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Anisotropic stiffness parameters for cross anisotropy of Kaolinite clay

Des paramètres de rigidité anisotropes pour le modèle cross anisotrope d'une argile kaolinite

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ABSTRACT

This paper presents the basic anisotropic small strain behaviour of a Kaolinite clay. Kaolinite clay is selected to perform anisotropic triaxial tests in order to prove the capability of the testing equipment to determine the five elastic parameters for the cross anisotropic model. These parameters are obtained by merging the small strain results and bender element data. This paper describes in full detail the test set-up and measurement capabilities, shows the test results and experimental investigation on the mechanical behaviour of Kaolinite clay. The Kaolinite clay sample is reconstituted in the standard proctor test and installed into the stress path cell. The sample is consolidated under K_0 condition where no lateral deformation occurs. Then it is sheared with Multiple Mini Stress Path Excursions (MMSPE) in order to investigate its mechanical properties at the very small strains. Using local strain sensors mounted on the sample, the stiffness parameters are more accurately obtained. In this research, multi-directional bender elements are also applied offering possibility to measure shear wave velocities in both vertical and horizontal directions. This shear wave velocity has a direct relation to the shear modulus in elastic continuum media. By the virtue of fact that in these tests shear waves are propagating in vertical and horizontal directions, the results of shear moduli in those directions are calculated. Combing these data with the MMSPE results, five elastic parameters for the cross-anisotropic elasticity model are established.

RÉSUMÉ

Cet article présente le comportement anisotrope aux petites déformations d'une argile kaolinite. L'argile kaolinite est choisie pour exécuter des essais triaxiaux anisotropes avec l'intention de montrer les possibilités de l'équipement de déterminer les cinq paramètres élastiques d'un modèle cross anisotrope. Ces paramètres sont obtenus par analyser les résultats des mesures des petites déformations et bender éléments. Cet article commente en grand détail l'équipement utilisé, donne des résultats des mesures et l'investigation du comportement mécanique de l'argile kaolinite.

L'échantillon est reconstitué en essais proctor normal, installé dans une cellule triaxiale et consolidé dans des conditions Ko sans déformations latérales. Ensuite l'échantillon est chargé avec des minis chemins de tensions différents pour investiguer les propriétés mécaniques aux petites déformations. En utilisant des détecteurs des déformations locales sur l'échantillon, les paramètres de la rigidité sont obtenus précisément. Les bender éléments multidirectionnels donnes la possibilité de mesurer les vitesses de propagation des ondes de cisaillement dans les directions verticales et horizontales. Ainsi c'est possible de calculer le module de cisaillement à la direction verticale et horizontale. Finalement les résultats des minis chemins de tensions combinés avec les modules de cisaillement donnes les cinq paramètres élastiques pour le modèle cross anisotrope de l'argile.

1 INTRODUCTION

An objective of this research is to investigate the anisotropic stiffness parameters of clays. Figure 1 is known as the "backbone" shaped curve. The shear modulus decays at larger strains. Soils are assumed to be an elastic material at the very small strains with constant shear modulus. At this very small strains, the soil stiffness obtaining from local strain measurements is identical to the soil stiffness received from dynamics methods.

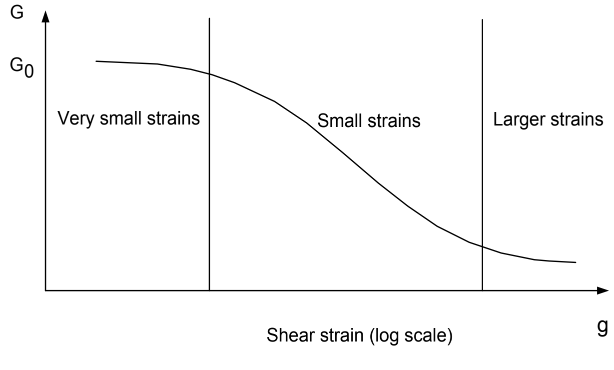

Figure 1. Typical variation of stiffness with strain for soil.

