Innovative Infrastructure Solutions (2023) 8:245
https://doi.org/10.1007/s41062-023-01216-4

PRACTICE-ORIENTED PAPER

Cyclic degradation of weakly cemented soil and artificial bedding plane in cyclic ring shear test

Nguyen Van Hai[1] · **Nguyen Thanh Duong**[2,3]

Received: 6 March 2023 / Accepted: 10 August 2023

Abstract
Cyclic degradation is a common phenomenon in the engineering practice of soil dynamics. In the literature, numerous earthquake-induced landslides occurred in slopes of naturally cemented soil or having a pre-existing shear surface. However, the cyclic degradation of naturally cemented soil and soil containing bedding planes needs to be sufficiently clarified, especially in the cyclic ring shear test. This study aims to elucidate the cyclic degradation of cemented soil and artificial bedding planes that simulate the actual slip surfaces using consolidation-constant volume cyclic loading ring shear apparatus. Accordingly, a small content of cement was added to kaolin clay to model the naturally cemented soil. The combined specimens of two halves were employed to simulate the bedding planes. The cyclic ring shear tests were conducted on four types of samples, including two normal samples (0% cement, 2% cement) and two combined samples (2% + 0% cement; 2% + 2% cement) under various test conditions to investigate the effects of normal stress, shear-torque amplitude, and overconsolidation ratio (OCR) on the cyclic degradation. The test results showed that the cyclic degradation parameter of all samples decreased with the increase in normal stress from 98 to 294 kPa, shear-torque amplitude from 30 to 90 kPa, and OCR from 1 to 4. The research results also indicated the significant role of cementation bonding in cyclic degradation behavior. Accordingly, the cyclic degradation of 2% cement sample is highly sensitive to the increase in normal stress levels, shear-torque amplitudes, and OCR.

Keywords Cyclic degradation · Bedding plane · Cementation · Normal stress · Shear-torque amplitude · OCR

Introduction

It is well known that under seismic loading, the stiffness and strength of soils decrease, and the generation of cyclic pore water pressure increases as the number of cycles (N) increases. The decrease in stiffness and strength with increasing N is known as cyclic degradation. This phenomenon is one of the most fundamental phenomena in the engineering practice of soil dynamics. Under cyclic loading, the stiffness and strength of saturated sandy soil can be completely lost, called liquefaction. So far, the cyclic degradation and generation of excess pore water pressure in different soil types under cyclic loading have been widely investigated [1–10]. In general, these investigations were conducted on cyclic triaxial, cyclic simple shear, or multi-directional cyclic simple shear apparatuses. The research results of these studies have shown that the number of cycles, frequency, and cyclic strain amplitude is the main factors affecting cyclic degradation and the build-up of pore water pressure. In addition, the cyclic degradation and cyclic pore water pressure generation during seismic loading significantly depend on the types of soil and stress history (overconsolidation ratio, OCR). Typically, Mortezaie and Vucetic [2] investigated the effect of frequency and normal stress on the cyclic degradation of clay using cyclic simple shear apparatus (NGI). The research results indicated that the degradation parameter, t, increased as the frequency increased from 0.001 to 0.1 Hz, and the normal stress increased from 216 to 680 kPa. Vucetic and Dobry [8], Matasovic and Vucetic [10] examined the cyclic degradation of different marine clays and VNP clay at OCR from 1 to 4 using the cyclic triaxial test. They reported that the cyclic degradation parameter of studied clays decreased with the increase in OCR from 1 to 4.

✉ Nguyen Thanh Duong
nguyenthanhduong@humg.edu.vn

[1] Mientrung University of Civil Engineering, Tuy Hoa, Vietnam

[2] Hanoi University of Mining and Geology, Hanoi, Vietnam

[3] Research Group of Engineering and Geoenvironment (EEG), Hanoi University of Mining and Geology, Hanoi, Vietnam

Published online: 23 August 2023

As recorded, earthquake-induced slope failures and landslides in naturally cemented clays occur frequently in many parts of the world. In particular, the natural slopes which contain a pre-existing shear surface (rupture, bedding plane, interface) are susceptible to failure, especially under earthquake loading [11–16]. Thus, the effect of earthquake-induced loading on the shear strength of cemented soil and shear strength mobilized along the bedding plane of naturally cemented soil slopes needs to be clarified. The cyclic degradation of naturally cemented soil has been examined using the cyclic triaxial test by some authors [17–19]. However, the cyclic degradation of cemented soil in natural slopes has rarely been evaluated. Additionally, the investigation of cyclic degradation of cemented soil using ring shear test has not been conducted yet. Suzuki et al. [20] investigated the shear behavior of cemented sand under seismic loading in ring shear apparatus, but no information about cyclic degradation was reported. As mentioned above, the cyclic degradation of different types of soil has been investigated. Nevertheless, the cyclic degradation was only evaluated based on cyclic triaxial test and NGI cyclic simple shear test. Therefore, the responses of cemented clays and soil containing a pre-existing shear surface subjected to earthquake-induced dynamic loading need to be conducted, especially in cyclic ring shear tests.

This study introduced a cyclic ring shear apparatus to investigate the cyclic strength degradation of non-cemented and cemented kaolin clay. Laboratory-simulated cementation was artificially reproduced by adding a cementing agent to kaolin clay. A series of cyclic ring shear tests were performed on reconstituted non-cemented and cemented kaolin clay specimens. Besides, the cyclic ring shear test was conducted on samples which are consisted of two halves to simulate the pre-existing shear surface in the soil layer. The cyclic experiments were conducted under different conditions to investigate the effect of parameters such as normal stress, shear-torque amplitude, and stress history (OCR) on the cyclic degradation mechanism.

Cyclic degradation index

When soils are subjected to cyclic loading in undrained conditions, their stiffness and strength decrease, accompanied by pore water pressure changes with the number of cycles. This decrease phenomenon of stiffness and strength is defined as cyclic degradation and is expressed in Fig. 1. For evaluation of cyclic degradation, the degradation index, ζ, and degradation parameter, t, were first introduced by Idriss et al. [21]. In cyclic shearing, the secant shear modulus, G_{sN}, is defined as follows:

