Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 376–381

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Cyclic stress-controlled tests on offshore clay

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ARTICLE INFO

Article history:
Received 4 April 2016
Received in revised form
10 May 2016
Accepted 7 June 2016
Available online 8 December 2016

Keywords:
Offshore clay
Cyclic degradation
Undrained cyclic loading
Shear strength
Pore pressure
Overconsolidation ratio (OCR)

ABSTRACT

One of the main concerns in cyclic behavior of soft clay is gradual degradation with the progression of loading cycle. A series of cyclic constant-volume direct simple shear (CDSS) loading tests was performed on Malaysia offshore clay to study its undrained degradation. The testing program consists of stress-controlled tests with cyclic shear ratio ranging from 0.34 to 0.83 at different overconsolidation ratios (OCRs). For a given cyclic stress ratio in stress-controlled tests, the accumulated cyclic strain and pore water pressure increase with elevated number of cycles. In heavily overconsolidated clay specimens, the negative cyclic pore water pressure is generated followed by positive cyclic pore water pressure as cyclic tests progress. The post-cyclic strength of offshore clay specimens is reduced by undrained cyclic stress-controlled loading.

1. Introduction

The study of cyclic loading behavior in saturated clay under undrained conditions is of utmost importance for stability of offshore geotechnical engineering structures. Over the past decades, many experimental studies have been undertaken to investigate the clay behavior under cyclic loading induced by storm waves and earthquakes. Undrained cyclic loading could lead to clay failure as a result of excess pore pressure and cyclic-induced shear strain developments (Seed and Chan, 1966; Andersen et al., 1980; Yasuhara et al., 1992; Zhou and Gong, 2001; Ni et al., 2014; Indraratna et al., 2016). As the number of cycles increases, excess pore pressure is developed and accumulated in clay, and thus clay structure is degraded followed by reduction in stiffness and strength of clay (Idriss et al., 1978; Vucetic and Dobry, 1988; Zhou and Gong, 2001; Moses et al., 2003; Yang et al., 2007). Sangrey et al. (1969) found that there is a critical level of repeated stress below which the clay behaves as elastic and remains in a state of nonfailure equilibrium, which has been further confirmed by Hanna and Javed (2008, 2014).

Idriss et al. (1976, 1978) introduced the concepts of degradation index δ and degradation parameter t to quantify the degradation of clay under cyclic loading. For the results obtained from cyclic strain-controlled testing when cyclic amplitude is constant, δ can be expressed in terms of shear moduli or shear stresses as

$$\delta = \frac{G_{sN}}{G_{s1}} = \frac{\tau_{cyN}/\gamma_{cy}}{\tau_{cy1}/\gamma_{cy}} = \frac{\tau_{cyN}}{\tau_{cy1}} \tag{1}$$

$$t = -\frac{\log_{10}\delta}{\log_{10}N} \text{ or } \delta = N^{-t} \tag{2}$$

where γ_{cy} is the cyclic shear strain, N is the cycle number, G_{sN} is the secant shear modulus at cycle N, G_{s1} is the secant shear modulus at the first cycle, τ_{cyN} is the maximum cyclic shear stress at cycle N, and τ_{cy1} is the maximum cyclic shear stress at the first cycle. Mortezaie and Vucetic (2013) also suggested that cyclic degradation in the cyclic stress-controlled tests can be denoted with a degradation index, δ^*, which also characterizes the reduction of the secant shear modulus with N:

$$\delta^* = \frac{G_{sN}}{G_{s1}} = \frac{\tau_{cy}/\gamma_{cyN}}{\tau_{cy}/\gamma_{cy1}} = \frac{\gamma_{cy1}}{\gamma_{cyN}} \tag{3}$$

where γ_{cyN} is the cyclic shear strain at cycle N, and γ_{cy1} is the cyclic shear strain at the first cycle. τ_{cy} is constant throughout the test

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Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2016.06.013

while γ_{cy} varies with N. The index δ^* decreases with N because γ_{cyN} increases with N.

Fully saturated clays subjected to cyclic loading conditions during earthquake and ocean wave storms can be simulated in the laboratory by cyclic constant-volume equivalent undrained direct simple shear tests (Matasovic and Vucetic, 1995). Simple shear device simulates the in-situ loading condition induced by vertically propagating shear waves (Boulanger et al., 1993; Navaratnavel, 2013). In this study, undrained constant-volume direct simple shear (CDSS) cyclic tests, which were modified from static drained simple shear tests, are performed to investigate the degradation and pore pressure response of Malaysia offshore clay as the study on the cyclic shear behavior of Malaysia offshore clay is limited.

2. Materials

Offshore clay specimens used in this study were recovered from Terengganu, Malaysia. The plasticity index, liquid limit and plastic limit of Terengganu offshore clay (TOC) are 27%, 54% and 27%, respectively. TOC specimen contains 43% clay fraction with diameter less than 0.002 mm and specific gravity of 2.58. Fig. 1 depicts the particle-size distribution curve for TOC specimen. The initial void ratio for reconstituted TOC specimen is about 0.6, while the angle of internal friction and cohesion of TOC specimens are 27° and 15 kPa, respectively (Thian and Lee, 2014).

3. Experimental program

The TOC specimens used in the present study were reconstituted from disturbed soil specimens. They were first oven-dried before water was added to achieve saturated soil with moisture content of about 40% and initial dry density of about 1.253 g/cm^3. Standard loading rate of 1.2 mm/min was applied on all normal/overconsolidated specimens at overconsolidation ratios (OCRs) of 1, 4 and 10.

