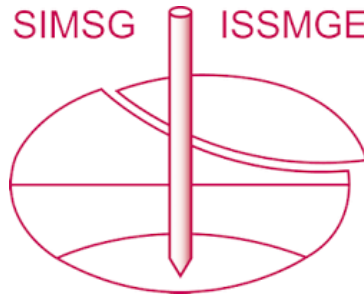


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The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Evaluation of threshold stress for high-speed railway foundation on Bangkok soft clay under cyclic loading

Évaluation de la contrainte de seuil pour la fondation du chemin de fer à grande vitesse sur l'argile molle de Bangkok sous chargement cyclique

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ABSTRACT: A high-speed railroad foundation with a fine-grained subgrade can potentially build up excessive pore water pressure under cyclic loading from the operation of the train. The generation of the excess pore water pressure in the foundation clay could result in progressive shear failure at a stress level less than its shear strength under static loading conditions. In this study, both static and cyclic undrained triaxial tests were conducted for the Bangkok soft clay. The cyclic triaxial tests were conducted under two loading frequencies of 2 and 4 Hz. Normally consolidated (NC) and over-consolidated (OC) Bangkok soft clays were tested to investigate the behavior of the soils under cyclic loading. The threshold stresses for the NC and OC clays under cyclic loading were determined in the study. The effect of the load frequency, deviator stress level, and stress history of the soil on the threshold stress was evaluated in this study. This study shows that the shear strengths of the NC and OC Bangkok soft clays under cyclic loading could reduce up to approximately 20 and 30%, respectively, compared to those obtained from the monotonic compression tests. This study also concluded that the frequency does not significantly affect the threshold stresses or plastic strain.

KEYWORDS: cyclic loading, soft clay, high-speed train, excess pore water pressure, and threshold stress

1 INTRODUCTION

Recently, accessibility and transportation systems among large cities and countries are rapidly developing all around the world. In Thailand, the Thai-Chinese high-speed railway with a total length of over 1,000 km is under construction since 2017. Some sections of the high-speed railway foundation are being built on the Bangkok soft clay. The failure of railway track foundation subgrade under repeated loading induced by high-speed train is one of the leading design concerns for railway design and construction, especially when the foundation is sitting on soft clay. The failure is primarily because the development of excess pore water pressure in the clay could occur under the cyclic loading, resulting in an excessive amount of plastic deformation of the soft clay.

The behavior of soft clays under cyclic loading was studied by numerous researchers (Larew, 1960; Idriss, 1978; Weerasinghe, 1983; Thammathiwat, 2004; Miller, 2000; Loh, 2011; and Krystian, 2018). Larew (1960) conducted cyclic compression triaxial tests on compacted cohesive soil and concluded that the sample experienced failure when cyclic stress was about peak shear stress under cyclic loading. The soil specimens loaded by deviator stress lower than peak stress will be stabilized under a significant number of loading and would never encounter shear failure.

The stress-strain behavior of Bangkok soft clay under cyclic loading was investigated by Weerasinghe (1983) & Thammathiwat (2004) with loading frequencies of 0.1 to 1 Hz. The studies reported that the soil sample would be subject to large deformation and high excess pore water pressure when the deviator stress level is approximately 93% of maximum shear strength obtained from triaxial constant strain rate tests. Under the critical deviator stress (threshold) with a large enough number of load applications, the resilient state of soil under cyclic loading is observed when there is no further development of plastic strain.

The soil's physical properties (i.e., plasticity, degree of saturation, water content, void ratio, and stress history) play a vital role in fluctuating the shear strength. Houston (1980) and Lefebvre (1988) indicate that the cyclic threshold stress trends to increase with the clay plasticity. Miller (2000) conducted experimental research on the behavior of stress-strain for the soil under cyclic loading and concluded that the tendency of the loops of hysteresis could represent the soil's elastic behavior when

subjected to cyclic loads. Moreover, the strain development under cyclic axial compression could be different with various degrees of saturation. The effect of the stress history on the cyclic shear strength of soil was studied by Loh (2011) using artificial soil called "Kaolin clay." It was reported that the reduction of shear strength of the soil is about 29% for normally consolidated clay. Moreover, the reduction of the cyclic shear strength of the over-consolidated clay can be as high as 36 and 39 % for clayey soils with OCR of 1.5 and 4.0, respectively.

