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Measuring the Small-Strain Stiffness Anisotropy of Glacial Clayey Tills of Southern Ontario

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Abstract. It is well accepted that the small strain stiffness (0.001% - 0.01%) of most natural soils is anisotropic to a certain degree. Hence, elastic moduli $G_h \neq G_v$ and $E_h \neq E_v$. It is also acknowledged that measuring the cross-anisotropic properties of soils is very difficult due to the complexity of determining the five independent parameters needed to describe a transversely isotropic soil. These parameters are the Poisson's ratios (μ_{vh} and μ_{hh}) and the stiffness parameters (G_{vh}, E_h, E_v). Glacial clay tills, and glacial deposits in general, have a complex formation history. Generally, they are over-consolidated, stiff, have low sensitivity, are primarily incompressible, and have relatively low moisture content. Very little investigation of the small strain anisotropy of Canadian glacial clay soils has been conducted. This paper reports on a study of a series of tests conducted using a resonant column device and orthogonal Bender element pairs to examine the degrees of anisotropy of five different natural deposits located in Canada. Comparisons have been made wit the results of other studies on stiff overconsolidated clays found in the literature.

Keywords. Anisotropy, small-strain, stiffness, clay, glacial, till.

1. Introduction

Glacial clay tills, and glacial deposits in general, have a complex formation history. Generally, they are over-consolidated, stiff, have low sensitivity, are primarily incompressible, and have relatively low moisture content [1]. They are highly variable and often cannot be characterized by following traditional empirical soil mechanics methods based on clay or sand. The geotechnical parameters and behaviour of glacial clay tills depend on the composition of the till (e.g. texture, density, and structure), and on their consolidation stress levels [2, 3]. The composition of the till depends on several factors, such as the materials that the glacier transported, how they were incorporated, as well as the effect of the transportation mechanism and the mode of deposition [4-6]. For clayey glacial tills, their basic engineering properties are also affected by the clay fraction.

Proper understanding of the structure and fabric of glacial tills is paramount to better understand the properties and the behaviour that they will exhibit. The fabric development of till will depend on the processes that led to its formation (e.g. transport of debris, deposition of the sediment, post-depositional history) and these will determine

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the preferred orientation of the soil particles within the till structure [4]. From different till-fabric investigations [e.g. 7] it has been found that the dominant fabric mode for tills deposited at glacier beds (e.g. basal tills, lodgment tills) tends to lie parallel to the flow direction of the ice during deposition and parallel to the direction of shearing [8]. The anisotropic fabric developed in these tills can be significant due to the highly clustered orientations associated with high bed shear strains [9]. [10] and [11] classified glacial tills into basal and ablation tills according to their deposition mechanism. [10] also added a third group of tills referred as waterlain tills, with the aim of describing a crudely stratified variety of till deposited in water, typically unsorted and originating from lacustrine sedimentation below floating ice.

The glacial deposits of the UK have been widely studied by different researchers (e.g. [12-4]). Such investigations have enabled a better understanding of their basic engineering properties such as particle size distribution, mineral content and range of Atterberg limits, and more advanced properties such as drained and undrained strength, one-dimensional consolidation behaviour, small-strain stiffness properties, and strength and stiffness anisotropy. These characteristics have been used to differentiate between glacial tills and 'till-like' materials (e.g. glaciomarine or glaciolacustrine materials). In Canada, similar efforts have been made to distinguish different types of glacial deposit, specifically tills. The work of [3, 15-17] have greatly contributed to our knowledge of the behaviour exhibited by glacial clays, from southwestern Ontario and other parts of Canada. It is recognized that many of these glacial till materials exhibit some degree of anisotropy, and any added load or change in stresses can cause the anisotropy to change [14]. These anisotropic fabrics lead to materials with directional dependence of their geotechnical properties (e.g. strength, stiffness). In the past few years, several studies have looked at the influence of fabric anisotropy on shear strength and stress-strain behaviour of a range of clays (e.g. [18, 19]). Whilst some of this work has concentrated on small-strain stiffness and anisotropy of stiff overconsolidated clays (e.g. [12, 13]) this is limited to European and Japanese soils. Much less work has been conducted on Canadian glacial clays and this study was designed to further investigate these materials.

