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Cyclic behavior of RT-cement treated marine clay subjected to low and high loading frequencies

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Abstract. The weakening and softening behavior of soft clay subjected to cyclic loading due to the build-up of excess pore water pressure is well-known. During the design stage of the foundation of highways and coastal high-rise buildings, it is important to study the mechanical behavior of marine soils under cyclic loading as they undergo greater settlement during cyclic loading than under static loading. Therefore, this research evaluates the cyclic stress-strain and shear strength of untreated and treated marine clay under the effects of wind, earthquake, and traffic loadings. A series of laboratory stress-controlled cyclic triaxial tests have been conducted on both untreated and treated marine clay using different effective confining pressures and a frequency of 0.5 and 1.0 Hz. In addition, treated samples were cured for 28 and 90 days and tested under a frequency of 2.0 Hz. The results revealed significant differences in the performance of treated marine clay samples than that of untreated samples under cyclic loading. The treated marine clay samples were able to stand up to 2000 loading cycles before failure, while untreated marine clay samples could not stand few loading cycles. The untreated marine clay displayed a higher permanent axial strain rate under cyclic loading than the treated clay due to the existence of new cementing compounds after the treatment with recycled tiles and low amount (2%) of cement. The effect of the effective confining pressure was found to be significant on untreated marine clay while its effect was not crucial for the treated samples cured for 90 days. Treated samples cured for 90 days performed better under cyclic loading than the ones cured for 28 days and this is due to the higher amount of cementitious compounds formed with time. The highest deformation was found at 0.5 Hz, which cannot be considered as a critical frequency since smaller frequencies were not used. Therefore, it is recommended to consider testing the treated marine clay using smaller frequencies than 0.5 Hz.

Keywords: marine clay; cyclic triaxial test; loading frequency; curing time; confining pressure

1. Introduction

The static and cyclic properties of marine soil are among the most studied and investigated areas in geotechnical engineering, but this remains a challenging topic due to the complexity of the soil. Marine clay is a problematic soil that exists in the coastal and offshore areas of the earth. It swells when it gains water and shrinks when it dries out (Al-Bared and Marto 2017a). Marine clay can be improved by different treatments using various additives and techniques in order to enhance its static and cyclic strength (Zainuddin *et al.* 2019). Marine clay is improved using chemical agents such as cement, which improves its physical and mechanical properties, e.g., (Al-Bared *et al.* 2019a, Damoerin *et al.* 2015, Jitsangiam *et al.* 2016, Kim *et al.* 2018, Nusit *et al.* 2016, 2015a, Nusit and Jitsangiam 2016). However, the percentage of cement required for the improvement of marine clay is considered high (Bushra and Robinson 2012) and due to the chemical formation of cement, it has a great effect on the surrounding environment. Recent studies focused on using environmentally friendly products to enhance the properties of soft soils such as using microbial biopolymers, e.g., (Chang *et al.* 2017, 2015, Chang and Cho 2019). One of the most modern stabilization methods is the incorporation of non-toxic waste material, such as ceramic tiles, to enhance the strength of the marine clay (Al-Bared *et al.* 2018b). The use of waste materials in the stabilization of marine clay would help to utilize the waste materials, it reduces their negative impact on the environment. The treated marine clay may experience lower settlement under static and cyclic loadings either offshore or onshore.

Cyclic loading is generated in the form of dynamic

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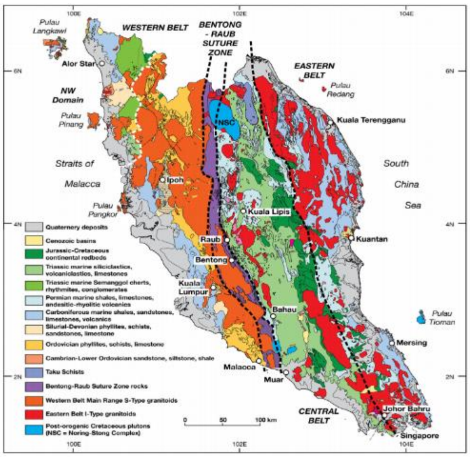
waves by earthquakes, wind, waves, and the vibrations created by the movement of traffic and heavy machinery (Andersen 2004). The design of the foundation for structures built along the coastal line or offshore are controlled by the soil's bearing capacity under cyclic loading (Andersen 2009, Wichtmann *et al.* 2013). Soft soil exposed to cyclic loading may experience degradation in strength and stiffness as a result of the build-up of excess pore water pressure and the accumulation of axial strain. This can be due to the generation of loops of stress and strain that are not perfectly closed. The excess pore water pressure and the subsequent loss of strength in the soil during the cyclic loading generated by an earthquake in a seismic area may lead to liquefaction (Wichtmann *et al.* 2005). Cyclic loading may result in large deformations in the soil used as a foundation due to the reduction of the shear strength. Therefore, in order to precisely design foundations for structures subjected to cyclic and static loadings, it is necessary to evaluate the cyclic strength and bearing capacity of the soils (Andersen and Lauritzsen 1988). According to the literature on cyclic loading, when the number of cycles is increased, the excess pore water pressure is increased and accumulates, which degrades the structure of the clay and decreases its stiffness (Moses *et al.* 2003, Vucetic and Dobry 1988).

The effect of cyclic loading on clayey soils has been investigated for the past 45 years, e.g., (Andersen *et al.* 1976, Ashango and Patra 2014, Kaya and Erken 2015, Lee and Jr 2008, Sağlam and Bakır 2014, Wichtmann and Triantafyllidis 2015, Chen *et al.* 2012). Yasuhara *et al.* (2017) performed several series of stress-controlled triaxial compression tests on remolded clay samples. The results showed the independence of the cyclic undrained strength from the frequency and loading time in terms of effective stress. From the point of view of a total stress analysis, the cyclic strength exceeded the static one by 5% and is not affected by the frequency. In addition, the effect of cyclic loading on marine clay treated with lime was studied by Wang *et al.* (2012). The results indicated a reduction in the cohesion and an increase in the internal friction angle with the increased number of cycles for the unsaturated samples, while both cohesion and internal friction angle were decreased for the saturated samples. Wang *et al.* (2013b) conducted a series of high cyclic (50,000 cycles) triaxial tests with various effective confining pressures and stress levels on samples of marine clay in order to investigate the build-up of excess pore water pressure and axial strain. The results showed that the resilient and permanent strains depend on the cyclic stress ratio (CSR) and when the CSR increases, the resilient strain increases constantly after 1000 cycles of loading, while the permanent strain increases linearly as the CSR increases. In addition, after 50000 cycles, the resilient strain keeps on increasing and the permanent strain increases rapidly when the CSR is large. Lei *et al.* (2016) conducted stress-controlled triaxial tests on soft clay to investigate the effect of the frequency and CSR on the creep behavior of clay. The tests used three different frequencies and four different values for CSR. The results showed that the cyclic loading induced greater compaction compared to the static loading. When the loading frequency was high, the failure of the clay was rapid and the limit frequency with safe load was observed at which the increase in the strain was slowly developed. The critical CSR was determined to be 0.26 at a certain frequency and effective stress. Wang *et al.* (2013a) investigated the cyclic behavior of soft clay using undrained cyclic triaxial tests. The samples of soft clay were subjected to initial shear stresses in order to simulate the real field conditions, in which pore water pressure is dissipated before the cyclic loading is applied. The results of testing revealed a rapid degradation of the cyclic strength with increasing number of cycles. Besides, samples subjected to initial shear stresses degraded more slowly than those tested without initial shear stresses. Ashango and Patra (2014) conducted a series of strain-controlled cyclic triaxial tests on clay treated soil to investigate the degradation index. The results indicated a steep reduction of the degradation index in the first 25–50 cycles of loading. Wang *et al.* (2017b) reported the cyclic deformation behavior of marine clay to be significantly dependent on the CSR. When a CSR value of more than 0.42 is applied, the cyclic strain increases rapidly after a few cycles.