This study focused on cyclic undrained shear strength and deformation behavior under cyclic loading for normally and over-consolidated Bangkok soft clays. The cyclic triaxial tests were conducted by using the GDS Enterprise Level Dynamic Triaxial Testing System (ELDYN). The tests were performed under different cyclic shear stress ratios, stress history ratios, and loading frequencies. The testing program and the experimental results are presented in the following sections.

2 SOIL DESCRIPTION AND INDEX PROPERTIES

The Bangkok soft clay samples used for this study were collected from the AIT site. A hand auger driller was used together with thin-walled tubes to collect undisturbed Bangkok clay samples at depths of approximately 4.0 to 6.0 m. The Bangkok clay is visually characterized as grey to greenish-grey clay and silt with no mottle.

Index properties of the soil samples were obtained and summarized in Table 1. As shown in Table 1, the Bangkok clay was classified as inorganic clay with high plasticity (CH) in accordance with the Unified Soil Classification System (USCS). The results of the index properties shown in Table 1 are consistent with the findings obtained by previous researchers who have studied Bangkok clay's index properties at the AIT site (Shibuya, 2003 and Suksan, 2007).

Table 1. Index properties of Bangkok soft clay

Property	Value
Liquid Limit (%)	98.5
Plastic Limit (%)	35.1
Plastic Index (%)	63.4
Specific Gravity (-)	2.68
Natural Water Content (%)	85.0 – 93.0
Soil Classification (USCS)	CH

3 TEST PROGRAM

3.1 One-dimensional consolidation tests

The one-dimensional consolidation (oedometer) tests were conducted according to the ASTM D2435/D2435M-11 Standard. The soil samples obtained from the depths of 4.5 m and 5.0 m were tested. The value of pre-consolidation pressure of the soil samples was determined to be approximately 230 kPa.

3.2 Monotonic triaxial tests

The monotonic consolidated undrained (CU) triaxial tests were performed to evaluate the undrained shear strength of the Bangkok soft clay. The triaxial compression tests were conducted according to the ASTM D4767-95 Standard. The constant shearing rate for the tests was determined using the results obtained from the oedometer tests (see Eq. 1).

$$\epsilon = 4\% / (10 \times t_{50}) \quad (1)$$

Where: t_{50} is time to achieve 50% of consolidation

3.3 Cyclic triaxial tests

To evaluate the behavior of soft clay under axial cyclic compression, the dynamic triaxial compression tests were conducted under the same condition as the standard triaxial compression tests, except that the cyclic compression axial load was applied with a stress-controlled loading module. A summary of the triaxial testing program is tabulated in Table 2. Details of the dynamic compression tests are provided in the following sections.

3.3.1 Dynamic triaxial apparatus

The cyclic triaxial tests were conducted using the GDS Enterprise Level Dynamic Triaxial Testing System (ELDYN) at the Geotechnical Engineering and Earth Resources (GTE) Laboratory located at the Asian Institute of Technology, Thailand. Figure 1 depicts the set-up of the ELDYN system at the GTE Laboratory.

The cyclic loading with a frequency of up to 5 Hz can be applied using the GDS ELDYN system. The loading frequencies of 4 and 2 Hz were used in this study to simulate the loading frequency of the Thai-China high-speed train at a maximum velocity of 250 km/hr and half of the maximum train velocity, respectively. The maximum train frequency was estimated by considering the maximum train velocity and the train span length of 17.4 m.



Figure 1. GDS Enterprise Level Dynamic Triaxial Testing System at the GTE Laboratory.

The triaxial chamber consists of three main components including cell base, cell body, and top cell assembly. The confining cell pressure can be controlled by either air or water pressurizing. In this study, the air entry pressurizing was used to apply for the confining pressure.

The internal submersible load cell was used with a load capacity of 1 kN. The accuracy of loadcell is $\pm 0.1\%$ of the full range output which allows a measurement error of 0.001 kN. The extension top cap was used to ensure sufficient contact between the specimen top cap and the internal submerged load cell. The configuration of the extension top cap is presented in Figure 2.

