Investigation of some anisotropic characteristics of Bangkok Clay

Enquête de certaines caractéristiques anisotropes de Bangkok Clay

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ABSTRACT
Some anisotropic properties of Bangkok Clay are investigated in the laboratory using advanced triaxial apparatus and in the field by self-boring pressuremeter. The triaxial apparatus incorporates local axial & radial strain measurement systems and bender element system. Isotropically consolidated undrained triaxial compression tests are performed on both vertically- and horizontally-cut undisturbed specimens. The anisotropic characteristics of interest are (i) deformation during isotropic consolidation, (ii) small-strain shear modulus, and (iii) modulus during undrained compression shearing. The observed behaviors are compared with other published data from bender element, triaxial, and seismic cone penetration tests. The anisotropic characteristics of Bangkok Clay, which is lightly-overconsolidated clay, are compared with those of London Clay, which is heavily-overconsolidated clay, and some discussions are addressed.

RÉSUMÉ
Certaines propriétés anisotropes argile de Bangkok ont été étudiés en laboratoire en utilisant des appareils triaxial et sur le terrain par l'auto-perçage pressiomètre. L'appareil triaxial intègre local axial et radial des systèmes de mesure de tension et bender élément du système. Isotrope de compression triaxiale consolidés undrained tests sont effectués sur les deux verticalement et horizontalement coupe spécimens intacts. Les caractéristiques anisotrope d'intérêt sont: (i) au cours de la déformation isotrope de consolidation, (ii) les petits-souche module de cisaillement, et (iii) le module de cisaillement au cours de undrained compression. Les comportements observés sont comparés à d'autres données publiées par bender element, triaxiaux et les essais de pénétration de cône sismique. Les caractéristiques anisotrope argile de Bangkok, qui est légèrement overconsolidated argile, sont comparés à ceux de Londres, l'argile, qui est fortement overconsolidated argile, et des discussions sont abordées.

Keywords : anisotropy, triaxial test, pressuremeter test, modulus, clay

1 INTRODUCTION

Natural soils are believed to possess cross-anisotropic behavior due to their mode of deposition, which is one dimensional in nature. Anisotropic consolidation stresses align platety particles and particle groups with their long axes perpendicular to the major principal stress. An anisotropic fabric and anisotropic stress state result in anisotropic mechanical behavior. Anisotropy is often categorised as; (i) inherent anisotropy, which comes from the anisotropic nature of soil fabric and persists even when the stress state changes, and (ii) stress-induced anisotropy, which is an anisotropy due to the change of soil fabric induced by an anisotropic stress state change. Since the change in stress state can in turn alter the soil fabric and hence modify its inherent anisotropy, these two types of anisotropy can sometimes be difficult to be separated.

Past studies on the anisotropic characteristics of Bangkok Clay concern mostly with strength. Very little is known about the stiffness anisotropy at small- and intermediate-strain levels. In this study, some anisotropic characteristics of Bangkok Clay are investigated which are (i) deformation during isotropic consolidation, (ii) small-strain shear modulus, and (iii) modulus during undrained compression shearing. This observed anisotropy may be considered as inherent anisotropy. The investigation is performed by laboratory test (i.e. triaxial test) and in-situ test (i.e. pressuremeter test). The observed anisotropic characteristics of Bangkok Clay, which is lightly-overconsolidated clay, are compared with those of London Clay, which is heavily-overconsolidated clay.

2 SPECIMEN CHARACTERISTICS

Undisturbed samples of Bangkok Clay were taken by piston sampler from Lad-Prao area at depth of 10-13 m BGL. The self-boring pressuremeter tests were performed at Sutthisan area at depth of 10-16 m BGL. Both tests were performed on medium stiff clay. The typical soil profiles of both sites are shown in Figure 1. The index and physical properties are summarized in Table 1.