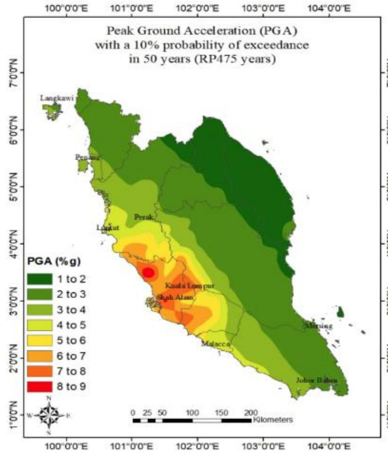
To the authors' best of knowledge, the cyclic undrained behavior of untreated and treated marine clay obtained from Nusajaya, Malaysia had never been investigated or explored. There was no effort undertaken to study the performance of treated marine clay under cyclic loading and the suitability of recycled additive to enhance the resistance between the soil particles to stand high number of cycles has yet to be achieved. Hence, in order to understand the deformation of untreated and treated marine clay under cyclic stresses, it is necessary to conduct cyclic loading tests under different testing conditions. The aim of this study is the evaluation and investigation of the cyclic behaviour of (1) remolded untreated marine clay and (2) treated marine clay samples under both traffic and earthquake loading frequencies. A series of cyclic triaxial tests was conducted on both remolded untreated and treated marine clay under a frequency of 1.0 Hz and under different effective confining pressures. The treated samples were cured for 28 days (short-term) and 90 days (long-term) and tested under a frequency of 2.0 Hz under different effective confining pressures. For the purpose of determining the behavior of untreated and treated marine clay under cyclic loading, marine clay was obtained from site and mixed with the stabilizing additive in the laboratory. This research aims to reduce the disposal of dredged marine clay into disposal areas and to also decrease the amount of cement used in marine clay stabilization by introducing environmentally friendly soil stabilizers to be applied directly at site.

2. Geological formation of the study area

Nusajaya is a city situated in the district of Johor, Malaysia. It is located at the end of the southern part of peninsular Malaysia. Its geological formation is mainly quaternary marine deposits, as shown in Fig. 1(a). The geological subsurface was found to be bed rock consisting of weathered sandstone and siltstone (Tan *et al.* 2014). In terms of mineralogy, the marine clay consists primarily of kaolinite, illite and montmorillonite which are responsible of its compressible and swelling behavior (Al-Bared and Marto 2017b). When these clay minerals exist in high



(a) Geological map of Peninsular Malaysia (Metcalfe 2013)



(b) Seismic hazard map (Shoushtari *et al.* 2019)

Fig. 1 Geological formation of the study area

percentage within the marine clay, the physical and mechanical characteristics of marine clay will be very poor. The seismic hazard map for peninsular Malaysia is shown in Fig. 1(b). It can be seen that the area of Nusajaya, Johor Bahru falls under the third category in the seismic hazard map and the peak ground acceleration was found to be 5.5 g (Shoushtari *et al.* 2019).

3. Experimental program for undrained cyclic triaxial testing

3.1 Material properties and sample preparation

The marine clay used in this study was obtained from a depth of 1-1.5 meter below the ground surface using an excavator and stored in black oil containers. This kind of soil has been studied by many researchers and has been categorized as a problematic soil for various reasons, such as its low shear strength and permeability, high compressibility and water content, and high amount of clay minerals (Al-Bared *et al.* 2018a, Ayub *et al.* 2018, Jin *et al.* 2018, Marto *et al.* 2014). The collected marine clay was first air dried, crushed, sieved through a 2-mm mesh, and stored in an air-tight container. The preparation of the samples was done using a predetermined maximum dry density and the optimum moisture content obtained from the compaction tests and the samples were remolded inside a triaxial mold of 80 mm height and 38 mm diameter. In order to prepare treated samples, the marine clay was mixed in a dry condition with 20% recycled waste tiles and 2% Portland cement. The percentage and size of the waste ceramic tile material to treat the soft clay was determined in previous study by Al-Bared *et al.* (2018). In this study, cement was chosen as an activator between the recycled tiles and marine clay for better reaction. This was based on a study conducted by Al-Bared *et al.* (2019b) which showed significant improvement of clay mixed with recycled tiles and various percentages of cement. The strength of the clay mixed with cement and recycled tiles was twice the one obtained from the control mix that used cement alone. In addition, various researchers proved the ability of cement when mixed with other filler materials to enhance the properties of soils e.g., (Jitsangiam *et al.* 2018, Nusit *et al.* 2015b). The mixture of marine clay, recycled waste tiles and cement was placed inside the triaxial mold in three equal layers. Each layer was compacted using a steel tamper for 27 blows (Ahmed 2015). The remolded samples were extruded using a steel plunger and trimmed to a size of 38 mm diameter and 76 mm height. The treated samples were wrapped with several layers of cling film to preserve their moisture content.

Samples were stored inside a controllable curing chamber with a temperature of 27°C and humidity of 97% for periods of 28 and 90 days. At the end of the curing time, the weight of the samples was re-checked and those samples that had more than 0.5% weight reduction were discarded and replaced with new samples. The physical and chemical properties of the marine clay and recycled waste of ceramic tiles are presented in Table 1.