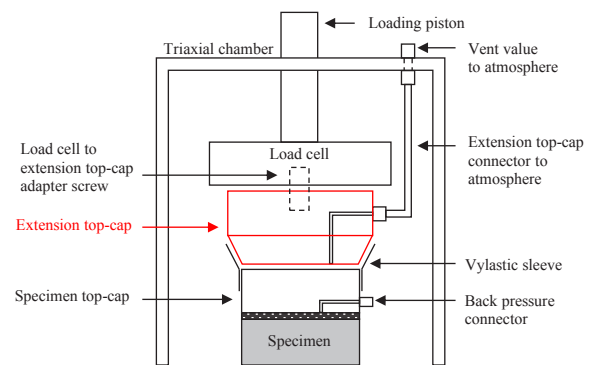


Figure 2. Configuration for extension top-cap and vylastic sleeve (modified after Sean, 2014).

3.3.2 Testing Procedure

3.3.2.1 Sample Preparation

The size of the cylindrical specimen used in this study is 100 mm in height and 50 mm in diameter. The soil samples were trimmed into that size using the undisturbed specimen extruded from Shelby tubes. The trimming process was done with a minimum time to minimize the loss of soil's moisture prior to the test.

3.3.2.2 Saturation

To achieve the full saturation state of the soil samples, the back-pressure controller was used to force air into the solution. During the sample saturation process, the cell pressure and back-pressure were applied simultaneously and the difference between the cell pressure and back-pressure was kept as 10 kPa, as shown in Figure 3.

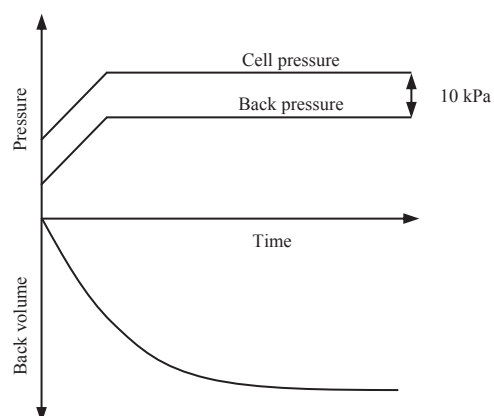


Figure 3. Specimen saturation by back-pressure (modified after Sean, 2013).

Table 2. Summary of undrained compression triaxial tests for Bangkok clay.

Test No.	Initial p' (kPa)	q (kPa)	OCR	Frequency (Hz)	Type of Test
NC series					
MONO_OCR1	300.0	-	1.0	-	Monotonic compression
DYN_2Hz_74kPa_OCR1	300.0	74.0	1.0	2.0	Constant cyclic amplitude compression
DYN_4Hz_74kPa_OCR1	300.0	74.0	1.0	4.0	Constant cyclic amplitude compression
DYN_2Hz_120kPa_OCR1	300.0	120.0	1.0	2.0	Constant cyclic amplitude compression
DYN_4Hz_120kPa_OCR1	300.0	120.0	1.0	4.0	Constant cyclic amplitude compression
DYN_2Hz_153kPa_OCR1	300.0	153.0	1.0	2.0	Constant cyclic amplitude compression
DYN_4Hz_153kPa_OCR1	300.0	153.0	1.0	4.0	Constant cyclic amplitude compression
OC series					
MONO_OCR2	150.0	-	2.0	-	Monotonic compression
DYN_2Hz_OCR2	150.0	59.9 - 91.2	2.0	2.0	Stepped cyclic compression
DYN_4Hz_OCR2	150.0	56.7 - 82.0	2.0	2.0	Stepped cyclic compression
MONO_OCR4	75.0	-	4.0	-	Monotonic compression
DYN_2Hz_OCR4	75.0	62.7 - 94.1	4.0	4.0	Stepped cyclic compression
DYN_4Hz_OCR4	75.0	53.9 - 87.8	4.0	4.0	Stepped cyclic compression

The confirmation of soil sample saturation was carried on by checking the Skempton B-value (refer to Eq. 2). The B-value was determined using Δu and $\Delta \sigma_3$, as illustrated in Figure 4. The minimum B-value of 0.95 was used for the determination of sample saturation.

$$B = \Delta u / \Delta \sigma_3 \quad (2)$$

Where: Δu is pore pressure change, and
 $\Delta \sigma_3$ is cell pressure change.

