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Strain and pore pressure development on soft marine clay in triaxial tests with a large number of cycles

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ABSTRACT

Soft marine clays may be subjected to tens of thousands of cyclic applications of waves or traffic loads over a long period of time. Therefore, its cyclic deformation behavior is one of the major concerns of geotechnical engineers. In this study, a series of high cycle (50,000 cycles) triaxial tests have been carried out on soft marine clay with various stress levels and different confining pressures to investigate the development of strain and pore water pressure. Some useful conclusions are obtained. Firstly, the development of resilient and permanent strain depends on the cyclic stress ratio (CSR) values. When CSR is small, the resilient strain nearly keeps at a constant value after 1000 cycles and the permanent strain increases slowly and almost linearly with increasing CSR. When CSR is large, the resilient strain increases even after 50,000 cycles and the permanent strain increases rapidly and exponentially with increasing CSR. Secondly, log (ε_p/N) and log N exhibit a nearly linear relationship after a certain number of cycles which is called the reference number of cycles. An empirical formula is established to predict the long-term permanent strain by making use of this relationship. Thirdly, the peak axial strain increases exponentially with the decrease of the distance between the effective stress path and the critical state line. A formula is proposed to characterize the relationship between the peak axial strain and the peak pore water pressure after 1000 cycles.

1. Introduction

The marine clay featured by high water content, high compressibility, low permeability and low bearing capacity is widely distributed in the southeast of China. Being one of the most developed areas in China, numerous buildings and infrastructures have been built in this area. The foundations of these structures may be subjected to tens of thousands of cyclic applications of waves or traffic loads over a long period of time. To guarantee the safety and normal use of these structures, the long-term cyclic behavior of the marine clay should be investigated.

Clay behavior under cyclic loading has been investigated by many researchers. For examples, Andersen et al. (1980) presented results from 129 triaxial and 103 simple shear cyclic and static tests on plastic Drammen clay and provided general knowledge about soil behavior under cyclic loading. Yasuhara et al. (1982) conducted several series of stress-controlled repeated triaxial compression tests on a remolded soft clay and analyzed the cyclic strength and deformation behavior in terms of both effective and total stress. Ausal and Erken (1989) studied the cyclic stress–strain–pore pressure and cyclic shear strength properties of clay samples. An empirical procedure to evaluate the cyclic response of normally consolidated clay samples was proposed. Hyde et al. (1993) presented the results from a series of one-way cyclic undrained triaxial tests on Ariake clay and developed related stability criteria for pore pressure and strains at different cyclic stress levels. Li et al. (2011) conducted two kinds of stress controlled cyclic triaxial tests on natural K_0-consolidated Wenzhou clay to study the undrained behavior of natural marine clay under cyclic loading. Most of the existing experimental studies on clay are conducted with only a few thousands cycles. The cyclic strength and cyclic degradation at high cyclic stress levels are the main concern in these studies. However, the soft marine clay may be subjected to tens of thousands cyclic applications of wave or traffic loadings at low cyclic stress levels. As a result, deformation is limited even after a very large number of cycles. In this case, the cyclic deformation behavior is the utmost concern instead of the cyclic strength.

According to previous studies, the total strain induced by cyclic loading can be divided to resilient strain and permanent strain. With the increase of the number of cycles, excess pore water pressure is generated and accumulated in clay, which degrades the clay structure and decreases the stiffness and strength of clay (Idriss et al., 1978; Vucetic and Dobry, 1988; Zhou and Gong, 2001;

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Moses et al., 2003; Yang et al., 2007). The degradation of clays will then significantly influence the development of resilient strain and permanent strain. It is therefore necessary to investigate the long-term cyclic behavior of the soft marine clay by experimental tests with a large number of load cycles.

In this study, a series of cyclic triaxial tests with 50,000 cycles have been carried out on soft marine clay to investigate the development of strain and pore water pressure. The test data were recorded at an interval of 0.02 s to obtain the real-time response of axial strain and pore pressure per cycle. The development of resilient strain, permanent strain, and pore water pressure were investigated with various stress levels under different confining pressures.

2. Sampling method and soil properties

The soft marine clay tested in this paper is from Wenzhou, a coastal city in southeast China. This type of clay is typically 30–100 m thick and has been recognized as one of the most problematic soils in China because of its high water content, high compressibility, low permeability and low bearing capacity. Many previous investigations have been done on this type of clay (Li et al., 2011; Gu et al., 2012; Guo et al., 2013).

