Measurement of shear modulus using bender elements and resonant-column

Cláudio PEREIRA [a,1], António GOMES CORREIA [a], Cristiana FERREIRA [b], Jaime SANTOS[c] and João SANTOS[c]
[a] *University of Minho, ISISE, Guimarães, Portugal*
[b] *University of Porto, Porto, Portugal*
[c] *University of Lisboa, Lisboa, Portugal*

Abstract. In recent times, new demands in geotechnical engineering, mainly in transportation geotechnics, require the use of advanced characterization techniques in order to accurately assess soil stiffness parameters. From this perspective, seismic wave-based techniques have received significant attention, since these allow performing the same basic measurement in the laboratory and field. With an enormous potential, bender elements are currently one of the most popular techniques used to measure reference soil properties in the very small strain range, namely the shear modulus. Bench and triaxial tests conducted on a wide range of geomaterials already demonstrated the applicability of this technique. However, the combined use of bender elements with other testing techniques, as the resonant column, is quite important in order to compare and validate some of the procedures used. In this context, bench bender elements tests were carried out on stiff sandy silt/silty sand specimens and the interpretation of seismic wave velocities was performed using time domain methods under a variety of excitations. Resonant column tests were also conducted on the same material to validate the obtained results with the bench bender elements setup. A critical discussion is made on the advantages and limitations of bender elements usage in contrast with the resonant-column for the assessment of the shear modulus, as well as some insights regarding damping. Additional tests were carried out in two distinct BE setups, one of which installed in the resonant column device, as well as ultrasonic measurements, with the purpose of validating the BE procedure and results interpretation. From this research, it was possible to compare and analyze the results obtained with the three different bender element setups and derive recommendations towards achieving reliable measurements.

Keywords. Bender elements, resonant-column, shear modulus.

1. Introduction

Presently, in geotechnical engineering - mainly in transportation geotechnical design and analysis -, laboratory and field investigations are commonly required to classify geomaterials and to assess their engineering properties, such as the stiffness parameters. Understanding stiffness and soil behavior is of extreme importance in order to describe the deformation characteristics of geomaterials that will help improve design and analysis of structural behavior [1], [2].

[1] Corresponding Author.

The importance of accurate stiffness measurements at very small strains has gained increasing relevance over the past years. The range of strain at this level is of approximately 10^{-6} to 10^{-5}, at which geomaterials exhibit a quasi-elastic behavior. At this strain level, the shear modulus is independent of strain amplitude, corresponding to a nearly constant maximum limit value, also called initial shear modulus (G_0) [3].

Accurate estimates of stiffness have been traditionally obtained by means of triaxial tests using precise local displacement transducers or resonant column devices [4], [5]. Widely accepted for their rapid, non-destructive, and low-cost evaluation methods, seismic wave-based techniques have received significant attention, since the same basic measurement can be performed in the laboratory and in situ.

Evidencing great potential, bender elements (BE) are currently one of the most popular techniques for measuring reference soil properties at the very small strain range, namely G_0 [5]–[8]. In this test, a voltage signal is applied to a piezoceramic element, which transmits a small shearing movement over one end of the soil specimen, thus generating a shear wave. This disturbance travels across the specimen length until the other end is reached, where a similar piezoceramic element receives the mechanical perturbation and generates a voltage. The time difference between the emitted and received signals enables to compute the shear wave velocity. The interval between the start of the transmitted and the received signals is considered the travel time (tt) of the shear wave, called S-wave first arrival. The shear wave travel distance is normally taken as the length between the tips (L_{tt}) of the bender elements [9]. From this, V_S and G_0 can be computed as indicated in Equations 1 and 2, for a known mass density (ρ) of the specimen:

