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New developments in bender element testing

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ABSTRACT: In the last decades, bender elements (BE) have become a routine laboratory tool for seismic wave velocity measurements. The ease of implementation and the advantage of simultaneously combining very small strain and larger strain stiffness measurements are among the reasons for its attractiveness. This paper aims to present new developments in BE testing, fundamentally resulting from the use of the different excitation frequencies. Changing the input frequency in BE measurements was originally advocated to improve its interpretation, often reported as the main difficulty in BE testing. On the other hand, this approach has inspired novel applications, namely the combined measurement of compression (V_P) and shear (V_S) wave velocities using a single BE. This application was derived from experimental evidence, and subsequently validated using laser measurements of the BE deformation under different frequencies. These enabled to prove the type of generated waves and consequently confirm soil response. In this paper, the specific procedures of this application will be discussed and analysed in detail.

1 INTRODUCTION

In the last decades, bender elements (BE) have become a routine laboratory tool for seismic wave velocity measurements. Since its development in the 1980s (Shirley & Hampton, 1978, Dyvik and Madshus, 1985), this testing technique has gained popularity, currently being available in many geotechnical laboratories worldwide in a variety of apparatuses, such as the oedometer, triaxial, simple shear box and resonant-column. The advantage of simultaneously combining very small strain stiffness measurements by means of BE, with the small to large strain stiffness measurements of each apparatus, coupled with its easy and low-cost implementation are the main reasons for its attractiveness.

A BE test consists of the application of an input voltage of defined shape and frequency to the transmitter to generate a shear wave, which propagates through a soil specimen and is received by the receiver element, producing an output signal. The output signal is heavily attenuated, more distorted and more complex than the input signal. While it is sometimes easy to determine the first arrival of the shear wave, it is often the cause of much uncertainty (Arroyo et al. 2003, Rio 2006, Ferreira 2009).

A bender element (BE) is a double piezoceramic transducer composed of two thin piezoceramic plates, rigidly bonded to a central metallic sheet, which acts as reinforcement, and to electrodes on its outer surfaces. Its operating geometry corresponds to that of a cantilever beam, fixed at one end, usually potted into a capsule, and free at the other end. The electrical connection to the piezoceramic plates is made in relation to the polarization directions of the two plates, in order to ensure proper flexural movement. Dyvik and Madshus (1985) introduced a detailed bender element design model, which formed the basis of much of the subsequent development and which is still followed at present (Ferreira, 2009). Lings and Greening (2001) described a new construction technique, in which a BE is modified by a few simple changes to the wiring (series or parallel, associated with different polarization) to become a hybrid element. This has been termed bender-extender element, capable of operating as bender transmitter and extender receiver, or vice-versa.

In the present study, the possibility of making use of the higher vibration modes of the BE, induced by the application of higher frequencies, is explored, as a means of directly measuring not only S-waves, but also P-waves with the same BE transducer and setup. For this purpose, a collaborative research plan has been established between the University of Porto (UPorto), Portugal and the University of Waterloo (UWaterloo), Canada. At UWaterloo, laser measurements of the deformation of a BE, manufactured in UPorto, have been made and analyzed for a wide range of input frequencies. At UPorto, a series of BE measurements on a loose sand in dry and saturated conditions were taken to demonstrate the applicability of the proposed approach.

2 LASER MEASUREMENTS OF A TRANSMITTING BENDER ELEMENT

2.1 *Experimental setup*

In order to take readings of the actual displacements for the bender element (BE), a state-of-the-art laser vibrometer was used in laboratory tests, in the University of Waterloo, Canada. The setup for these tests included a BE transmitter on air, peripheral electronics and a laser vibrometer. All the devices needed for the tests were set over an isolation table, which ensured there was no external vibrations affecting the tests. The BE tested in the lab, originally manufactured at the University of Porto, had the following dimensions: length 13 mm, height 5 mm, and thickness 1.5 mm. A schematic of the experimental setup, including a cross-section of the BE, is shown in Figure 1.