3.3.2.3 Isotropic consolidation

To fully control the stress history of the soil, the isotropic consolidation can be divided into two phases, including (i) the normally consolidation phase and (ii) the rebound phase. To ensure the soil was in the normally consolidation phase, the confining pressure was applied in an amount higher than the pre-consolidation pressure determined by the oedometer tests.

The complete consolidation is achieved when the excess pore pressure is fully dissipated (see Figure 5). The consolidation process of the Bangkok soft clay used in this study usually took 3 to 5 days to achieve a 95% degree of consolidation or higher.

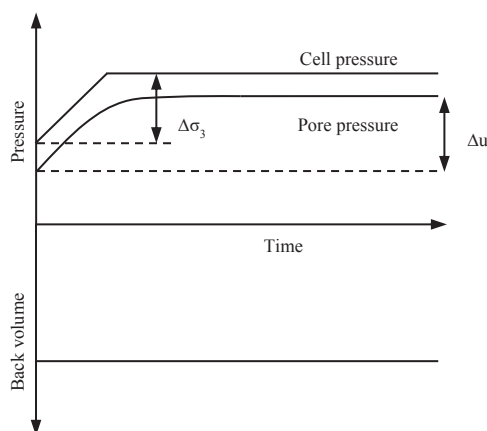


Figure 4. Specimen saturation by back-pressure (modified after Sean, 2013).

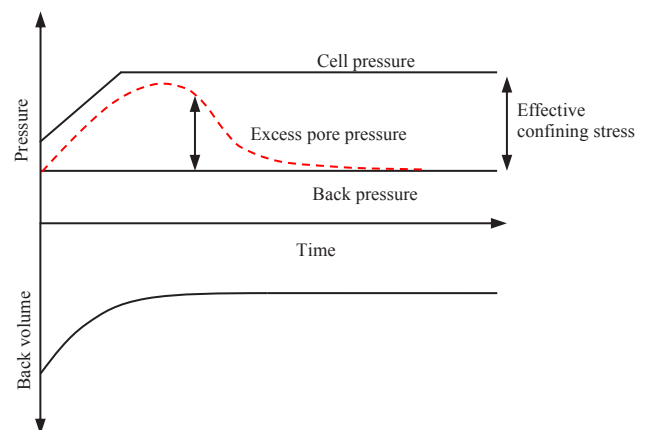


Figure 5. Specimen saturation by back-pressure (modified after Sean, 2013).

After the completion of the first phase of the consolidation, a lower effective confining pressure was applied in the test to allow the sample to swell under the rebound phase (refer to Figure 6). The sample was considered as over-consolidated at this phase.

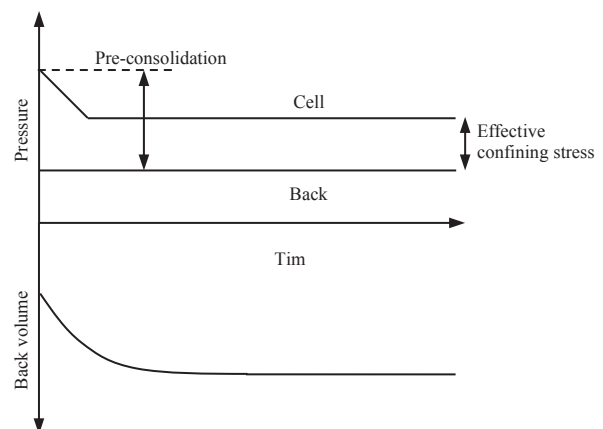


Figure 6. Plot of pressures vs. time during the rebound phase.

3.3.2.4 Cyclic undrained compression

In the cyclic undrained compression tests, the specimen was subject to axial loading and unloading under constant cell

pressure conditions. Any drainage was not allowed throughout the dynamic loading steps, and the variation of pore water pressure was measured at the bottom of the specimen at a regular interval (10 times per cycle) within each cycle.

The stress-controlled cyclic compression loading was used in this study. Figure 7 shows the load cell measurements during the stress-controlled cyclic compression loading tests. The loading amplitude and the datum of the sinusoidal cyclic axial stress were set to be equal (refer to Figure 7). The purpose of this setting is to prevent the tension force from occurring throughout the cyclic compression process.