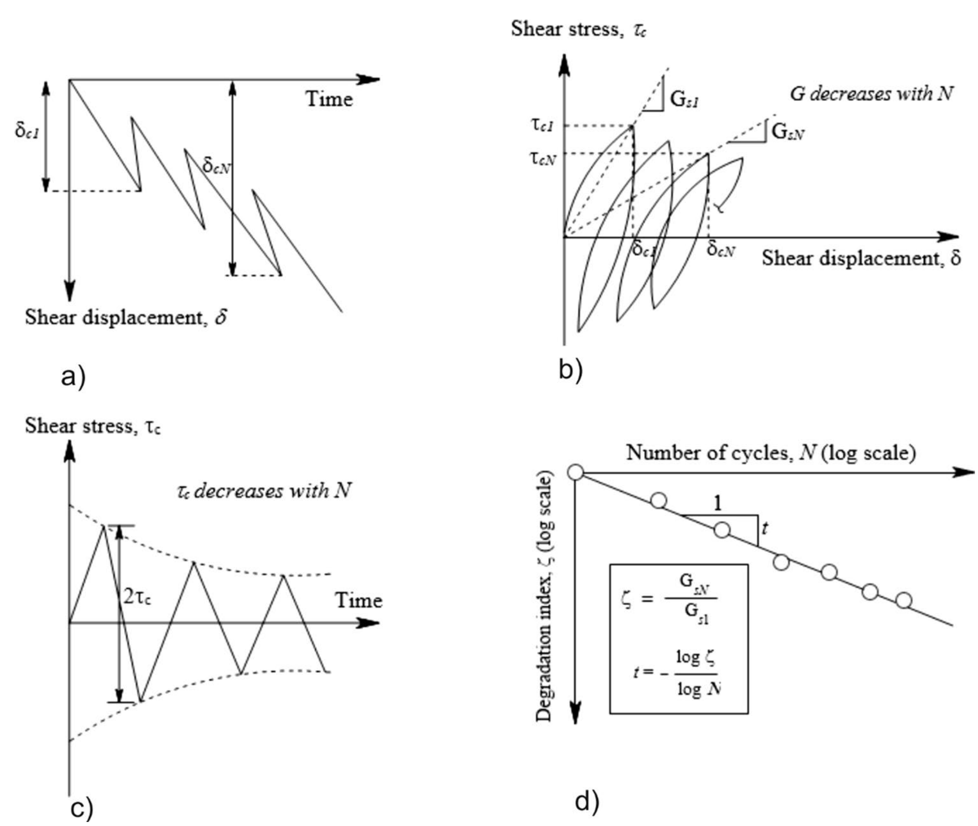

Fig. 1 Schematic diagram illustrating the phenomenon of cyclic degradation

$$G_{sN} = \frac{\tau_{cN}}{\gamma_{cN}} \tag{1}$$

γ_{cN}: cyclic shear strain amplitude in the Nth cycle.

τ_{cN}: the average of cyclic shear resistance in the Nth cycle.

In the cyclic strain-controlled mode, the degradation index can be expressed as follows:

$$\zeta = \frac{G_{sN}}{G_{s1}} = \frac{\tau_{cN}/\gamma_c}{\tau_{c1}/\gamma_c} = \frac{\tau_{cN}}{\tau_{c1}} \tag{2}$$

In the cyclic stress-controlled mode, the cyclic degradation with N can be defined with the degradation index, ζ^*, which is the same as ζ [2].

$\zeta^* = \frac{G_{sN}}{G_{s1}} = \frac{\tau_{cN}/\gamma_{cN}}{\tau_{cN}/\gamma_{c1}} = \frac{\gamma_{c1}}{\gamma_{cN}} = \frac{\delta_{c1}}{\delta_{cN}}$ 3).

δ: shear displacement is defined as an intermediate circular art between the inner and outer rings.

δ_{c1}, δ_{cN}: shear displacement at cycles 1 and N.

$\delta_{c1} = \delta_{cN}$ in the first cycle of the shearing process.

The relationship between ζ and N in a log–log scale (Fig. 1d) for many clays is approximately a straight line. The slope of this line is the degradation parameter, t, under the applied constant shear-torque τ_c. The degradation parameter, t, is determined as follows:

$$t = -\frac{\log \zeta^*}{\log N} \tag{4}$$

The degradation parameter, t, is one of the essential parameters to access the cyclic degradation in the process of the continuously increasing number of cycles, N. This parameter has been extensively used in previous research to evaluate the cyclic degradation of many clays [2, 7, 10, 18, 19].

Material and method

Test apparatus

In this study, a consolidation-constant volume cyclic loading ring shear test apparatus was used to investigate the cyclic degradation. Figure 2 shows the test apparatus, which is almost similar to the Bishop-type apparatus [22]. The cyclic ring shear apparatus includes a pneumatic servo controller, two bellofram cylinder, data logger, and a computer for data recording. This apparatus uses ring-shaped specimens which has an inner diameter of 4.2 cm, an outer diameter of 7 cm, and a wall thickness of 2 cm. The maximum shear speed in the center of the sample is 10 cm s^{-1}, maximum frequency of cyclic loading is 5 Hz. The specimen is sheared by rotating the lower half of the shear box in both directions, while the upper half of the shear box is restrained by two resistance transducers, from which shear resistance is measured. During shearing, the shear stress, normal stress, and horizontal and vertical displacement were all measured and automatically recorded. However, the generation of pore water pressure during shearing is not measured in this apparatus. Thus, the samples will be sheared under the drained condition.

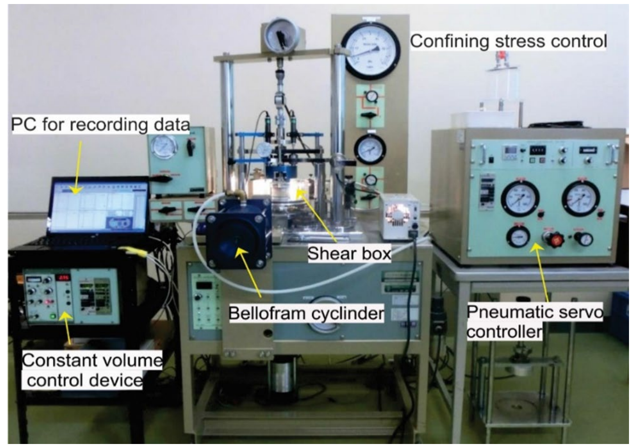

Fig. 2 Cyclic ring shear apparatus

Table 1 Some physical properties of kaolin and cemented kaolin clay [25]

Sample	Index	Value
Kaolin	Liquid limit (%)	62
	Plasticity index	21.8
	Clay fraction (< 2 μm) (%)	35.3
Kaolin	Specific gravity (g cm^{-3})	2.618
2% cemented kaolin clay		2.620

Specimen preparation

In this study, commercial common kaolin clay in the form of powder was used to ensure purity and uniformity. Some physical properties of the sample are given in Table 1. To create weakly cemented soil, a small content of OPC cement (2% cement) was used for preparing artificial cementation [23]. The specimen used in the cyclic ring shear apparatus has an outer diameter of 7 cm, an inner diameter of 4.2 cm, and a height of 2 cm. Two types of specimens were employed to investigate the cyclic degradation of weakly cemented soil and soil containing the bedding plane, including normal and combined specimens. The combined specimen is comprised of 2 halves with 1 cm in height for each half. This study used four types of specimens, including two normal specimens (pure kaolin, 2% cement) and two

