Stiffness anisotropy of Boom clay

Rigidité anisotrope de l'argile de Boom

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ABSTRACT
This paper presents an investigation on the anisotropic stiffness behavior of the overconsolidated Boom clay sampled at the research site Sint-Katelijne-Waver in Belgium. Triaxial tests with multi-directional bender element technique are preformed consolidating undisturbed and reconstituted Boom clay samples under isotropic and anisotropic stress conditions (K = 2) for the purpose of investigating the stress-induced, the strain-induced and the inherent anisotropy. The stress-induced anisotropic parameters of the undisturbed Boom clay are consistent with results from six Italian clays. The inherent anisotropy resulting only from the current structure and fabric of the undisturbed soil, is significantly pronounced for the undisturbed Boom clay while results from reconstituted samples show a cross-anisotropic material.

RÉSUMÉ
Cet article présente une étude sur le comportement anisotrope de l'argile de Boom prélevée au site de recherche de Sint-Katelijne-Waver en Belgique. Des tests triaxiaux avec bender éléments multidirectionnels ont été exécutés sur des échantillons intacts d'argile de Boom et sur des échantillons reconstitués, sous conditions isotrope et anisotrope (K = 2) des contraintes. L' étude met l'accent sur l'anisotropie induite par les contraintes, l'anisotropie induite par les déformations et l'anisotropie inhérente. Les paramètres d'anisotropie induite par les contraintes de l'argile de Boom non perturbée sont cohérents avec les résultats de six autres argiles italiennes. Cette étude montre aussi qu'une anisotropie inhérente due la structure actuelle du sol non remanié, est présente alors que les résultats sur l'argile de Boom reconstituée montrent un matériau cross-anisotrope.

Keywords : anisotropy, elastic stiffness, laboratory testing, bender element, Boom clay

1 INTRODUCTION

The initial shear modulus, G_0, is widely considered to be a fundamental soil stiffness property and is a parameter for geotechnical studies, both in earthquake engineering and in the prediction of dynamic soil-structure interactions. The initial shear modulus can be measured in the triaxial test with bender element technique. This paper presents a possibility to evaluate the initial shear moduli, $G_{0(ij)}$, of Boom clay material at very small strains by measuring G_{vh}, G_{hh} and G_{hv} on the same sample at any stress state with independent control of the vertical and the horizontal stresses. Hardin & Blandford (1989) presented the possibility of expressing the dependence of the initial shear modulus, $G_{0(ij)}$, on the current state of a clay through the relationship:

$$G_{0(ij)} = S_{ij} \cdot F(e) \cdot (OCR)^k \cdot p_a^{(1-ni-nj)} \cdot (\sigma_i')^{ni} \cdot (\sigma_j')^{nj} \quad (1)$$

where S_{ij} is a non-dimensional material constant of a given soil reflecting also its fabric; F(e) is a void ratio function; OCR is the overconsolidation ratio; k is an empirical exponent depending on the plasticity index of the clay; p_a is the atmospheric pressure (100 kPa); ni and nj are empirical exponents and σ'_i and σ'_j are the effective principal stresses acting on the plane in which G_0 is measured. In the case of seismic body waves the i and j directions correspond to propagation and particle motion direction respectively.

Jamiolkowski et al. (1995) evaluated the constants for a number of clays and found that k=0. Therefore OCR is not an independent variable and does not influence the magnitude of the initial shear modulus, $G_{0(ij)}$. The multi-directional shear moduli G_{vh}, G_{hh} and G_{hv} of clay soils at very small strains are thus expressed as

$$G_{vh} = S_{vh} \cdot e^{-x} \cdot p_a^{(1-nv-nh)} \cdot (\sigma_v')^{nv} \cdot (\sigma_h')^{nh} \quad (2)$$

$$G_{hh} = S_{hh} \cdot e^{-x} \cdot p_a^{(1-2nh)} \cdot (\sigma_h')^{nh} \cdot (\sigma_h')^{nh} \quad (3)$$

$$G_{hv} = S_{hv} \cdot e^{-x} \cdot p_a^{(1-nh-nv)} \cdot (\sigma_h')^{nh} \cdot (\sigma_v')^{nv} \quad (4)$$