3.3.3 Determination of cyclic threshold stress

In this study, the Equilibrium State Line method referenced in Loh (2011) was used to identify the threshold stress. For the normally to slightly over-consolidated clays (i.e. $OCR = 1 - 2$). The threshold stress of each series was determined by the intersection between the Line of Cyclic Stress Equilibrium State (LCSES) and the Critical State Line (CSL), which can be obtained by monotonic compression test in the p' - q diagram.

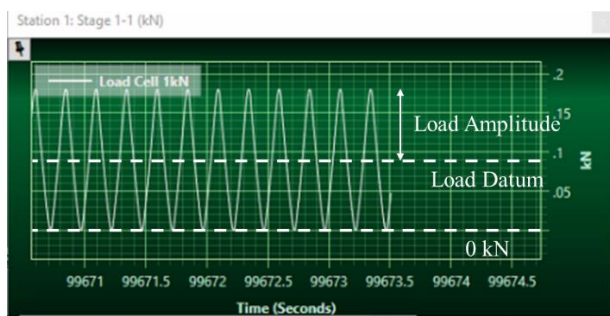


Figure 7. Load cell measurements during cyclic compression triaxial tests.

For the over-consolidated clays, the threshold stress was identified by a gradually increase of cyclic compression stress till the soil sample was failed under large strain conditions.

There are two methods used in this study to increase the stress level until the failure of soil was observed. The first method is called the “constant cyclic stress amplitude loading method”. This first method was used in the dynamic compression tests for the normally consolidated clay in the study. This method was conducted by applying only one stress level to the sample resulting in constant cyclic shear stress throughout the loading step (see Table 2 for the NC series). Then after the resilient state was achieved (i.e., no further development in both plastic strain and excess water pressure), the cyclic triaxial test was repeated from the beginning with a new undisturbed soil sample for a higher applied stress level.

The second method is called the “stepped loading method”. The stepped loading method was used in the dynamic compression tests for the over-consolidated clay. When the sample had reached a resilient state, the cyclic stress was increased to shear the sample further until the failure of the soil was observed. Thus, the threshold of stress was obtained. This method helps to obtain the threshold stress by using only one sample for the entire stress cycle instead of using one sample per one stress cycle (see Figure 8).

4 EXPERIMENTAL RESULTS

4.1 Monotonic triaxial tests

The monotonic compression tests were conducted for both the NC series and OC series. The details of the tests for each series are referred to in Table 2. The constant strain rate loading was used to apply the axial compression loading via a load frame to

the soil specimen. Figure 9 shows the results of the monotonic compression tests for three samples with OCR values of 1, 2, and 4. As shown in Figure 9, the maximum deviator stress values of 166.74, 128.09, and 118.55 kPa were obtained for the samples with OCR values of 1, 2, and 4, respectively.

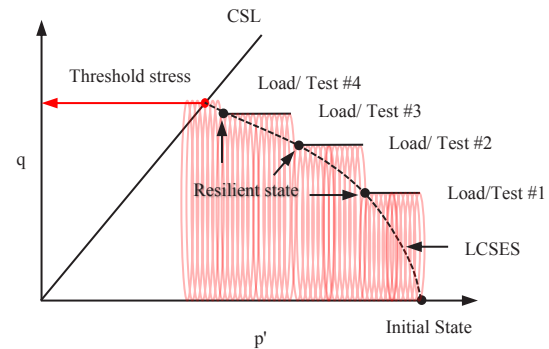


Figure 8. Stress paths of a dynamic triaxial test in p' - q diagram.

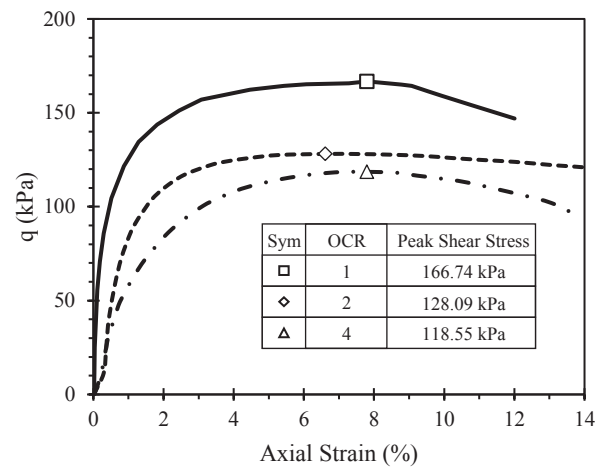


Figure 9. Test results of the monotonic undrained compression.

