Evaluating the maximum shear modulus (G_0) for different bender-soil coupling loads

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Abstract. The current paper aims to test the effects of vertical loads on the maximum shear modulus (G_0). The tests were undertaken with unsaturated soils in unconfined conditions. As a material, was used a set of granite-gneiss soil samples collected in the Quinta do Paraíso Campus, at the Centro Universitário Serra dos Órgãos (UNIFESO), Teresópolis – Brazil. To perform it, cylindrical samples were submitted to bender elements under four vertical loads (200 g, 400 g, 500 g, and 600 g). Further, the readings were done with the same amplitude and frequency values. The results revealed a decrease in the shear wave's velocity reducing the volumetric water content. Besides, the shear modulus increased with the vertical loads' addition.

1 Introduction

Bender elements are piezoceramic transducers surrounded by an epoxy body that converts mechanical energy to or from electrical energy. The equipment induces shear and/or compressive waves through the specimen and measures the wave propagation time between the emission and receiver.

Dyvik and Madshus [1] introduced the purpose of this equipment to the soil mechanics approach. However, only with the insulation upgrade [2], responsible to eliminate the noise that disturbed the signal emitted by the transducer, was possible to increase its uses for geotechnical purposes.

Despite bender element testing being widely used, it is still not a standard procedure [3]. It happens because the variability of the signal is influenced by different factors such as near-field effects, directivity, travel distance, boundary effects, sample geometry and size, cross-talking and, the amplitude of signal and frequency [4].

Although it evolved from the last decades, as far as it is concerned with soil samples testing, the analysis are still surrounded by unpredictability related to structure, mineralogy, density and saturation degree [5].

In the matter of the unconfined investigations, Mattsson et al. [6], Chan [7] and Motta [8] revealed a valuable use of the bender even for experiments performed outside the triaxial cells. However, for both types of researches, the unconfined tests depicted remarkable difficulties such as unsatisfactory ground and the weak coupling of the transducer to the soil (at the top of the specimen. Thus, it is not only difficult but also uncertainties-holder to get reliable data for wave measurements in unconfined and non-saturated cases.

For unsaturated soils, Marinho [9], Ng & Yung [10], Hoyos [11], and Motta [8] presented outcomes for

different levels of suction and water content. However, the behaviour of the materials under unsaturated conditions (including the coupling effects between the hydraulic and mechanical characteristics), point out the subject are still demanding further investigations.

This research fits within the applied sciences given its attempt to represent bender elements tests performed with unsaturated and unconfined tests, and its relationship with vertical loads (200 g 400 g, 500 g, and 600 g) for determining G_0 .

2 Materials

2.1. Characterisation

The mountainous region of Rio de Janeiro State is in the escarpment and in the reverse of the Serra do Mar, in the geomorphological unit identified as Serra dos Órgãos. In this site, rocks of the crystalline complex, such as granites, gneisses, and migmatites are sectioned by fractures and faults of regional extents [12] dated from the Precambrian-Eopaleozoic era [13, 14].

Concerning pedological aspects, it is possible to observe colluviums essentially consisting of sandy-clay soils in Teresópolis and its surroundings [15]. Their yellowish-red tone is associated with weathering and erosion processes. Besides, primary clay-minerals (kaolinite), quartz and oxides of iron and aluminium are noticeable because of the weathering of biotite-gneiss rocks [16].

For the sampling depths and the soil characterisation, we attempted two points (Pt 01 – 25 cm and Pt 02 – 75 cm), at Campus Quinta do Paraíso - UNIFESO (geographic coordinates: 22°23'35.02" south, and 42°57'40.78" west). Further, we used the ABMS standard methods NBR-6457 and NBR-6508 [17, 18].

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Table 2. Physical properties.

Sample	Pt 01	Pt 02
Specific Gravity	2,65	2,67
γ_t (kN/m ³)	17,5	18,5
Void ratio	0,9	0,95
Liquid Limit (%)	47,2	54
Plastic Limit (%)	35,9	27,8
Plasticity Index (%)	11,3	26,2

In the matter of Grain Size Distribution, was used the coupled method of sieving and hydrometer (NBR-7181) [19], and the soil classification was based on the Unified Soil Classification System (USCS).

Pt 01: Colluvial, silty-sand (SM);

Pt 02: Colluvial, clayey-sand (SC).

The soil-water characteristic curves were based on the filter paper method [20]. The moisture/suction values obtained by two branches (moistening and drying) revealed similar geometries for both soils (Figure 1). It is important to emphasize that we did not evaluate the effect of hysteresis.

Fig. 1. Soil-water characteristic curves.

2.2. Equipment

To perform tests using bender elements a set of materials is required.

- Bender elements / piezoceramic transducers;
- Wave generator;
- Oscilloscope
- Computer

Manufactured by Controls Group, the piezoceramic transducer used in the current research is commonly used to perform tests under confined conditions, inside the triaxial cell. The arrangement comprises a plastic cylindric body with a porous stone and the transducer is located at the centre (Figure 2).

Fig. 2. Bender elements manufactured by Controls Group.