Jovicic (1998) clearly described the terminology of anisotropy as follows:

- *Stress-induced anisotropy* results only from the current stress condition and is independent of the stress and strain history of the soil.
- *Inherent anisotropy* results from the current structure and fabric of the soil. For clays, the inherent anisotropy might be expected to be related to the plastic strain history the soil has been undergone but it also includes the development of structure. Inherent anisotropy will be used to describe the anisotropy of natural clays for their in-situ state.
- *Strain-induced anisotropy* describes the non stress-induced anisotropy of reconstituted samples where the influence of diagenetic processes related to the passage of geological time is small. As reconstituted samples are recreated from a slurry and have not enough time to create any modified bonding, the structure may be expected to be predominantly related to the one-dimensional strain history rather than the mode of deposition. This is contrary to sand where inherent anisotropy may result predominantly from the fabric resulting from the depositional process.

2 EXPERIMENTAL SETUP

2.1 *Boom clay*

The geological condition at the research site consists of Boom clay to a large depth. The Boom clay belongs to the Oligocene series (Rupelien stage). At the beginning of the continental Pleistocene erosion, the Boom clay was covered by about 40 m of Neocene sand (Antwerpian). This load has acted on the Boom clay for 5-7 million years, while the unloading due to the Pleistocene erosion started about 500,000 years ago. According to the geological data the Boom clay should never have been subjected to larger loads than those corresponding to the 40 m of Neocene sand. In its upper part the Boom clay exhibits horizontal layering and has a medium to high degree of fissuring. Many of the fissures have a slickensided appearance. Therefore the Boom clay in its upper part has to be described as a "stiff, fissured, layered overconsolidated clay".

For laboratory testing, Boom clay is sampled from the research site. The details of the in situ testing are reported in Mengé (2001). Two samples are taken from the depth of 5.0m (sample A) and 8.0m (sample B) respectively. Table 1 shows the index properties of these samples.

Table 1. Index parameters of Boom clay.

Parameters	unit	A	B
w_{LL}	(%)	65.38	57.51
w_{PL}	(%)	22.23	21.02
I_p	(%)	43.15	36.49
G_s	(-)	2.71	2.70
w	(%)	29.42	28.25
ρ	(kg/m³)	2030	2042

where w_{LL} is the liquid limit, w_{PL} is the plastic limit, I_p is the plastic index, G_s is the specific gravity, w is the water content and ρ is the mass density.

Reconstituted Boom clay samples are prepared with the same water content and void ratio as the in-situ samples using the techniques presented in Pennington (1999).

2.2 *Multi-directional bender element technique in triaxial testing*

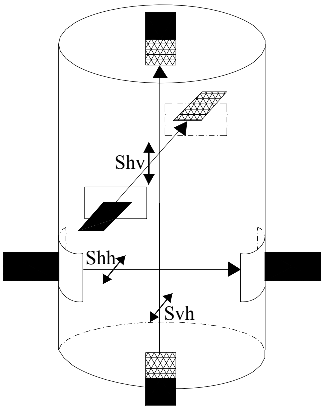

Figure 1. The multi-directional bender element test.

This technique uses piezoceramic transducers for a direct measurement of shear wave velocity. The shear wave is generated and received by transducers placed at opposite sides of the soil sample. The propagation velocity is calculated from the distance between the two transducers and the time required by the wave to cover this distance. This research adopts a multi-directional bender element technique as presented in Fioravante & Capoferri (2001). This technique can generate shear waves in both vertical and horizontal directions. Figure 1 presents the polarised shear waves transmitted by the multi-directional bender elements evaluating $V_{s(vh)}$, $V_{s(hh)}$ and $V_{s(hv)}$ in the triaxial test set-up.