The critical state line can be obtained by plotting the results of the monotonic triaxial compression tests on the p' - q diagram. Figure 10 plots the results of the tests in the p' - q diagram for the samples with OCR values of 1, 2, and 4. The slope of the critical state line using the data presented in Figure 10 was estimated to be approximately 0.72. The slope of the critical state line was used for the determination of cyclic threshold stress in Section 4.2.

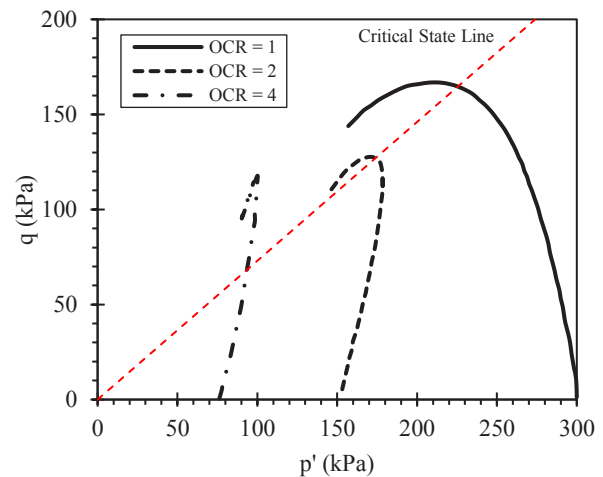


Figure 10. Stress paths of the monotonic triaxial tests in p' - q space.

4.2 Cyclic triaxial tests

The cyclic triaxial compression test program was listed in Table 2. The results presented in this section were divided into two test series, including (i) NC series and (ii) OC series. The results of the tests for the series are provided in the following sections.

4.2.1 NC series

The developments of total axial strain and excess pore water pressure for the samples of the NC series with both 2 Hz and 4 Hz loading frequencies are presented in Figure 11. Figure 11 indicates that, for the cases with the deviator stresses, σ_d , of 74 and 120 kPa, the non-failure condition was observed for the number of cycles of up to 10,000 cycles. The resilient state was observed for these tests. When the soil samples were subjected to deviator stress of 153.0 kPa, the axial strain and excess pore pressure rapidly developed. These phenomena were described in the literature as “Cyclic Softening” when the development of significant strain or strength loss is observed in fine-grained soils exhibiting clay-like behavior (Eric, 2016). As shown in Figure 11, the failure was observed at approximately 400 and 2000 loading cycles for 2 Hz and 4 Hz load frequencies, respectively.

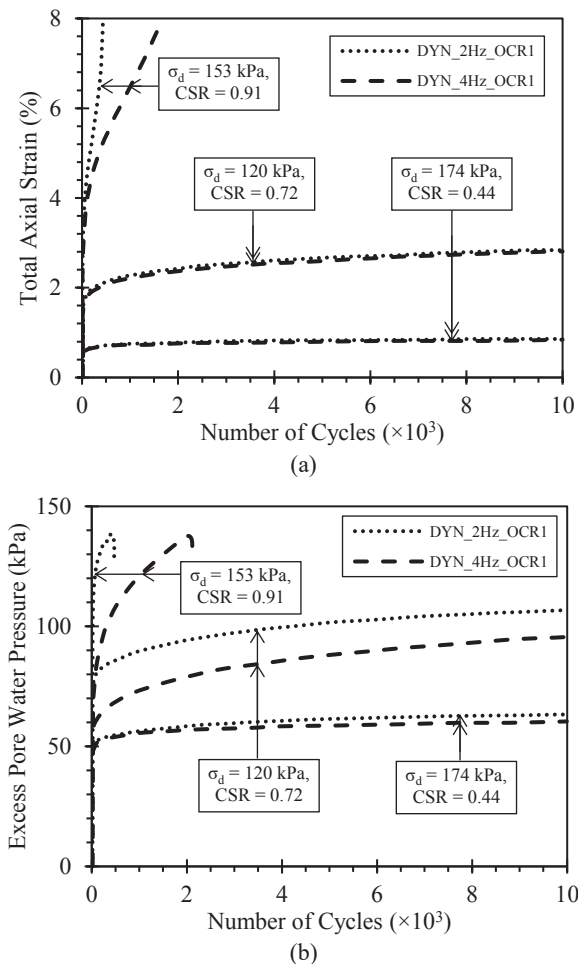


Figure 11. Developments of (a) total peak strain and (b) excess pore water pressure over each cycle for various CSR values.