In the past many soil mechanics theories assumed that behaviour of soils is isotropic. However, several soils behave as an anisotropic material. Therefore over the past three decades a number of researches in the understanding of anisotropic soil behaviour have been published Fioravante (2000), Nash et al. (1999), Jovičić and Coop (1998), Rampello et al. (1997), Shibuya et al (1997), Jamiolkowski et al. (1994). Most soils have anisotropy imposed through the processes by which they are formed. Gravity influences soil formations and the vertical direction consequently retains importance with the variation of properties reflecting this vertical significance. This type of anisotropy usually known as cross-anisotropy is described by five independent parameters E_v, E_h, μ_{vh}, μ_{hh} and G_{hv}.

For this research project, an anisotropic triaxial apparatus by Bishop and Wisley (1975) is used. A Labview program is written in order to verify a real K_0 consolidation and to apply several stress path directions in the very small strains (less than 0.001%). In this region, soils are assumed to be an elastic material and the elastic anisotropic parameters of soils can be evaluated by bender element tests and local strain measurements. One of the cross-anisotropic parameters is the initial shear modulus, G, obtained by bender element tests. Bender elements are installed in the triaxial apparatus, using designs similar to those described in detail by Dyvik and Madshus (1985), Brignoli et al. (1996) offering possibility to apply different stress levels on a soil specimen and measuring shear wave velocities. This technique uses piezoceramic transducers for a direct measurement of the shear wave velocity. The shear wave (S-wave) is generated and received by transducers placed at opposite ends of a soil specimen. The shear velocity is calculated from the distance between the two transducers and the time required by the wave to cover this distance. Currently within the framework of this research, a new technique is adapted allowing shear waves to propagate through a specimen in horizontal direction as described by Fioravante and Capoferri (2001). Therefore, multi-directional elastic shear wave velocities can be measured in the triaxial test and allow G_{vh}, G_{hh} and G_{hv} to be evaluated. Since the specimen is not disturbed during bender element tests, the measured stiffness can be compared with the stiffness from local strain measurements at the very small strains.

2 ANISOTROPIC ELASTICITY

The most appropriate form of anisotropy to describe soils with a one-dimensional strain history is cross-anisotropy. Elastic cross-anisotropy is described by five elastic parameters. The relationship between increments of stress and strain for a cross-anisotropic material is described in equation 1:

$$\begin{bmatrix} \delta\varepsilon_{xx} \\ \delta\varepsilon_{yy} \\ \delta\varepsilon_{zz} \\ \delta\gamma_{yz} \\ \delta\gamma_{zx} \\ \delta\gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_h} & \frac{-\mu_{hh}}{E_h} & \frac{-\mu_{vh}}{E_v} & & & \\ \frac{-\mu_{hh}}{E_h} & \frac{1}{E_h} & \frac{-\mu_{vh}}{E_v} & & & \\ \frac{-\mu_{vh}}{E_v} & \frac{-\mu_{vh}}{E_v} & \frac{1}{E_v} & & & \\ & & & \frac{1}{G_{hv}} & & \\ & & & & \frac{1}{G_{hv}} & \\ & & & & & \frac{2(1+\mu_{hh})}{E_h} \end{bmatrix} \cdot \begin{bmatrix} \delta\sigma_{xx} \\ \delta\sigma_{yy} \\ \delta\sigma_{zz} \\ \delta\tau_{yz} \\ \delta\tau_{zx} \\ \delta\tau_{xy} \end{bmatrix} \qquad (1)$$

where the stress and strain increments are referred to rectangular Cartesian axes, with the z-axis vertical. Notation of these parameters is expressed as follows:

σ = normal stress
τ = shear stress
γ = engineers shear strain
ε = normal strain
E_v = Young's modulus in the vertical direction
E_h = Young's modulus in the horizontal direction
μ_{hh} = Poisson's ratio for horizontal strain due to horizontal strain at right angles
μ_{vh} = Poisson's ratio for horizontal strain due to vertical strain
G_{hv} = Shear modulus in the horizontal plane

Lings et al (2000) used an alternative three-parameter formulation to investigate anisotropy in triaxial testing by MMSPE performed at constant σ'_v and at constant σ'_h.