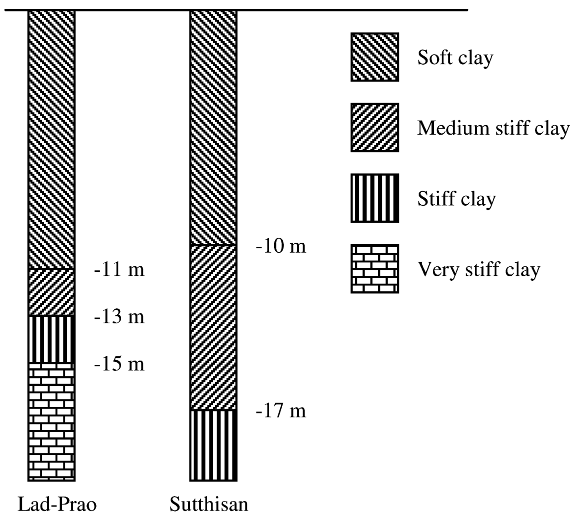


Figure 1. Soil profiles.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)
© 2009 IOS Press.
doi:10.3233/978-1-60750-031-5-1068

Table 1. Index and physical properties of tested clays.

Location	Depth (m)	Water content (%)	Total unit weight (kN/m^3)	LL	PL
Lad-Prao site	10-13	45-60	16.1-17.3	77	31
Sutthisan site	10-16	53-69	15.8-16.6	87	25

3 DESCRIPTION OF APPARATUS

The stress-strain behaviors were studied in the laboratory using triaxial apparatus incorporated with local strain measuring systems and bender element system. The local LVDTs (Cuccovillo & Coop, 1997) and the proximity transducers (Hird & Yung, 1989) were used for local axial and radial strain measurements, respectively. A bender element system (e.g. Viggiani & Atkinson, 1995) was employed to measure the small-strain shear modulus. The set-up of specimen in triaxial test is shown in Figure 2. The stress-strain behaviors were studied in the field by the self-boring pressuremeter (SBPM) test (e.g. Clarke, 1995).

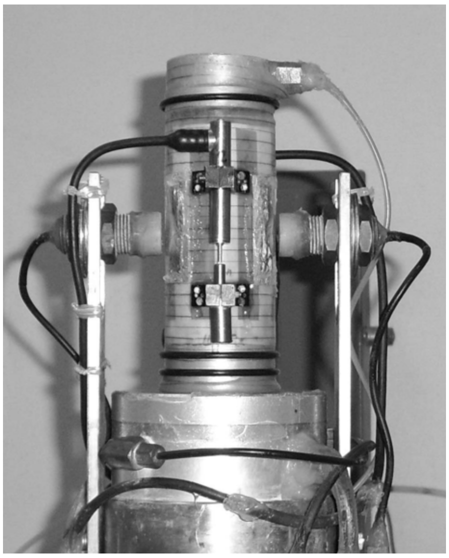


Figure 2. Set-up of triaxial specimen.

4 TESTING PROCEDURES & PROGRAMS

Isotropically consolidated undrained triaxial compression tests were performed on the vertically- and horizontally-cut specimens. The specimens were initially isotropically consolidated to 1 or 2 times of their in-situ isotropic stress ($p'_{in-situ}$). The constant-rate-of-stress consolidation was employed and this involved continuously increasing the cell pressure at a constant rate of 0.05 kPa/min to ensure fully drainage. The undrained compression loading was of strain-controlled condition with external axial strain rate of approximately 0.15%/hr which was slow enough to allow pore pressure changes to equalize throughout the specimen. The triaxial test program is shown in Table 2. The pressuremeter results were derived from unload-reload loop. The pressuremeter test program is shown in Table 3.

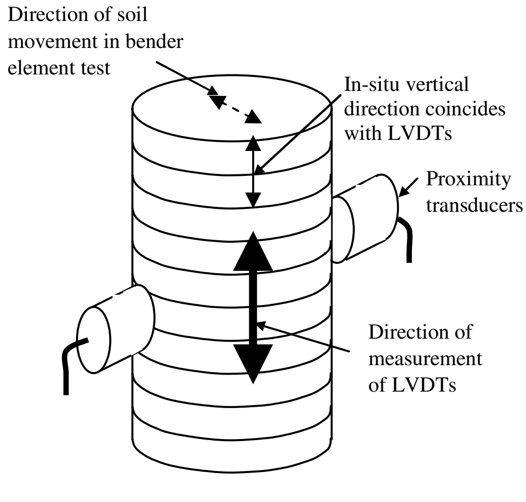
Table 2. Triaxial test program.