The peak stress paths of all the tests for the soil samples under the failure and stable conditions were combined in Figure 12. Figure 12 includes the results for the tests with 2 and 4 Hz load frequencies. A line of equilibrium state (LCSES) was drawn by connecting the equilibrium stress points of each test. The line of equilibrium state (LCSES) represents the peak level of stress path where the excess pore water pressure becomes stabilized, and

total axial strain remains fairly constant after a certain number of loading. The intersect of the LCSES line, and the critical state line can be utilized to determine the threshold stress of the soil. As indicated in Figure 12, the threshold stress values of the NC samples with 2 and 4 Hz load frequencies were determined to be 134 and 140 kPa, respectively.

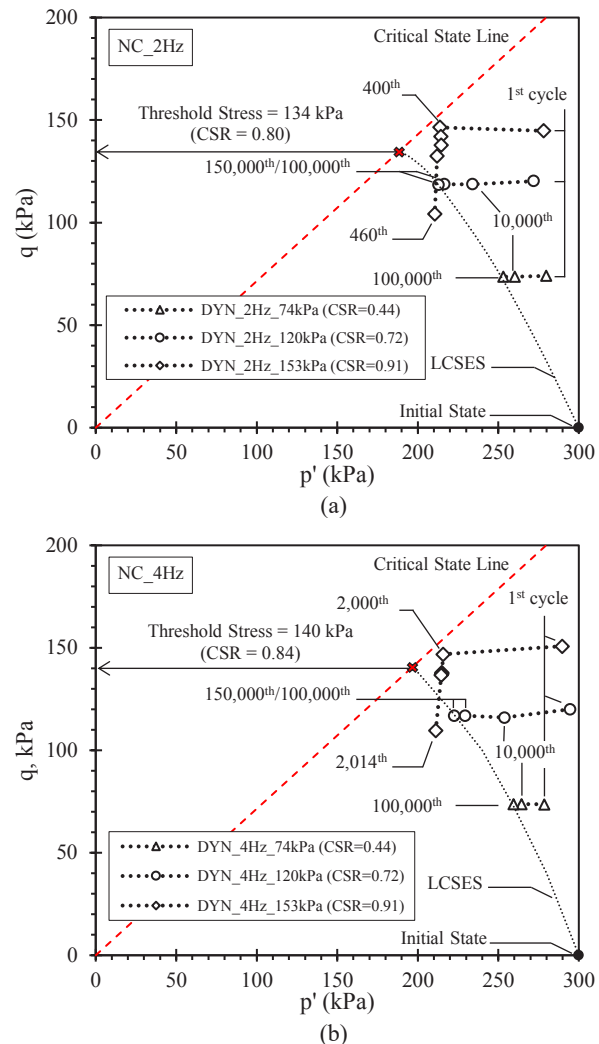


Figure 12. Peak stress path in p' - q diagram for (a) 2 Hz load frequency and (b) 4 Hz load frequency.

4.2.2 OC series

The cyclic triaxial compression tests were performed with the controlled stress history level to evaluate the effect of stress history on the soft clay behavior and threshold stress under cyclic loading. As discussed in Section 3.3.3 for the samples of the OC series, when the resilient state was observed, the stepped loading method was then taken place until the soil sample failed under significant strain conditions.

Figure 13 presents the strain data developed in the cyclic triaxial tests with a frequency of 4 Hz for the OC samples with OCR values of 2 and 4. The strain of each test was developing while the cyclic stress was employed. After the soft clay sample reached the resilient state or the equilibrium state, the cyclic stress was increased by increasing the loading magnitude. The stepped loading was repeated until the soil failure was observed as the significant strain developed over the load cycle.