$$V_S = \frac{L_{tt}}{tt} \tag{1}$$

$$G_0 = \rho \times V_S^2 \tag{2}$$

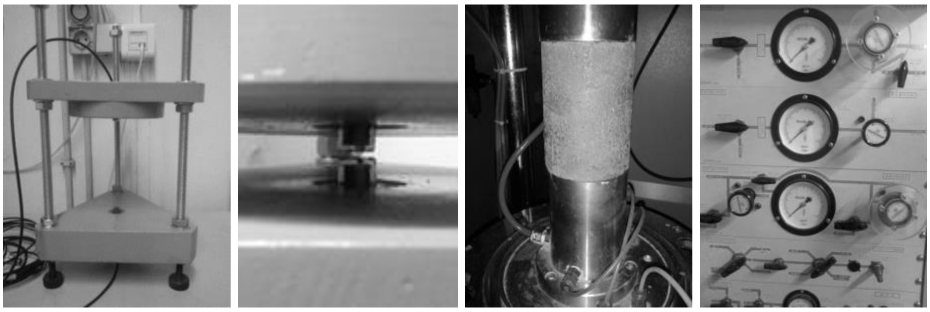
Bench and triaxial tests conducted on a wide range of geomaterials have already demonstrated the applicability of this technique. However, there are still some limitations related to implementation, strain range with measurable response and some accuracy restrictions. To face these issues, different signal analysis methodologies combining time and frequency domain techniques are often used [7], [10], [11]. More recently, new configurations considering the combined use of BE and accelerometers (AC) have helped reducing uncertainty in the measurements [12], [13]. Another way to minimize subjectivity of BE interpretation consists of the use of more than one type of test [14], [15]. The reason for using more than one type of test arises from the possibility of measuring specific soil characteristics more quickly or accurately with one method than others. In sum, an ideal situation would be based on a varied set of tests designed to obtain all the information needed from the same specimen [5].

In the present work, a set of BE bench tests, designated BE1 setup, were performed at the University of Minho, on clay specimens and the interpretation of the shear wave velocities was based on time domain techniques, namely first arrival (tt_0). In order to compare and validate some of the procedures used in this setup, the same material was tested in different sets of tests such as the resonant column test (RC) and with ultrasonic transducers (US), namely shear plates (SP). Additional BE readings were performed using two other BE setups – BE2 and BE3. These refer to additional BE setups implemented at different institutions: BE2 is available at the University of Porto, while BE3 corresponds to the setup installed in the RC device at the Technical University of Lisbon. Since the resonant column is considered the laboratory test reference for shear modulus determination, RC results will play a key role in the critical discussion on the advantages and limitations of the use of BE. Therefore, much of the analysis herein presented will focus on this comparison, together with some insights on damping.

2. Materials and Methods

As mentioned above, the set of tests carried out involved the use of different equipment. Firstly, a set of bench BE tests (BE1) was performed in order to determine G_0. In order to validate some of the procedures, additional series of tests were performed in different laboratories, involving another BE system (BE2), the use of RC and BE in the same device (BE3), and ultrasonic transducers (US) for shear and compression wave measurements.

The BE system used in the bench tests at the University of Minho consists of an aluminum support with two platens, each of these equipped with a "T-shaped" BE, with the following transducer dimensions: 11 mm width, 1.8 mm total thickness and 7 mm of cantilever length. The base platen is fixed whereas the top one is adjustable according to the height of the test specimens - Figure 1a and 1b.



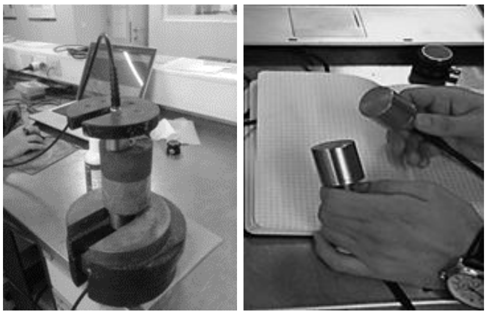
a) b) c) d)

Figure 1. Aluminum support and resonant column details: a) general view of the aluminum support; b) “T-shaped” bender elements alignment detail; c) Resonant column test specimen; d) Resonant column electronic system control panel.

The electronic equipment used to perform the multi-wave measurements included a function generator (TTi, Huntingdon TG2511) and a digital oscilloscope (PicoScope, model 4424). The oscilloscope was connected to a PC and the determination of travel time (tt) was performed by means of specific software from PicoScope.

The RC equipment used is a Drnevich-type manufactured by Seiken Inc. in 1992 that contains three subsystems: pneumatic, electro-mechanical and electronic. The pneumatic subsystem provides the conditions to the control of cell pressure, backpressure and axial force; the electro-mechanical subsystem allows the torsional vibration and the electronic subsystem provides the input signal and measures the response of the system - Figure 1c and 1d.

