Low-strain shear modulus dependence on water content of a natural stiff clay

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ABSTRACT: This paper shows the results of an experimental programme aimed at evaluating the low-strain shear modulus of a stiff clay (Boom clay, Belgium) and its dependency on water content changes (or, alternatively, degree of saturation or suction) and hydraulic history. Resonant column and bender element tests were carried out at different hydraulic states. Drying and wetting paths were followed using vapour equilibrium technique, in which samples were allowed to equalise in sealed chambers at controlled relative humidity (44% to 97%). Time domain technique has been used to determine the travel time in bender element tests. The evolution of the shear modulus was carefully monitored along these hydraulic paths. Shear moduli results and their dependence on water content (suction or degree of saturation) and stress/hydraulic history, are discussed and interpreted. In addition, discrepancies observed in the results between the two dynamic techniques are evaluated and discussed.

KEYWORDS: low-strain shear modulus, natural stiff clay, resonant column, bender elements.

1 INTRODUCTION

Since 1974, Belgium investigates the design for disposal of its High Level Radioactive Wastes in a deep clay formation, the 'Boom clay' (Mol, Belgium). To study this clay, an underground laboratory at 230m depth was constructed (HADES, High Activity Disposal Experimental Site). This Tertiary clay is located between 190 and 210m deep and belongs to the Lower Oligocene period. This clay is the subject of an extensive research programme dealing with all phenomena that may possibly affect the performance of this potential disposal site during gallery construction and final operation. Specifically, during excavation of the deep underground facility some de-saturation can be induced on the formation by ventilation of the gallery. In addition, the initial suction of the cementitious backfill surrounding the waste may also induce some drying on the clay formation. On the other hand, the high temperatures emitted by the wastes may also affect the behaviour of the clay formation, therefore it is necessary to examine more systematically partial saturation consequences on the hydro-mechanical response of natural Boom clay. In particular, the low-strain shear modulus is of great importance for geo-technical analysis due to the non-linear behaviour of soils. In addition to its well known dependence on strain level and confining stress, water content -or, alternatively, degree of saturation or suction- and temperature play an important role on this parameter, especially in water and heat sensitive geomaterials. Regarding these aspects, the study of the influence of wetting and drying paths on the evolution of the low-strain shear modulus is important to monitor degradation and stiffness loss due to cyclic geoenvironmental actions.

This paper shows results of an experimental programme aimed at evaluating the low-strain shear modulus of natural Boom clay and its dependency on water content changes and hydraulic history. The study was performed using two low-strain dynamic techniques, namely, resonant column equipment under torsional mode of vibration and pulse transmission / detection technique using bender elements. In addition, it presents the detailed characterisation of the stiff clay (micro-structural analysis and water retention properties). The results obtained are evaluated and discussed.

2 TESTED MATERIAL AND EXPERIMENTAL PROGRAMME

2.1 Basic characterisation and micro-structural analysis

Boom clay presents a clay fraction between 30% and 70% (average 55%). From this percentage, illite is the main mineral (50%), followed by smectite (30%), interstratification of illite-smectite and kaolinite (10%). Non-clayey fraction is composed of quartz (25%) and feldspar (Coll, 2005). Table 1 summarises the basic characterisation and the main volumetric and gravimetric properties of the natural material, which is slightly overconsolidated.

Table 1. Geotechnical properties of Boom clay.

Property	Value
Density, ρ	19.9 to 20.5 kN/m^3
Dry density, ρ_d	16.5 to 17.1 kN/m^3
Gravimetric water content, w	21 to 25 %
Initial total suction, Ψ	2 - 4 MPa
Density of soil solids, ρ_s	26.7 kN/m^3
Void ratio, e	0.560 to 0.618
Porosity, n	0.358 to 0.382
Degree of saturation, Sr	91 to 100 %
Liquid limit (SBCW), w_L	(55.7 ± 0.9) %
Plasticity index, PI	(26.9 ± 1.0) %
Permeability	3 x 10^{-12} m/s

In order to have a direct observation of the microstructure of the Boom clay an Environment Scanning Electronic Microscopy test (ESEM) was made using the Electroscan 2020 device. One sample of natural Boom was analyzed showing a more or less homogeneous and compact arrangement of clay particles with no inter-aggregate porosity as it can be observed on Figure 1.