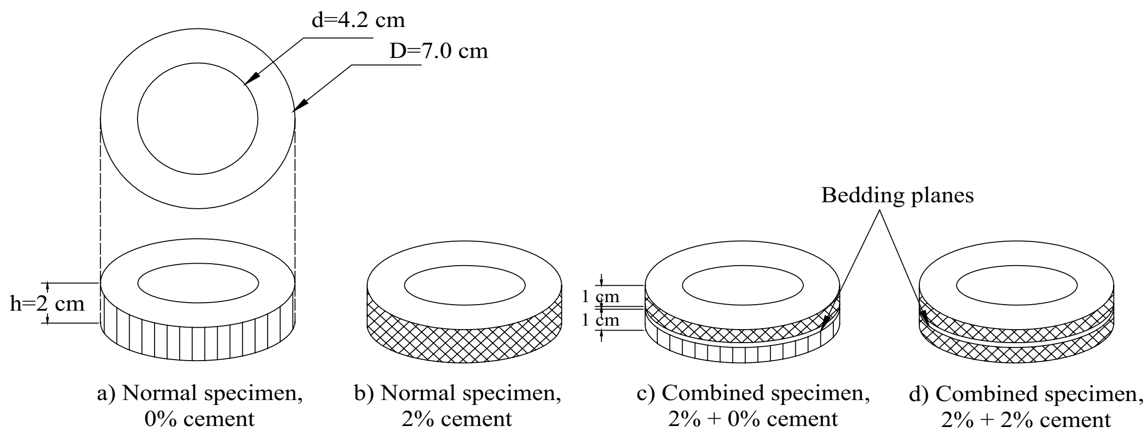

Fig. 3 Normal and combined specimens showing the bedding plane used in this study

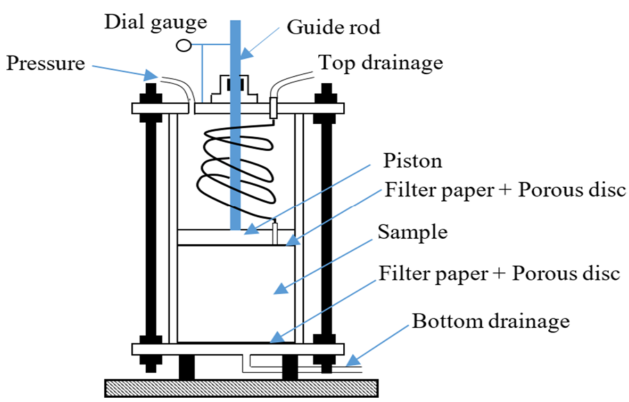

Fig. 4 Consolidation tank for sample preparation [27]

combined specimens (2% + 0% cement, 2% + 2% cement), as shown in Fig. 3.

In this study, a pre-consolidation method was used to create the sample for the cyclic ring shear test. This method for sample preparation has been conducted and reported in previous studies [24–27]. Accordingly, the dry powder kaolin was mixed with distilled water in the form of a slurry with a water content of about 1.5 times its liquid limit. For cemented samples, 2% cement was added to the slurry of kaolin. The sample in the form of the slurry was then poured into a large consolidation tank (Fig. 4). The air bubbles inside the slurry were released by applying a vacuum pressure of about 70 kPa for 1 h. The slurry was then preconsolidated under the desired pressures until the primary consolidation stage was finished. The samples, after pre-consolidation, were cut and trimmed to produce the ring-shaped specimens with the size mentioned above.

Test procedure

The testing parameters for cyclic ring shear are listed in Table 2. The ring-shaped specimens, after preparation, were placed in the ring shear box and re-consolidated under different normal stress levels of 98 kPa, 196 kPa, 294 kPa, and 392 kPa before testing. After consolidation, a reversal shear stress with a shear-torque amplitude of 30, 60, and 90 kPa and a loading frequency of 0.5 Hz was applied. After each test, the ratio of the maximum cyclic shear resistance to the normal stress (τ_{cN}/σ_{No}) was measured at the last cycle of loading to compare the obtained results for different specimens. To maintain a constant volume condition of the specimen, the normal stress was gradually reduced during testing. As reported by Suzuki et al. [20], the cyclic failure of the specimen occurred when the shear displacement reached around 2 mm.

Table 2 Testing conditions for cyclic ring shear

Sample	Testing parameters			
	OCR	Normal stress (kPa)	Shear-torque amplitude (kPa)	Frequency (Hz)
0% cement	1, 2, 3, 4	98, 196, 294, 392	30, 60, 90	0.5
2% cement	1, 2, 3, 4	98, 196, 294, 392	30, 60, 90	0.5
2% + 0% cement	1	98, 196, 294	30, 60, 90	0.5
2% + 2% cement	1	98, 196, 294	30, 60, 90	0.5

Test results and discussions

Test results

In this study, a total of 26 cyclic ring shear tests were conducted. Typical results of cyclic loading behavior are presented in Fig. 5. This figure presents the typical results of cyclic loading behavior, depicting time series data of normal stress, shear stress, and shear displacement. The results of all the cyclic ring shear tests are summarized in Table 3. Table 3 also presents the test data for 0% cement and 2% cement samples, which were consolidated at different OCR values. In this table, the value of the degradation parameter, t, was calculated at the cycle of 20 (t_{20}). In the cyclic ring shear test, it was assumed that the failure of the sample occurred at the shear displacement, δ, of 2 mm [20].

