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Combined Bender Elements and Accelerometers System: Measurement and Interpretation

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***Abstract* – Useful to define the stiffness of geomaterials at very small strains, the assessment of seismic wave velocities in the laboratory is currently a worldwide common practice. The combined use of piezoelectric transducers such as bender elements and accelerometers, already proved to be a simple but powerful laboratory tool for seismic wave measurements, helping decrease some subjectivity inherent to BE when used individually. Additionally, the simultaneous use of time and frequency domain signal analysis techniques is considered a useful alternative to reduce error in seismic wave measurements. This paper presents a combined bender elements and accelerometers test setup implemented on a stress-path triaxial chamber as well as a seismic-wave acquisition software that allows simultaneously time and frequency domain analyses on soil samples. Finally, an application study is presented for a monogranular sand tested in triaxial compression at different isotropic stress levels.**

I. INTRODUCTION

In the past couple of decades, the definition of geomaterial stiffness at very small strains has become an area of interest following the development of new testing techniques in field and laboratory conditions. In the laboratory, one of the methods currently used to assess very small strain stiffness makes use of piezoelectric transducers, named bender elements (BE). Shear (S) waves are transmitted and received through the soil specimen allowing the calculation of the shear velocity (V_S) and consequently the initial shear modulus (G_0). The ease of implementation and operation of these transducers has stimulated its use in a variety of geotechnical testing apparatuses [1, 2, 3].

Despite its simplicity, there are still some uncertainties related to S-waves travel time (tt) determination and its interpretation methodologies [4]. Coupling [5], alignment between transducers [6], electrical noise [4, 7], wave reflection [4], as well as specimen geometry [8], are some of the factors that may affect the quality of the signals and consequently compromise its analysis. Different materials and different test conditions can also contribute to a poor performance of some of the signal analysis methods. In order to avoid this, some authors suggest the combined use of different interpretation methods. The recommended methods are the identification of the first arrival of the wave (time domain) and the sine sweep of frequencies (frequency domain) [9, 10].

Alternatively but complementary to signal analysis methods, the use of different types of tests is also recommended. Thus, some authors suggest the combined use of accelerometers (AC) and BE [1, 11]. Such setup provides additional information about the validity of BE signals and thereby minimizes subjectivity. Also, since the AC signals are from the same nature and therefore directly comparable, the signal analysis can be performed either in the time or frequency domain [1].

This paper presents a combined BE and AC system implemented on a stress-path triaxial chamber [1, 3, 11] as well as an implemented facility of seismic-wave acquisition software that allows simultaneously time and frequency domain analysis. These developments were validated by testing a monogranular sand at different isotropic compression stresses (50, 100, 200 and 400 kPa).

II. MATERIALS AND METHODS

The combined system comprises a stress-path triaxial chamber equipped with a total of four sensors: two bender elements (from GDS Instruments) and two accelerometers (Fig. 1a and 1b) [3, 11, 12]. The transmitter BE sends seismic S-waves, which travel through the specimen, and are received by the remaining transducers, the receiver BE and the two AC. The AC used are from Bruel & Kjær (type 4513-001, 100 mV/g sensitivity, ±50 g measuring range, 1 Hz to 10 kHz frequency range, 12.7 mm in diameter, 15.65 mm in height, 9.0 g in weight). Its attachment to the specimen is possible by means of threaded head pivots.

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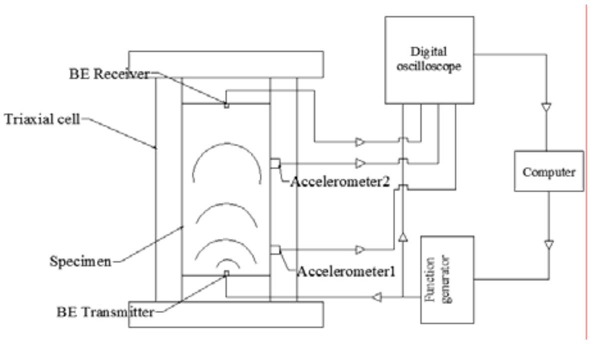
Accelerometer1 (AC1) is placed 30 mm from the specimen base and accelerometer2 (AC2) 100 mm from AC1. (Fig. 1c) [1].