As described before, a wave generator (WG) and an oscilloscope are required to perform the test (Figure 3 a and b). Because of this, was used the WG equipment manufactured by Aim & Thurlby Thandar Instruments – Model TG5011A. The main specifications described by datasheets are:

- 0.001 mHz to 50 MHz or 25 MHz range;
- 14 digits or 1 μ Hz resolution;
- True pulse generator with variable delay and variable rise/fall;
- Arbitrary waveforms of up to 128 K points at up to 125 MS/s;
- 20 mV to 20 V peak-peak output from 50 Ω ;
- Multi-function aux. out;
- Storage for multiple instrument set-ups in non-volatile memory.

Further, the PicoScope – PC oscilloscope – Serie 4224 was used. The equipment is comprised by:

- Bandwidth - (10 MHz on ± 50 mV range);
- Enhanced vertical resolution - 16 bits;
- Input sensitivity - 10 mV/div to 20 V/div;
- Input ranges (full scale) - ± 50 mV to ± 100 V in 11 ranges;
- Maximum post-trigger delay – 50 s;
- Display modes- Magnitude, peak hold, average.

Fig. 3. a) Wave generator. b) Oscilloscope.

3 Methods

A field campaign collected undisturbed soil blocks. Afterward, it was kept into the wet chamber of the UNIFESO laboratories, where the sampling process was carefully achieved.

In complement, the specimens were moistened by dripping (Figure 4) and dried in the air to reach the desired water contents.

Fig. 4. Dripping.

Due to the focus of this research to be related with the increase of vertical loads, we used the intermediary threshold of the soil-water characteristic curve to verify the results for small changes of moisture contents.

The volumetric water content was calculated, removing the volume of the transducer, and the dimensions of the samples were taken for every stage (Table 3).

It is important to highlight that the sample remained covered to equalise the moisture for 24 hours. Further, the natural water content of the soils was close to the intended values, and the dripping was done to make a thin adjust.

Table 3. Volumetric water content during the tests.

	VWC (%)	Vertical Loading (g)			
Pt 01	28,05	200	400	500	600
	27,55	200	400	500	600
	27,18	200	400	500	600
	26,5	200	400	500	600
Pt 02	32,6	200	400	500	600
	32,24	200	400	500	600
	31,75	200	400	500	600
	31,48	200	400	500	600

The tests were performed in 4 stages (Figure 5). The first consisted only of the top cap height (200 g). The next stages added 200 g, 100 g, and 100 g, respectively.

Fig. 5. Test procedure and disposition of bender-soil coupling.

Since the tests were performed outside the triaxial cell, the grounding was strongly required. In this way, the whole system was grounded in a different circuit, separated to the build grounding network, to reduce or eliminate the noises induced to the equipment. In this context, the ground/insulation used was based in the NBR-5410 [21].

For testing, the waves inputted remained unchanged during all the procedures. The amplitude was 20 Vdc (peak to peak), frequency 1 kHz, and period 20 ms.

3.4. Calculations

To calculate the velocities of the waves (v_s) acquired by bender elements and maximum shear modulus (G_0) was used [22] the following equations:

$$G_0 = \rho \times v_s^2 = \rho \times \frac{L^2}{t^2} \quad (1)$$

Where:

v_s is the shear waves velocities;
 G_0 is the maximum shear modulus;
 ρ is the soil specific mass;
 L is the distance between the benders;
 T is the shear wave travel time.

4 Results

The results show a reduction of wave travel time with the increase of bender-soil coupling energy for Pt 01 and Pt 02. In addition, was verified for both soils a reduction of wave travel time with the increase of the volumetric water content (Figure 6).

Fig. 6. Shear wave travel time vs. VWC (%). a) Pt 01 - b) Pt 02.

3D graphs revealed (Figure 7) the relationship between volumetric G_0 , water content/suction, and vertical loads.

A graphic rotation exposed a comparison of G_0 and suction. At this point, it is clear that higher suction values produced higher values of the maximum shear modulus (Figure 8).

Fig. 7. Maximum shear modulus (G_0) vs. VWC (%) vs suction (kPa). a) Pt 01 and b) Pt 02.

Fig. 8. Graph rotation. Maximum shear modulus (G_0) vs. VWC (%) vs suction (kPa). a) Pt 01 and b) Pt 02.

Evaluating the coupling of vertical loads with G_0 and volumetric water content, it is clear that high levels of volumetric water content and high vertical coupling loads produced high values of maximum shear modulus.

The results express accordance with the content presented by the literature. The effect of the vertical loads might be compared with the increase of confining stress tested by Hoyos [11]. Here is observed that higher values of vertical loads, increases the coupling of the transducers and the soils, as such the increase of confining stress.

For unconfined tests, in comparison with Motta [8], the results present similarities for a bimodal soil-water characteristic curve. However, considering the short variation of moisture content, we did not evaluate the effect suctions that exceeded the air-entry value of the corresponding soils.

5 Final considerations

The use of bender elements is a valuable procedure as documented by the literature. However, it uses in unconfined tests and is still demanding several answers related to producing reliable data.

Different coupling energies affect the wave travel time and hence the maximum shear modulus (G_0).

Finally, it must be emphasised the massive challenge that the grounding system required. For instance, all equipment connected to the same power source must be replaced for a specific ground circuit in separate of the building regular network.

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