A function generator (FG) was used to generate an input voltage signal and send it to the BE, passing first through a piezo-driver in order to get it amplified. The amplified signal made the BE vibrates and then the displacements were measured using a laser vibrometer. The displacement readings were recorded in different locations along the top edge of the BE, both in vertical and horizontal directions. The laser head was vertically or horizontally oriented according with the displacement being measured at the time of the test. The pattern followed

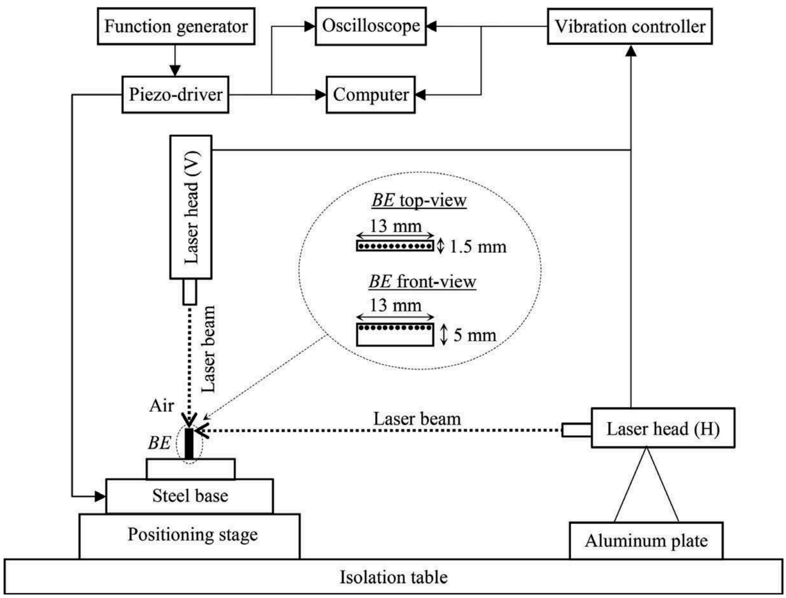

Figure 1. Schematic of the experimental setup.

to take the reading was a horizontal row of 27 points with spacing of 0.5 mm, in such a way that the full length of the BE was covered by readings. The same pattern was followed for vertical and horizontal readings. The laser head was managed by a controller device to assure precision in the measured locations. A reflecting paper was glued on the BE surface to enhance the signal quality of the laser vibrometer. The length of the laser beam was set at 0.5 m for all tests and the time signals were recorded for a total time of 2.5 ms with a sampling frequency of 25.6 MHz.

2.2 *Resonant frequencies in the BE movement*

The first step in the laboratory testing was to identify the resonance frequencies for the first three vibration modes (f_1, f_2, and f_3) of the BE. They were identified by sending a sinusoidal sweep to the *BE* with a range of frequencies going from 4 kHz to 100 kHz. This sinusoidal sweep test was performed using a spectrum analyzer (HP-35670A) which calculates the transfer function between two signals in real time. Horizontal and vertical displacements readings were taken on the top of the BE with the laser vibrometer and the signals were processed to obtain the frequency spectrums. Then, for horizontal and vertical displacements, the resonance frequencies identified were f_1=12kHz, f_2=29kHz, and f_3=46kHz.

The second step in the laboratory testing was to use each resonant frequency as the central frequency (f_c) of a sine pulse which is used as input to measure the *BE* response in air. By using different central frequencies, it is possible to excite different vibration modes in the *BE*. The amplitude for the sine pulse in the input signal was 10 Volts peak-to-peak (V_{PP}). For each resonance frequency, vertical and horizontal displacements were measured on top of the *BE* for points with a spacing of half of a millimeter.

2.3 *Analysis of vibration modes*

The displacement signals were processed in order to filter each mode according to the central input frequency. In Figure 2 the first and third vibration modes are presented for the envelopes of the vertical (right) and horizontal (left) displacements on top of the BE, along the full width of the transducer, represented in the horizontal axis.