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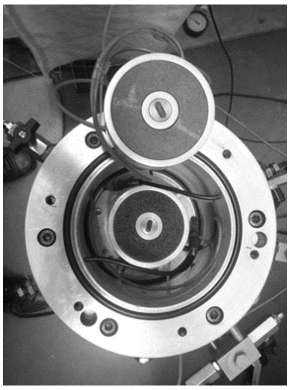
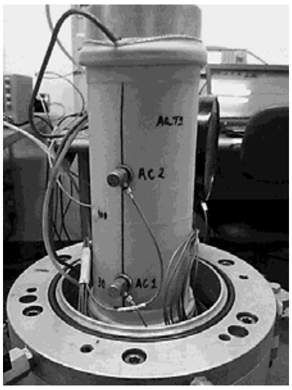



b) *c)*

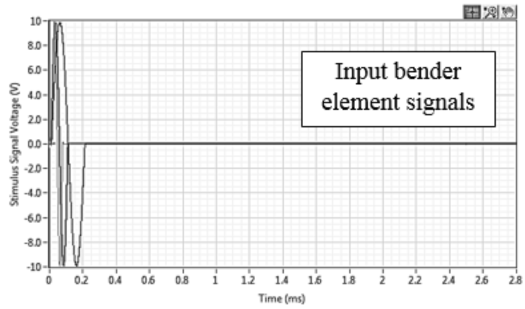
Fig. 1. a) Schematic view of the combined system; b) Bender elements accommodated in the stress-path chamber; c) Overview of the accelerometers located in the specimen.

The associated electronic equipment includes a function generator from Thurlby Thandar Instruments (TTi TG2511) and a digital oscilloscope PicoScope model 4424, with 4 channels (1 or 2 channels at a sampling rate of 80 MS/s and 3 or 4 channels at 20 MS/s, with 12 bits of resolution) for data acquisition.

The seismic-wave software developed makes the link between all the previous devices. To perform measurements, the software generates a number of sinusoidal waves with a single period and frequencies set by the user (usually according to the geometry, type of material and the quality of the response signals among others) that are transmitted to the BE transmitter. Each generated signal is captured by the BE receiver and the two AC, which are registered by the software (Fig. 2).

In order to reduce potential electrical noise of the received signals, the software performs an average of several measurements for each signal. The transmitted and received signals are plotted and the selection of the arrival time (tt) is performed using measurement cursors.

The computed tt as well as the several transmitted and received signals are automatically saved, for post-processing.



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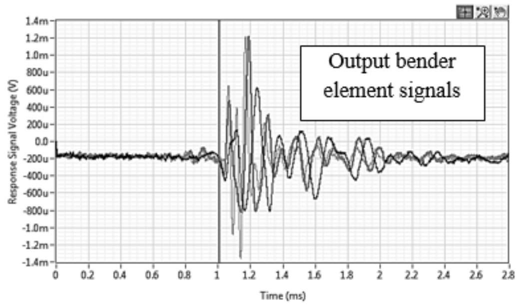

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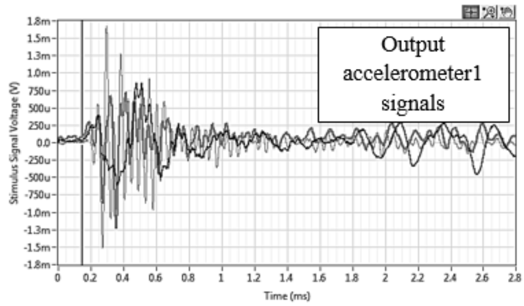

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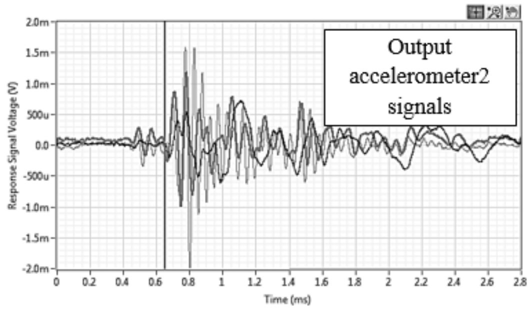
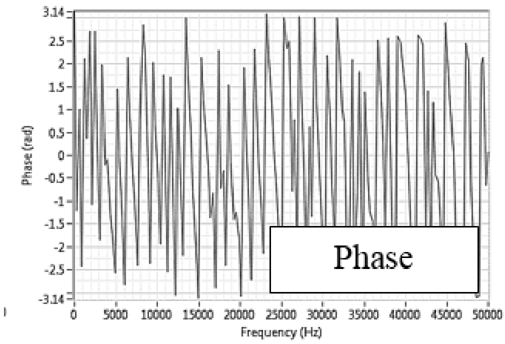


d)

Fig. 2. Software signal analysis – time domain charts: a) Input bender element signals; b) Output bender element signals; c) Output accelerometer1 signals; c) Output accelerometer2 signals.

