT were also compared with subjective estimates provided by a geotechnical academic, demonstrating good agreement between calculated V_S and G_0 values. This has led to the preliminary conclusion that BEAT can provide accurate, objective interpretation of bender element test data via a simple user interface, however caution and engineering judgment are still recommended when making final decisions regarding the most suitable shear wave travel time estimate for further geotechnical calculations.

GDS BEAT is available for free download from www.gdsinstruments.com/gds-bender-elements-analysis-tool, which also includes further technical information and video demonstration of the software tool.

6 ACKNOWLEDGEMENTS

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