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ABSTRACT

The present paper describes a new triaxial apparatus which allows the measurement of low strain stiffness by means of both bender elements and resonant column test. In a previous paper Squeglia et al. (2009) described the innovative use of bender elements as receivers for the measurement of shear wave velocity. The proposed technique is synthetically described with the further development of apparatus which allow to perform resonant column test during a triaxial test. Since the apparatus has not been designed as a resonant column device, some critical points have been dealt with. Some tests have been dedicated to solve the problem of apparatus calibration, in particular it was not clear which type of restraint was introduced by some mechanical details concerning the ram for application of axial load. After calibration, some results have been presented. Tests carried out with the new apparatus have been compared with results of tests carried out with a Drnevich type resonant column apparatus showing a good agreement.

INTRODUCTION

Shear modulus (G) and damping ratio (D) of soils are fundamental parameters for seismic response analyses and dynamic soil – structure interaction. The small strain shear modulus (G0) can be inferred from in – situ measurements of the propagation velocity of shear or surface waves by means of appropriate geophysical testing. Reliable experimental methods for the in – situ assessment of the small strain damping ratio are not available in practice. On the other hand, the shear modulus (G) and damping ratio (D) can be determined in the laboratory by means of several experimental techniques: Resonant Column Tests – RCTs, Cyclic Torsional Shear Tests – CTSTs, Cyclic Triaxial Tests – CTXTs equipped with local gauges for small strain measurements, Bender Element Tests – BETs. There is a wide technical literature concerning advantages and disadvantages of each experimental technique. Table 1 summarizes the Authors perspective, based on their own experience, as far as advantages and disadvantages of each experimental technique are concerned.

As far as BETs are concerned, recently Pallara et al (2008) suggested using BEs only as receivers in order to reduce the interpretation uncertainties. Squeglia et al. (2009) implemented a drive-system, similar to that used in Resonant Column tests, in a stress-path triaxial cell. This system was used as exciting source while two BEs located at top and bottom of the specimen were used as receivers. In principle the same drive system could operate as a Resonant - Column and Torsional Shear equipment. Actually it has been used as a Resonant Column by installing an accelerometer in order to determine the resonance frequency of the specimen plus drive system.

The paper shows the new equipment and some preliminary results obtained on clayey samples (Santa Maria a Monte – Pisa). More specifically the experimental results concern:

- RCT performed on a clayey specimen isotropically consolidated at an effective consolidation pressure of 200 kPa;
- BET performed on a clayey specimen isotropically consolidated at an effective consolidation pressure of 200 kPa using both BEs as receivers with frequency of excitation ranging from 2 to 15 kHz.

The results are compared with those obtained from conventional Resonant Column tests and those obtained using BE’s in a conventional way (source – receiver). The comparisons mainly concern the shear modulus.

EQUIPMENT

Figure 1 shows a scheme of the equipment. The main features of such a triaxial cell can be summarized as follow (some of the described characteristics are not relevant for the present paper):

- two local gauges for axial strain measurements having a capacity of 5 mm and a resolution of 0.0033 mm;
- a load cell is located inside the triaxial cell and crewed onto a steel frame which make unnecessary the suction cap (Kvasnicka et al. 2007). The load cell has a capacity of 5 kN and a resolution of 0.01 kN;
- maximum cell pressure of 1 MPa controlled by means of a servo - valve with a resolution of 5 kPa;
- maximum back pressure of 1 MPa controlled by means of a servo – valve with a resolution of 5 kPa;
- maximum vertical load of 5 kN controlled by means of a servo - valve with a resolution of 0.01 kPa. The vertical load is applied to the specimen bottom by means of a piston/bellofram system;
- the steel frame supporting the load cell is rigidly screwed to the top platen;
- the cell is screwed at the base to a rigid steel plate which mass is 25 kg. The passive end mass is in the end more than 100 times the specimen mass;
- the electro – magnetic drive system consists of two parts: a magnet fixed onto the loading ram and counterbalanced for axial rotation, and two coils resting on a support clamped onto the lower part of the cell. The support can be easily re – positioned in the vertical direction in order to be centred with respect to the magnet.
- a piezoceramic accelerometer has been located onto the loading ram by means of a rigid cantilever;
- application of effective stresses and stress path are controlled by a dedicated computer
- application of torque and acquisition of data from BEs have been carried out by means of a high rate sampling device supplied by National Instruments and controlled by means of a software written by Authors

The drive – system operates with current control and has the following characteristics: maximum current 4.8 A, maximum voltage 30 V and frequency range 0 – 15 kHz. When the coils are excited by means of an AC current the loading ram performs cyclic rotations of small amplitude. Both bellofram and ball-bearing dissipate energy. It is therefore not possible to obtain reliable measurements of the specimen damping ratio because the system damping is too high and difficult to be calibrated.