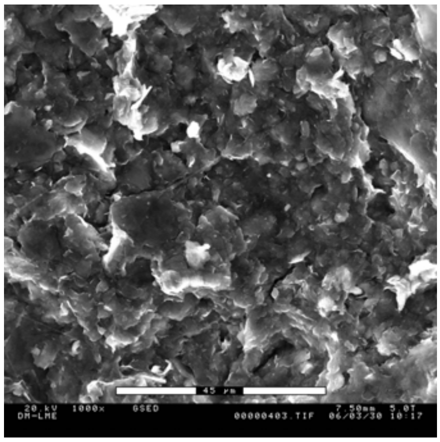

Figure 1. Photomicrograph of the Boom clay taken with a zoom of 1000x.

In order to verify this qualitative observation a Mercury Intrusion Porosimetry (MIP) test was performed on an 'AutoPore IV 9500 – Micromeritics Instrument Corp' porosimeter to quantify the porosity network of a freeze-dried sample. Figure 2 presents the pore size density function plotted against the entrance pore size. The graphic shows one dominant pore mode at 90nm, as expected for a matrix type microstructure.

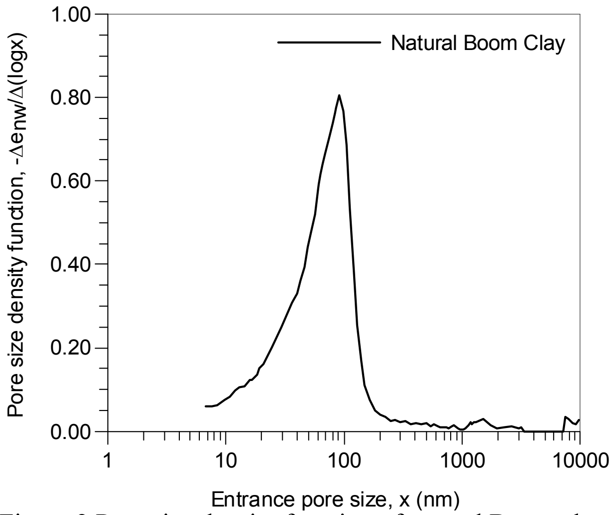

Figure 2.Pore size density function of natural Boom clay.

2.2 Water retention properties

The soil water retention curve was obtained by a chilled-mirror dew-point psychrometer (WP4, Decagon Devices, Inc, USA) under unstressed conditions. This instrument measured the temperature at which condensation first appeared (dew-point temperature) of an environment in equilibrium with a sample (37mm in diameter and 7mm height). An air drying procedure was followed to induce suction increase. The wetting path was followed by adding small water drops to the sample. With this procedure, the range of total suction studied was between 4MPa and 100MPa.

Higher suction data were obtained via vapour equilibrium technique (Delage et al, 1998; Romero, 2001). This technique is based on the control of the relative humidity inside a closed system, in which the soil is immersed. In our case, lithium chloride (LiCl) was used to apply a relative humidity of around 15%. Readings of total suction on WP4 were registered after 24 hours to ensure sample equalisation, and data corrected according to the calibration equation proposed by Cardoso et al. (2007). Figure 3 shows the drying and wetting branches of the water retention curve. A small hysteretic loop between drying and wetting paths for suction values higher than 20MPa is observed.