For the vertical displacements, corresponding to a compression-extension deformation, the maximums for the first mode are relatively low; however, for the third mode, which was mainly excited by a frequency of 46kHz, the vertical displacements are roughly twice the values obtained for the first mode. This means the higher the input frequency, the more important the vertical displacements become in the BE vibration, which corresponds to an increase in the compressional components of the transmitted wave.

In turn, the observed maximum horizontal displacements decrease considerably with the frequency increase, from the first to the third mode, which evidence a reduction in the flexural component of the transmitted wave.

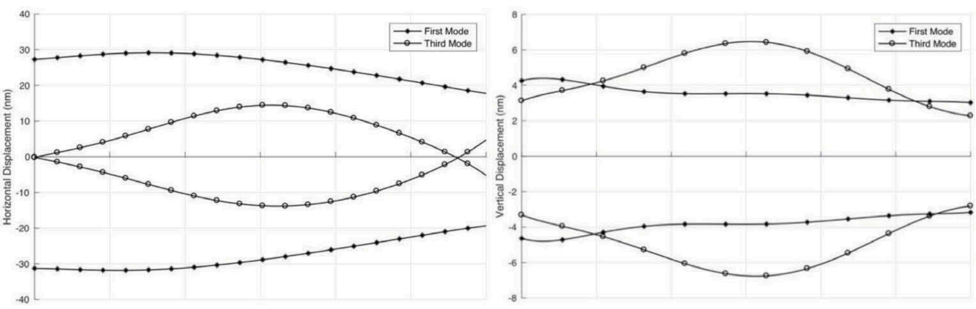

Figure 2. First and third vibration modes for horizontal and vertical displacements on top of the BE, along its width.

The results obtained in these laser measurement tests demonstrate how the input frequency strongly affects the BE movement. These results also explain why it is possible to identify the P-wave arrival, when high frequencies are used in the BE test. As the high frequencies tend to excite more the third mode, rather than the first or the second, more energy is oriented in vertical direction creating a stronger P-wave front, which allows its detection in the receiver BE.

3 BENDER ELEMENT MEASUREMENTS

3.1 *Experimental setup*

The Geotechnical Laboratory of the Faculty of Engineering of the University of Porto has been routinely using bender element for more than 15 years (Viana da Fonseca et al., 2009). Seismic wave measurements using bender elements have been made in a large variety of geomaterials, from very soft to very stiff soil specimens. As a result, there is a vast database of results and significant experience in bender element testing, from manufacturing the transducers to its interpretation and its application to geotechnical design and practice (e.g. Viana da Fonseca et al., 2009, Ferreira et al., 2011).

The experimental program developed in this research comprised a series of bender element measurements in a stress-path triaxial chamber, equipped with a pair of piezoelectric transducers (bender elements), installed on the base and top caps, for measurement of both compression (V_P) and shear (V_S) seismic wave velocities.

For this work, a Portuguese sand (NB) was used, with the following properties: FC = 2.9%, D_{50} = 0.45, C_U = 2.16, e_{max} = 0.84, e_{min} = 0.54, G_s = 2.64 (Ramos et al., 2019). A loose sand specimen was prepared by dry pluvation, at a high void ratio, close to e_{max}. The specimen were moulded to about 100mm of height and 50mm of diameter. A series of isotropic confining stresses were applied at two different state conditions: dry and fully saturated. The confining stresses, where seismic wave velocities were measured, were 30, 50, 75, 100, 150, 200, 250, 300, 350, 400 kPa. The percolation involved two phases: (i) percolation with CO_2, and (ii) percolation with de-aired water. The saturation was performed increasing both the back-pressure