All the simple shear tests were performed on cylindrical TOC specimens of 70 mm in diameter and 25 mm in height. Undrained CDSS tests were done in accordance with ASTM D6528-07 (2007), in which undrained conditions are simulated by maintaining constant volume of test specimen. The TOC specimens were confined by stacked rings which prevented radial deformation, but allowed the specimens to deform vertically. Overconsolidated TOC specimens were consolidated at 400 kPa vertical stress and then they were unloaded to achieve the required OCR before shearing started to achieve the desired vertical stress.

The CDSS equipment was designed to allow soil specimen to be consolidated and then sheared under constant volume to achieve undrained condition. A modified computer-controlled simple shear testing apparatus incorporated with a data logging system was used. The change in soil sample vertical stress is assumed to be equal to the change in pore water pressure that would have taken place during a truly undrained test condition (Bjerrum and Landva, 1966; Dyvik et al., 1987). Fig. 2 illustrates the test specimen assembly for CDSS used in the present study.

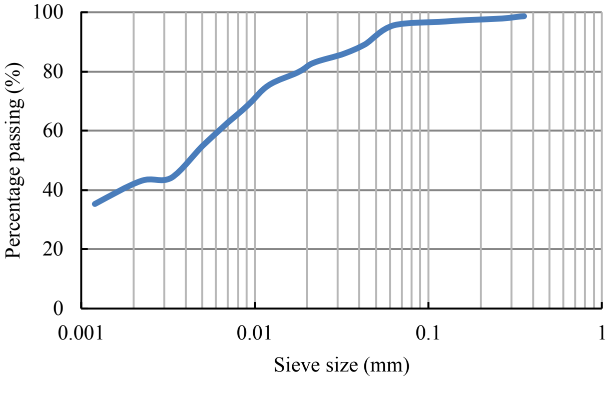

Fig. 1. Typical particle-size distribution curve for TOC specimen.

In the present investigation, a series of one-way and two-way stress-controlled undrained CDSS tests was performed on TOC specimens. Quasi-static cyclic loading was undertaken instead of dynamic loading due to the limitation of laboratory equipment. Cyclic tests were performed with failure criterion of cyclic shear strain reaching $\gamma_{cf} = \pm 15\%$ (double amplitude) for one-way and two-way cyclic loading. The similar failure criterion was also employed by Andersen (2009) and Le et al. (2014) on offshore clay in Norway. The typical stress–strain loops for one-way and two-way cyclic loadings are illustrated in Fig. 3. One-way cyclic strain and pore pressure are denoted by γ and u, respectively; while two-way cyclic shear strain and pore pressure are represented by γ_{cy} and u_{cy}, respectively. The loading amplitude was characterized in terms of cyclic stress ratio (CSR), which is defined as $CSR = \tau_{cy}/s_u$, where τ_{cy} is the cyclic shear stress in single amplitude and s_u is the undrained static strength. Static tests on TOC specimens have been conducted and explained in previous publications (Thian and Lee, 2014, 2015a, 2015b). All the cyclic tests were discontinued after 500 numbers of cycles or when the cyclic shear strain failure criterion was reached. The summary of CDSS cyclic test conditions undertaken in this study is listed in Table 1.

4. Results and discussions

Two-way stress-controlled CDSS tests are conducted at different cyclic stress ratios. The soil failure is defined by strain-based criteria at ±15% double amplitude (DA) shear strain or 7.5% single amplitude (SA) shear strain. The developments of shear strain at failure (7.5% SA), indicated by $\gamma_{cf} = 7.5\%$, and pore pressure of TOC specimens at OCR = 1, 4 and 10 under two-way cyclic undrained simple shear tests at various CSRs are presented in Figs. 4–6, respectively. As CSR increases, the development of γ_{cf} increases rapidly with the number of cycles N, which is in accordance with the published studies (Andersen et al., 1980; Erken and Can Ulker, 2007; Safdar and Kim, 2013; Le et al., 2014; Ni et al., 2014). The value of mean γ_{cy} (i.e. $(\gamma_{max} - \gamma_{min})/2$) increases significantly over each cycle and leads to a failure state due to excessive amount of γ_{cy}, especially if the specimen is subjected to high CSR (Le et al., 2014; Ni et al., 2014). Higher load degrades the soil structures more severely, as well as contributes to larger pore pressure accumulation in each cycle, and hence fewer cycles are required to cause soil failure (Erken and Can Ulker, 2007; Le et al., 2014; Ni et al., 2014). Andersen (2004) also explained that the generation of pore pressure in clay specimen under two-way simple shear loading reduces the effective stresses in clay. As OCR increases, the TOC specimens tend to fail under two-way cyclic loading at lower number of cycles, which indicates that the stress history decreases the resistance of TOC specimen to cyclic loading.

Higher pore pressure is generated with the number of cycles as CSR increases for normal and overconsolidated TOC specimens. It is noted that during the initial cyclic loading for overconsolidated TOC specimens at OCR = 4 and 10, negative pore pressure is generated because of the dilation due to the overconsolidated state of the clay (Le et al., 2014). Negative pore pressure development is more pronounced when TOC specimens are heavily consolidated at OCR = 10. The negative pore pressure decreases in subsequent cycles and positive pore pressure is developed.

Fig. 7 indicates the degradation index δ^* for stress-controlled CDSS tests at various values of CSR and OCR. The δ^* values decrease with the increases of N and CSR. The decrease in δ^* reflects the