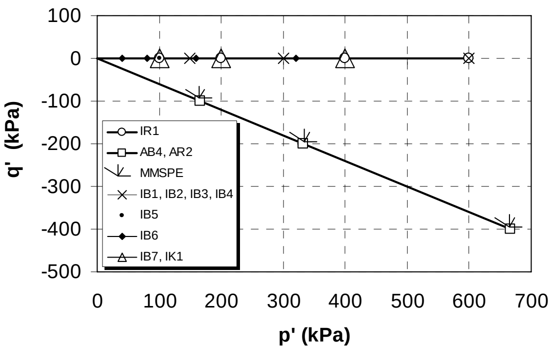

Figure 2. Stress paths in the triaxial tests.

Several tests IBx were performed on the undisturbed samples A and B, consolidating this samples under isotropic conditions. In a similar way, tests ABx were performed on the undisturbed sample B, consolidating the sample under anisotropic stress conditions (K=2). Similar to these tests on the undisturbed samples, tests IRx and ARx were preformed on the reconstituted samples under isotropic and anisotropic stress conditions respectively. Figure 2 summarises the stress paths followed in these tests.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 *Void ratio function*

Piriyakul & Haegeman (2007) found a void ratio function of the Belgian Boom clay, $F(e)=e^{-x}$, with a value of x=1.21. Therefore the analyses of the stress-induced, inherent and strain-induced anisotropy for undisturbed and reconstituted Boom clay throughout this research take into account this x value.

3.2 *Tests on undisturbed Boom clay material*

3.2.1 *Stress-induced anisotropy*

The stress-induced anisotropy results only from the current stress condition and is independent of the stress and strain history of the soil. This effect of the stress-induced anisotropy is shown in the values of nv and nh as seen from Equation 1. The undisturbed Boom clay test data of IB1, IB2, IB4, IB7 and AB4 are divided into two groups, the initial load data and the unload-reload data, in order to investigate the effect of overconsolidation. Figure 3 shows the results on undisturbed Boom clay at initial load conditions and depicts a value of nv of 0.28 and a value of nh of 0.17. Since the value of nv is higher than the value of nh, the Boom clay has a higher stress-induced stiffness in the vertical direction than in horizontal direction. In a similar way, Figure 4 presents the results on undisturbed Boom clay at unload-reload conditions and shows a value of nv of 0.21 and a value of nh of 0.14. The stress-induced anisotropic parameters of both groups are almost similar due to the fact that Boom clay still behaves as an overconsolidated material even at initial load conditions in the tests. These stress-induced anisotropic parameters of the Boom clay are consistent with results from other clays. Table 2 summarizes the properties from six Italian clays as reported in Jamiolkowski et al. (1995) .

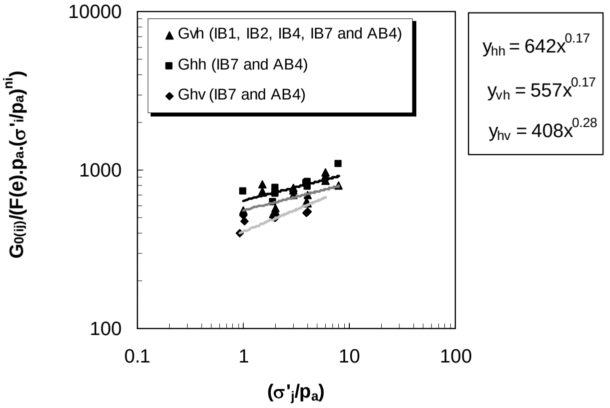

Figure 3. Normalized shear moduli of undisturbed Boom clay at initial loading.

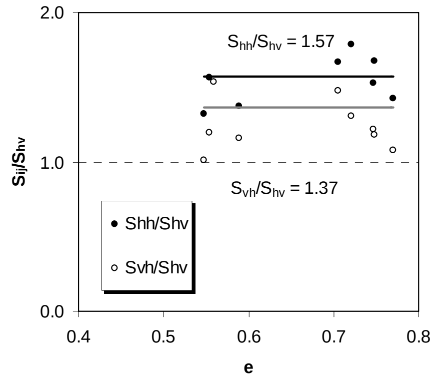

Figure 5. S_{ij} normalised by S_{hv} versus void ratio at initial loading.