2. Anisotropy in clayey soils

It has been noted that many soils will likely be fully anisotropic or at least cross-anisotropic due to their deposition processes and complex stress history [20]. To describe an anisotropic elastic material, 21 independent elastic constants are required [21]. If cross-anisotropy is assumed, then only 7 parameters are necessary to define the horizontal plane of isotropy [3]. These parameters are the Poisson's ratios (μ_{vh}, μ_{hv}, and μ_{hh}) and the stiffness parameters (G_{vh}, G_{hh}, E_{hh}, E_{vh}), where the subscripts h and v relate to horizontal or vertical directions in which the stiffness is measured. Due to thermodynamic energy strain considerations, the compliance matrix of an elastic material must be symmetrical [22]. These constraints reduce the number of parameters needed from 7 to 5 (μ_{hvh} and μ_{hh}, and G_{vh}, E_{hh}, E_{vh}). Elastic anisotropy can be categorized as either stress-induced or inherent. Stress-induced anisotropy is caused by strain or stress changes after material deposition, particularly those resulting from post-depositional application of different effective stresses in the vertical and horizontal directions. Inherent anisotropy is intrinsically related to the grain characteristics and depositional processes of the material. [3] proposed a simplified version of the cross-anisotropic model, that consisted of only three independent parameters instead of the usual five. The three parameters are defined in Eq. (1) to (3) (anisotropy factor α, modified Poisson's ratio μ^*, and modified elastic modulus E^*):

$$\alpha = \sqrt{E_h/E_v} = G_{hh}/G_{vh} \tag{1}$$

$$\mu^* = \mu_{hh} \tag{2}$$

$$E^* = E_v \tag{3}$$

3. Methodology

3.1. Materials

Six different clay soils were used for this study. Five of these soils were naturally deposited in a glacial environment, and the sixth material was created under controlled laboratory conditions. Four of the glacial materials, belong to areas located in southwestern of Ontario, specifically from Port Alma, Windsor, Wallaceburg and Blenheim; whereas the remaining material was retrieved from a site near Winnipeg, Manitoba. The sixth material is a manufactured clay called Edgar plastic kaolin 'EPK' clay. Table 1 presents a summary of the geotechnical properties of the studied materials.

Table 1. Summary of critical state parameters and properties of the different materials tested.

	Port Alma	*Windsor*	*Blenheim*	*Wallaceburg*	*EPK kaolin*	*Winnipeg*
I_p (%)	13.00	30.30	6.40	24.60	25.40	33.00
M (CSL)	1.14	1.00	1.28	1.40	1.21	0.793*
ϕ' (°)	28.62	25.41	31.90	34.67	30.33	20.50*
λ (NCL)	0.041	0.174	0.062	0.175	0.162	0.159
k (URL)	0.011	0.049	0.018	0.031	0.043	0.060
N	0.646	1.646	0.743	1.620	1.802	1.766
Λ	0.732	0.718	0.714	0.821	0.735	0.621
Γ	0.625	1.559	0.712	1.520	1.720	1.697
CF (%) (<2μm)	31.0	70.0**	25.0	46.0**	68.0	71.0
Activity (I_p/CF)	0.419	0.433	0.256	0.535	0.373	0.465

CF: clay fraction; *[3]; **[17]

Figure 1 shows the Casagrande plasticity chart showing the range of plasticity values for glacial lake clays reported by [23] and an envelope obtained by [15] for different glacial clay soils from southern Ontario. Data published by [17] for other glacial materials from different parts of southern Ontario have also been compiled and plotted for reference. The Atterberg limits of Port Alma clay, Wallaceburg clay and Blenheim clay correspond well with the envelope reported by [15] and lie within the limits reported by [23]. Very close to the right side of the envelope lies the Windsor clay, which also sits within the upper limit established by [23] known as the "T-line". Winnipeg clay lies on top of the "A-line", farther away from the envelope of the southwestern Ontario glacial clays suggesting that the matrix of the material is mainly clay, and that the sedimentary minerals present in the soil may differ from those of the southwestern Ontario glacial soils due to the nature of its parent material. It is also noticeable that the Atterberg limit values indicate that the plasticity of the studied materials ranges from low to medium (6 < PI < 33), which correspond to typical values of plasticity index reported in the literature for different glacial clay tills and 'till-like' materials [e.g. 6, 16, 17].