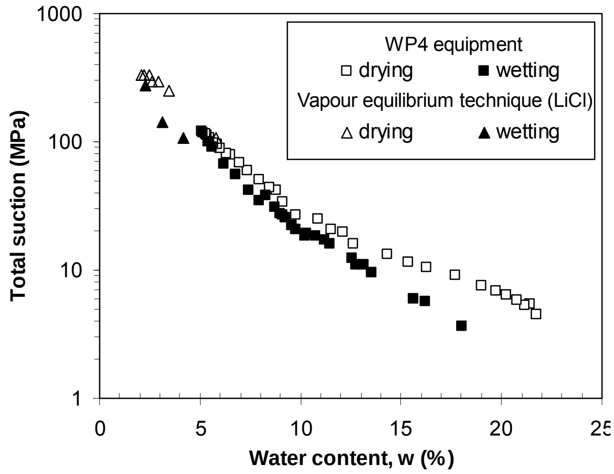

Figure 3. Water retention curve of the natural Boom clay.

2.3 Experimental programme to evaluate the shear modulus G_{max}

The influence of hydraulic paths on the shear modulus was studied by using two different techniques. Resonant column and bender element tests were carried out on samples starting at different initial states. Besides evaluating the influence of relatively small total suction changes on shear stiffness, resonant column tests also allowed studying the influence of the stress state.

On the other hand, the water content dependency on the shear modulus G_{max} along a drying / wetting cycle was studied using bender element transducers on a sample that was subjected to a previous drying process. A relatively small sample size was chosen to ensure a faster equalisation along the hydraulic paths. The hydraulic cycle was applied using vapour equilibrium technique. The procedures and results will be described hereafter.

3 G_{max} RESULTS USING RESONANT COLUMN

Resonant column tests at constant water content were performed to obtain shear moduli variation on a wide range of small shear strains ($\leq 10^{-3}$%). The influence of degree of saturation was evaluated using two different samples that were previously equilibrated at different relative humidity values (corresponding to total suctions of 4 and 10MPa). The description of the equipment is detailed in Suriol (1993).

The main properties of samples used in resonant column tests are indicated in Table 2 where the confining stress values applied were 200 and 700kPa. Size samples were 38mm in diameter and 76mm height.

Figure 4 shows the low-strain shear modulus plotted against the shear strain. Test results are also summarised in Table 2. As observed, comparable increases in the shear stiffness were obtained when increasing confining stress and total suction.

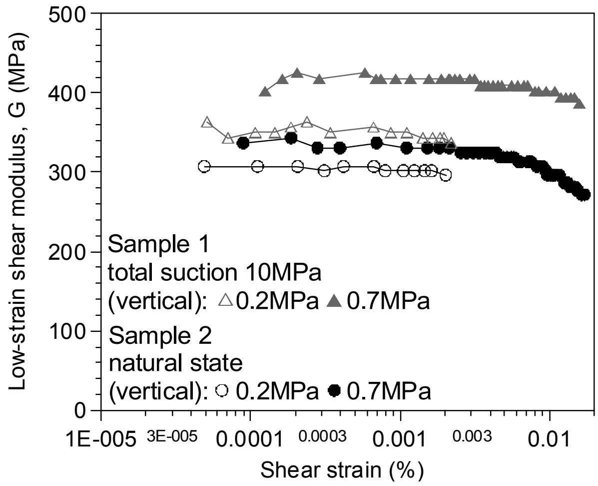

Figure 4. Variation of shear modulus G_{max} with stress level and suction changes.

Table 2. Main properties of Boom clay samples tested in resonant column tests.

Samples (nº)	ψ (MPa)	w_0 (%)	e	σ_3 (kPa)	G (MPa)
1	4 *	21.35	0.58	200	300
				700	340
2	10	15.21	0.62	200	360
				700	420

* Initial condition of Boom clay sample.

4 G_{max} RESULTS USING BENDER ELEMENTS

As described in section 2.3, sequential bender element tests were performed following a drying / wetting cycle on a sample (38mm in diameter and 28mm high) that was previously dried. This drying process originated some degradation of the sample, which ended in a slightly larger initial void ratio of e = 0.68. The starting water content was w = 19.5% (degree of saturation around 75%). An air drying process was followed at a relative humidity of the laboratory of 50% and T≈20ºC. Distilled water was used to transfer water vapour inside a desiccator and induce the progressive wetting of the sample.

