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The use of seismic wave velocities in the evaluation of stiffness, damping and anisotropy of geomaterials in routine laboratory and field tests

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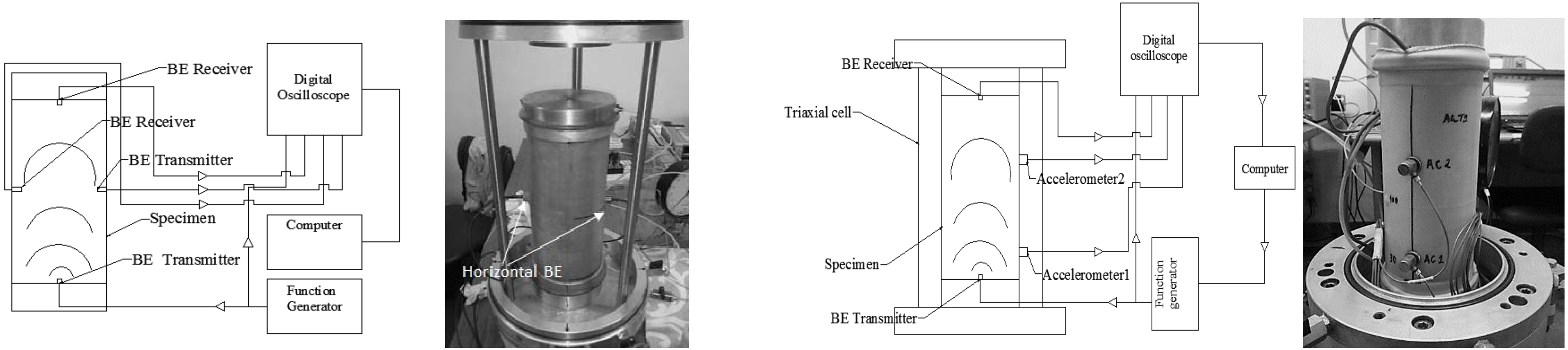
Introduction

- Anisotropy of ground materials plays an important role on geotechnical design;
- Materials anisotropy is affected by its geological characteristics, compaction method and stress conditions;
- The present study is based on the use of bender elements (BE), which allow the assessment of shear modulus in different directions;
- BE have become an increasingly common technique for direct and non-destructive measurement of P and S wave velocities;
- With these velocities, elastic stiffness parameters and other relevant features namely anisotropy, sampling quality, liquefaction evaluation, cementation, porosity and damping, can be directly computed;
- This study aims to evaluate inherent and stress-induced anisotropy of a monogranular sand by means of BE measurements in vertical and horizontal directions;
- To improve results consistency, namely in terms of scale effect and BE interpretation:
  - Tests were carried out in two different triaxial chambers with different dimensions; and,
  - Two sets of BE (vertical and horizontal) and accelerometers (AC) were used.

Materials and Methods

- Tests were performed in two distinct triaxial cells using specimens with 100mm and 150mm diameter



a) b) c) d)

Figure – a) Systematic view of the 150mm triaxial chamber system; b) Detail of the horizontal Bender Elements assemble; c) Systematic view of the 100mm triaxial chamber system; d) b) Detail of the horizontal Accelerometers assemble;

Materials and Methods

- 150mm Triaxial Cell
  - “T-Shaped” bender elements (BE): 11mm wide x 1.8mm total thickness x 2mm cantilever length;
- 100mm Triaxial Cell
  - Two bender elements from GDS Instruments;
  - Accelerometers from Bruel & Kjær (type 4513-001, 100mV/g sensitivity, ±50g measuring range, 1Hz to 10kHz frequency range, 12.7mm in diameter, 15.65mm in height, 9.0g in weight);
  - Its attachment to the specimen is possible by means of threaded head pivots; and,
  - Accelerometer1 (AC1) is placed 30mm from the specimen base and accelerometer2 (AC2) 100mm from AC1.
- Associated Electronic Equipment
  - Function generator from Thurlby Thandar Instruments (TTi TG2511); and,
  - Digital oscilloscope PicoScope model 4424, with 4 channels (1 or 2 channels at a sampling rate of 80MS/s and 3 or 4 channels at 20MS/s, with 12 bits of resolution) for data acquisition.