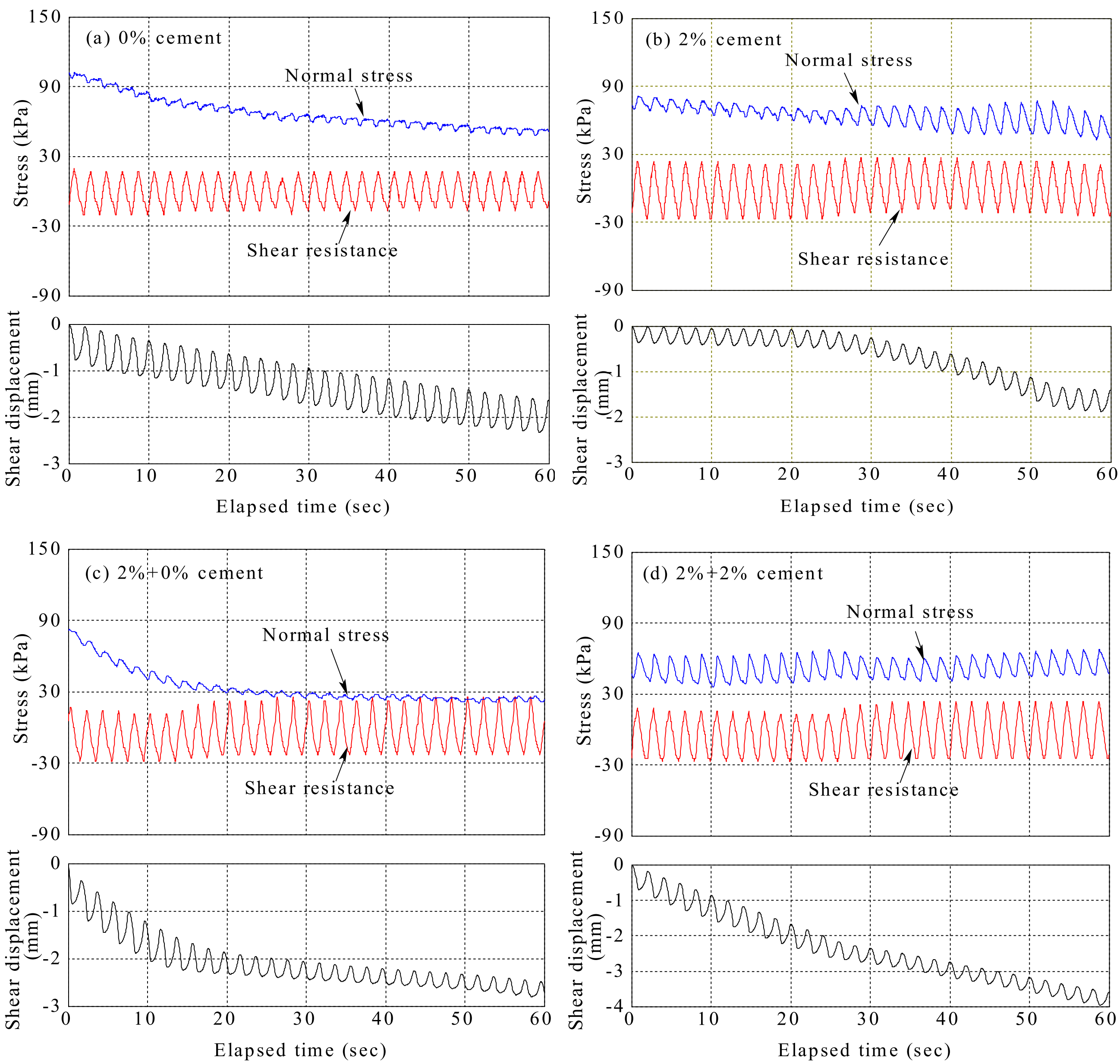

Fig. 5 Typical test data on 0%, 2%, 2% + 0%, and 2% + 2% cemented kaolin specimens: f = 0.5 Hz; shear-torque amplitude = 60 kPa; normal stress = 196 kPa

Table 3 Test results of cyclic ring shear test

Sample	No. Test	σ_c (kPa)	σ_N (kPa)	OCR	Shear-torque amplitude (kPa)	τ_f (at $\delta = 2$ mm) (kPa)	(τ_{cN}/σ_{No})	Degradation parameter, t (at $N = 20$)
0% cement	1	98	98	1.0	30	17.0	0.174	0.522
	2	98	98	1.0	60	11.4	0.116	0.441
	3	98	98	1.0	90	14.2	0.145	0.462
	4	196	196	1.0	60	22.7	0.116	0.376
	5	294	294	1.0	60	28.4	0.097	0.304
	6	196	98	2.0	90	12.8	0.130	0.427
	7	294	98	3.0	90	15.6	0.159	0.414
	8	392	98	4.0	90	19.9	0.203	0.343
2% cement	1	98	98	1.0	30	17.0	0.174	0.815
	2	98	98	1.0	60	17.0	0.174	0.440
	3	98	98	1.0	90	14.2	0.145	0.456
	4	196	196	1.0	60	21.3	0.109	0.351
	5	294	294	1.0	60	31.2	0.106	0.180
	6	196	98	2.0	90	21.3	0.217	0.417
	7	294	98	3.0	90	24.1	0.246	0.401
	8	392	98	4.0	90	31.2	0.319	0.189
2% + 0%cement	1	98	98	1.0	30	12.8	0.130	0.506
	2	98	98	1.0	60	15.6	0.159	0.454
	3	98	98	1.0	90	17.0	0.174	0.381
	4	196	196	1.0	60	15.6	0.080	0.429
	5	294	294	1.0	60	21.3	0.072	0.400
2% + 2% cement	1	98	98	1.0	30	18.5	0.188	0.617
	2	98	98	1.0	60	21.3	0.217	0.504
	3	98	98	1.0	90	21.3	0.217	0.427
	4	196	196	1.0	60	27.0	0.138	0.388
	5	294	294	1.0	60	29.8	0.101	0.324

* σ_c: Consolidation pressure (kPa); σ_N: Normal stress (kPa); OCR: Overconsolidation ratio

Effect of normal stress on the cyclic degradation

*Effect of normal stress on the normalized cyclic stress ratio

In this study, the normalized cyclic stress ratio (NCSR) is defined as the ratio of maximum shear resistance at each cycle (τ_{cN}) to the initial effective normal stress (σ_{N0}). Figure 6 shows the normalized cyclic stress ratio (τ_{cN}/σ_{N0}) versus the number of cycles under the different normal stress levels. It can be seen from this Figure that the τ_{cN}/σ_{N0} increases with the decrease in the number of cycles (N) at a constant vertical consolidation value under a shear displacement of 2 mm. Conversely, the NCSR of pure kaolin (0% cement) seems not to be influenced by increasing normal stress, which demonstrates an approximately straight line as the number of cycles increases. The τ_{cN}/σ_{N0} and N_f curve for 2% and 2% + 2% cemented specimens was almost approximately similar and higher than that for other samples. This indicates that the effect of cementation on the cyclic stress ratio is identified and remained to a certain degree, even in discontinuous planes. It can be stated that the increasing

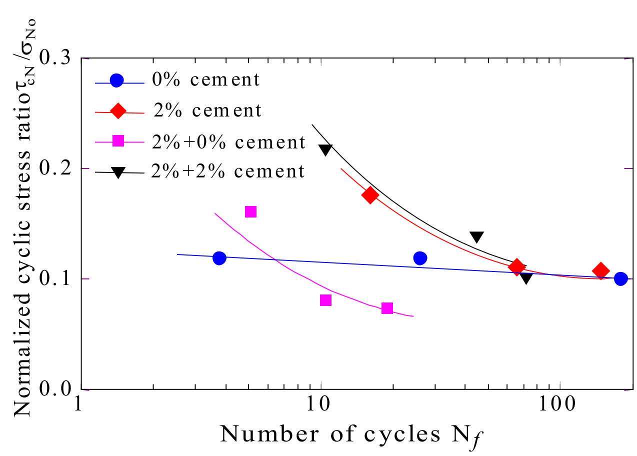

Fig. 6 Normalized cyclic stress ratio versus the number of cycles under the different normal stress at shear displacement, $\delta = 2$ mm

cyclic stress ratio is due to the addition of cement into the kaolin clay, which increases the hardness and bonding inside the specimen that influences on cyclic behavior of cemented kaolin. As the number of cycles increases approximately beyond 100, τ_{cN}/σ_{N0} of 0%, 2%, and 2% + 2% seem to be identical. This trend may be due to the complete damage of cementation by increasing a great number of cycles, by which the behavior of cemented specimens is like that of non-cemented specimens.

In Table 2, τ_f is the cyclic shear resistance at the shear displacement of 2 mm. The relationship between τ_f/σ_{N0} and normal stress is plotted in Fig. 7. As shown, the τ_f/σ_{N0} decreases as the normal stress increases from 98 to 294 kPa. Similarly, in the static ring shear test, the ratio of shear stress to normal stress was observed to be decreased with the increase in normal stress [22, 28, 29]. Specifically, when the normal stress increases from 98 to 294 kPa, the normalized cyclic stress ratio (NCSR) is decreased by 16.4%, 39.1%, 54.7%, and 53.4% for 0%, 2%, 0% + 2%, and 2% + 2% cemented kaolin specimens, respectively. It can be seen that the decrease in NCSR for two combined specimens (0% + 2% cement and 2% + 2% cement) is almost similar. This is due to the existence of bedding planes inside the specimen. In contrast, with the increase in normal stress from 98 to 294 kPa, the decrease in NCSR for 2% cemented kaolin specimen is over two times higher than that for the pure kaolin (0% cement) specimen. This phenomenon can be attributed to the failure of cementation in 2% cemented specimens. The cementation bonding will enhance the strength of 2% cement sample. However, the cementation bonding can be broken under high-normal stress, resulting in a decrease in shear resistance and NCSR.