The remolded marine clay and the treated marine clay samples were prepared in the geotechnical laboratory. For all prepared samples, distilled water was used for

Table 1 Physical and chemical characteristics of untreated marine clay and recycled waste of ceramic tiles

Property	Marine clay	Recycled tiles, % (Al-Bared *et al.* 2018)
Natural moisture content (%)	59	-
Color	Black powder	White powder
Organic content (%)	2.74	-
Unconfined compressive strength (kPa)	50	-
Maximum dry density (kg/m^3)	1590	-
Specific gravity, G_s	2.52	2.57
Chemical compositions		
SiO_2	36.75	65.83
Al_2O_3	16.83	24.37
Na_2O	0.27	3.19
FeO	30.02	2.81
MgO	0.47	5.84
K_2O	8.66	2.33
CaO	0.44	1.64

Table 2 Summary of the results from the consolidated undrained cyclic triaxial tests

Curing time (days)	Frequency (Hz)	Sample type	[a]Maximum static deviatoric stress, q_{static} (kPa)	Effective confining pressure (kPa)	Cyclic deviatoric stress, q_{cyc} (kPa)	[b]Cyclic stress ratio, CSR	Permanent excess pwp at 10% limiting strain (kPa)	Time to achieve 10% limiting strain (s)	Water content after testing (%)	Remarks
NA	0.5	Untreated marine clay	55.2	50	50	0.90	-38.5	20	24	
	0.5		85.9	100	50	0.58	-4.7	20	23	
	0.5		215	200	50	0.23	-14.5	14	22	
	1.0		55.2	50	50	0.90	23.4	20	22	
	1.0		85.9	100	50	0.58	1.1	16	21.5	
	1.0		215	200	50	0.23	-2	15	21	
28	0.5	Optimum RT-cement treated marine clay	650	50	203	0. 31	-5.6	36	23	
	0.5		700	100	203	0.29	17.9	123	22.5	
	0.5		720	200	203	0.28	-6.9	514	21.3	
	1.0		650	50	203	0. 31	20.5	84	22.5	
	1.0		700	100	203	0.29	-3.4	351	22.1	
	1.0		720	200	203	0.28	-14.3	444	21.6	
	2.0		650	50	203	0. 31	10.5	1000 (13.07%)	22.7	Limiting no of cycles (N=2000) was achieved
	2.0		700	100	203	0.29	-1.3	1000 (2.2%)	21.8	
	2.0		720	200	203	0.28	13.7	1000 (7.32%)	21	
90	2.0		650	50	203	0. 31	13.8	1000 (0.42%)	23	
	2.0		700	100	203	0.29	4.5	1000 (0.52%)	22.6	
	2.0		720	200	203	0.28	13.8	1000 (0.25%)	22	

[a]Results obtained through the tests using the GDS ELDYN triaxial test equipment similar with the equipment used for cyclic loading tests

[b]CSR is the cyclic stress ratio, which is equal to the cyclic deviatoric stress divided by the static deviatoric stress, CSR= q_{cyc}/q_{static}

the samples to attain saturation and to reduce the presence of air within the remolded samples. In order to start with the saturation stage of triaxial test, the sample was placed inside a latex rubber membrane designed to stand high pressures during cyclic triaxial tests and manufactured by global digital systems (GDS), UK. The sample was then installed on top of the pedestal at the base of the apparatus in the triaxial cell and ceramic porous stones and filter papers were placed at the bottom and top of the sample. The purpose of the filter papers was to prevent the soil fine particles from clogging the porous stone and preventing the hole for the pore water pressure measurement and the other tubes connected to the sample during the triaxial testing to be blocked. The pore water pressure was measured using a pressure transducer at the bottom of the sample through a hole in the middle of the pedestal at the base of the triaxial cell (Wang *et al.* 2013b). The triaxial cell was partially filled with de-aired distilled water prior to saturation in order to reduce the amount of pressure required to fill the cell and for reasons of safety. The samples were initially saturated using a cell pressure of 100 kPa and a back pressure of 90 kPa to have an effective confining pressure of 10 kPa. Then, the saturation process was monitored by measuring Skempton's pore water pressure parameter, B which is the ratio of the changes of the pore pressure to the changes of cell pressure during the B-check stage. For the B-check stage, the effective confining pressure was maintained at 50 kPa in order to measure the saturation. Those steps were repeated until the B-check was found to be above 0.97, which is considered an acceptable value, and then the test proceeded to the next consolidation stage (Moses and Rao 2007, Zhang *et al.* 2018a).