Values of activity (I_p/CF) reflects the mineralogy of the clay fraction [15] and for the studied soils, the activity ranges from 0.26 to 0.54. This suggests that these materials are within the range of inactive clay soils (activity < 0.75) and are close or within the range for previously studied glacial soils (0.29 < activity < 0.49). These low values of activity indicate that the materials do not have significant amounts of active clay materials, such as vermiculite or montmorillonite. Previous studies on the sediment minerals present in different Ontario glacial clays showed the presence of carbonates, quartz, chlorite, feldspar and illite [24]. Similar findings were reported by and [25] when studying local glacial deposits around the Chicago area in the United States.

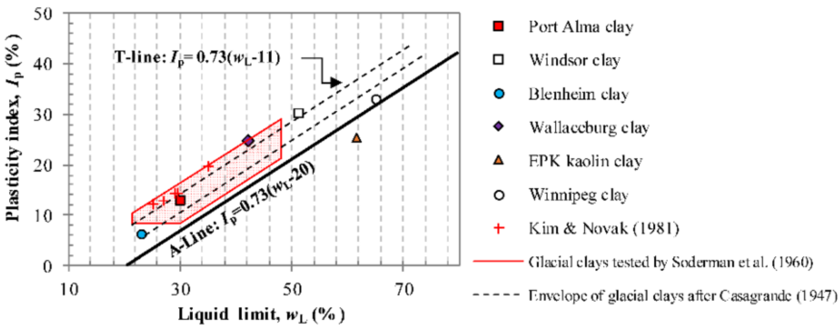

Figure 1. Relationship between plasticity index (I_p) and liquid limit (w_L) of different materials.

3.2. Laboratory testing methods

High quality Shelby and large piston samples were obtained from site investigation for the testing. The samples quality was assessed following the method proposed by [26], the samples fell within the categories of 'very good to excellent' and 'good to fair'. A combination of resonant column testing and complementary orthogonal plane bender elements were used to characterize the small-strain anisotropy and stiffness degradation behavior of the materials. The soil specimens for the resonant column (RC) testing were prepared according to ASTM D4767-11 guidelines, with a variation to the sample preparation; test specimens were trimmed from the same material at different orientations with respect to the sample in-situ vertical axis (e.g. 0° equal to vertical cut samples, 90° to horizontally cut samples). This preparation method was employed previously by [27] for anisotropy studies on natural deposited cohesive materials.

RC tests were carried out in accordance with ASTM D4015-15. The resonant column apparatus used is a Stokoe fixed-free type. A Bishop & Wesley type stress-path triaxial cell was used for the bender element testing of the isotropically consolidated specimens. To prepare soil specimens the methods outlined by ASTM D4767-11 were adopted. The three pairs of orthogonal bender element (BE) transducers were arranged as follows: one pair of BEs were placed on the top and bottom of the soil specimen (vertical direction), while the other two pairs were laterally mounted (horizontal direction) on the soil specimen. The vertical pair of BE allowed the measurement of vertically propagating and horizontally polarized wave velocities (V_{svh} and V_{pvh}). The horizontal pairs of BE allowed the measurement of horizontally propagating and vertically polarized waves velocities (V_{shv} and V_{phv}), and horizontally propagating and horizontally polarized waves velocities (V_{shh} and V_{phh}).

4. Experimental results

The modulus degradation curves from the resonant column tests for the different clays are shown in Figure 2 along with those proposed by [28] and [29]. These seems to follow accepted patterns of behaviour seen for cohesive soils, with increasing threshold shear strain values [30] and reducing degradation rates with increasing plasticity index [28]. These show the reduction of the shear modulus (normalized by G_{max}) with shear strain. The OCR also appears to have little effect on the observed results. The variations of the vertical small-strain shear modulus (G_{vh}) with pressure from both bender elements and resonant column are shown in Figure 3. The shear modulus has been normalized by $F(e) = (2.973-e)^2/(1+e)$, as recommended by [31]. Also shown are best-fit lines for stiff overconsolidated clays found by other researchers. The data from the bender elements and the resonant column are comparable, and whilst the tested materials seem to show slightly lower relationships with higher gradients, they still seem to fit within a narrow band of the other results in the literature. Similar plots of horizontal shear modulus variation with pressure have also been produced, but due to limitations of space they are not shown in this paper.