*Effect of normal stress on the degradation parameter, t

To investigate the effect of normal stress on cyclic degradation, the cyclic ring shear tests were conducted under different normal stress levels with a shear-torque amplitude of 60 kPa and a frequency of 0.5 Hz. The influence of σ_N on the cyclic degradation is plotted in Fig. 8 for all specimens conducted under different normal stress levels. It can be seen that for all specimens at all normal stress levels, the degradation index, ς^*, decreases with the increasing number of cycles. However, for 0% cement and 2% + 0% cement samples, the tendency of decreasing of degradation index, ς^*, with the number of cycles under different normal stress levels is almost identical, especially for 2% + 0% cement samples. By contrast, for 2% cement and 2% + 2% cement samples, the relationship between the degradation index, ς^*, and the number of cycles under different normal stress levels are significantly different, especially for 2% cement sample. This indicates that the effect of normal stress on the degradation index of the sample with cementation is higher than that of the sample without cementation.

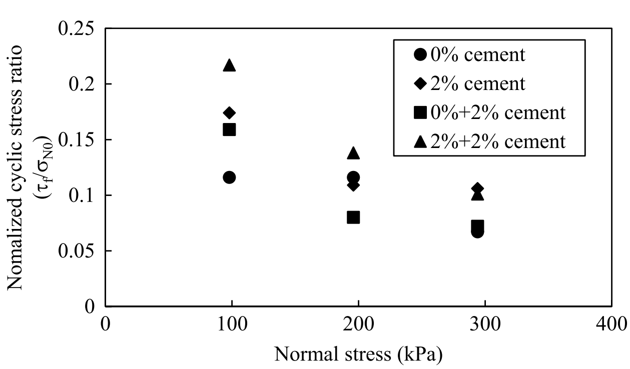

Fig. 7 Relationship between the ratio of τ_f/σ_{N0} and normal stress

The relationship between the degradation parameter, t, at $N = 20$ cycles (t_{20}) and normal stress is presented in Fig. 9. It can be seen that for all samples, the degradation parameter decreases as the normal stress increases from 98 to 294 kPa. This result is well consistent with the result of previous studies [1, 2, 5, 7]. Particularly, Mortezaie [1], Mortezaie and Vucetic [2] showed that in the NGI simple shear apparatus, the cyclic degradation of kaolinite clay was decreased by 20–38% with the increase in effective normal stress from 216 to 680 kPa. The results in Table 3 reveal that when σ_N increases from 98 to 294 kPa (3 times), the parameter, t, decreases by 31.1%, 59.1%, 11.9%, and 35.7% for 0%, 2%, 2% + 0%, and 2% + 2% cement samples, respectively. It can be seen that in this study, the decrease in cyclic degradation of kaolin clay with the increasing of normal stress is within the range of cyclic degradation decrease as reported by Mortezaie [1], Mortezaie and Vucetic [2]. The results of the present study also show that the value t of 2% cement sample is approximately two times higher than that of 0% cement sample. This tendency is similar to the tendency observed for NCSR mentioned above. This can be attributed to the cementation existing in 2% cement sample. In the 2% cement sample, the cementation bonding can be broken under the high vertical normal stress and leading to an increase in cyclic degradation. For 2% + 0% cement sample, the effect of increasing vertical compression on the parameter t is identified not to be significant. This low cyclic degradation may result from a pre-existing shear surface inside the combined specimen. The 2% + 0% cement combined specimen consists of two halves with different degrees of hardening, and the bond between 0 and 2% is not significant. Furthermore, the reorientation of clay particles in the shearing direction of combined specimens was well developed than that of the normal cemented specimens. Therefore, the degradation of 2% + 0% combined specimen was lower than that of the other specimens. Although the 2% + 2% cement also has a pre-existing surface, the value t decreases nearly the

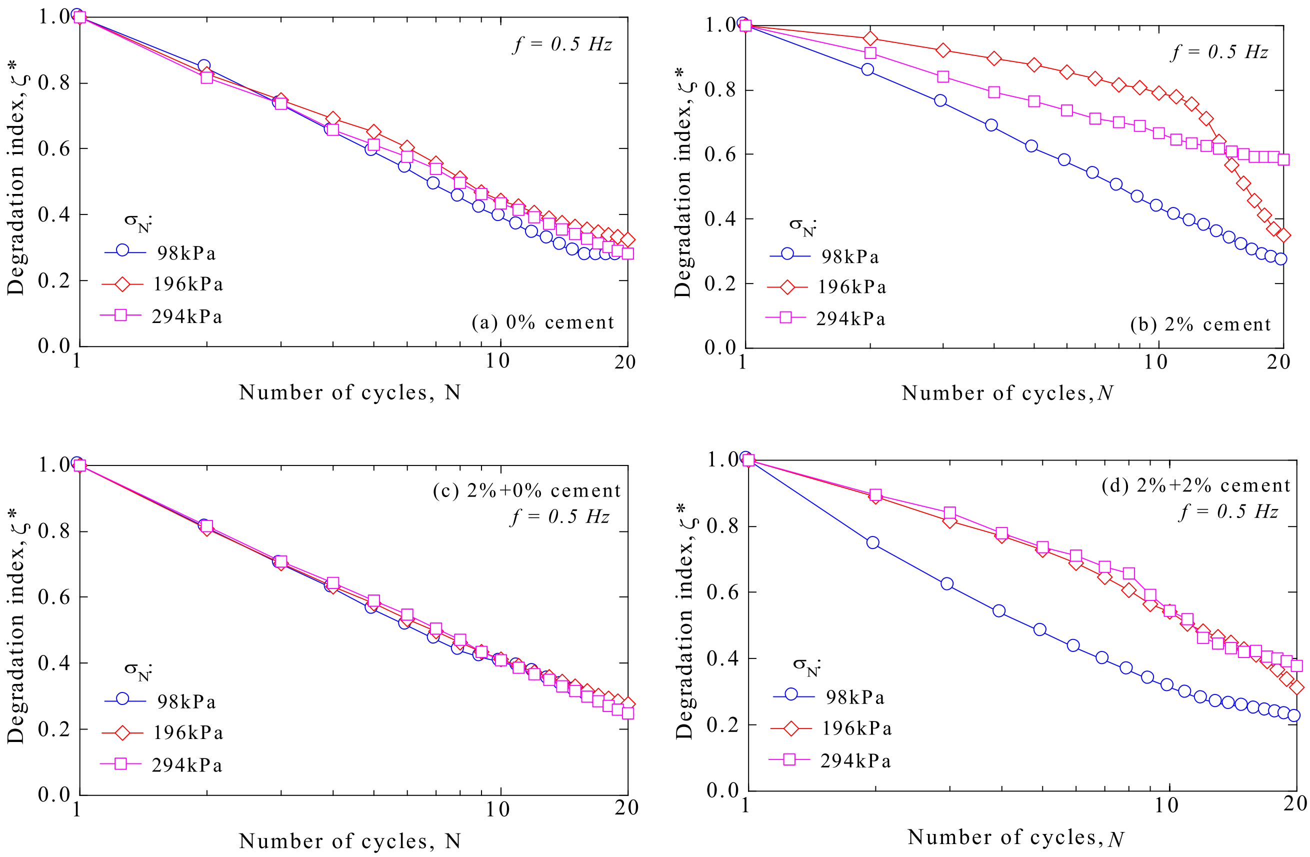

Fig. 8 Relationship between cyclic degradation index, δ^*, and number of cycles, N, for all types of the specimen under different normal stress