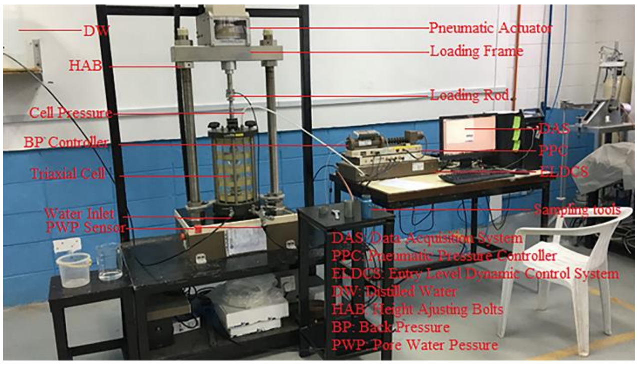


Fig. 2 ELDYN GDS cyclic triaxial machine used for the testing

3.2 Testing procedure and test apparatus

The determination of the soil's stress-strain characteristics under cyclic loading requires a reliable and controlled test. Cyclic triaxial tests are considered as one of the most useful and reliable geotechnical tests for the purpose of understanding and evaluating the soil behavior under static and cyclic loadings (Zhang *et al.* 2017). Testing soil under cyclic triaxial loading is a simulation of the soil condition and the forces acting on it in the field. This testing allows the measurement of the excess pore water pressure and this could be the reason why its results are globally accepted compared to all other laboratory tests (Gu *et al.* 2014, Kaya and Erken 2015, Sağlam and Bakır 2014, Zhang *et al.* 2018b, 2017). The results of cyclic triaxial strength tests are usually used for the evaluation of the soil's ability to resist the shear stresses induced by earthquake, traffic, or wave action. The machine used for testing was Enterprise Level Dynamic Triaxial Testing System (ELDYN) manufactured by GDS, UK. Fig. 2 shows the cyclic triaxial machine used for testing and an elaborated description on the experimental set-up and methodology on the marine clay under cyclic loading. The machine is equipped with an automatic control system and controlled data acquisitioning unit that is linked to a personal computer to provide control over all the transducers. The setting of the cyclic machine used during testing was the frequency range of 0.1-5 Hz, maximum axial load of 10 kN, and maximum axial displacement of ± 100 mm (Zhang *et al.* 2017). The standards used for testing were the standard test methods for the determination of the modulus and damping properties of soils using the cyclic triaxial apparatus (D 3999 – 91) and standard test method for load controlled cyclic triaxial strength of soil (D 5311 – 92) (ASTM 2014, 1996). After achieving full saturation, the samples were isotropically consolidated under effective confining pressures of 50, 100, and 200 kPa until all the water and air were removed from the sample. This can be seen in the consolidation curve window that is shown during the testing. The consolidation process was terminated when the volume change was insignificant or approximately 95% of the excess pore water pressure was dissipated, which ever was encountered first. Following the saturation and consolidation stages, a cyclic loading test was run under confining stress condition. The cyclic load in this study was applied in the vertical direction (one-way loading); the applied frequencies were 0.5 and 1.0 Hz for both untreated and treated marine clay and 2.0 Hz for treated marine clay cured for 28 and 90 days. The testing parameters and the program are shown in Table 2. The frequencies (0.5-2.0 Hz) were applied to simulate the cyclic loading during wind action, earthquake and traffic loadings (Ishihara 1996, Saglam and Bakir 2014, Zhang *et al.* 2017). In the present work, the treatment of marine clay was considered to stabilize the pavement subgrade layer. Pavement layers are subjected to cyclic loading generated by earthquake and traffic loadings. In order to simulate the actual field conditions, pavement subgrade subjected to cyclic loading could be tested using different frequencies.

The termination criteria or the failure limit of the test was set at either when 2000 loading cycles were achieved or when the cyclic axial strain exceeded the limiting value of 10%. This 10% strain is considered as the failure point of the sample. However, the machine did not stop the test automatically although 10% axial strain was achieved. Hence, it was manually stopped after passing the limiting strain although it has not achieved the 2000 loading cycles. If the number of cycles achieved 2000 cycles, the test was automatically stopped by the machine.

4. Experimental results and discussion

4.1 Untreated marine clay tested under frequency of 0.5 Hz and 1.0 Hz

Compacted remolded untreated marine clay samples were tested under undrained triaxial cyclic loading with frequencies of 0.5 and 1.0 Hz to best simulate the conditions under wind and earthquake loadings, respectively in the laboratory. Six samples were consolidated under effective confining pressures of 50, 100, and 200 kPa tested in a stress-controlled condition in CU cyclic loading tests. The amplitude (q_{cyc}) was chosen as 50 kPa.

Figs. 3-6 show the cyclic axial strain versus the time and the excess pore water pressure versus axial strain of untreated marine clay tested under 1.0 and 0.5 Hz, respectively. The axial strain increased with the increase of time for all the different effective confining pressures as shown in Fig. 3 for samples tested under 1.0 Hz and Fig. 4 for samples tested under 0.5 Hz. The higher the effective confining pressure, the lower the axial strain when the time is constant. This is due to the increase in the friction between the soil particles as a result of the higher consolidation state of samples consolidated under higher consolidation pressure. The higher consolidation pressure reduces the voids within the soil particles, and this causes smaller deformation during cyclic loading compared to the samples consolidated with lower effective confining pressure. According to Moses and Rao (2007), the development of cyclic axial strain of marine clay is rapid in the first 1000 cycles of loading and then the deformation starts to stabilize with the subsequent cycles of loading. However, the samples prepared for the untreated marine clay are considered to be over consolidated. This can be due

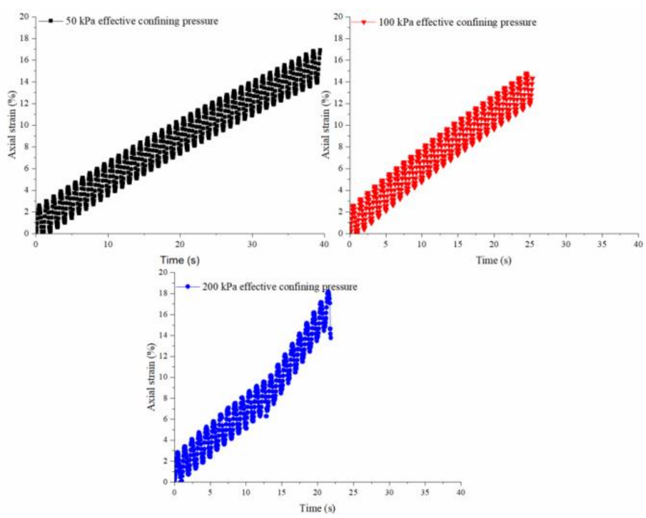


Fig. 3 Cyclic axial strain versus time for untreated marine clay under frequency of 1.0 Hz

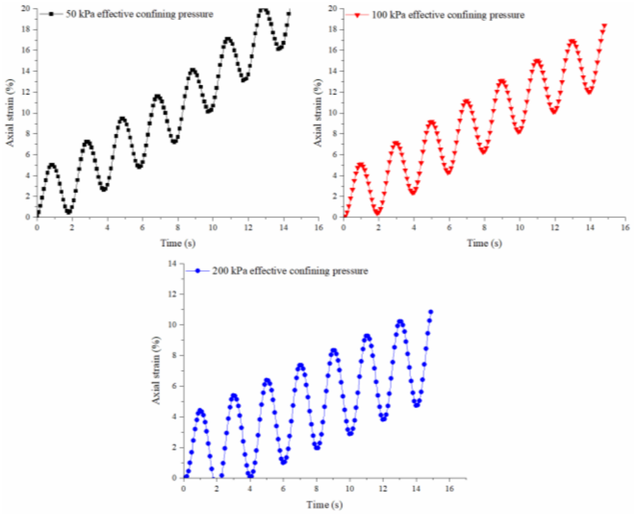


Fig. 4 Cyclic axial strain versus time for untreated marine clay under frequency of 0.5 Hz

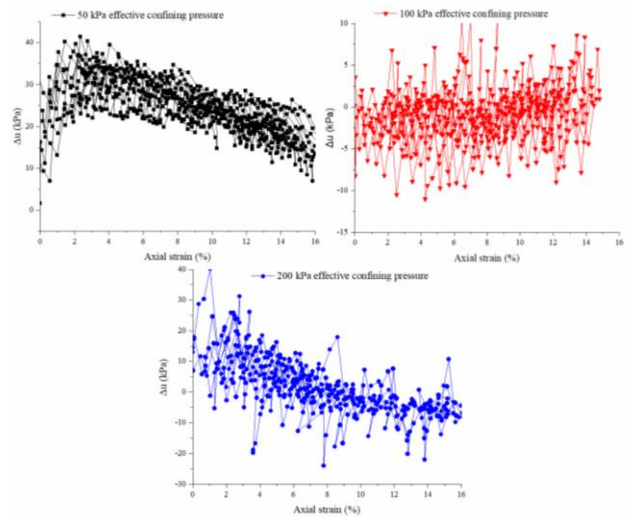


Fig. 5 Excess pore water pressure versus axial strain for untreated marine clay under frequency of 1.0 Hz

to the compaction during the preparation of the samples.