Figure – Overview of the test setup.

Materials and Methods

- Physical properties of the material tested.
  - D50 = 0.28mm; and,
  - Cu = 1.22.

Table – Physical properties of material tested.

	$\rho_{d\ max}$(g/cm^3)	$\rho_{d\ min}$(g/cm^3)	e_{max}	e_{min}
LEC_UM	1.589	1.397	0.882	0.655

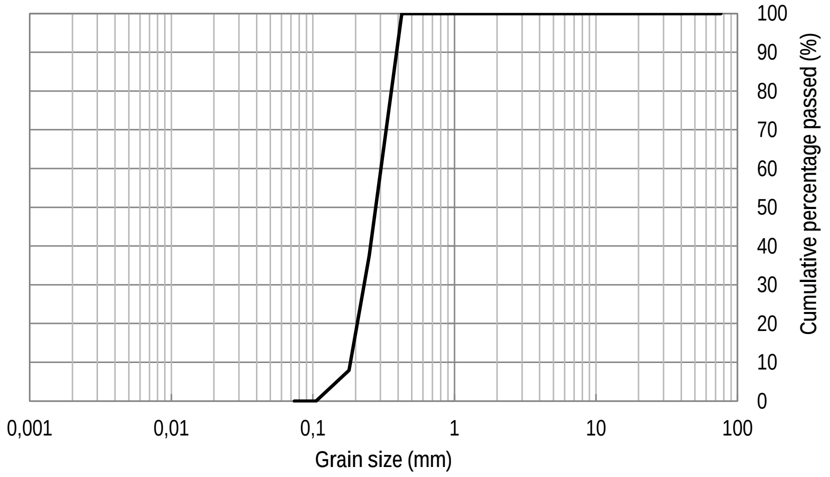


Figure – The particle size distribution obtained according the NP EN 933-1 200.

- The travel time (tt) determination was conducted using time domain methods of signal analyses namely, first direct arrival (t0).

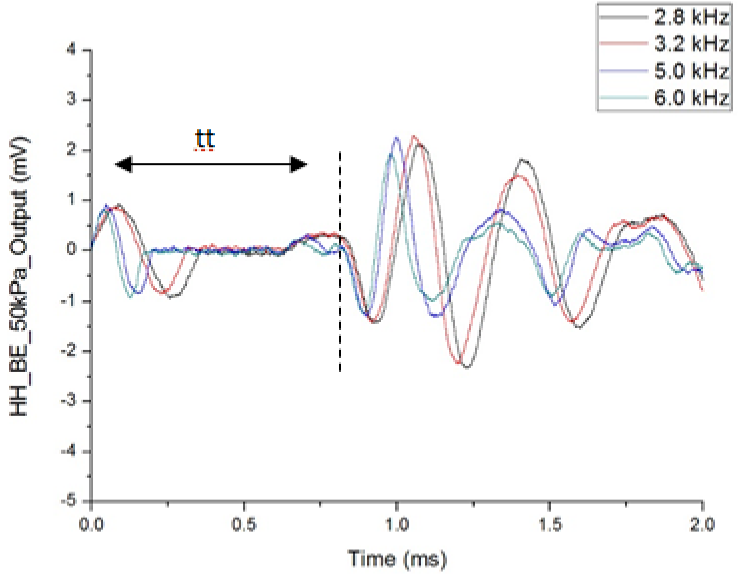


Figure - Example of travel time (tt) determination: First arrival for horizontal Bender Elements for 50 kPa of isotropic effective stress.