Test No.	Depth (m)	e_o	p_o'	Specimen direction
CIUC-1V	10.9	1.69	80*	Vertical
CIUC-2V	13.1	1.27	100*	Vertical
CIUC-5V	13.1	1.31	200**	Vertical
CIUC-5H	12.3	1.39	180**	Horizontal

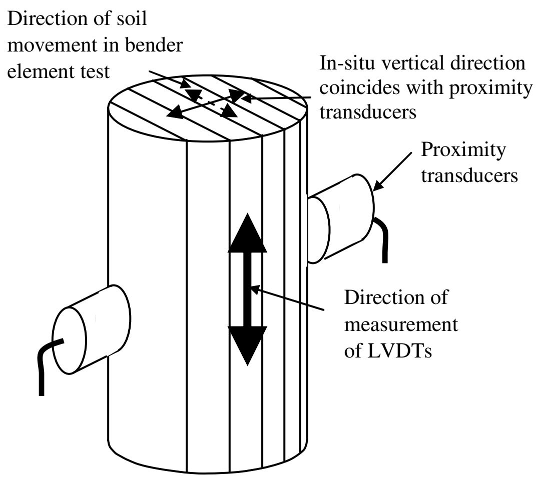
* isotropically consolidated to $p_o' = p'_{in-situ}$
** isotropically consolidated to $p_o' = 2(p'_{in-situ})$
p_o' = triaxial isotropic consolidation stress
$p'_{in-situ}$ = in-situ isotropic consolidation stress

Table 3. Pressuremeter test program.

Test No.	Depth (m)
SBPM-1	9.8
SBPM-2	12.8
SBPM-3	15.8



(a) Vertically-cut specimen



(b) Horizontally-cut specimen

Figure 3. Set-up of local strain measurement and bender element.

The set-up of local strain measurement and bender element is shown in Figure 3. For a vertically-cut specimen, the direction of the axial strain ε_a (measured by the LVDTs) is perpendicular to the bedding plane and coincides with the in-situ vertical direction, whereas the direction of the radial strain

ε_r (measured by the proximity transducers) is parallel to the bedding plane and coincides with the in-situ horizontal direction. For a horizontally-cut specimen, the direction of the radial strain ε_r (measured by proximity transducers) is perpendicular to the bedding plane and coincides with the in-situ vertical direction, whereas the direction of the axial strain ε_a (measured by the LVDTs) is parallel to the bedding plane and coincides with the in-situ horizontal direction. Also, it can be seen that G_{max} measured from the vertically-cut specimen is G_{vh}, whereas G_{max} from the horizontally-cut specimen is G_{hh}.

5 TEST RESULTS

5.1 *Anisotropic deformation during isotropic consolidation*

During the isotropic consolidation, both local axial and radial strains were independently monitored; therefore, it was possible to directly study the anisotropic deformation of the specimens when they were isotropically consolidated. The test results are shown in Figure 4. It is found that the deformation under isotropic consolidation is anisotropic. For the vertically-cut specimen, the change in the axial strain is greater than the change in the radial strain ($\Delta\varepsilon_a > \Delta\varepsilon_r$), and vice versa for horizontally-cut specimen. The test results are summarized in Table 3.

The average ratio of $\Delta\varepsilon_a/\Delta\varepsilon_r$ during the isotropic consolidation stage (for stress range of $p' < p'_{in\text{-}situ}$) is approximately 1.8. It can be seen that the common assumption of isotropic deformation during isotropic consolidation in triaxial test is not the case for Bangkok Clay. However, the obtained value of Bangkok Clay is much less than the value of London Clay of 3.5 (Yimsiri, 2001). As also shown in Figure 4, the ratios of $\Delta\varepsilon_a/\Delta\varepsilon_r$ are quite constant when isotropic consolidation stress is below $p'_{in\text{-}situ}$; however, the ratios decrease (more isotropic) as p' is larger than $p'_{in\text{-}situ}$. This may be due to the fact that the clay changes from over-consolidated to normally consolidated state.

Table 3. Anisotropic deformation during isotropic consolidation.