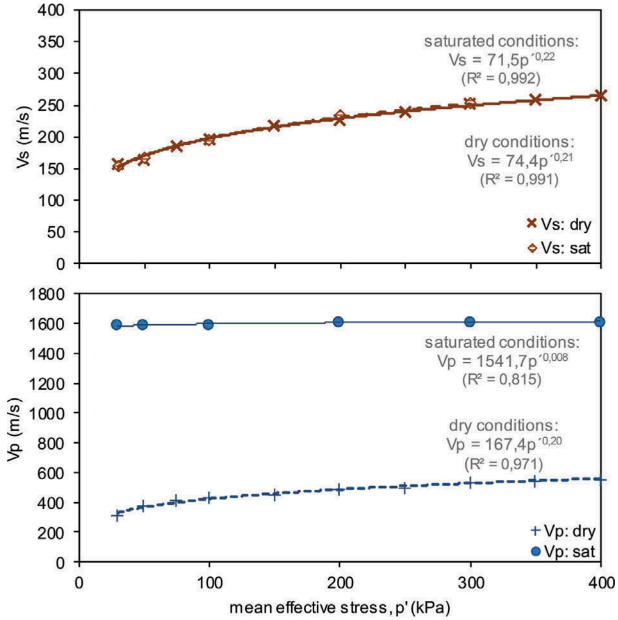

Figure 3. V_S and V_P evolution with isotropic confinement in dry and saturated conditions

and the cell pressure, at a constant effective stress of 10kPa, until 300kPa of back-pressure. To check the specimen's saturation, both Skempton's B-value and the compression wave velocity were measured. The specimen was considered saturated for values of B higher than 0.96 and values of V_P above 1500 m/s (Ferreira, 2009, Soares and Viana da Fonseca, 2016).

At each confining stress level, the measurement of compression and shear wave velocities was made using a single pair of bender elements. The input waves are sine-wave pulses and, based on the methodology described by Viana da Fonseca et al. (2009), at least four different input frequencies were used, selected according to the observed response signals. In this case, for S-wave measurement, the input frequencies of 1, 2, 4, 6 and/or 8 kHz were used, while for P-wave measurement, 25, 50, 75 and 100 kHz were applied. The identification of the arrival time of both seismic waves was made considering the first direct arrival of the output wave, common to all input frequencies. In this approach, it is assumed that the travel time of the seismic waves is independent of the input frequency, which is acceptable within the adopted frequency range.

3.2 *Main results*

The general overview of the evolution of the seismic velocities with confining isotropic stress is illustrated in Figure 3 for dry and saturated conditions.

From Figure 3, it is clear that the evolution of shear-wave velocities (V_S) with increasing stresses is nearly identical, whether in dry or saturated conditions. The obtained stress-dependency exponent β of 0.21-0.22 is within the typical values for natural sands (Cho et al. 2006, Ramos