In order to obtain undisturbed clay samples, a test pit with a depth of about 3 m was excavated at a site 2 km away from the Wenzhou Airport. The ground water level at this site is about 0.8 m below the ground surface. All samples were obtained by pressing thin-walled stainless steel tubes (with a diameter of 160 mm and a length of 250 mm) slowly into a horizontal bench prepared in the pit. Each tube was excavated carefully, sealed at the ends, transported to the laboratory, and stored in a humidity room. The quality of the samples had been checked according to the recommendations given by Lunne et al. (2006). Results showed that the sample quality could be classified as "good to fair". The index properties of the soft clay used are shown in Table 1.

3. Test apparatus and procedures

3.1. Test apparatus

An electromechanical dynamic triaxial testing system, the DYNTTS manufactured by GDS Instruments Ltd., UK, is used in this study. It complies with ASTM D3999-91 and ASTM D5311-92. In this apparatus, the deviatoric stress is applied by a servo-loading system and the confining pressure is applied through an oil pressure type piston. It can vary the deviatoric stress and confining pressure simultaneously with a range of frequencies between 0.00001 Hz and 10 Hz. The key parameters of the apparatus are listed in Table 2. With high control and measurement precision, and powerful real-time data acquisition function, this apparatus enables long-term cyclic loading tests under different loading frequencies.

Table 1
Index properties of tested soft clay.

Index properties	Value
Specific gravity, G_s (g/cm^3)	2.75
Natural water content, w_n (%)	56–59
Initial density, ρ_0 (g/cm^3)	1.68–1.71
Initial void ratio, e_0	1.55–1.59
Liquid limit, w_L (%)	64
Plasticity index, I_p	36
Clay fraction, (%)	55
Silt fraction, (%)	41

Table 2
Key parameters of DYNTTS.

Parameters	Values
Displacement range	100 mm
Displacement accuracy	35 μm in 50 mm (i.e. 0.07%)
Displacement resolution	0.208 μm
Axial force accuracy	$<$0.1% of load cell range
Axial force resolution	16 bit (i.e. $<$0.4 N for 10 kN load cell)
Control data points	10,000 points/sec
Maximum saved data points	100 points/cycle

Table 3
Summary of undrained cyclic traxial tests.

Confining pressure, p'_0 (kPa)	Cyclic stress ratio, CSR$=q_{cyc}/2\ q_f$	Loading frenquency, f (Hz)	No. of cycles, N
100	0.14 0.20 0.28 0.31 0.33 0.40 0.42	1	50,000
50	0.16 0.25 0.32 0.35	1	50,000
200	0.19 0.24 0.32 0.38	1	50,000

3.2. Test procedures

Four test specimens, each with a size of 50 mm in diameter and 100 mm in height, were trimmed from the core of the block sample by a wire saw. The specimens were then installed on the base of the apparatus. Sintered bronze end platens were placed in between the specimen and the apparatus to reduce friction. Drainage was fulfilled by filter paper side drains connected to the bronze platens and pore pressures were measured through a hole in the center of the rubber sheets covering the lower pedestal. All the specimens were first saturated at a back pressure of 300 kPa with an effective mean pressure of 10 kPa, followed by a B value check to guarantee B value greater than 0.97. After that, the test specimen was isotropically consolidated under a certain value of effective confining pressure. Finally, monotonic triaxial tests and one-way stress-controlled cyclic triaxial tests were performed under undrained conditions.

Monotonic triaxial tests were performed for the determination of shear strength parameters. Four tests were conducted at an effective confining pressure of 50 kPa, 100 kPa, 200 kPa, and 300 kPa, respectively. They were all strain-controlled tests with a strain rate of 0.01 mm/min.

Cyclic triaxial tests with different effective confining pressure and cyclic stress level were carried out. Three effective confining pressures were considered, i.e., 50 kPa, 100 kPa and 200 kPa. For each effective confining pressure, tests with different cyclic stress levels were conducted. The cyclic stress ratio, CSR$=q_{cyc}/2q_f$, where q_{cyc} is cyclic deviatoric stress and q_f is the peak deviatoric stress of specimens determined by monotonic test, was employed to discern the various cyclic stress levels. In total, 15 cyclic triaxial tests as summarized in Table 3 have been carried out. The loading waveform was a semi-sine wave type and the loading frequency was 1 Hz. All specimens were subjected to 50,000 cycles. In the first 100 cycles, test data in each cycle were recorded and 50 data points registered per cycle. After that, test data were recorded every 20 cycles.

4. Test results and discussions

4.1. Monotonic triaxial tests

Fig. 1 presents the results of monotonic triaxial tests with different confining pressures. In this figure, ε_a, $q=\sigma'_1-\sigma'_3$, Δu, and