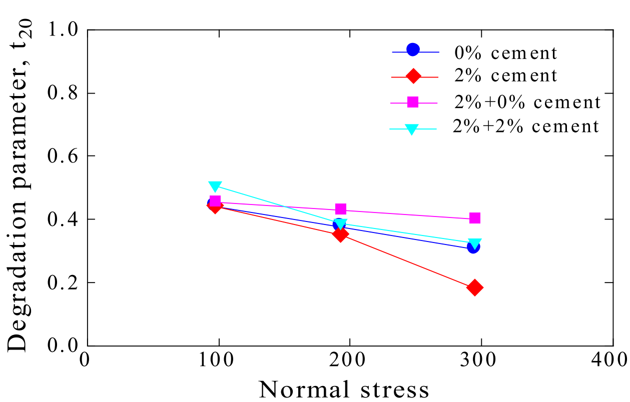

Fig. 9 Effect of σ_N on degradation parameter, t_{20}, for all types of specimen

same with 0% cement sample because the bond is available on two halves of cemented specimens. It is suggested that cohesion remains significant on the bedding plane. Both trends observed for 2% and 2% + 2% cement samples indicate that cementation has a significant effect on cyclic degradation.

Effect of the shear-torque amplitude on the cyclic degradation

In this study, the cyclic shear responses are evaluated at different shear-torque amplitudes at the same cyclic loading frequency of 0.5 Hz. A series of cyclic ring shear tests were conducted under different shear-torque amplitudes (Table 3). The constant normal stress of 98 kPa was adopted through this test series. To analyze the results of the effect of different shear-torque amplitude on the cyclic degradation, the ratio of applied shear-torque to the initial normal stress, $CSR = \tau_c/\sigma_{N0}$, was used in this section. The relationship between the degradation index and the number of cycles at different CSR values is plotted in Fig. 10. It can be seen that for all the specimens, the degradation index nearly linearly decreases with an increase in the number of cycles (N). This tendency is similar to that observed in Matasovic and Vucetic [10]. A detailed comparison of the effect of CSR on the degradation parameter, t, for all types of specimen, is presented in Fig. 11. In this figure, the cyclic degradation at the cycle of 20 (t_{20}) is evaluated. As shown in Fig. 11, the cyclic degradation parameter tends to decrease as the CSR values increase. In which, the degradation parameter for 2% cemented kaolin is seen to be decreased the most in

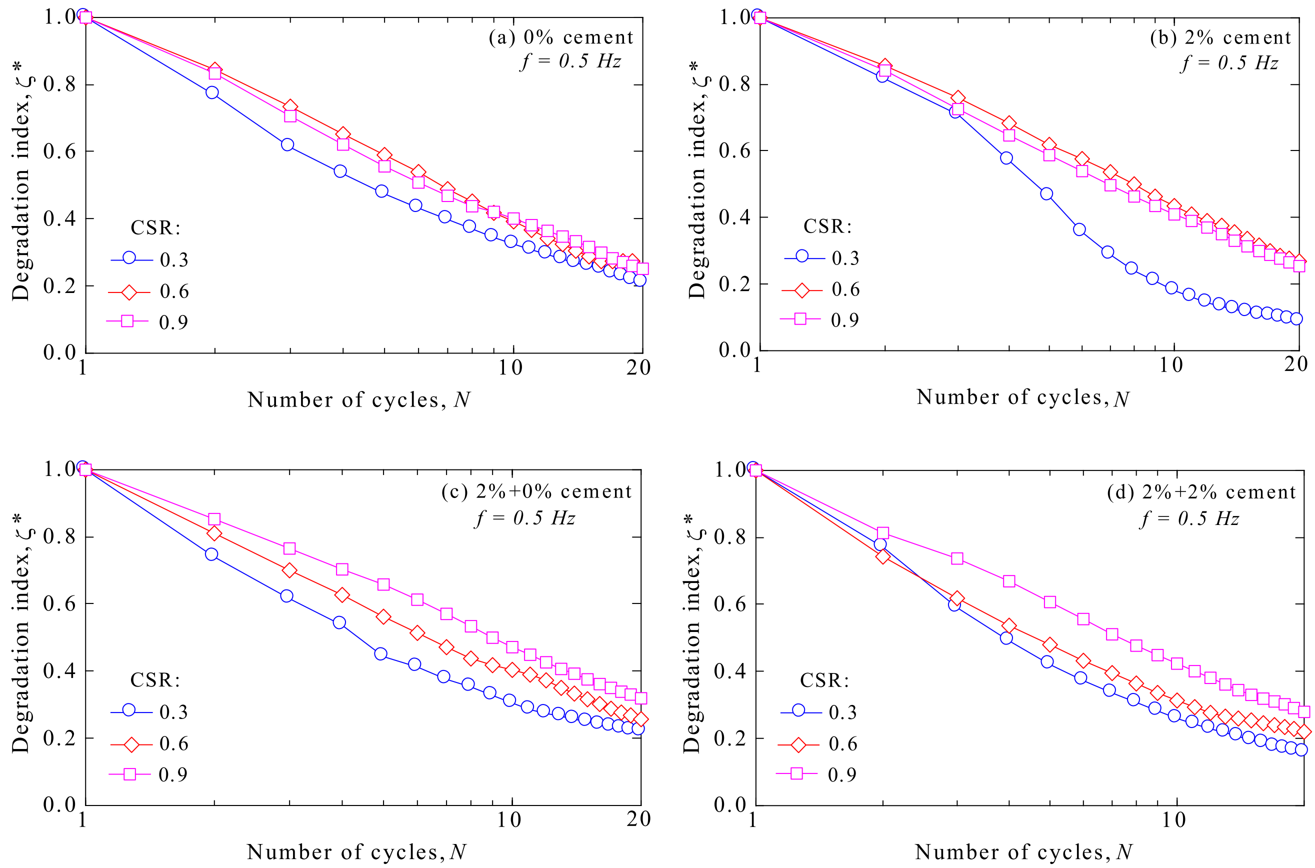

Fig. 10 Relationship between cyclic degradation index, δ^*, and number of cycles, N, for all types of the specimen under different cyclic stress ratios

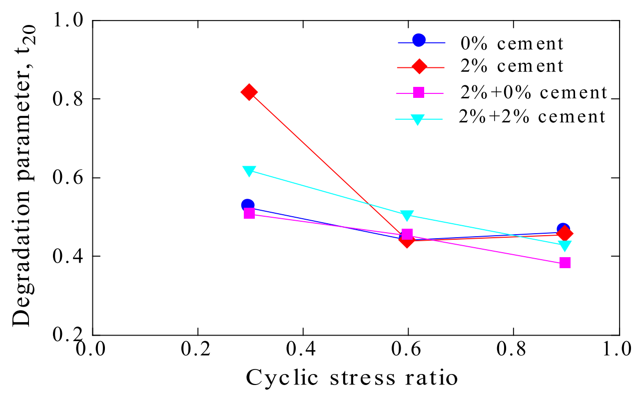

Fig. 11 Effect of cyclic stress ratio, CSR, on degradation parameter, t_{20}

comparison with the other specimens. On the other hand, the decreasing trend of the two combined specimens (2% + 0% cement; 2% + 2% cement) appears to be the same. As the CSR approximately increases from 0.3 to 0.9, the parameter t decreases by 11.5%, 44.0%, 24.7%, and 30.8% for 0%, 2%, 2% + 0%, and 2% + 2% cement samples, respectively.