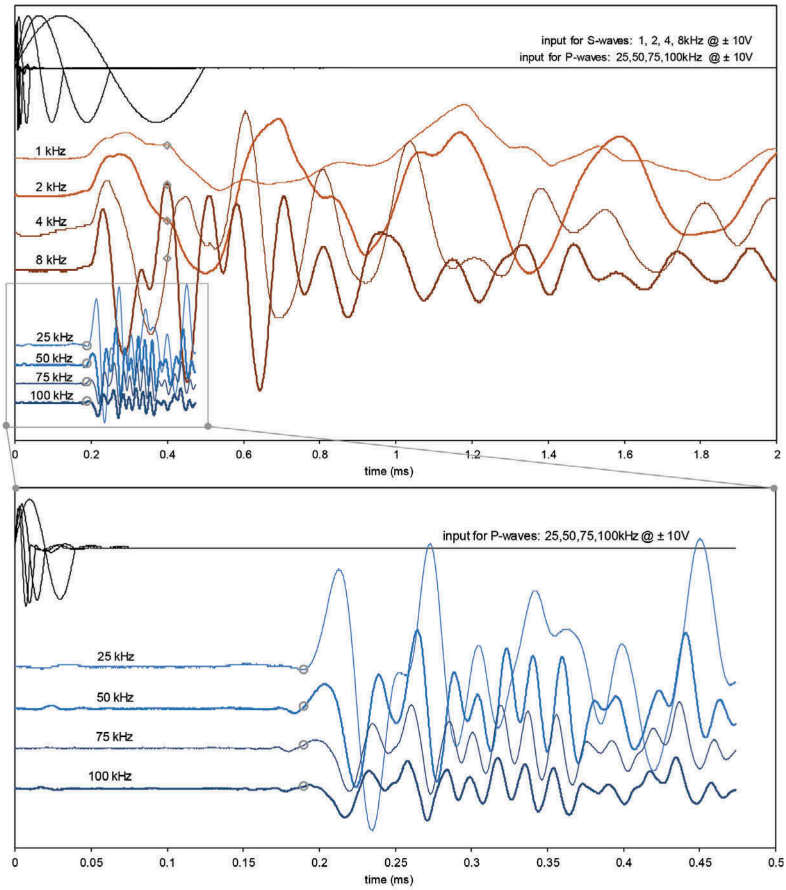

Figure 4. BE measurements for S- and P-waves: dry conditions, at 300 kPa isotropic confinement

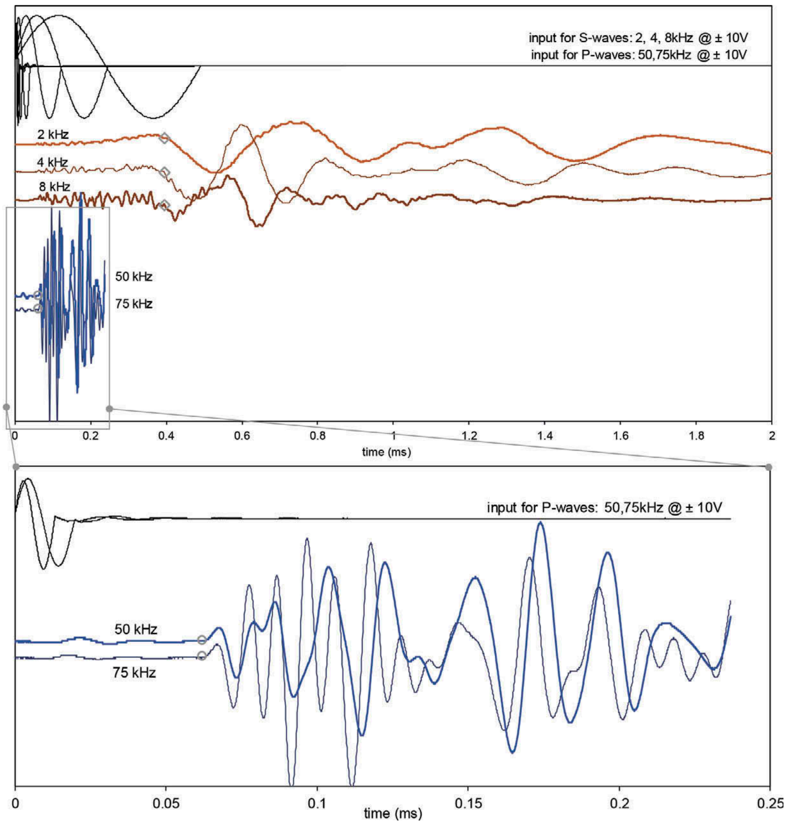

Figure 5. BE measurements for S- and P-waves: saturated conditions, at 300 kPa isotropic confinement