A summary of threshold stress of the Bangkok soft clay under different stress history and loading frequency were summarized in Table 3. Table 3 includes the computed values of the cyclic stress ratio (CSR), which is defined as the threshold stress under cyclic loading conditions divided by the shear strength under

monotonic loading conditions. For the entire samples of the NC and OC series, the CSR values range from 0.67 to 0.84. This finding is consistent with the common range of the threshold stress observed for high plasticity soft clay (Lefebvre, 1988 and Loh, 2011). The OC soil samples with OCR = 2 and OCR = 4 have CSR values of 0.67 to 0.71, whereas the NC soil samples have CSR values of 0.80 to 0.84. It was observed that the threshold stress tends to decrease when the over-consolidation ratio increases.

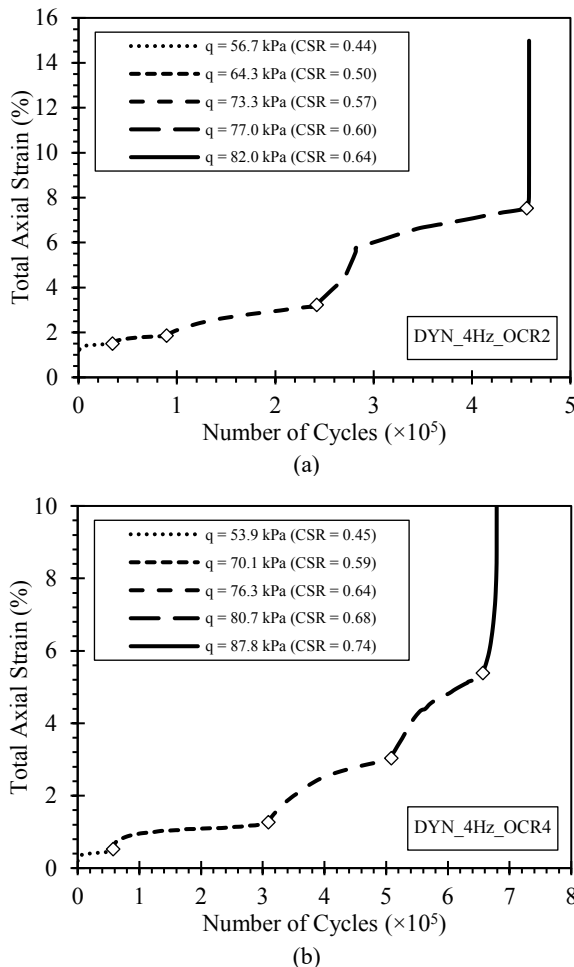


Figure 13. Developments of total peak strain vs. time for various CSR values (a) frequency = 4 Hz and OCR = 2 and (b) frequency = 4 Hz and OCR = 4.

Table 3. Cyclic threshold stresses of Bangkok soft clay.

Test No.	Monotonic Strength (kPa)	Threshold Stress (kPa)	CSR
DYN_2Hz_OCR1	166.74	134	0.80
DYN_4Hz_OCR1		140	0.84
DYN_2Hz_OCR2	128.09	91	0.71
DYN_4Hz_OCR2		85	0.67
DYN_2Hz_OCR4	118.55	81	0.68
DYN_4Hz_OCR4		82	0.70

5 CONCLUSIONS

This paper presented the results of the threshold stress evaluation for the Bangkok soft clay under cyclic loading. The following conclusions were drawn from the findings of the study:

- The threshold stress of clayey soil under cyclic loading is dependent on the stress history of the soil. This study indicates that the threshold stresses are approximately 80% and 70% of the undrained shear strength under static loading for the NC and OC soft clays, respectively.
- Over-consolidation tends to decrease the CSR compared to those obtained for the NC clay. It was found that the critical cyclic stress ratio decreases by approximately 16% with an increase of OCR from 1 to 4.
- The cyclic stress lower than the threshold stress of soft soil could cause the resilient behavior of the soil. When the soft clay is subject to the cyclic shear stress higher than its threshold stress, the failure of the soil is expected with rapid strain and excess pore water pressure development. This failure mechanism of soft fine-grained soils under cyclic loading is known as cyclic softening when the accumulative strain is rapidly developed and the soil strength is lost over the load application.
- The results of this study concluded that the frequency in the range of 2 to 4 Hz that was used in this study does not significantly affect the threshold stresses or plastic strain.

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