The ratio of the shear moduli in the horizontal and vertical directions (α) with pressure is shown in Figure 4. Again, this is data compared with results of small-strain stiffness anisotropy with pressure from other materials reported in the literature. Where the pressure variation data is absent, a horizontal line is used. This shows the wide range of stiffness anisotropy for these overconsolidated clay soils, which are predominantly stiffer in the horizontal direction. The slight gradients of some of the curves, suggest that the pressure induced anisotropic fabric changes may be different in the horizontal and vertical directions. The materials tested by the authors generally lie in a narrow band within $\alpha = 1.1$ to 1.3, with slightly increasing gradients with pressure. It is assumed that these materials are all cross-anisotropic (which may not necessarily be the case). They are also predominantly isotropically consolidated, which has been assumed not to have an effect on the observations of small-strain anisotropy. Following a study of the anisotropy of six Italian clays, [32] proposed the equation below to estimate the small-strain anisotropy (α):

$$\alpha = \frac{G_{hh}}{G_{vh}} = \frac{S_{hh}}{S_{vh}} {K_o}^n \tag{4}$$

where K_o is the earth pressure at rest, n is an empirical exponent and S_{hh} and S_{vh} are material fabric parameters. This relationship is plotted in Figure 5 for the data and materials shown in Figure 4. The best-fit values for the equation are n = 0.476 and $S_{hh}/S_{vv} = 1.422$, which are a little higher than those found by [32] for their materials, but the coefficient of determination (R^2) is still reasonably good. The tested Canadian clays tend to lie towards the lower end of this curve and it should be noted that all of the plotted values are for the in-situ stress state. Whilst this relationship provides a reasonable fit to the current database, the small-strain anisotropy is complex and will likely be dependent upon the clay fraction, clay structure, mineralogy, depositional origin and post-depositional environment. In addition, the majority of the clays tested are likely to be cross-anisotropic, since they are waterlain tills, true glacial clay tills may display more complex anisotropic characteristics.

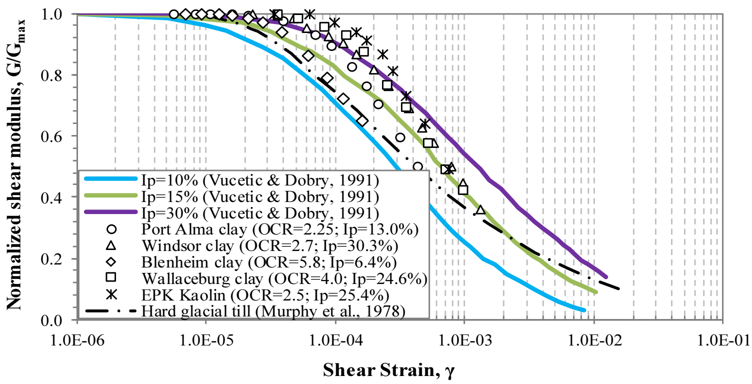

Figure 2. Normalized shear modulus degradation with increasing of strain for the materials tested.