Volume and mass measurements were registered during the application of the hydraulic paths in order to obtain the variation of water content, void ratio and degree of saturation. Moreover, relative humidity and temperature were monitored using a hygrometer installed inside the desiccator (refer to Figure 5).

Shear modulus G_{max} was evaluated by means of bender element transducers developed to determine the shear wave velocity of soils (Shirley & Hampton, 1978). In this technique, two polarised piezoceramic transducers (one transmitter and one receiver) are used to transmit and capture a dynamic signal which travels through the soil sample. The time delay (or travel time) between emitted and received signals is used to determine the shear wave velocity (V_s) where the travel length has been commonly taken as the tip-to-tip distance between piezoceramics (e.g., Viggiani & Atkinson, 1995; Jovicic et al, 1996). Thus, the low-strain shear modulus (G_{max}) can be obtained from the total density (ρ_t) and the shear wave velocity, Equation 1.

$$G_{max} = \rho_t V_s^2 \qquad (1)$$

In this study a pair of 'bender-extender' transducers (Lings & Greening, 2001) designed at Bristol University, UK, were used to determine the shear wave velocity of Boom clay samples. Travel time was obtained form the output signal by direct detection of the first significant deflection. To avoid masking the true travel time due to near field effects (Sanchez-Salinero et al, 1986) a sine pulse with a high frequency of 40kHz (amplitude = $20V_{pp}$) was used as input signal. By using this high input frequency (f), the wave number is observed in Equation 2.

$$R_d = \frac{l \cdot f}{V_s} \qquad (2)$$

where l is the travel distance, was higher than 1.5 as recommended by Arulnathan et al. (1998). Input signal was generated and emitted by a programmable function generator, while both input and output signals were acquired through a digital oscilloscope. Due to the good quality of the output signal further amplification was not necessary. Figure 5 shows the setup used during the application of hydraulic paths and bender element tests presented in this paper.

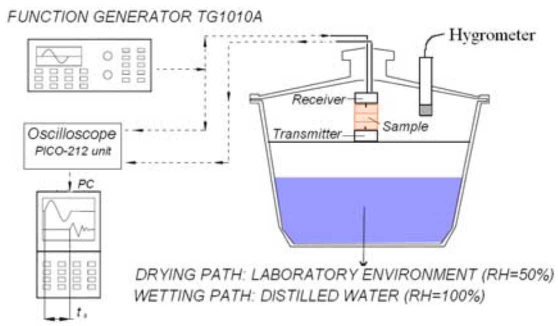

Figure 5. Setup of bender element tests. Bender element tests during the application of hydraulic paths.

Figure 6 shows the evolution of the shear wave velocity (V_s) with the gravimetric water content (w) during the application of the drying and wetting paths. As complementary information, the V_s - void ratio (e) relationship is presented in Figure 7.

The evolution of the shear wave velocity displays a hysteretic behaviour during the application of the hydraulic cycle. For the initial condition (w = 19.5%, e = 0.68) the measured shear wave velocity was equal to 326m/s. From this point on, shear wave velocity shows a quasi-linear increase as water content decreases. On the other hand, as shown in Figure 7, this increase in V_s is also associated with the decrease of void ratio observed during the shrinkage path. Once a void ratio of e = 0.55 is reached, a further increase in V_s is detected, which is only associated with the decrease in water content. It is assumed that for reductions in water content beyond 6%, in which no appreciable volume changes were detected (near the shrinkage limit), changes in V_s are a consequence of the changes in stiffness of the clay aggregations (micro-structure scale). This statement is based on the assumption the water content is held within clay aggregations at these relatively high total suction values (around 100MPa, as observed in Figure 3).