Shear Waves Velocity

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

Shear Modulus

$$G = \rho \times Vs^2$$

Anisotropy Factor

$$a = \frac{G_h}{G_v}$$

Materials and Methods

- Specimens were assembled by the pluviation method;
- In order to assess the inherent and stress-induced anisotropy, a specimen was tested at 3 different stages:
  - Stage 1 - The specimen was submitted to different levels of isotropic stress conditions, with horizontal and vertical BE measurements, for the assessment of the inherent/fabric anisotropy of the sand;
  - Stage 2 - The specimen was submitted to an anisotropic stress state with an effective stress ratio (K=sh/sv) of 0.5 and BE measurements were performed in order to evaluate the anisotropy of the sand under anisotropic stress conditions; and,
  - Stage 3 - The specimen was once again tested under isotropic conditions for the evaluation of the stress-induced anisotropy of the sand.

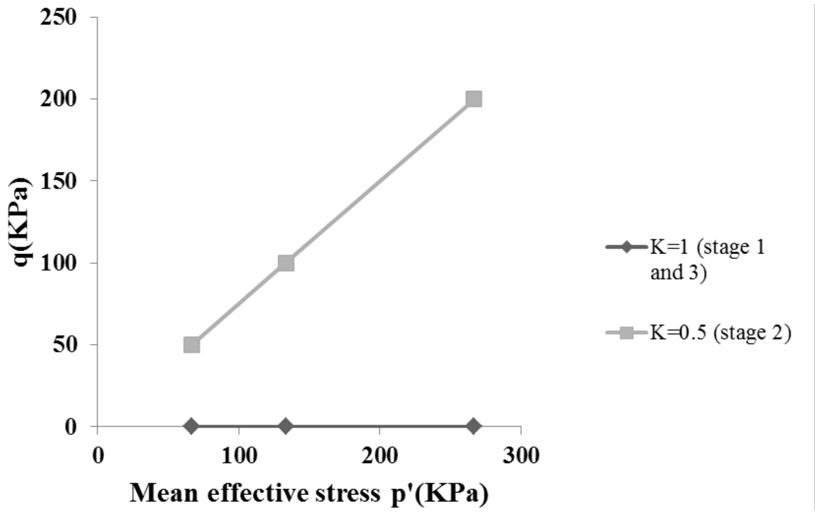


Figure – Stress path for the first specimen.

Materials and Methods

- A secound specimen was assembled in the150mm triaxial chamber through the pluviation method and test sequence followed next steps (numbers represent the order by which the test was carried out):
  - The specimen was submitted to an anisotropic stress level with the BE measurements (points 1,4,7);
  - Unloaded the deviatoric stress (q) for the assessment of the correspondent induced anisotropy (points 2,5,8); and,
  - Return to the previous anisotropic stress level and increase the mean effective stress (anisotropically) to repeat the process (points 3,6).

- The main purpose of this part of the experiment was to evaluate the stress-induced anisotropy at each stress state with cycles of loading and unloading.

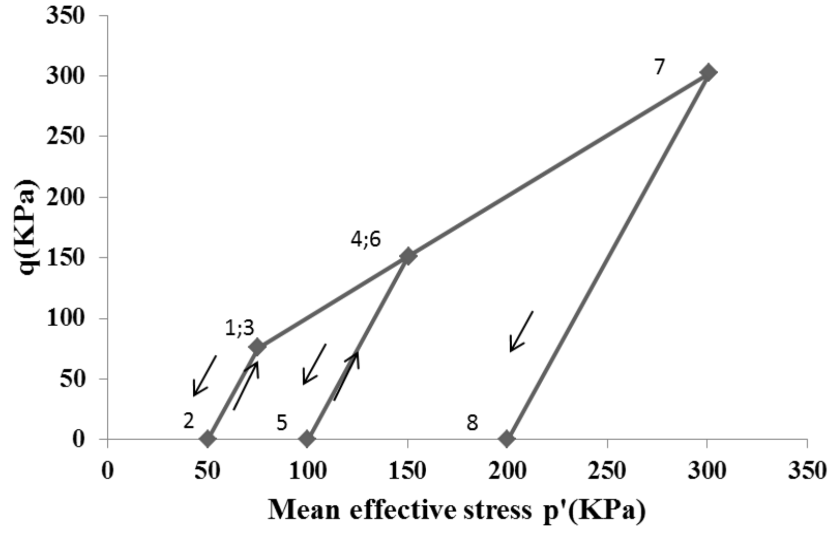


Figure – Stress path for the secound specimen.