BE2 and BE3 configurations are generically very similar to BE1. A detailed description of both configurations is presented elsewhere in [15] and [5], respectively. In addition, ultrasonic (US) wave measurements were carried out using a pair of compression transducers (CT) from Proceq (82 kHz nominal frequency) used in direct contact with the specimens (Figure 2). These ultrasonic P-wave measurements were made with the main purpose of assessing potential interference of compressional waves in the shear wave results, while also allowing computation of Poisson's ratio.



a) b)

Figure 2. a) Ultrasonic tests; b) Detail of the compression transducers used.

The material employed in this set of tests was a sandy silt/silty sand (ML/SM) originally from Alentejo, a region in the south of Portugal. Figure 3 displays two particle size distribution curves of this material.

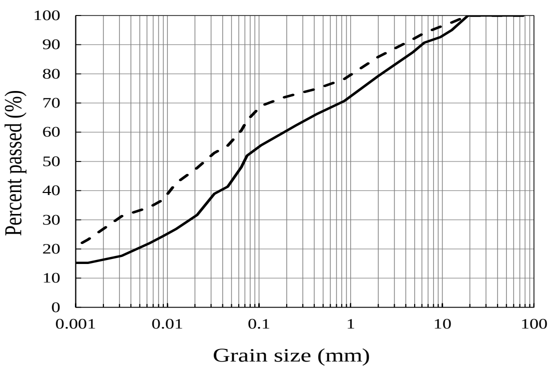


Figure 3. Particle size distribution curves.

Table 1 summarizes the values obtained for the Atterberg limits (according to NP143-1969 standard) and specific gravity of solid particles (according to NP83-1965 standard).

Table 1. Atterberg limits (NP143-1969) and specific gravity of soil solids (NP83-1965).

Atterberg limits (%)			Specific gravity of soil solids
LL	**PL**	**PI**	**G_S**
28	26	2	2.65

LL – Liquid Limit; PL – Plastic Limit; PI - Plasticity Index.

The preparation of the specimens involved special attention, especially the protrusion of the BE. On each end of the specimen, two slots were opened to allocate the BE, in order to induce minimum disturbance and ensure perfect alignment. On the other hand, for the RC tests the samples were leveled at the top and bottom with plaster to improve the contact surface between the equipment and the material. Table 2 summarizes the dimensions used for the specimens and the characteristics of the tested materials.

Table 2. Specimen characteristics.

Specimen	Height (m)	Diameter (m)	Mass (kg)
A	0.0973	0.0713	0.750
B	0.0989	0.0718	0.822

As previous mentioned, only time domain (TD) techniques were applied in order to determinate the travel time (tt). For this study, the TD technique used was the first direct arrival of the shear wave (tt_0), taken from the interval between the start of the input signal and the first deflection of the output signal. In order to reduce the uncertainty in the travel time measurements, a minimum of 4 input signals at different frequencies were used and the response signals plotted in the same graph in order to determine a "common point" indicating the first direct arrival. The tests were carried out using sinusoidal waves at a frequency range between 1 kHz and 6 kHz and for an amplitude of 20 Vpp (±10 V). The option for this range of frequencies is justified by the analysis of the frequency spectra of response signals. Figure 4 show an example of the methodology previously described.

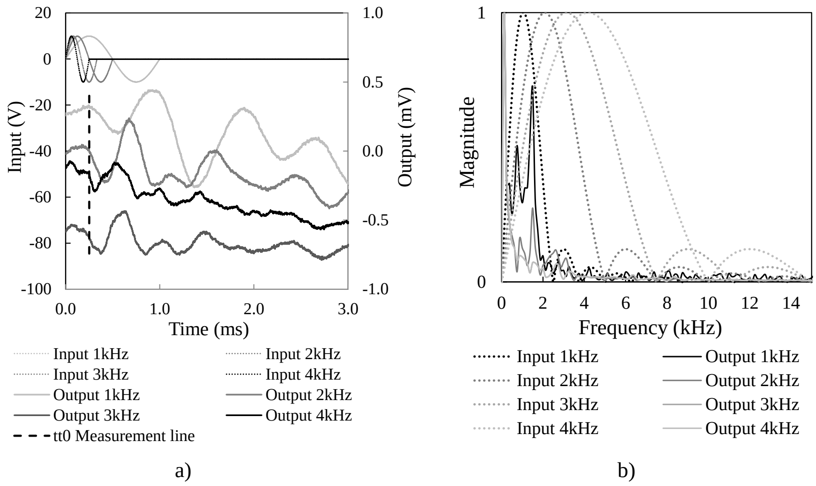


Figure 4. BE1 setup – specimen A: a) Example of travel time determination; b) Frequency spectra of the input and output signals.