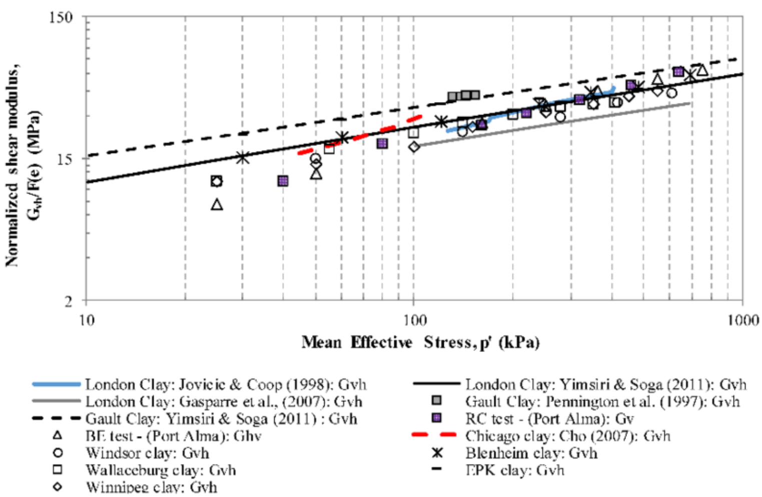

Figure 3. Comparison of obtained small-strain shear modulus in the vertical plane (G_{vh}) with published data.

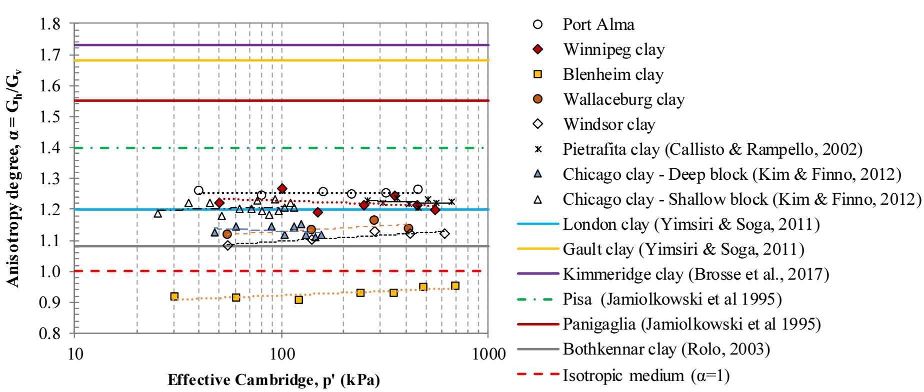

Figure 4. Comparison of obtained anisotropy degree with published data.

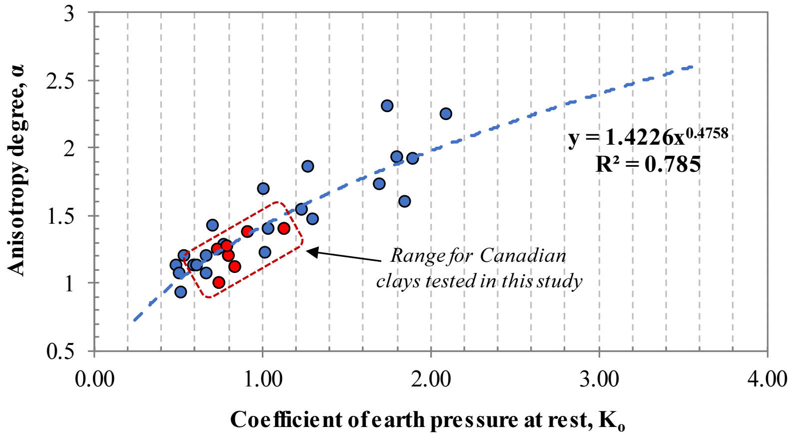

Figure 5. Relationship between anisotropy degree (α) and the coefficient of earth pressure at rest (K_o).

5. Conclusions

A study of the small-strain stiffness and anisotropy of a number of Canadian glacial clays was conducted using a combination of resonant column testing and bender elements. The results of this study have compared to the findings of other investigations of similar materials found in the literature. The major conclusions from the study are:

- The Canadian clays tested fit the general small-strain behavior displayed by other low plasticity stiff clay materials;
- These materials also show similar small-strain anisotropy to other stiff overconsolidated clays;
- For the materials tested, the pressure induced changes to the vertical and horizontal fabric and stiffness appears to be slightly different;
- The general equation proposed by [32] appears to fit the database well and provides a useful method to predict anisotropic small-strain stiffnesses;
- Further work needs to be conducted to investigate other glacial clay tills to confirm the findings of this work;
- Post-depositional effects, such as ageing may also be important for these types of materials but were not investigated in this study. High carbonate contents are found in some of the materials [17], but it is unclear whether this carbonate occurs as discrete clasts or is disseminated through the material at particle contacts.

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