Results

- Horizontal shear moduli (Gh) is significantly higher than the vertical shear moduli (Gv);
- Low variation of the anisotropy with the mean stress, raging 1.25-1.27;
- Results similar to those obtained under isotropic stress conditions by Amat (2007) in the Hostun sand and by Kuwano et al. (1999) with the Toyura sand, observing a Gh/Gv of 1.2;
- According to Fioravante (2000), the higher values associated with the Gh when compared to Gv may be caused by the pluviation technique, which results in a slightly oriented structure.

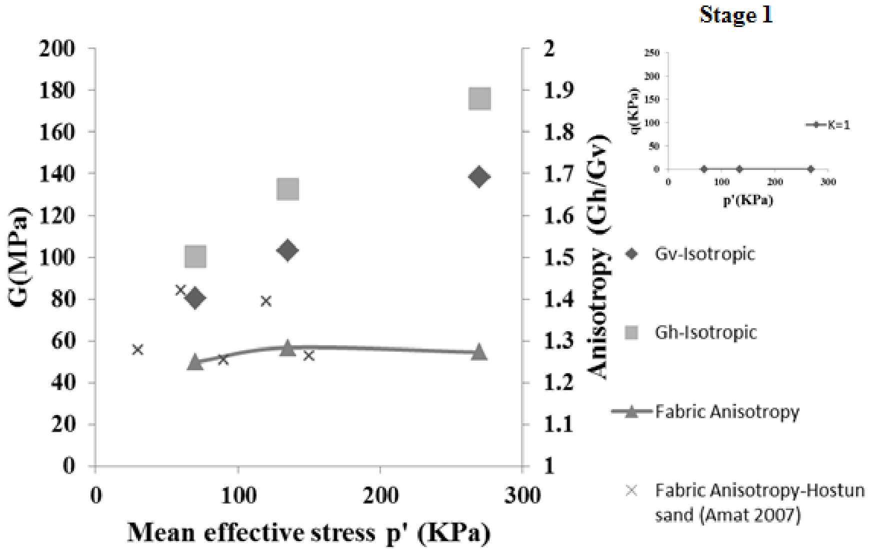


Figure – Shear modulus of the sand under isotropic conditions and fabric anisotropy.

Results

- Anisotropic stress conditions (stage 2) have a significant influence on the sand shear modulus;
- Its possible to observe a reduction of the Gh and an increase of the Gv for the same mean effective stress;
- Anisotropy presented a stress-induced modification, in the range of 1.04-1.06, which are similar to the results obtained by Kuwano et al. (1999) with the Toyura sand (Gh/Gv=1.02), although relatively higher than those obtained by Belloti et al. (1996) with the Tiscino sand ;
- This difference may be partially explained by the differences in the fabric anisotropy, which influences results in a slightly oriented structure.