In addition, the cyclic excess pore water pressure is plotted versus the axial strain in Fig. 5 for samples tested under 1.0 Hz and in Fig. 6 for samples tested under 0.5 Hz for the three different effective confining pressures. For all the tested samples under both frequencies, it is clearly seen that the cyclic excess pore water pressure increases negatively with the increase in both the effective confining pressure and the axial strain. The negative development of the excess pore water pressure is due to the over consolidation state of the remolded compacted marine clay samples. When the soil is highly consolidated, the development of pore water pressure during cyclic loading is very small and therefore the excess pore water pressure is negative. Meanwhile, the cyclic pore water pressure and axial strain first increased monotonically with an increase in the number of loading cycles. However, due to the low cyclic shear strength of untreated marine clay, the tests were terminated before the stabilization of the pore water pressure. Similar results of the development of negative

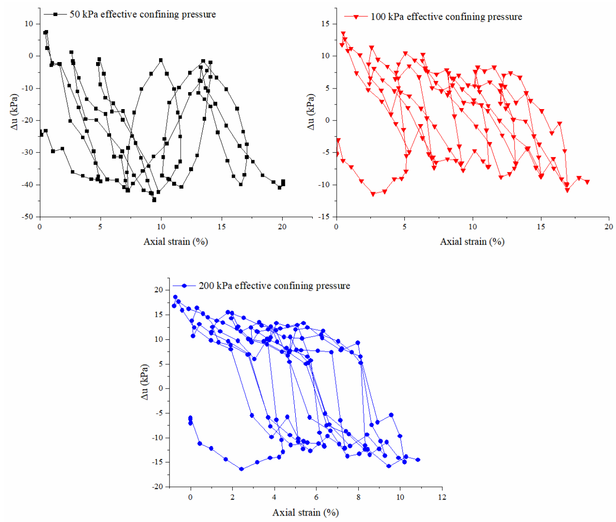


Fig. 6 Excess pore water pressure versus axial strain for untreated marine clay under frequency of 0.5 Hz

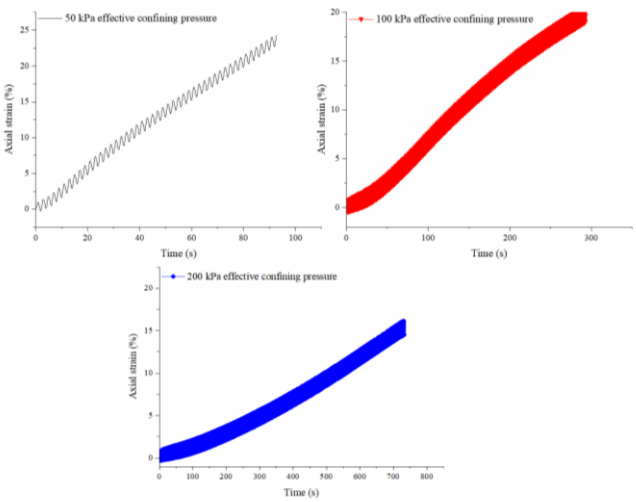


Fig. 7 Cyclic axial strain versus the time for treated marine clay under 0.5 Hz

pore water pressure in compacted clays during cyclic loading testing were found by Soralump and Prasomsri (2016) and Kamruzzaman *et al.* (2009).

4.2 Treated marine clay tested under frequency of 0.5 Hz

RT-cement treated marine clay samples were cured for 28 days and tested under CU cyclic loading using a frequency of 0.5 Hz and an amplitude of 203 kPa. Fig. 7 shows the cyclic axial strain and time relationships for samples tested using a frequency of 0.5 Hz and effective confining pressures of 50, 100, and 200 kPa. The illustration shows that, the cyclic axial strain increases with the increase of time for all the effective confining pressures. Besides, the cyclic axial strain was also decreased with the increased of the effective confining pressure at a constant time. For example, at time of 90 seconds (N=45), the cyclic axial strain was 22, 6 and 3% at 50, 100, and 200 kPa effective confining pressures, respectively. This is due to

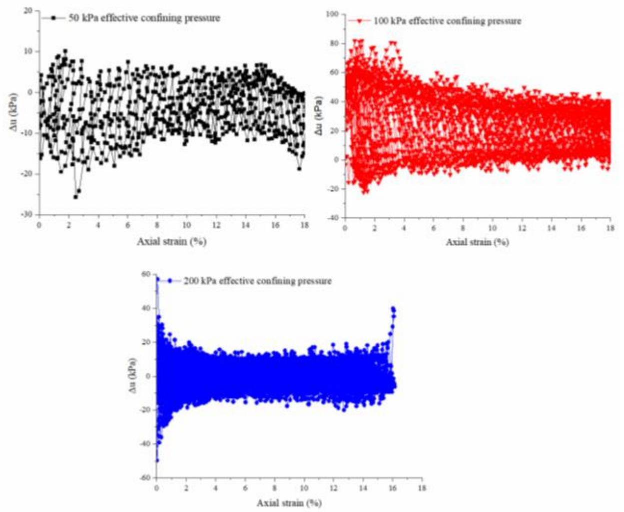


Fig. 8 Excess pore water pressure versus the axial strain for treated marine clay under frequency of 0.5 Hz

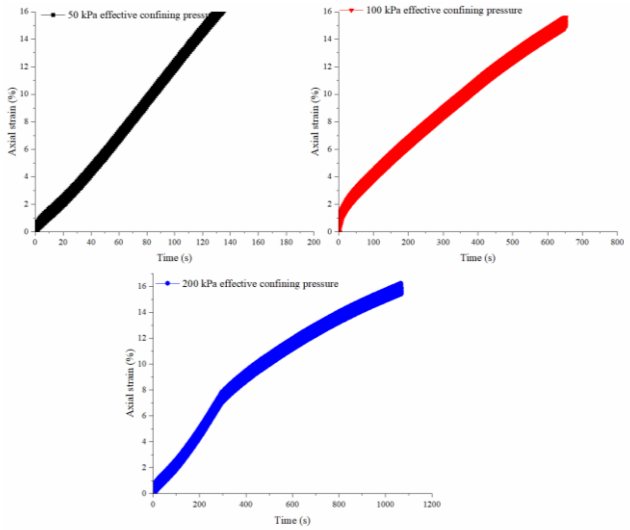


Fig. 9 Cyclic axial strain versus time for treated marine clay tested under 1.0 Hz

the better consolidation achieved with higher effective confining pressure as explained earlier for the untreated compacted marine clay samples. Besides, the formation of cementitious compounds due to soil stabilization decreases the deformation with time of treated samples compared to the untreated marine clay. The time taken to approach the limiting axial strain (10%) was longer than that observed for the samples of untreated marine clay. Even the amplitude used to test the RT-treated samples was very much higher than the one used for untreated marine clay samples, the treated samples were able to sustain more than 200 cycles (400 seconds) under the same frequency compared to only 7 cycles (14 seconds) for untreated marine clay samples.