The Bender Elements, series – type with grounding, are located at the centre of specimen pedestal and top – cap, as usual. For the specific application described in this paper, it should be better to have the BE located far from the centre, anyway the BE have been installed before developing the new measuring system and their position has not yet been changed. Furthermore the present location allows traditional use of BE, which is essential for the comparison presented in the paper.

Table 1. Main advantages and disadvantages of various experimental methods (Authors perspective)

Experimental Technique	Advantages	Disadvantages
RCT (*)	Quite easy, repetitive and consistent results	Variable frequency during the test, the test - frequency interval depends on soil properties. No direct measurement of stress-strain curves
CTST	Possible to investigate effects of frequency (strain rate) and number of loading cycles	Very complex equipments available only in few research laboratories
CTXT	Possible to investigate effects of frequency (strain rate) and number of loading cycles	Very complex equipments available only in few research laboratories. Typical stress-paths are different than those occurring during earthquakes
BET (**)	Simple and quite cheap equipment, easy to be used (at least apparently)	Only the small strain stiffness can be obtained. Test interpretation may be questionable especially in stiff and coarse soils.

(*) The experimentally determined resonant frequency enables one to determine the “average” propagation velocity of body waves (mainly shear waves);
(**) Under some circumstances, the experimentally determined shear wave velocity may represent that travelling along stiffer chains

Two different types of calibration have been carried out in order to determine the apparent inertia of the drive system. In both calibrations, the system has been considered as a SDOF. In one case it has been assumed that the specimen is fixed (at the top) and free of rotating at the bottom. In the other case it has been assumed a specimen partially free of rotating at the bottom. The calibrations were carried out considering different cell pressures and shear strain levels.

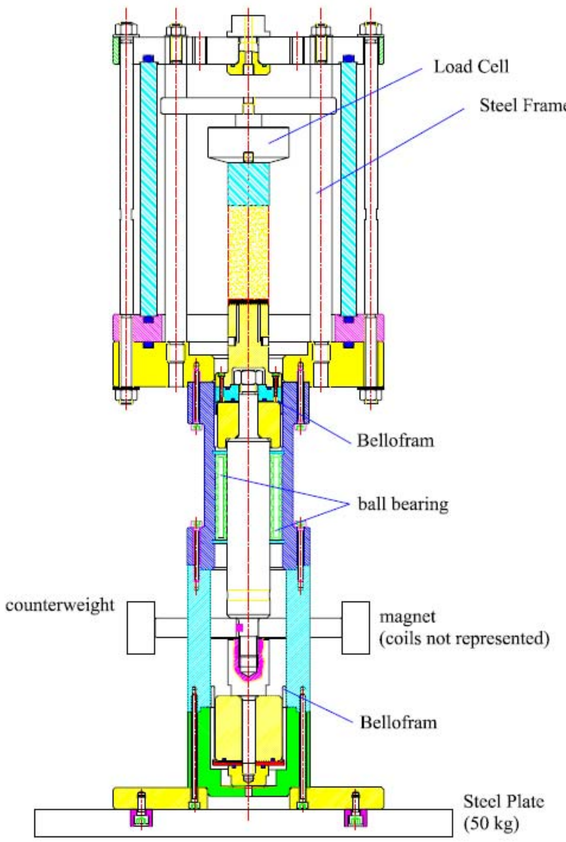

Fig. 1. Scheme of equipment and main features.

Anyway, the calibration results were quite random, for the fixed – partially free SDOF. Therefore it was not possible to achieve a meaningful interpretation in this case and, consequently only the calibration (fixed – free SDOF) was used. For this calibration an aluminum rod (l = 76 mm; d = 9 mm) was used. The rod was screwed onto the load cell and fixed at the base pedestal.

Figure 2 shows the variation of the drive – system apparent inertia J_0 with the cell pressure and voltage applied to the coils. It is quite evident that the drive system inertia is mainly affected by the cell pressure. It is worthwhile to remember that an increase of the cell pressure involves the increase of the pressure acting on the loading piston (lower chamber - Figure 1). Therefore, it seems that the increase of cell pressure produces a restraint due to the Bellofram less relevant.

Detailed information about the triaxial equipment can be found in Megaris (2009).