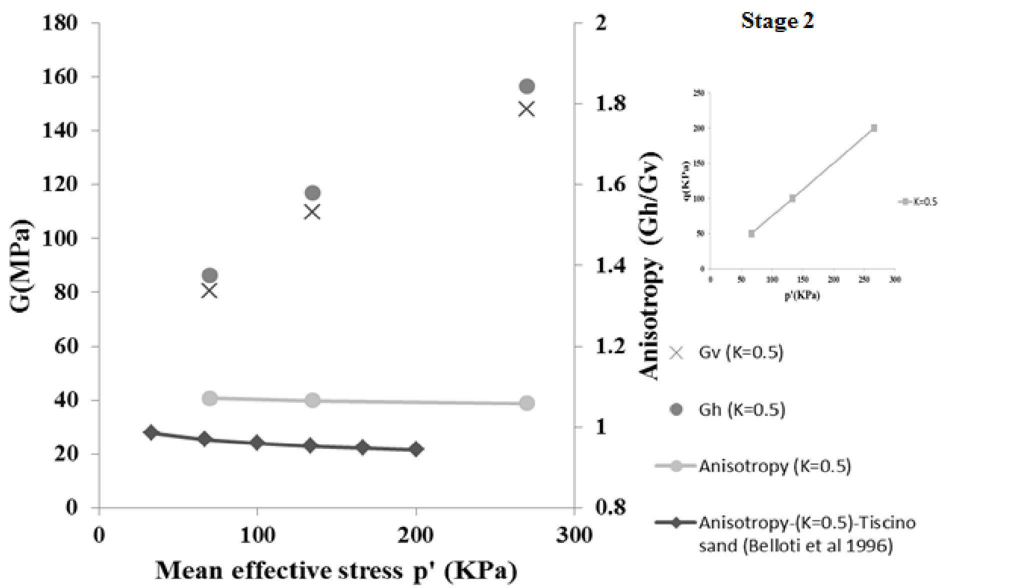


Figure – Shear modulus of the sand under anisotropic conditions and induced anisotropy.

Results

- Anisotropy variation between the 3 stages is clearly evident;
- Anisotropy results in the final stage of the experiment fall between the fabric results (stage 1) and the anisotropic stress results (stage 2);
- The specimen under isotropic conditions (stage 3) recovers some of its initial properties when compared with stage 2, but it does not reach the anisotropy levels of stage 1, due to its stress history.

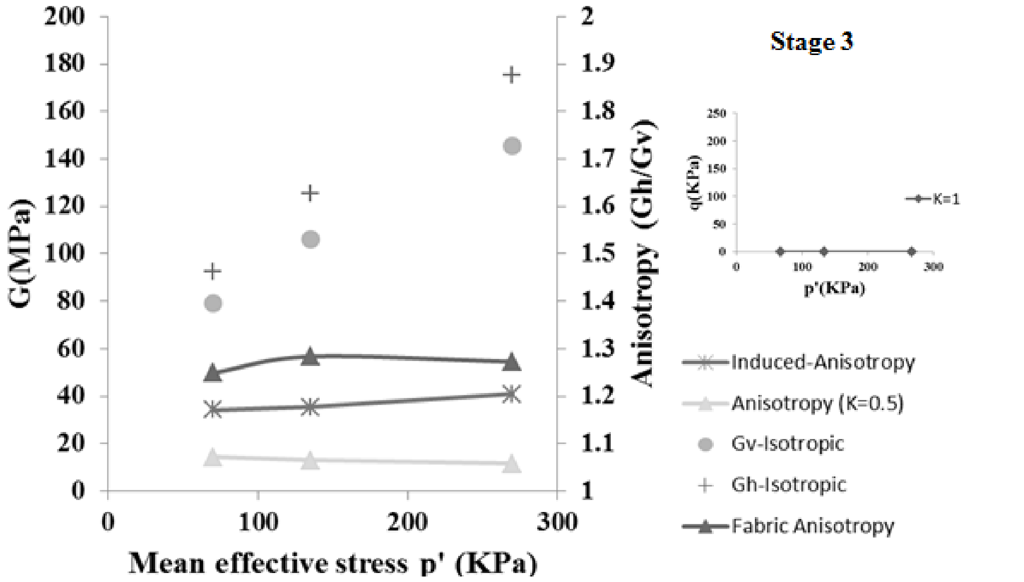


Figure – Shear modulus of the sand under isotropic conditions and comparison of anisotropies.

Results

- The K influence on the anisotropy was reported by several authors (Kuwano et al. 1999; Belloti et al. 1996; Fioravante 2000; Rampelo & Viggiani 2001);
- The results obtained with this sand present a good agreement with results from other authors, particularly in terms of observed tendency;
- Even though this work did not consider tests with stress ratios above 1, it appears that these have a much smaller impact on the anisotropy than stress ratios below 1.