$$E_v = \left(\frac{\delta\sigma'_v}{\delta\varepsilon_v}\right)_{\delta\sigma'_h=0} \qquad (2)$$

$$\mu_{vh} = -\left(\frac{\delta\varepsilon_h}{\delta\varepsilon_v}\right)_{\delta\sigma'_h=0} \qquad (3)$$

$$F_h = \left(\frac{\delta\sigma'_h}{\delta\varepsilon_h}\right)_{\delta\sigma'_v=0} \qquad (4)$$

$$E_h = \frac{4F_h G_{hh}}{F_h + 2G_{hh}} \qquad (5)$$

$$\mu_{hh} = \frac{F_h - 2G_{hh}}{F_h + 2G_{hh}} \qquad (6)$$

where F_h is horizontal modulus ($=E_h/(1-\mu_{hh})$).

3 APPARATUS AND PROCEDURE

3.1 *Stress path cell*

A cylindrical Kaolinite clay specimen 53 mm in diameter and 101 mm in height is installed in a stress path cell designed by Bishop and Wesley (1975) as shown in Figure 2. Figure 3 shows the q´-p´ stress path curve where the sample is consolidated under K_0 condition and sheared with mini-stress path. The sample is consolidated to a vertical effective stress of 400 kPa under K_0 condition. Using Multiple Mini Stress Path Excursions (MMSPE) as described in Pennington (1999), the sample is loaded with constant σ'_h and then unloaded again to the consolidation point within at a shearing rate of 1 kPa/hour. In the same way, the sample is again loaded and unloaded with constant σ'_v. Variation of deviatoric stress in the MMSPE is 20 kPa.

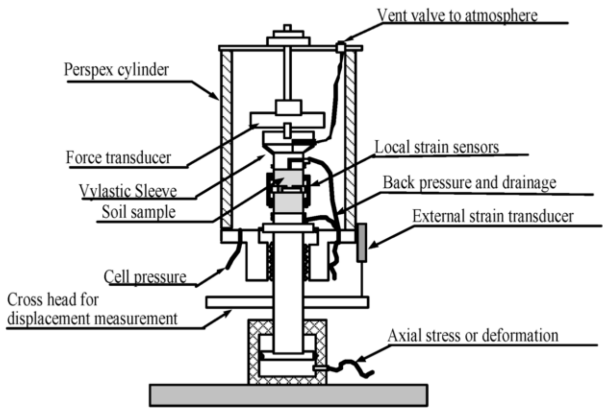

Figure 2. Diagrammatic layout of the stress path cell.

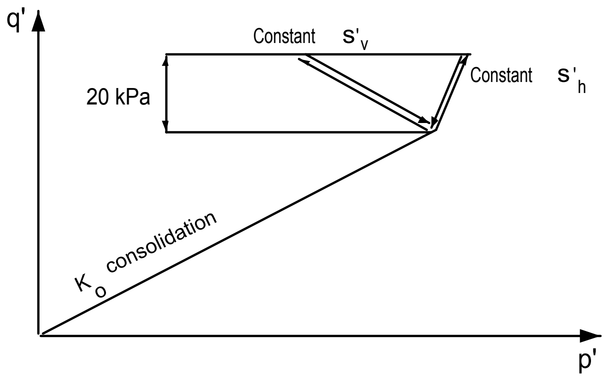

Figure 3. Mini-stress path testing.