Fig. 8 shows the cyclic excess pore water pressure generated during the cyclic tests versus the cyclic axial strain for samples tested using a frequency of 0.5 Hz and effective confining pressures of 50, 100, and 200 kPa. The accumulation of cyclic axial strain resulted in the increased of excess pore water pressure that was stabilized at higher

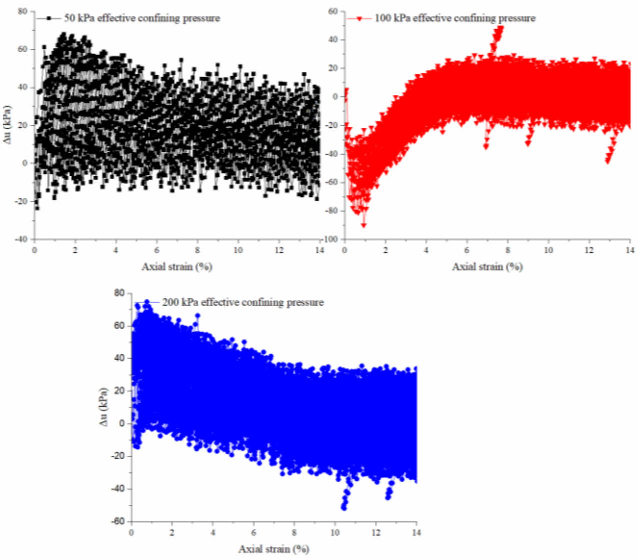


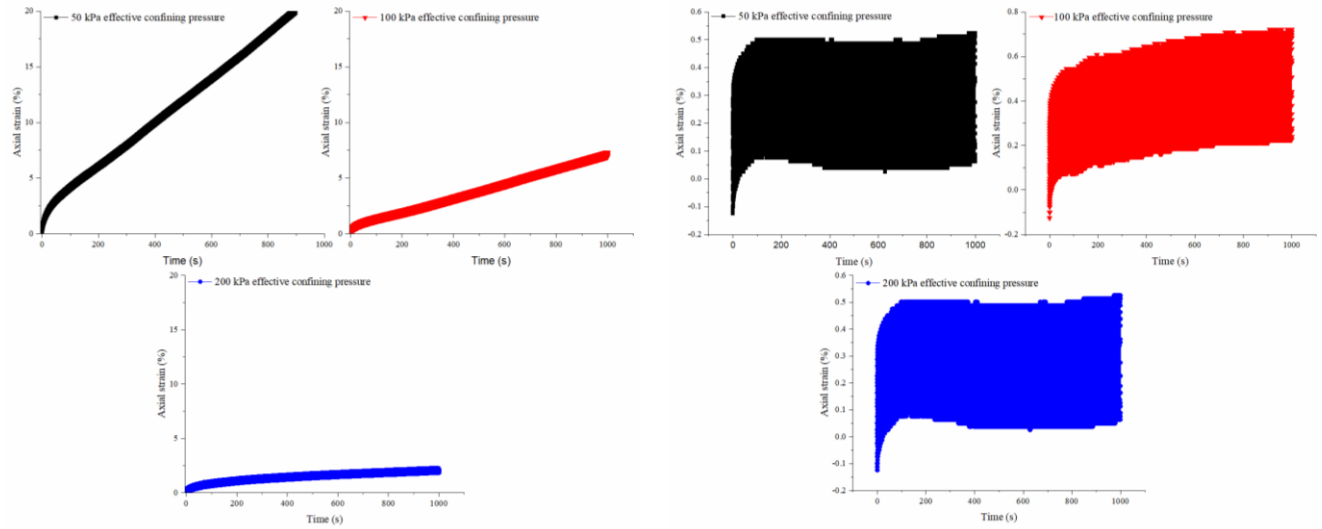
Fig. 10 Excess pore water pressure versus the axial strain for treated marine clay under 1.0 Hz

axial strain. The plots show that the excess pore water pressure increased with the increased of effective confining pressure (particularly from 50 to 100 kPa) that is similar to the observations found by Zhang *et al.* (2017).

4.3 Treated marine clay tested under frequency of 1.0 Hz

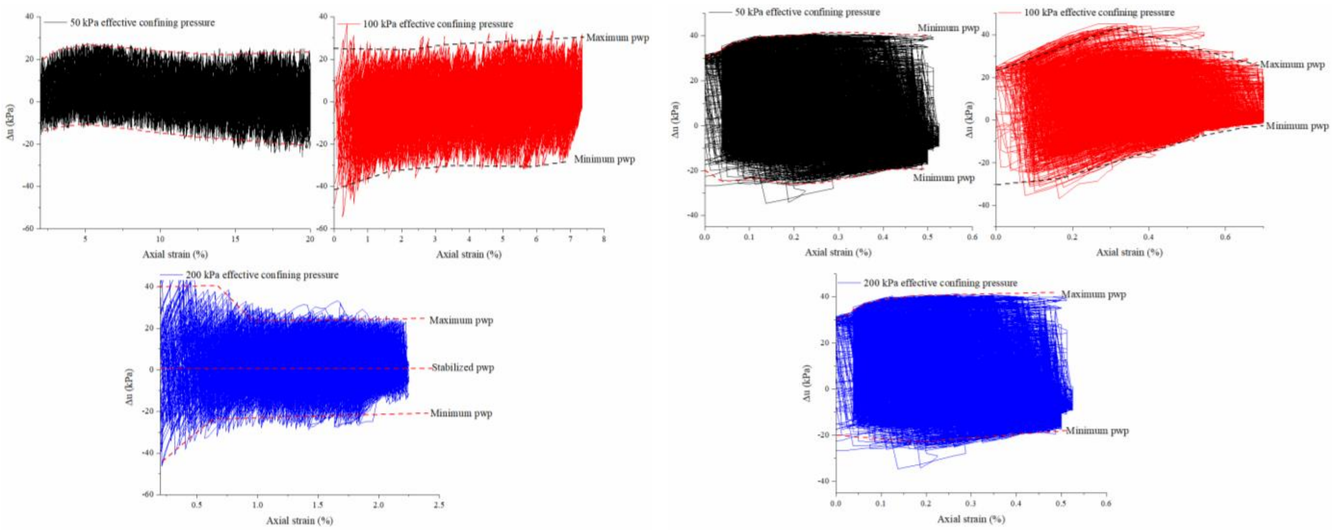
RT-cement treated marine clay samples were cured for 28 days and tested under cyclic loading condition with a frequency of 1.0 Hz to simulate earthquake loading under 50, 100, and 200 kPa effective confining pressures. The plots of the cyclic axial strain versus time of the treated samples tested under 50, 100, and 200 kPa are shown in Fig. 9. The cyclic axial strain increased with the increased of time. When compared with the samples tested under 0.5 Hz (at constant time), the development of the cyclic axial strain of samples tested under 1.0 Hz was lower. However, similar to 0.5 Hz, the cyclic axial strain decreased with the increased in the effective confining pressures at 1.0 Hz frequency.