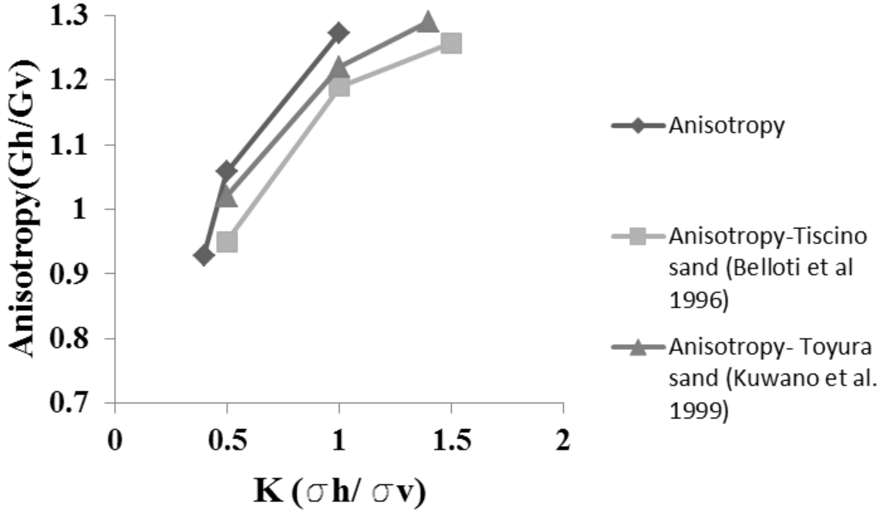


Figure – Anisotropy as function of K.

Results

- The results between chambers are very similar and the scale effect seems to be reduced;
- The tendency for higher shear modulus values in small specimens as reported by Omar & Sadrekarimi (2015) was not found;
- The results obtained in other stress conditions (in terms of comparing triaxial chambers) were similar;
- The use of accelerometers brings robustness to the comparison as it validates the obtained results.

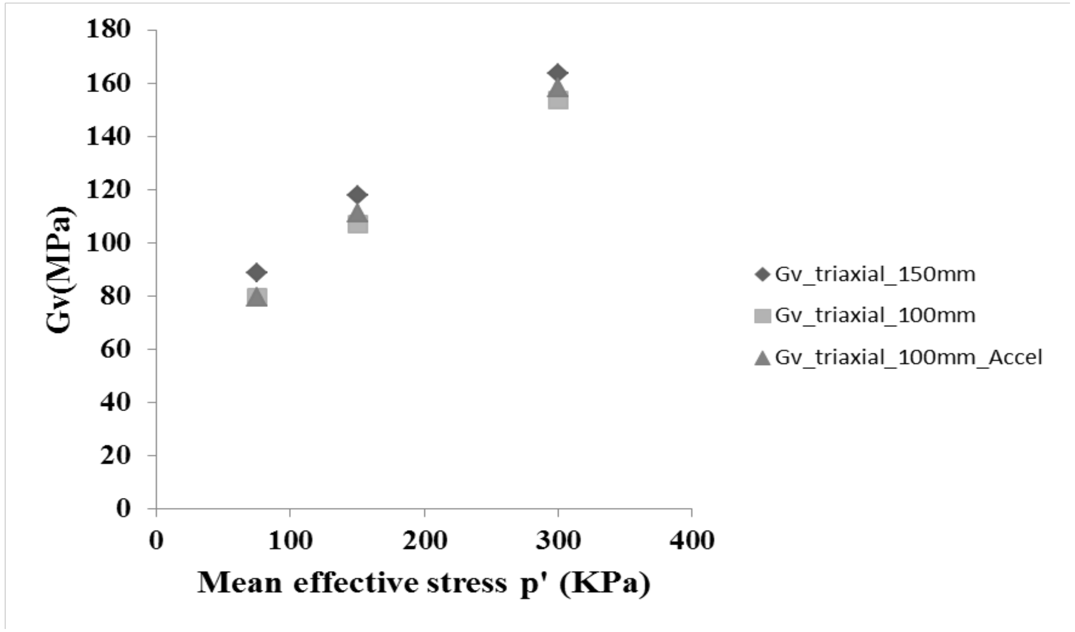


Figure – Vertical shear modulus in different triaxial chambers considering an anisotropic state with a K of 0.4.