The highest decrease level of parameter t is observed for 2% cement sample. As mentioned above, the cementation bonding inside cemented sample can be broken under high vertical normal stress. Thus, the addition of 2% cement content to kaolin is thought to be the main reason for the significant decrease in parameter t for 2% cement sample.

Effect of overconsolidation ratio on the cyclic degradation

The results of the evaluation of the degradation parameter t for two types of specimens with OCR from 1 to 4 are illustrated in Fig. 12. In general, the cyclic degradation decreases with increasing the number of cycles at all OCR values. In Fig. 12b, at OCR = 4, the relationship between the number of cycles and the degradation index of 2% cemented kaolin specimen seems to be an apparent curve. The reduction levels of parameter t at 20 cycles (t_{20}) under different OCRs for 0 and 2% cement samples are compared and shown in Fig. 13. It can be seen that as the OCR increases, the cyclic degradation tends to decrease. The data in Table 3 show that when the OCR values increase from 1 to 4, the degradation

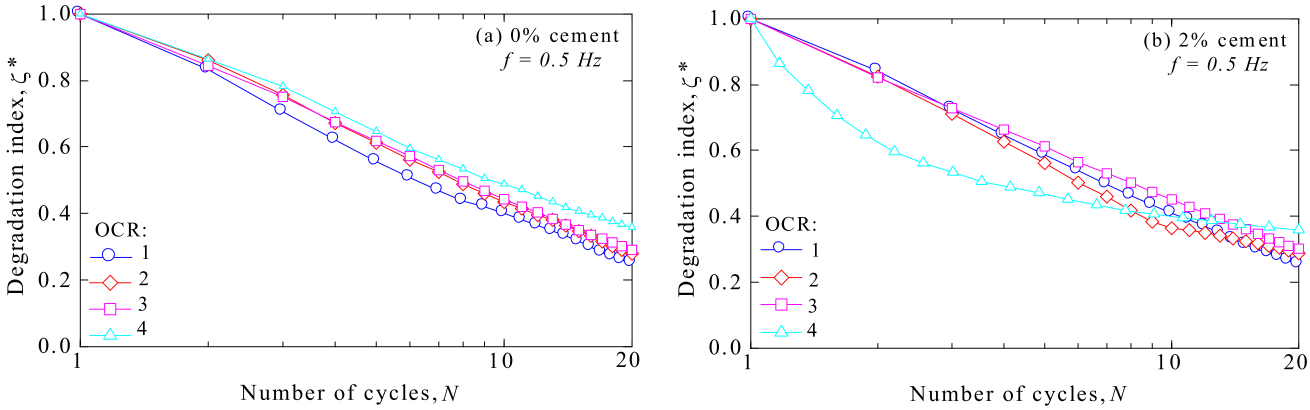

Fig. 12 Relationship between cyclic degradation index, δ^*, and number of cycles, *N,* at different OCR values

parameter t decreases by 25.7% and 58.5% for 0% and 2% cemented kaolin, respectively. The decrease in parameter t for 2% cement sample is over two times higher than that for pure kaolin (0% cement). Some previous studies also indicated that soil with a high OCR would exhibit a low cyclic degradation [7–9]. Typically, Vucetic and Dobry [8] concluded that when OCR is increased from 1 to 4 for clay having plasticity index (PI) between 25 and 55, the degradation parameter t may decrease by 35–40%. Additionally, the research result of Zhou and Gong [9] showed that the cyclic degradation of clay decreased with the increase in OCR from 1 to 4. In this study, it is noted that when the OCR increases from 1 to 3, the cyclic degradation for the two types of samples is almost identical and slightly decreases. Nevertheless, the cyclic degradation significantly decreases as the OCR increases from 3 to 4, especially for 2% cement sample. At OCR = 4, the parameter $t20$ for 2% cement sample is significantly lower than that for 0% cement sample (pure kaolin). This phenomenon is most likely because the cementation bond forms due to the addition of 2% cement content into kaolin clay. According to Hanzawa and Adachi

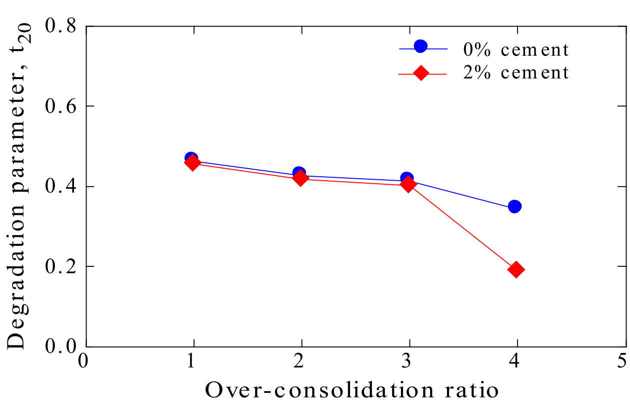

Fig. 13 Effect of OCR on degradation parameter, t_{20}, for 0% and 2% cemented kaolin specimens

[30], the overconsolidated state of soil can be formed and increased due to chemical bonding (cementation). Thus, under the high OCR of 4 and the existence of cementation bonding, the OCR and stiffness of 2% cement sample can be further enhanced. As mentioned above, the high OCR and stiffness would cause a low decrease level of cyclic degradation [7–9]. However, the cyclic degradation of soil at OCR > 4 should be further investigated.

Conclusions

In this study, a series of cyclic ring shear tests were conducted at different conditions to investigate the effect of normal stress, shear-torque amplitude, and overconsolidation ratio on the cyclic degradation of weakly cemented soil and soil containing a bedding plane. Based on the analysis of test results, some main conclusions can be drawn as follows:

1. The experimental results showed that degradation parameter t consistently decreased with increasing normal stress, shear-torque amplitude, and OCR for all samples.
2. The effect of vertical consolidation stress on the parameter t for 2% + 0% cemented kaolin sample appeared to be insignificant. On the other hand, if σ_N increases from 98 to 294 kPa, the parameter t is decreased by 31.1%, 59.1%, and 23.0% for 0%, 2%, and 2% + 2% cemented kaolin, respectively. The highest reduction level of parameter t of 2% cement sample means that the cyclic degradation of 2% cemented kaolin is highly sensitive to the variation in normal stress.
3. The normalized cyclic stress ratio (τ_{cN}/σ_{N0}) significantly decreased with the increase in the number of cycles (N) at a constant vertical consolidation value for all samples except for the pure kaolin sample. For this sample, the

ratio of τ_c/σ_{N0} seems not to be influenced by increasing normal stress.