Fig. 10 shows the relation between the excess pore water pressure and the cyclic axial strain for all samples tested under 50, 100, and 200 kPa effective confining pressures. The excess pore water pressure increased rapidly during approximately the first 100 cycles of the cyclic loading stage and then started to dissipate and stabilize with further cycles until it was nearly constant. According to Marto (1998), positive pore water pressure development is usually achieved with normally consolidated clays while negative pore water pressure is developed for over consolidated clay. The negative pore water pressure development is achieved at the beginning of the test for the peak extension of the loading cycles. The excess pore water pressure appeared to be dependent on the effective confining pressure. The higher the effective confining pressure, the higher was the build-up in the cyclic pore water pressure.



(a) 28 days curing time (b) 90 days curing time

Fig. 11 Cyclic axial strain versus time for the treated marine clay tested under a frequency of 2.0 Hz



(a) 28 days curing time (b) 90 days curing time

Fig. 12 Excess pore water pressure versus axial strain for treated marine clay tested under 2.0 Hz

4.4 Treated marine clay tested under frequency of 2.0 Hz

Marine clay samples treated with optimum recycled tiles and 2% cement cured for 28 and 90 days were subjected to CU cyclic loading under the frequency of 2.0 Hz at 50, 100, and 200 kPa effective confining pressures. From the cyclic loading test results, the cyclic axial strain development with time are plotted in Fig. 11(a) and 11(b), respectively for 28 and 90 days curing periods. The strain development in specimens cured for 90 days was very minimal compared to that of 28 days curing period. The reason is due to the development of higher amount of cementitious compounds within the specimens cured for 90 days as the strength improves with time. The stabilization over long period of time densified and solidified the treated samples cured for 90 days. The development of strain under cyclic loading increased with the increased of time for both curing periods. For instance, the accumulated axial strain was more than 2% for the sample cured for 28 days and tested under 200 kPa effective confining pressure, while the strain development in the sample cured for 90 days under the same effective confining pressure did not exceed 0.6%. The deformation of treated samples cured for 28 days was found to be dependent on the effective confining pressure. When the effective confining pressure was increased, the cyclic axial strain was decreased. This is in agreement with the research conducted by Zhang *et al.* (2018a). They found the undrained cyclic strength of red clay to be dependent on the effective confining pressure and the over consolidation ratio. On the other hand, the treated samples cured for 90 days were insensitive to the effective confining pressure due to its strong structure as the stabilization with cement is time-dependent process. Moreover, it can be observed that the maximum strain developed after 2000 loading cycles at 50 kPa effective confining pressure was 20 and 0.7% for

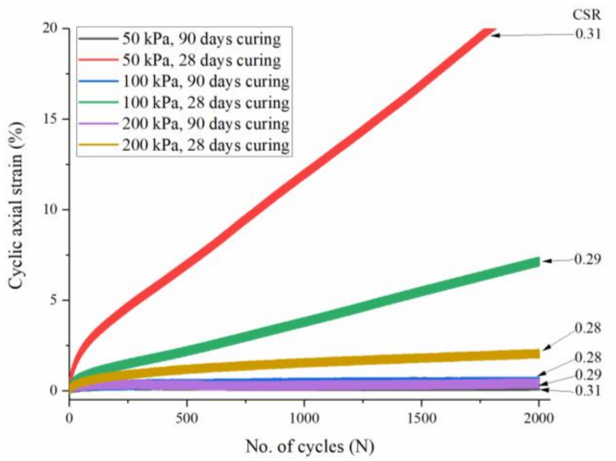


Fig. 13 Cyclic axial strain versus the number of cycles for treated marine clay cured for 28 and 90 days and tested under frequency of 2.0 Hz

treated samples cured for 28 and 90 days, respectively. This indicated that the long-term curing period played a significant role in increasing the bonding between the improved clay particles due to the RT-cement treatment. The effect of the effective confining pressure on the response of the soil during cyclic loading was in agreement with the previous studies found in the literature, e.g., (Bray and Sancio 2006, Saglam and Bakir 2014, Zhang *et al.* 2018a).

Fig. 12(a) and 12(b) shows the relation between the generated excess pore water pressure and the cyclic axial strain during the cyclic undrained triaxial testing. The plots revealed that the generated excess pore water pressure increased with the increased effective confining pressure and number of loading cycles of all treated samples cured for 28 and 90 days. The excess pore water pressure increased rapidly until it reached its maximum and then further increase in the number of cycles was accompanied with approximately constant excess pore water pressure. According to Hyde and Ward (1985) and Hyde *et al.* (1993), the cyclic pore water pressure usually increases with an increasing number of cycles during cyclic loading tests. The history of the soil and the cyclic stress path plays an important role in determining the rate at which the pore water pressure develops. When the cyclic deviatoric stress is high, the number of cycles required to achieve the constant permanent pore water pressure decreases. The development of permanent pore water pressure decreases the effective stress and results in the failure of the soil.

For RT-cement treated samples tested under 2.0 Hz frequency, the samples were subjected to cyclic loading having cyclic stress ratio ranging from 0.29 to 0.31. Fig. 13 plots the axial strain versus the number of cycles at constant cyclic amplitude to show the effect of CSR and the different effective confining pressures during the cyclic tests. For the samples cured for 28 days, the cyclic axial strain was found to increase gradually with the increase of the CSR and decrease with the increase of the effective confining pressure. This is in agreement with the study performed by Chen *et al.* (2017), who studied the undrained cyclic behavior of soil under long-term cyclic loadings. They found that the increased of CSR resulted in the increased of the cyclic axial strain of soil, while the influence of the effective confining pressure was not significant under constant cyclic stress amplitude. However, for samples cured for 90 days, even under a high value of CSR such as 0.31, treated samples were not affected and the deformation caused during cyclic loading was still very slight. This could be due to the very strong bonding between soil particles after the stabilization.