From the analysis of the frequency spectra of the signals, namely the magnitude and frequency of the output signals, it is possible to observe that the ideal frequency response is located around 1kHz and also that after 4kHz there is no discernible response from the system. This confirms the validity of the time domain results and the range of frequencies adopted for this specific test.

3. Results and discussion

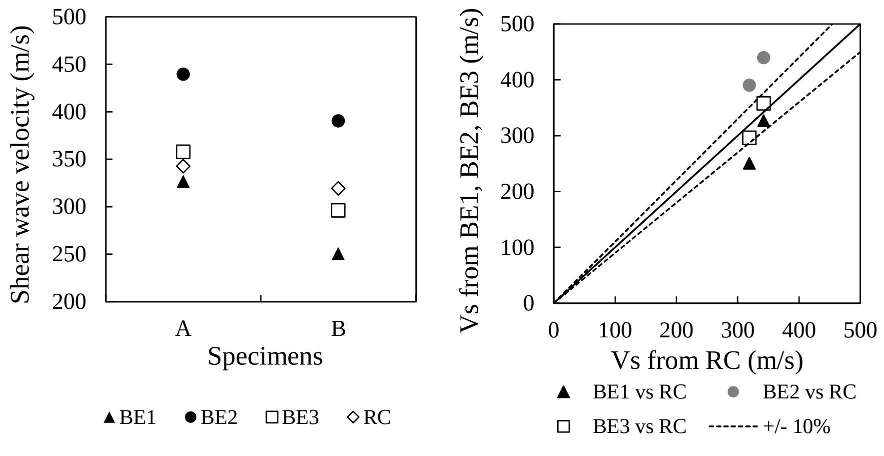
The results obtained with the three BE setups, the resonant column (RC) and the ultrasonic P-wave measurements using CT are summarised in Table 3, in terms of shear and compression wave velocities. Damping ratio (ξ) values obtained in the RC are also included. From the two seismic wave velocities, it was possible to estimate the Poisson's ratio (ν) of the soil specimens, according to Equation 3.

$$\frac{V_P}{V_S}\sqrt{\frac{2(1-\nu)}{1-2\nu}} \Leftrightarrow \nu = \frac{\left(\frac{V_P}{V_S}\right)^2 - 2}{2\left(\frac{V_P}{V_S}\right)^2 - 2} = \frac{V_P^2 - 2V_S^2}{2\left(V_P^2 - V_S^2\right)} \tag{3}$$

Table 3. Seismic wave velocities, Poisson's ratio and damping ratio results for the tested soil specimens.

Test setup	BE1		BE2		BE3		RC		US	
Specimen	1	2	1	2	1	2	1	2	1	2
V_S (m/s)	327	251	340	390	357	296	343	319	…	…
V_P (m/s)	…	…	…	...	…	…	…	…	1390	1383
ν	0.41	0.45	0.33	0.37	0.39	0.43	0.40	0.42	…	…
ξ (%)	…	…	…	…	…	…	3.7	4.7	…	…

These results in terms of shear velocity (V_S) are directly compared in Figure 5 where some discrepancies between the results can be observed. The maximum differences occur for BE2 results, which differ from the RC by about 28%. On the other hand, the results obtained simultaneously in the same device, with BE3 setup and the RC, are remarkably similar, differing by less than 7%.



a) **b)**

Figure 5. Shear wave velocity results: a) bender element and resonant column tests; b) bender element setups versus resonant column test.

With the exception of BE2 results, it is possible to observe that the computed Poisson's ratios are very similar, and in agreement with typical values for partially saturated soils.

By definition, damping ratio decreases with the increase in depth (or confining pressure), and increases with shear strain amplitude. Damping properties are usually also influenced by the plasticity characteristics of the materials: low-plasticity soils tend to present higher damping ratios than high-plasticity soils, for the same strain amplitude. In the present case, the damping values obtained by means of resonant column seem to be in agreement with the test conditions, that is, unconfined testing. This is also corroborated by the low Plasticity Index (PI=2) of the tested soil.