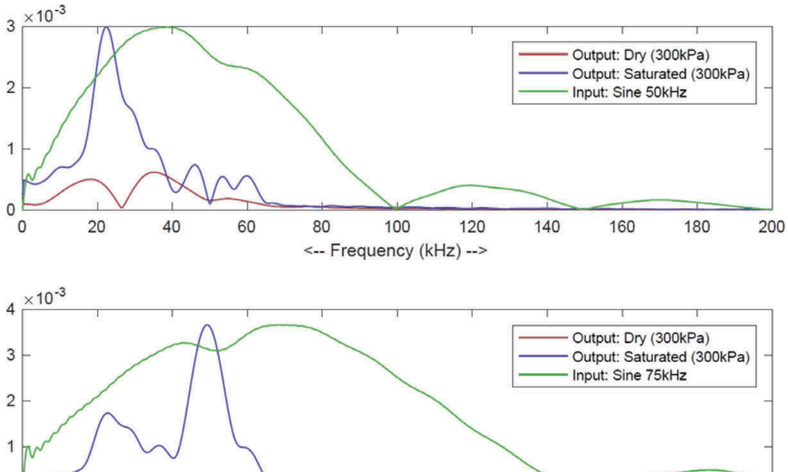

Figure 6. Frequency spectra for BE signals for 50kHz and 75kHz input frequencies, for dry and saturated conditions, at 300 kPa confining stress

et al. 2019). A similar evolution, expressed by the obtained stress exponents, can be observed for compression-wave velocities (V_P), but only in dry conditions. In fact, V_P changes to a nearly constant plateau once the soil is saturated. This behavior is expected, once all pores are filled with water; the velocity of P-waves is then controlled by the fluid velocity (Marczak 1997, Santamarina et al. 2001). What is important to highlight is that all of these measurements were obtained with a single BE transducer, simply by adjusting the input wave frequencies.

For the purpose of comparison, two of the acquired BE measurements have been selected, at the same 300 kPa isotropic confinement, for dry (Figure 4) and for saturated (Figure 5) conditions. At this stress level, the travel time of the shear wave is 0.400 and 0.395ms in dry and saturated conditions, resulting in a shear-wave velocity of 250 m/s. On the other hand, the P-wave travel time changes from 0.188 to 0.062ms, corresponding to V_P of 532 and 1612 m/s, in dry and saturated conditions, respectively.

These two sets of BE measurements evidence significant changes in shape and amplitude of the received waves due to the change in saturation conditions. In dry conditions, the output signals at low frequencies, corresponding to S-waves, are complex and difficult to interpret, not only due to the higher wave dispersion, but also due to the proximity to the travel times of the two waves, since t_P is nearly half of t_S. In saturated conditions, the S-wave signals exhibit lower amplitudes, but are simpler, therefore easier to interpret. The presence of P-waves is visible at frequencies as low as 8 kHz.

A more informed analysis can be made, looking at the Fourier transform (FFT) spectra of the high-frequency signals in dry and saturated conditions, as illustrated in Figure 6. From Figure 6, it can be seen that the frequency spectra confirms the observed differences in the signals, in terms of amplitude and natural frequency. At 50 kHz input frequency, the BE output signal changes to a much sharper spectrum after saturation, centered near 20 kHz. Similar response is obtained for 75 kHz input frequency, however in this case the natural frequency in saturated conditions reaches 50 kHz, at an even higher amplitude.

4 CONCLUSIONS

The results obtained in the laser measurement tests have clearly demonstrated how the input frequency strongly affects the movement of a bender element. These results also explain why it is possible to identify the P-wave arrival, when high frequencies are used in the BE test. As the high frequencies tend to excite higher vibration modes, more energy is oriented in vertical direction creating compression-extension movements and thus a stronger P-wave front, which allows its detection in the receiver BE.

The triaxial BE measurements have also demonstrated the capability of a single BE pair to transmit and detect not only S-waves but also P-waves. These results were obtained without any changes in the wiring or setup of the BE pair, therefore different from the bender-extender configuration proposed by Lings and Greening (2001). The obtained results fit well with the expected shear and compression wave velocities of a loose sand, both in dry and in saturated conditions.

Nonetheless, these results must be considered preliminary as the BE was tested on air, while the real test constrain the BE into the soil. The next stage in experimental work will include embedding the BE inside a sample of transparent synthetic soil in order to be able to read displacements through soil.

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