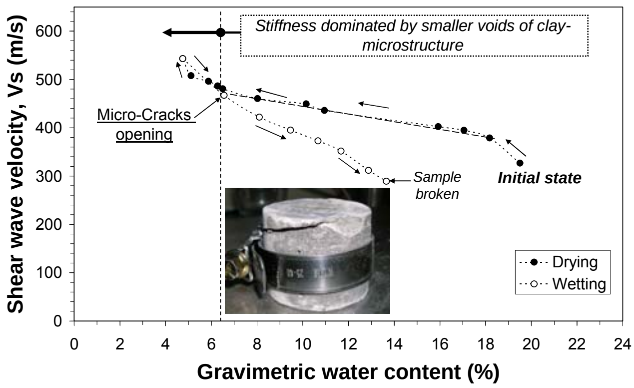

Figure 6. Variation of shear wave velocity with gravimetric water content along drying-wetting paths.

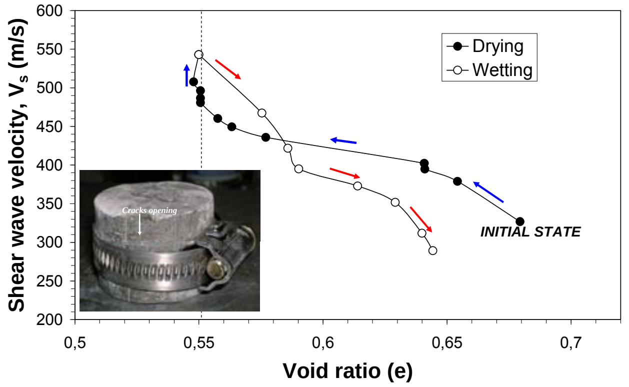

Figure 7. Variation of shear wave velocity with void ratio along drying-wetting paths.

During the first stage of the wetting path, V_s quickly reduced, as a consequence of crack opening that could be detected (see Figure 7). Subsequent wetting, led to a faster decrease of the shear wave velocity compared to the drying path. Comparison of both drying and wetting paths demonstrate clearly the hysteretic behaviour of V_s for Boom clay subjected to hydraulic effects. Crack opening also evolved on progressive wetting, leading to sample breakage during the seventh wetting step (see Figure 6). It is assumed that these microcraks could also affect the observed response, due to the fact that V_s is transmitted trough the solid structure of the material. Final values before sample breakage were V_s = 289m/s, w =13.6% and e = 0.64.

Figure 8 shows a comparison of the results using both techniques. Shear strains for resonant column were obtained directly from the torsional motion of the apparatus, while in the case of bender elements the determination of shear strain was based on the piezoceramic properties, bender size and sample size. Several authors have determined that strain applied for bender elements could be lower than 0.001% (e.g., Dyvik & Madhus, 1985). In our case, based on the ceramic properties (PZT-5B piezoceramic; Vernitron, 1992) and the dimensions of the transducer (length, width and thickness) the strain generated by the transmitter elements was about 0.001% for an input voltage of $20V_{pp}$. This value is in agreement with the upper limit suggested (e.g., Dyvik & Madhus, 1985; Sulkorat, 2007). In addition, it is also expected that deflections generated in receiver elements are always smaller due to signal attenuation through the soil sample. As shear strain in the receiver element is unknown, the strain used to compare resonant column results with bender element tests was the one obtained for the transmitter element (0.001%).

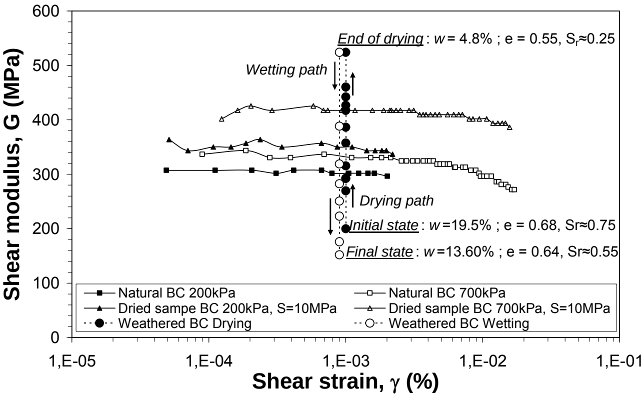

Figure 8. Comparison between shear moduli G_{max} obtained with resonant column and bender elements.