In addition to time domain, the software also process data by means of frequency domain analysis. In this case, the generated input signal is a sweep of frequencies with duration and frequency range defined by the user (again according the geometry, type of material and the quality of the response signals among others). After acquiring the signals (transmitted and received) the software stores the data and computes the tt in the frequency domain making use of the transfer function between the signals (phase) (Fig. 3a). The coherence is also computed, to evaluate the quality of the transfer function (Fig. 3b). For this, it is necessary to perform a procedure called "Unwrapped" i.e. remove the leaps of the transfer function. The result of this operation is shown in Fig. 3b. Based on the "unwrapped phase angle" function, the slope of the linear regression is determined for a frequency range corresponding to maximum coherence, from which tt is automatically calculated [10].



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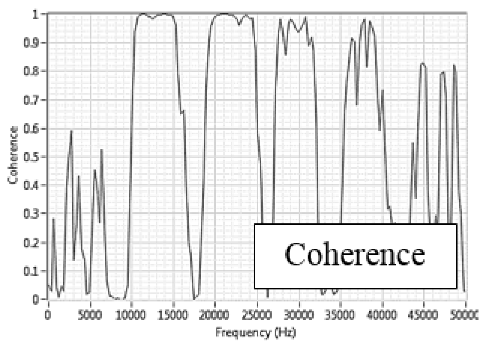

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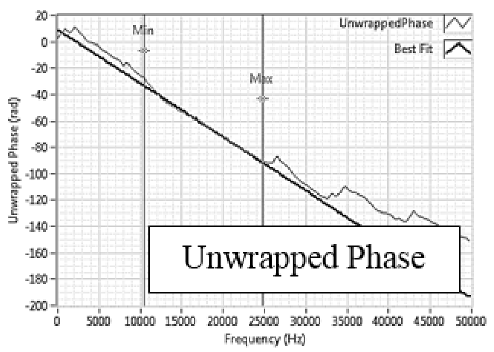
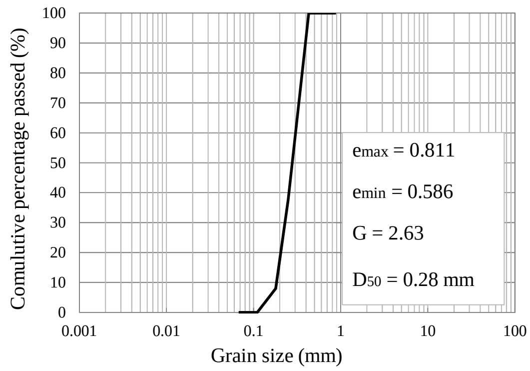


c)

Fig. 3. Software signal analysis – frequency domain charts: a) Phase angle; b) Coherence; c) Unwrapped phase angle.

III. APLICATION STUDY: RESULTS AND DISCUSSION

A monogranular or uniformly graded sand was used as tested material for the presented application study. The tested specimen was prepared according the "Dry Tamping" method in five layers, with 80 % of relative density, 99.9 mm in diameter and 202.5 mm in height [13]. Fig. 4a shows the grain size distribution curve and some of the physical properties of this material.



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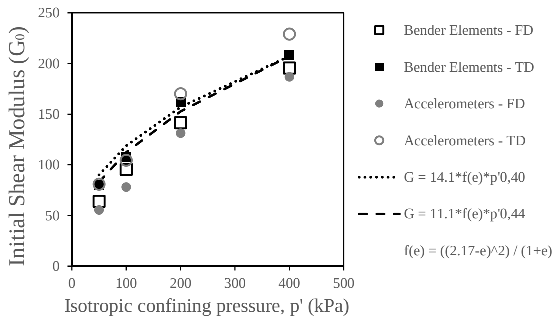

b)

Fig. 4. a) Grain size of the uniformly graded sand; b) Initial shear modulus vs Isotropic confining pressure: time domain, frequency domain and empirical equations.

The obtained measurements are provided in Fig. 4b, showing a good agreement between BE and AC results and between the different signal analysis methods. Also, the measurements appear to be in good agreement when compared with reference expressions in the literature. These results are an extract on an extensive research project on this topic, which has enabled to validate not only the interpretation methods and the software used as well as the testing setup and procedures, forming the basis on a BE testing standardization proposal.

ACKNOWLEDGEMENTS

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