4. Conclusions

The resonant column is the most common laboratory test used to assess small-strain properties of soils and therefore considered a reference. However, the bender elements (BE) technique has become common practice, due to its simplicity and ease of implementation and application. New developments in electronics and signal analysis tools have provided new impetus to this technique as is widely recognized.

According to the present research, BE technique provides shear wave velocity (V_S) values similar to those obtained by the RC. Nevertheless, taking as example the results achieved using BE system 2 (BE2), this technique appears to be very sensitive to the coupling conditions of the sensors. This is particularly relevant for stiffer soil specimens, as the ones tested in this study, not only in the coupling with the BE transducers but also with the top cap of the RC.

Still regarding BE technique issues, the determination of travel time requires careful analysis and some degree of judgment. The selection of the input signal frequencies must be performed taking into consideration the magnitude and frequency of the output signals towards avoiding noise contamination as well as the presence of compression waves.

Over the past years and based on the tests presented in this paper, it is also possible to say that important steps were taken in improving the reliability of the results obtained by means of BE technique. It was possible to observe a reasonable agreement between BE and RC test, across different setups installed in various institutions. This can be considered an important achievement in order to focus the use of BE technique in assessment of another important dynamic parameter: damping.

Acknowledgements

This work was developed with the financial support provided by FCT (Portuguese Foundation for Science and Technology) under the research project WaveSoil - PTDC/ECM/122751/2010 from FCOMOP-01-0124-FEDER-020365 project.

References

[1] A. Sawangsuriya, *Wave propagation methods for determining stiffness of geomaterials*, 2012.
[2] C. R. I. Clayton, Stiffness at small strain: research and practice, *Géotechnique*, **61** (1993), 5–37.
[3] A. Gomes Correia, Características de deformabilidade dos solos que interessam à funcionalidade das estruturas, *Geotecnia*, (2004), 103–122.
[4] D. C. F. Lo Presti, S. Shibuya, and G. J. Rix, Innovation in soil testing, Pre-failure Deformation Characteristics of Geomaterials, in *Swets and Zeitlinger*, (2001), 1027–1076.
[5] J. Camacho-Tauta, *Evaluation of the small-strain stiffness of soil by non-conventional dynamic testing methods*, Technical University of Lisbon, Lisbon, 2011.
[6] R. Dyvik and C. Madshus, Laboratory measurements of Gmax using bender elements., in *ASCE Annual Convention: Advances in the art of testing soils under cyclic conditions*, (1985), 186–196.
[7] G. Viggiani and J. Atkinson, Interpretation of bender element tests, *Géotechnique*, **45** (1995), 149–154.

[8] S. Yamashita, T. Kawaguchi, and Y. Nakata, Interpretation of international parallel test on the measurement of Gmax using bender elements, *Soils Found.*, **49** (2009), 631–650.
[9] E. Brignoli, M. Gotti, and K. Stokoe, Measurement of shear waves in laboratory specimens by means of piezoelectric transducers, *ASTM Geotech. Test. J.*, **2** (1996).
[10] A. Viana da Fonseca, C. Ferreira, and M. Fahey, A framework interpreting bender element tests, combining time-domain and frequency-domain methods, *ASTM Geotech. Test. J.*, **32** (2009), 91–107.
[11] P. D. Greening and D. F. T. Nash, Frequency domain determination of G0 using bender elements, *Geotech. Test. J.*, **27** (2004), 1–7.
[12] C. Ferreira, J. P. Martins, and A. Gomes Correia, Determination of the small-strain stiffness of hard soils by means of bender elements and accelerometers, *Geotech. Geol. Eng.*, **6** (2013), 1–7.
[13] J. Martins, *Compaction and its influence on the structural behaviour of high speed railways*, Universidade do Minho, Guimarães, 2011.
[14] J. Camacho-Tauta, G. Cascante, J. A. Dos Santos, and A. Viana da Fonseca, Measurements of shear wave velocity by resonant-column test, bender element test and miniature accelerometers, in *Pan-Am Geotechnical Conference*, (2009), 1–9.
[15] C. Ferreira, *The use of seismic wave velocities in the measurement of stiffness of residual soil*, University of Porto, Porto, 2009.