Test No.	Specimen orientation	Stress range	$\Delta\varepsilon_a/\Delta\varepsilon_r$
CIUC-1V	Vertical	30 → 80	1.09
CIUC-2V	Vertical	40 → 100	2.00
CIUC-5V	Vertical	40 → 200	1.54*
CIUC-5H	Horizontal	40 → 180	0.41*

* for stress range of $p' < p_{in\text{-}situ}'$

5.2 *Anisotropy of small-strain shear modulus*

During isotropic consolidation, the small-strain shear modulus is measured. In Figure 5, the relationships between G_{vh}, G_{hh} and p' of the undisturbed Bangkok Clay specimens are presented. The empirical equation in the form suggested by Hardin & Black (1968) is used to fit the relationship between G_{max} and p' as shown in Equations. (1) and (2).

$$\frac{G_{vh}}{F(e)} = 6942p'^{0.102} \tag{1}$$

$$\frac{G_{hh}}{F(e)} = 6593p'^{0.102} \quad \text{(by keeping the same power as } G_{vh}\text{)} \tag{2}$$

where $F(e) = \dfrac{(2.973-e)^2}{1+e}$

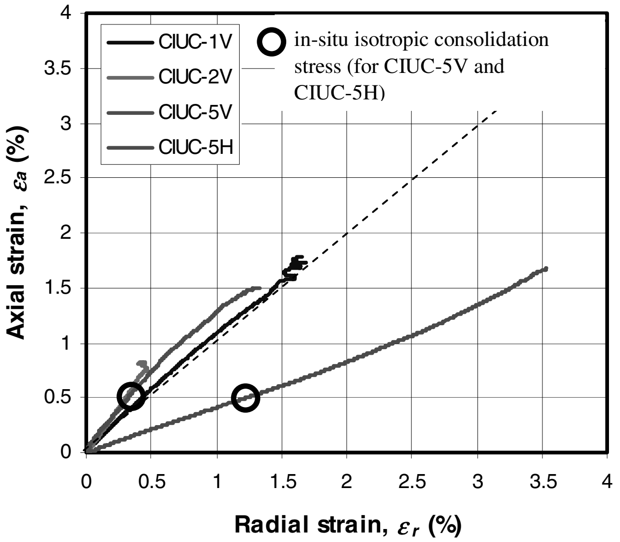


Figure 4. Anisotropic deformation during isotropic consolidation.

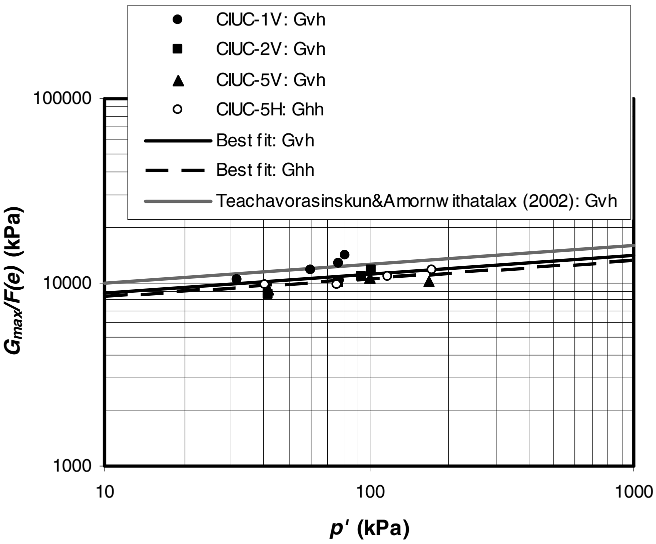


Figure 5. Anisotropy of small-strain shear modulus.

The results from this study are consistent with the published experimental results of Teachavorasinskun & Amornwitayalux (2002) (for OC range). Moreover, the obtained results of G_{vh} and G_{hh} are reasonably similar with G_{hh}/G_{vh} of 0.95 which indicates small degree of small-strain shear modulus anisotropy. This value are much smaller than the value of London Clay of 1.20 (Yimsiri, 2001).

5.3 *Undrained anisotropy at intermediate-strain range*

The pressure-normalized stiffness degradation curves $(E_u)_{sec}/p_o'$ vs ε_a from the undrained triaxial compression tests (vertically-cut specimens) are summarized and compared with the published data by Shibuya et al. (2001) and Teachavorasinskun et al. (2002) in Figure 6. The obtained data are consistent with both published data but with better agreement with Shibuya et al. (2001).