As observed in Figure 7, shear moduli Gmax show a strong dependency on water content (the initial value of 200MPa increases to a maximum of 524MPa at the end of the drying path). As previously indicated, this increase in shear stiffness was also a consequence of the void ratio decrease observed on drying. On the other hand, the degradation induced on the wetting path on the unconfined sample, led to a final shear modulus of 152MPa, considerable lower than the obtained during the drying path at equivalent water content. Shear moduli results using both techniques compare well, despite the degradation problems detected on the unconfined sample.

4 SUMMARY AND DISCUSSION

The main properties of the material used in the experimental programme (natural Boom clay) were described in detail (initial state, water retention properties and pore size distribution).

Shear stiffness results along drying and wetting paths were continuously monitored using bender elements installed inside a desiccator. The results were compared with resonant column data, in which total suction effects also induced higher shear stiffness. A quite good agreement was observed between the different techniques used, despite some degradation was detected in the unconfined sample with bender elements.

The drying results showed an important dependency of the shear stiffness with water content and void ratio. At the ultimate drying stage, the stiffness increased only as a consequence of water content changes, due to the fact that no important volume changes were detected below w = 6% (near the shrinkage limit). This response was assumed to be associated with the increase in stiffness of the clay aggregations, where water is held at elevated total suctions (around a total suction of 100MPa).

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REFERENCES

Arulnathan R., Boulanger R.W. & Riemer M.F. (1998) *Analysis of bender element tests*. ASTM Geotechnical Testing Journal, vol XXI, n 2, pp. 120-131.

Cardoso, R., Romero, E., Lima, A., Ferrari, A. (2007). *A comparative study of soil suction measurement using two different hight-range psychrometers*. Mechanics of unsaturated soils. Weimar.

Coll C. (2005) *Endommagement des Roches Argileuses et Perméabilité Induite au Voisinage d'Ouvrages Souterrains*, PhD Thesis, Université Joseph Fourier, Grenoble.

Delage, P., Le, T.-T., Tang, A.-M., Cui, Y.-J. & Li, X.-L (2007). *Suction effects in deep Boom Clay block samples*. Géotechnique 57, No. 1, 239–244.

Dyvik, R. & Madhus, C. 1985. *Lab measurement of Gmax using Bender Element*s. Proc. ASCE Annual convention.: Advances in the art of testing soils under cyclic conditions. Detroit, Michigan.

Jovicic, V., M.R. Coop, and M. Simic (1996), *Objective criteria for determining Gmax from bender element tests*, Geotechnique, 46(2), 357-362.

Lings M.L. & Greening P.D. (2001) *A novel bender/extender element for soil testing*. Technical Note Geotechnique, 51, n 8, pp. 713-717.

Romero E.E. (2001) *Controlled suction techniques*. Proc. 4º Simposio Brasileiro de Solos Nao Saturados. Gehling and Schnaid Edits. Porto Alegre, Brasil, pp. 535-542.

Sanchez-Salinero I., Roesset J.M. & Stokoe K.H. (1986)

Analytical studies of body wave propagation and attenuation. (Geotechnical Engineering Report N0. GR86-15) Civil Engineering Department, University of Texas at Austin.

Shirley D.J. & Hampton L.D. (1978) *Shear-wave measurements in laboratory sediments*. J. Acoustical Soc. Am. 63, n 2, pp. 607-613

Sukolrat J. (2007) *Structure and destructuration of Bothkennar clay*. PhD Thesis, University of Bristol, UK, 396p.

Suriol, J. (1993). *Medida de la deformabilidad de suelos mediante el equipo de columna resonante*. Revista de Obras Públicas, n 3 (319) 140, pp. 57-66, Madrid.

Vernitron (1992) *Ceramic acoustic elements in bimorph and multibimorph, for pick up cartridges, microphones paging systems and other law frequency uses*. Bulletin 66012/D.

Viggiani G. & Atkinson J.H. (1995) *Interpretation of Bender Element Tests*. Geotechnique, 45, n 1, pp. 149-154.