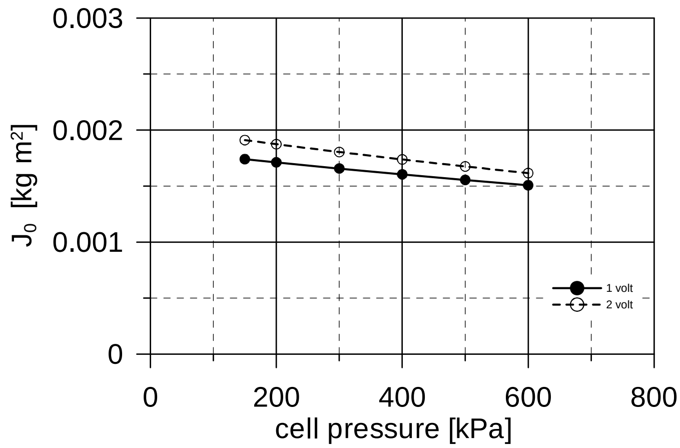

Fig. 2. Calibration of J_0.

EXPERIMENTAL RESULTS

Tests were performed on three different specimens obtained from two samples retrieved at Santa Maria a Monte (Pisa) from a depth of about 12 and 26 m. Tested soil is classified as CL – ML. The following tests have been carried out:

- two RCTs (using a RC apparatus – Drnevich type) on specimens isotropically reconsolidated at 200 kPa (samples retrieved from 12 and 26 m depths);
- BET (using the new equipment) carried out using both BEs as receivers (RR) and in the conventional way, i.e. source – receiver (SR). Exciting frequencies ranged (with a step of 0.5 kHz) from 2 to 15 kHz. The specimen has been isotropically consolidated in the triaxial cell using at 200 kPa (sample retrieved from 12 m depth);
- RCT (using the new equipment). The specimen has been isotropically consolidated at 200 kPa in the triaxial cell (sample retrieved from 27 m depth).

Figure 3a and 3b show the BET's results concerning the sample retrieved from 12 m depth. More specifically the G_0 values are plotted as function of the exciting frequency. Figure 3a refers to the conventional way of performing BET (i.e. using a BE as source and the other as receiver, SR). Three different types of interpretation have been carried out: 1) considering first arrival (FA), 2) considering the time delay between the first peaks (PP) and 3) through cross – correlation (CC). Figure 3b refers to the innovative proposed method (i.e. using the drive – system as exciter and both BEs as receivers – RR). In this case data have been interpreted considering the time delay between first peaks (PP) and the cross – correlation (CC). In addition to results deduced from BETs, Figures 3a and 3b also show the G_0 value obtained from the RCT carried out in the RC equipment (Drnevich – type) on a specimen from the same sample isotropically consolidated at 200 kPa (12 m depth). The advantages of RR method in minimising interpretation uncertainties are quite evident, both for interpretation and dependence from frequency.

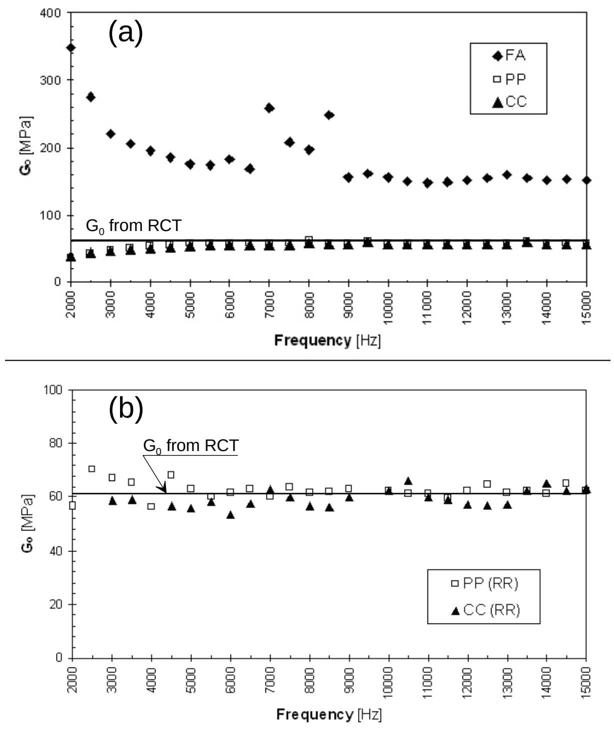

Fig. 3. Measured values of G_0: a) bender elements as source and receiver; b) both bender elements as receiver.