Results

- The anisotropy of the sand is lower for lower values of K, emphasizing the importance of the sh/sv relationship on the anisotropy;
- Regarding the trends of the induced anisotropy assessed under different conditions, they seem to have different evolutions (anisotropy increases for K=0.5, and decreases for K=0.4);
- Previous point may be explained by the fact that when the induced test using K=0.5 was performed, the sand had already experienced much higher stress levels;
- In contrast, the K=0.4 experiment was made in reloading and unloading stages ;
- The path of stress level appears to influence the induced anisotropic results.

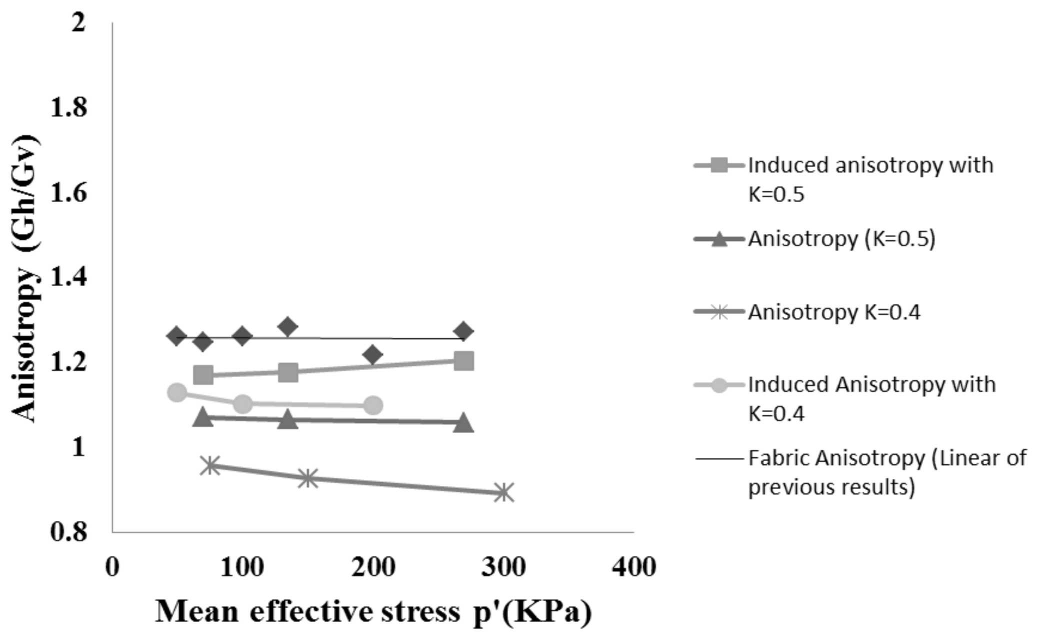


Figure – Effect of the anisotropy stress on the anisotropy of the material.

Conclusions

- The anisotropy of the material was found to be dependent of the fabric of the material (inherent anisotropy), the applied effective stress ratio (induced anisotropy) during testing and the stress paths history;
- The results obtained corroborate other previous research works, showing the predominance of the horizontal modulus over the vertical modulus, which reflects the compaction method, as well as the fabric of the sand ;
- The anisotropic stresses caused an increase of the vertical modulus of the sand over the horizontal modulus;
- After the anisotropic loading, some recovery of inherent anisotropy can be observed under isotropic stresses;
- The scale effects of the tested specimens seams to be not very relevant ;
- Test setup used combining bender elements and accelerometers present considerable reliability and precision.

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