4. As the applied cyclic stress ratio (CSR) increased from about 0.3 to 0.9, the parameter t was decreased by 11.5%, 44.0%, 24.7%, and 30.8% for 0%, 2%, 2% + 0%, and 2% + 2% cemented kaolin, respectively. The highest effect of CSR on the parameter t is observed for 2% cement sample. The addition of 2% cement content to kaolin confirms again that the parameter t of 2% cemented kaolin is highly sensitive to the variation in shear-torque amplitude.
5. As OCR increased from 1 to 4, the value of parameter t reduced by approximately 25.7% and 58.6% for 0% and 2% cemented kaolin samples, respectively. At OCR = 4, the parameter t of 2% cement sample is significantly lower than that of 0% cement sample. This is attributed to the fact that when 2% cement content is added to pure kaolin and consolidated at a high OCR, the stiffness and hardness of 2% cement sample will be significantly increased and resulting in a low cyclic degradation level.
6. This is the first study using the cyclic ring shear apparatus to investigate the cyclic degradation of soil. The research has evaluated the effective vertical normal stress, shear-torque amplitude, and OCR on the cyclic degradation of weakly cemented soil and bedding planes. However, the effect of these factors and frequency, f, on the cyclic degradation of soil at OCR > 4 should be further studied.

Declarations

Conflict of interest The authors declare that they are not aware of any conflict of interest.

Ethical approval Presented results do not contain studies with human or animal subjects.

Informed consent For this type of study, formal consent is not required.

References

1. Mortezaie AR (2012) Cyclic threshold strains in clays versus sands and the change of secant shear modulus and pore water pressure at small cyclic strains. Doctor of Philosophy in Civil Engineerin University of California, LA
2. Mortezaie AR, Vucetic M (2013) Effect of frequency and vertical stress on cyclic degradation and pore water pressure in clay in the NGI simple shear device. J Geotech Geoenviron Eng 139(10):1727–1737
3. Nhan TT, Matsuda H, Phuong ATT, Thanh NNT, Van TP, Quang TD (2022) Effects of physical properties and undrained cyclic shear conditions on the pore water pressure responses of saturated sands and clays. Sci Earth 2022:1–16
4. Nhan TT, Matsuda H (2020) Pore water pressure accumulation and settlement of clays with a wide range of Atterberg's limits subjected to multi-directional cyclic shear. Vietnam J Earth Sci 42(1):93–104
5. Okur DV, Ansal A (2007) Stiffness degradation of natural fine grained soils during cyclic loading. Soil Dyn Earthq Eng 27(9):843–854
6. Samir El-Kady M, ElMesmary MA (2018) Cyclic strengths for high density soils related to pore water pressure. Innov Infrastruct Solut 3(46):1–10
7. Soralump S, Prasomsri J (2016) Cyclic pore water pressure generation and stiffness degradation in compacted clays. J Geotech Geoenvironl Eng 142(1):1–13
8. Vucetic M, Dobry R (1988) Degradation of marine clays under cyclic loading. J Geotech Eng 114(2):133–149
9. Zhou J, Gong X (2001) Strain degradation of saturated clay under cyclic loading". Can Geotech J 38(1):208–212
10. Matasović N, Vucetic M (1995) Generalized cyclic-degradation-pore-pressure generation model for clays. J Geotech Eng 121(1):33–42
11. Bromhead EN, Ibsen ML (2004) Bedding-controlled coastal landslides in Southeast Britain between Axmouth and the Thames Estuary. Landslides 1(2):131–141
12. Chigira M, Yagi H (2006) Geological and geomorphological characteristics of landslides triggered by the 2004 Mid Niigta prefecture earthquake in Japan. Eng Geol 82(4):202–221
13. Has B, Nozaki T (2014) Role of geological structure in the occurrence of earthquake-induced landslides, the case of the 2007 Mid-Niigata Offshore Earthquake, Japan. Eng Geol 182:25–36
14. Wang HB, Sassa K, Xu WY (2007) Analysis of a spatial distribution of landslides triggered by the 2004 Chuetsu earthquakes of Niigata Prefecture. Japan Nat Hazards 41(1):43–60
15. Hussain MA, Chen Z, Zheng Y, Shoaib M, Shah SU, Ali N, Afzai Z (2022) Landslide susceptibility mapping using machine learning algorithm validated by persistent scatterer In-SAR technique. Sensors 22(9):3119
16. Shoaib M, Yang W, Liang Y, Rehman G (2021) Stability and deformation analysis of landslide under coupling effect of rainfall and reservoir drawdown. Civil Eng J 7(7):1098–1111
17. Mendoza J, Lombardi D, Ahmad S (2019) Cyclic response of artificially cemented soils. In Geotechnical Engineering in the XXI Century: Lessons learned and future challenges: Proceedings of the XVI Pan-American conference on soil mechanics and geotechnical engineering, Cancun, Mexico, pp 253–259.
18. Moses GG, Rao SN (2003) Degradation in cemented marine clay subjected to cyclic compressive loading". Mar Georesour Geotechnol 21(1):37–62
19. Sharma SS, Fahey M (2003) Degradation of stiffness of cemented calcareous soil in cyclic triaxial tests. J Geotech Geoenviron Eng 129(7):619–629
20. Suzuki M, Umezaki T, Takahara H (2012) Fast and cyclic shearing of cemented sand in Earthquake induced landslide. In Proc. 15th World Conference on Earthquake Engineering, Lisboa
21. Idriss IM, Dobry R, Singh RD (1978) Nonlinear behavior of soft clays during cyclic loading. J Geotech Eng Div 104(12):1427–1447
22. Bishop AW, Green GE, Garga VK, Andresen A, Brown JD (1971) A new ring shear apparatus and its application to the measurement of residual strength. Geotechnique 21(4):273–328
23. Lee KH, Lee S (2002) Mechanical properties of weakly bonded cement stabilized kaolin. KSCE J Civ Eng 6(4):389–398
24. Duong NT, Suzuki M, Hai NV (2018) Rate and acceleration effects on residual strength of kaolin and kaolin–bentonite mixtures in ring shearing. Soils Found 58(5):1153–1172

25. Duong NT, Hai NV (2021) Residual strength of weakly cemented kaolin clay in multi-stage ring shear test. Arab J Sci Eng 47:4437–4451
26. Duong NT, Suzuki M (2022) Rate effects on peak and residual strengths of overconsolidated clay in ring shear tests. Periodica Polytechnica Civil Eng 66(1):298–309
27. Duong NT, Hao DV (2020) Consolidation characteristics of artificially structured kaolin-bentonite mixtures with different pore fluids. Adv Civil Eng 2020:1–9
28. Li Y, Chan LS, Yeung AT, Xiang X (2013) Effects of test conditions on shear behaviour of composite soil. Proc Instit Civil Eng-Geotech Eng 166(3):310–320
29. Xu C, Wang X, Lu X, Dai F, Jiao S (2018) Experimental study of residual strength and the index of shear strength characteristics of clay soil. Eng Geol 233:183–190
30. Hanzawa H, Adachi K (1983) Overconsolidation of alluvial clays. Soils Found 23(4):106–118