3.2 *Bender element testing*

Figure 4 shows the triaxial apparatus with the bender elements setup. A personal computer generates a sinusoidal signal through a sound card with 5V peak to peak as suggested by Mohsin (2003). This signal is amplified to 20V peak to peak. A Hewlett-Packard dynamic signal analyzer model 3562A is used to measure the arrival time between a transmitted signal and a received signal. A voltage pulse is applied to the transmitter element, this causes it to produce a shear wave. When the shear wave reaches the other end of the specimen, distortion of the receiver element produces another voltage pulse. The receiver bender element is directly connected to the analyzer to compare the difference in time between the transmitter and the receiver. The shear wave velocity measurements are usually performed with frequencies ranging between 2 to 10 kHz, at strains estimated to be less than 0.001 %. In most cases, signals are averaged 20 times in order to get a clear signal. Shear wave velocity measurements are carried out applying a single-frequency sinusoidal pulse from the transmitter bender element and detecting the first arrival shear wave at the receiver bender element. The effective distance, L, and the corrected travel time required by the shear wave to cover this distance, t, are used to calculate the propagation velocity of the shear wave as shown in equation 7. The effective traveling length is taken as the distance between the tips of the elements as recommended by Dyvik and Madshus (1985). For the horizontal bender elements, the distances between the internal surfaces of the metal plates are used as described by Fioravante and Capoferri (2001) with the assumption that the specimen deforms as a cylinder.

$$V_s = \frac{L}{t} \tag{7}$$

where V_s is shear wave velocity.

After determining the shear wave velocities, it is possible to calculate the initial shear modulus, *G*, using the relationship of elastic continuum mechanics in equation 8.

$$G = \rho \cdot V_s^2 \tag{8}$$

where ρ is mass density of the material.

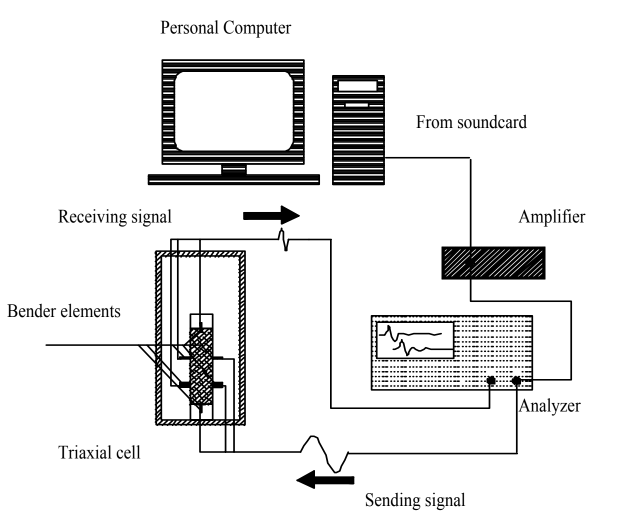

Figure 4. Triaxial cell with bender element set-up.

4 EXPERIMENTAL RESULTS

4.1 *Kaolinite clay tested*

A reconstituted Kaolinite clay specimen is prepared in the standard Proctor test. Using this method, a homogeneous sample is taken by means of a cylindrical tube 53 mm in diameter and 101 mm in height. The specific gravity of the reconstituted sample, G_s, is 2.65, the water content is 27.9 % and the mass density, ρ, is 1963 kg/m³.

4.2 *MMSPE results*

At constant σ'_h, the Kaolinite specimen is sheared by increasing the vertical stress at the rate of 1 kPa/hour. Figure 5 shows the related stress-strain curve measured with local strain devices. Using equation 2 and 3, E_v and μ_{vh} can be determined. Similar but at constant σ'_v and decreasing horizontal stress, F_h is obtained using equation 4 from the data in Figure 6. Through equation 5 and 6, we obtain E_h and μ_{hh}.

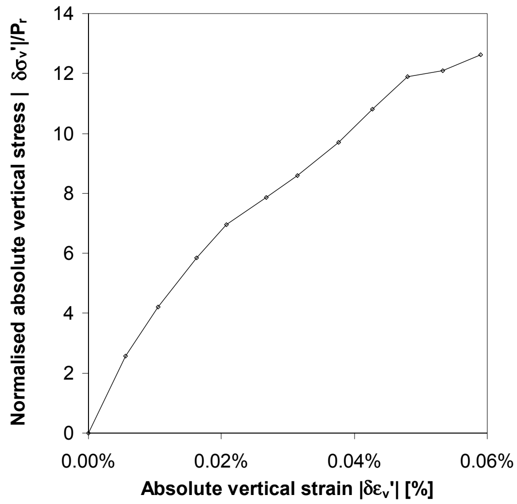

Figure 5. Normalized vertical stress-strain curve at constant σ'_h.