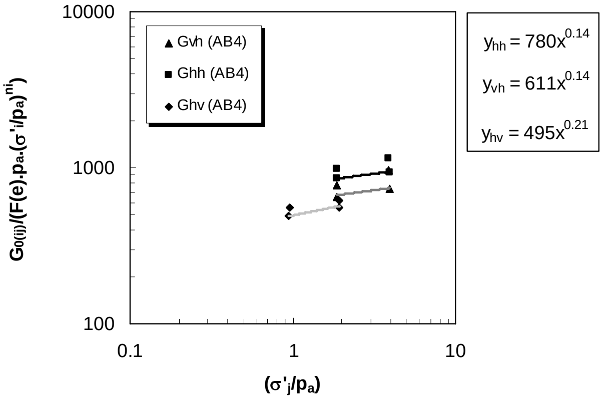

Figure 4. Normalized shear moduli of undisturbed Boom clay for unload-reload data.

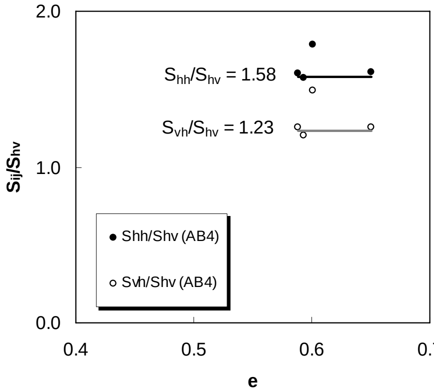

Figure 6. S_{ij} normalised by S_{hv} versus void ratio for unload-reload data.

Table 2. Parameters of six Italian clays after Jamiolkowski et al. (1995).

Clay Soil	nv=nh	x	Svh
Fucino	0.20	1.52	640
Avezzano	0.23	1.27	810
Garigliano	0.29	1.11	560
Panigaglia	0.25	1.30	520
Pisa	0.22	1.43	640
Montalto	0.20	1.33	632

3.2.2 *Inherent anisotropy*

The inherent anisotropy results only from the current structure and fabric of the soil. This effect of inherent anisotropy is seen in the non dimensional material constant, S_{ij}, as shown in Equation 1.

For initial load data, the ratio S_{hh}/S_{hv} is 1.57 and the ratio S_{vh}/S_{hv} is 1.37 as presented in Figure 5. In a similar way, for unload-reload data normalizing the S_{ij} values by S_{vh}, the ratio S_{hh}/S_{hv} is 1.58 and the ratio S_{vh}/S_{hv} is 1.23 (Figure 6). Again no difference is found in comparing the ratio at different loading conditions.

Since the ratio S_{vh}/S_{hv} is not equal to 1.00, no cross-anisotropic behavior of the undisturbed Boom clay is found. Possible reasons are the fissuring characteristic of the undisturbed Boom clay sample or the inclination of the Boom clay formation in relation to the boring and testing directions which invalidates the assumption of the cross-anisotropy.

3.3 *Tests on reconstituted Boom clay material*

3.3.1 *Stress-induced anisotropy*

Similar to the analysis of the stress-induced anisotropy from undisturbed Boom clay results, the reconstituted Boom clay testing data of IR1, AR2 and AR3 are divided into two groups. Figure 7 shows the stress-induced anisotropy of reconstituted Boom clay for initial load data and reports a nv value of 0.27 and a nh value of 0.21. Again, the value of nv is higher than the value of nh. This phenomenon is consistent with the test results of undisturbed Boom clay and shows that the reconstituted Boom clay at initial loading also has a higher stress-induced stiffness in the vertical direction than in the horizontal direction. In a similar way, Figure 8 presents the stress-induced anisotropy of reconstituted Boom clay for unload-reload data. The value of nv is lower than the value of nh and both parameters are significantly different from the initial load data due to the swelling effect of the reconstituted Boom clay. The stress-induced anisotropic parameters are different due to the fact that reconstituted Boom clay behaves as a normally consolidated material at initial loading conditions.