Figure 6 also presents the comparison of the results from undrained triaxial compression, pressuremeter, and seismic cone penetration tests (SCPT). It is noted that SCPT measures G_{vh} and pressuremeter measures G_{hh}. The pressuremeter results are derived by Palmer's method (1972) after adjustment of the strains according to Wood (1990). The relationship of E_u=3G is used to derive undrained Young's modulus (E_u) from shear modulus (G). This calculation inherently assumes isotropic elastic behavior, which is often done in practice. Overall, it can be seen that the results from SCPT consistent with triaxial results. The results from SBPM lie above triaxial results due to anisotropy. However, the ratio of $(E_u)_{tx}/(E_u)_{SBPM}$ (at ε_a = 0.02%) of Bangkok Clay from this study is 0.55 which is smaller than the value of 0.64 reported from London Clay (Yimsiri, 2001).

The triaxial data from vertically- and horizontally-cut specimens (NC state) are compared in Figure 7. The data from the horizontally-cut specimen shows stiffer characteristics than those of the vertically-cut specimen. The obtained ratio of $(E_u)_h/(E_u)_v$ is 1.3 which is smaller than that of 1.8 reported from London Clay (Yimsiri, 2001).

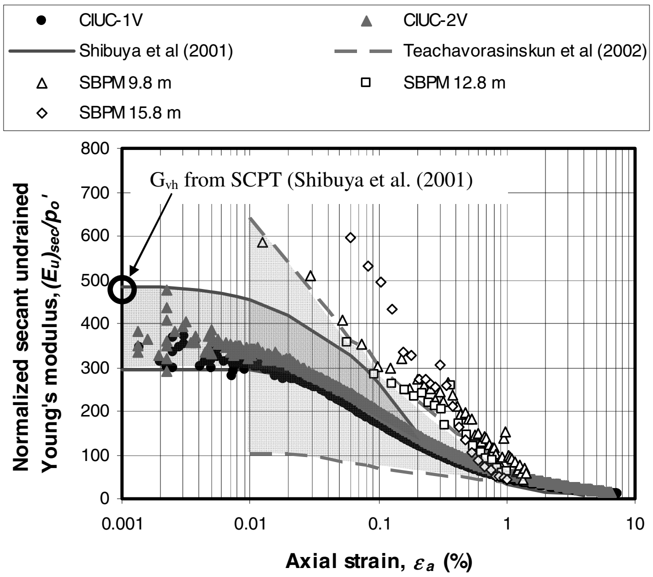


Figure 6. Pressure-normalized stiffness degradation curves.

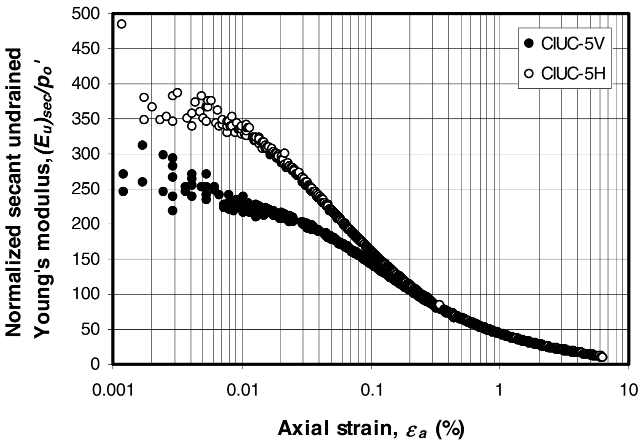


Figure 7. Anisotropy from undrained triaxial test.

6 CONCLUSIONS

This paper presents investigation of some anisotrpic characteristics of Bangkok Clay during isotropic consolidation undrained compression shearing. During the isotropic consolidation stage, the ratios of $\Delta\varepsilon_a/\Delta\varepsilon_r$ of the vertically-cut specimens is around 1.8. During the undrained compression shearing stage, the ratio of $(E_u)_h/(E_u)_v$ is around 1.3. The experimental results conclusively indicate that the behavior of the undisturbed Bangkok Clay is anisotropic and it is stiffer in the horizontal direction.

Comparison of the anisotropic characteristics of Bangkok Clay, which is normally consolidated clay, with those of London Clay, which is highly-overconsolidated clay, indicates that Bangkok Clay has less degree of anisotropic characteristics. However, the comparison of triaxial and pressuremeter test does not yield consistent results and further investigation is required.

ACKNOWLEDGEMENTS

This research is partly supported by the Department of Civil Engineering, Burapha University, through its Research and Development Fund No. 20/2552. Cambridge Insitu kindly provides the self-boring pressuremeter test data.

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