Figures 4 show the response curves in terms of accelerometer output with frequency as obtained using the new equipment for different excitation voltages. In figure 4a the response curves refer to the calibration rod, whereas in figure 4b they refer to the soil specimen.

Figure 5 shows the G-g curve obtained from a conventional RCT (Drnevich – type equipment) on specimen isotropically consolidated at 200 kPa (26 m depth). The same figure shows, for comparison, the G-g curve obtained in the triaxial cell using the new equipment. Obviously a specimen of the same sample isotropically consolidated at 200 kPa was considered too. As for the drive system inertia, the average value corresponding to the applied cell pressure was used. As a consequence no effect of the shear strain level on the drive system inertia was considered.

The agreement is quite satisfactory and encouraging for the continuation of developing and using the new equipment.

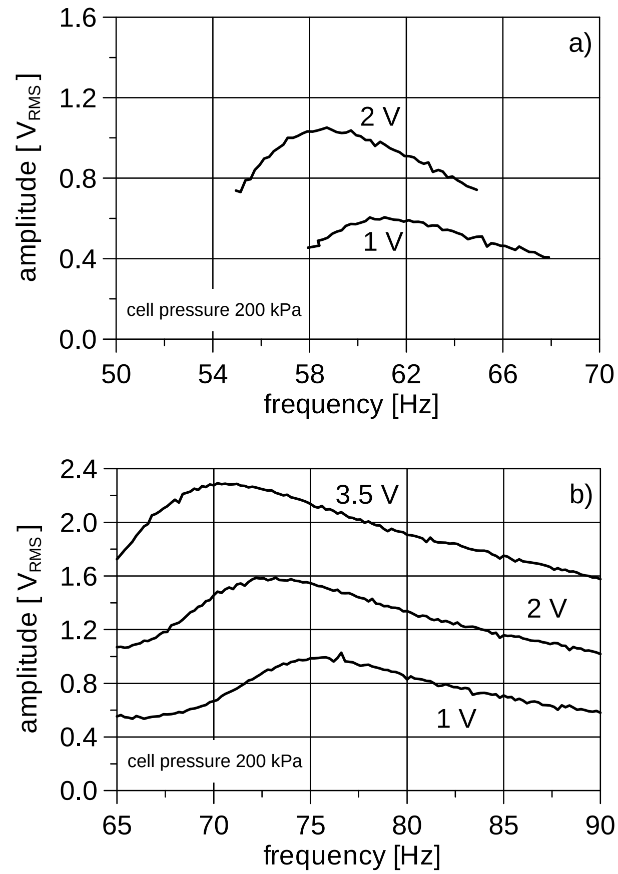

Fig. 4. Response curves in terms of accelerometer output with frequency: a) aluminum rod; b) soil specimen.

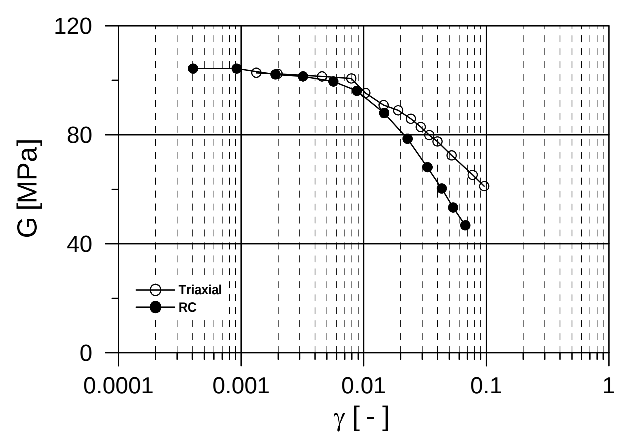

Fig. 5. Comparison between results of RCT obtained with new apparatus and conventional one.

CONCLUSIONS

The paper describes a new triaxial/RC equipment with the following characteristics: 1) possibility of applying any triaxial stress-path, 2) accurate stress and strain measurements in order to determine the soil stiffness from small strain to peak, 3) possibility of performing RCTs at any stage of a conventional triaxial test, 4) possibility of performing BETs during any stage of a conventional triaxial test using an innovative technique which reduces the interpretation uncertainties.

The new equipment offers several advantages:

1) repetitive and consistent BE measurements;
2) possibility of performing RCTs under isotropic or anisotropic consolidation stresses;
3) possibility of performing repetitive and consistent BE or RC measurements during any stage of a conventional triaxial test;
4) possibility of performing triaxial tests with continuous rotation of principal axes. This last possibility requires further developments of the equipment (i.e. use of a torque load – cell and sensors monitoring the specimen rotation.

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