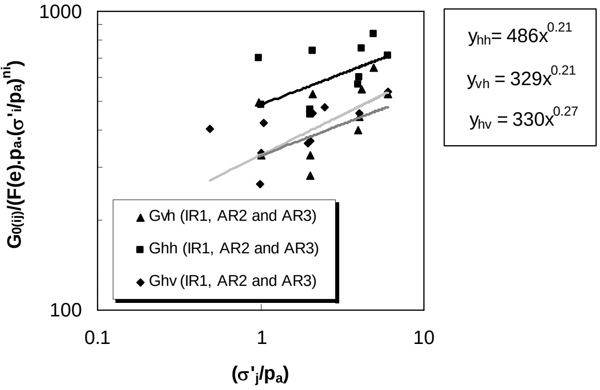

Figure 7. Normalized shear moduli of reconstituted Boom clay at initial loading.

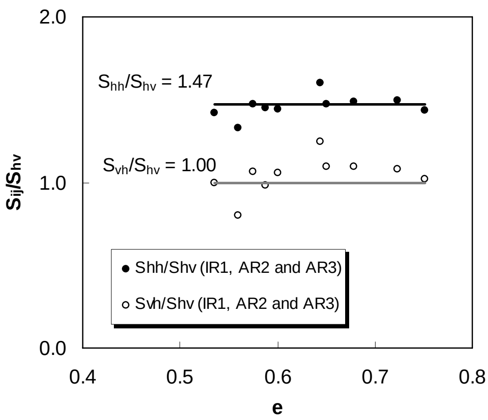

Figure 9. S_{ij} normalised by S_{hv} versus void ratio at initial loading.

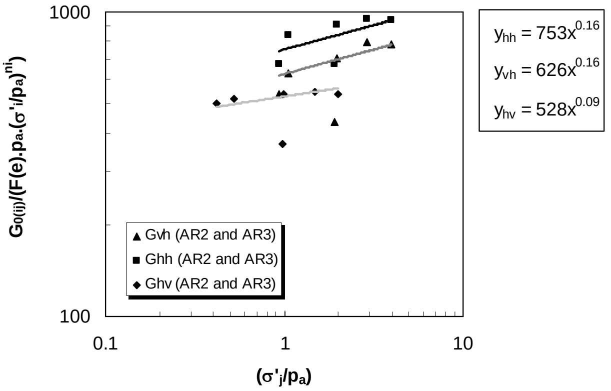

Figure 8. Normalized shear moduli of reconstituted Boom clay for unload-reload data.

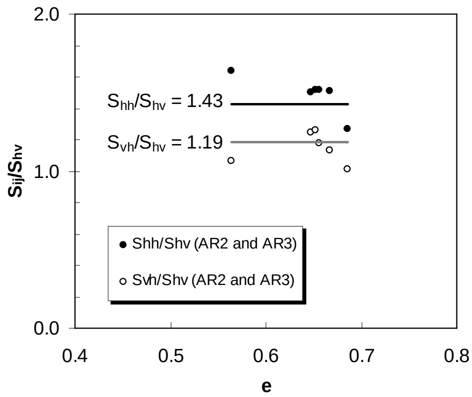

Figure 10. S_{ij} normalised by S_{hv} versus void ratio for unload-reload data.

3.3.2 *Strained-induced anisotropy*

Reconstituted samples are formed from a slurry and particles have no time to create any modified bonding. The effect of the strain-induced anisotropy is shown in the non dimensional material constant, S_{ij}, as seen in Equation 1. In Figure 9 it can be seen that the ratio S_{hh}/S_{hv} is 1.47 and the ratio S_{vh}/S_{hv} is 1.00. The ratio S_{hh}/S_{hv} is not equal to 1.00 reflecting a structure predominantly related to a 1-D strain history. The ratio S_{vh}/S_{hv} gives evidence of the cross-anisotropy. In a similar way, Figure 10 shows the ratio S_{hh}/S_{hv}= 1.43 and the ratio S_{vh}/S_{hv}= 1.19 which are consistent with the undisturbed Boom clay results since the material is overconsolidated.

4 CONCLUSIONS

Triaxial test results with multidirectional bender elements on undisturbed samples of Boom clay show a higher stress-induced stiffness in the vertical direction than in the horizontal direction. The presented data is consistent with results from other clays. The inherent anisotropy is significantly pronounced while the results on reconstituted Boom clay samples show the existence of a cross anisotropy.

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