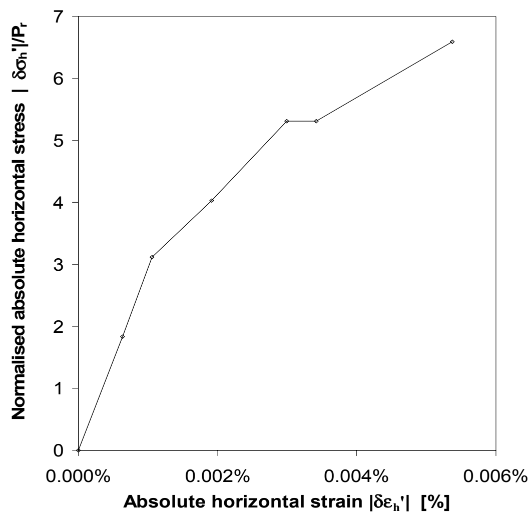

Figure 6. Normalized horizontal stress-strain curve at constant σ'_v.

4.3 *Bender element results*

Determination of travel time as an elastic shear wave propagates through the soil specimen is very difficult. Viggiani and Atkinson (1995) tried to avoid the difficulty in interpreting the square wave response by using a sine pulse as the input signal. To examine the first arrival time of the shear wave, the cross-correlation technique in the time domain is applied. Figure 7 shows an example of the transmitted signal, the received signal and the cross-correlation function. It presents the traveling time of the S_{hh}-wave through the reconstituted Kaolinite clay specimen at a frequency of 4 kHz. By using the cross-correlation method, results show a first arrival time of 195 μs.

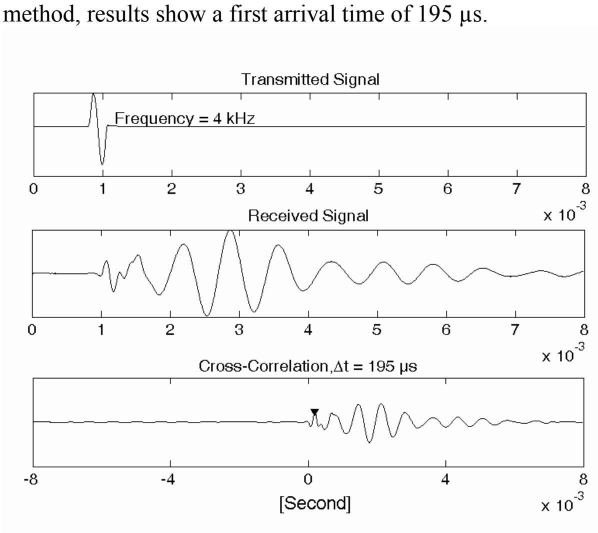

Figure 7. Typical traces of S_{hh}-wave through a Kaolinite clay sample.

4.4 *Parameters for the cross-anisotropic model*

Table 1 presents all five elastic parameters for a cross-anisotropic model of Kaolinite clay. By MMSPE test, four elastic parameters E_v, E_h, μ_{vh} and μ_{hh} are obtained. And by using bender element test, the G_{hv} is directly measured. Table 1 confirms that μ_{vh} and μ_{hh} are very small and close to zero as discussed by Pennington (1999). Since the clay sample is reconstituted in a proctor test, the horizontal stiffness is extremely high as expected.

Table 1: Parameters for an elastic cross-anisotropic model

Parameters	Testing results
E_v (MPa)	45.72
E_h (MPa)	298.19
μ_{vh}	0.104
μ_{hh}	-0.016
G_{hv} (MPa)	157.82

5 CONCLUSIONS

Using MMSPE and multi-dimensional bender element test, five elastic parameters are evaluated and the cross-anisotropic model for a reconstituted Kaolinite clay is established. This paper presents the possibility to obtain these five elastic parameters at very small strains. The values μ_{vh} and μ_{hh} are very small and close to zero.

Several naturally deposited soils will show cross-anisotropy due to their one-dimensional loading history and therefore the five independent parameters should be determined. In this aspect research still continues on undisturbed and reconstituted Belgian Boom clay.

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