4.5 Effect of loading frequency and curing periods

The effect of the loading frequency and curing periods on untreated and treated marine clay samples tested under 50, 100, and 200 kPa effective confining pressures are both demonstrated in Figs. 14-16. Fig. 14 shows the effect of loading frequency at 50 kPa effective confining pressure on untreated marine clay tested under 0.5 and 1.0 Hz, treated marine clay samples cured for 28 days tested under 0.5, 1.0, and 2.0 Hz and treated marine clay cured for 90 days tested under 2.0 Hz. For untreated sample, it reveals that the axial strain increased with the decreased of the frequency. When comparing the untreated and treated marine clay samples, the strain development of untreated marine clay was accumulated rapidly and reached up to 10% (limiting strain) within few seconds under both frequencies. But the strain development of treated samples cured for 28 days developed slowly and reached the limiting strain after 253 seconds (N=253) loading cycles for 1.0 Hz frequency. Under 0.5 Hz, the treated sample reached the same axial strain at much lower time (t=33 seconds, N=66). This could be due to the strong structure developed within the treated samples after 28 days of curing. When looking at the effect of frequency on the treated samples cured for 28 days and tested under 1.0 and 2.0 Hz, the magnitude of the strain was greater for the former than for the latter at a constant time. The effect of curing period on the treated samples cured for 28 and 90 days subjected to 2.0 Hz, tested under 50 kPa effective confining pressure was also analyzed. For 2.0 Hz, it is found that the magnitude of the strain was very high and reached 20% strain at 1000 seconds (N=2000) for treated samples cured for 28 days, while those samples

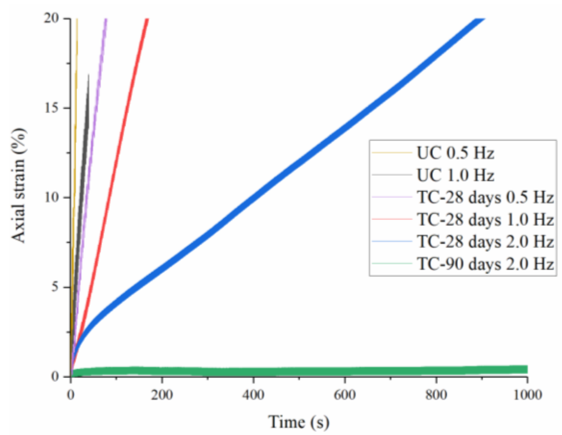


Fig. 14 Effect of frequency and curing periods on axial strain of untreated and treated marine clay at 50 kPa effective confining pressures

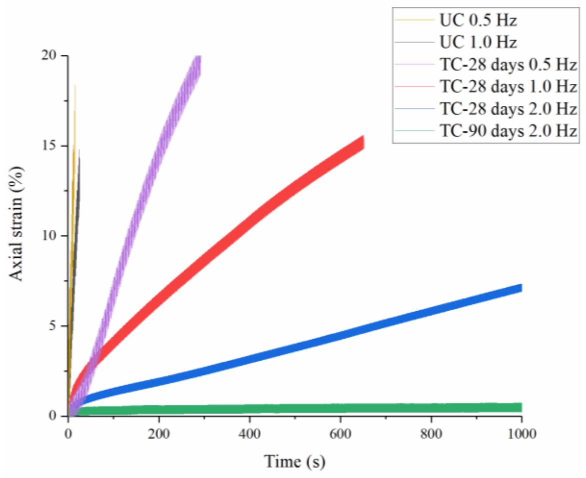


Fig. 15 Effect of frequency and curing periods on axial strain of untreated and treated marine clay at 100 kPa effective confining pressures

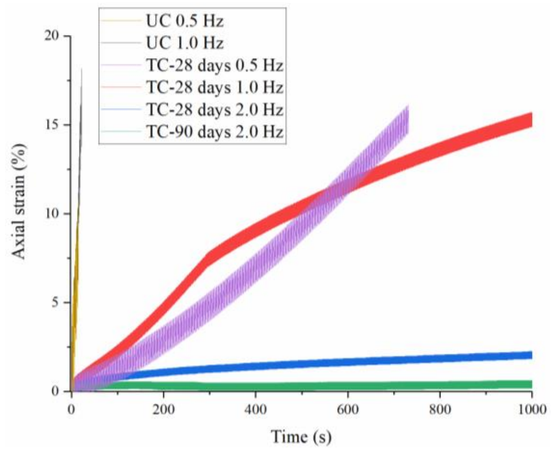


Fig. 16 Effect of frequency and curing periods on axial strain of untreated and treated marine clay at 200 kPa effective confining pressures

cured for 90 days showed very minimal and insignificant strain accumulation (0.65%) at the same time. This is due to the strong particle bonding at 90 days curing period as a result for the completion of the pozzolanic reaction.

Fig. 15 shows the effect of 100 kPa effective confining pressure on untreated marine clay under 0.5 and 1.0 Hz, treated marine clay cured for 28 days under 0.5, 1.0, and 2.0 Hz and treated marine clay cured for 90 days under 2.0 Hz. The effect of frequency for samples tested at 100 kPa effective confining pressure is similar to that encountered with 50 kPa. The strain development under 0.5 and 1.0 Hz of untreated marine clay was rapid and reached the limiting strain within few seconds, while the strain development for the treated marine clay cured for 28 days reached the limiting strain after 138 seconds (N=276) loading cycles and 358 seconds (N=358) loading cycles for 0.5 and 1.0 Hz, respectively. For samples tested under 2.0 Hz, treated and cured for 28 and 90 days, the strain development was minimal for both and after 1000 seconds (N=2000) loading cycles, the recorded strain was 7% for samples cured for 28 days and 0.7% for samples cured for 90 days.

Furthermore, Fig. 16 shows the effect of frequency and curing time on untreated marine clay under 0.5 and 1.0 Hz, treated marine clay cured for 28 days under 0.5 and 1.0 Hz and treated marine clay cured for 28 and 90 days under 2.0 Hz at 200 kPa effective confining pressure. The untreated marine clay samples tested under 0.5 and 1.0 Hz had similar behavior and reached the limiting strain within few seconds. While the treated samples cured for 28 days reached the limiting strain after 522 seconds (N=255) loading cycles and 472 seconds (N=472) loading cycles, respectively. Samples tested under 2.0 Hz and cured for 28 and 90 days reached 2.0 and 0.5% strain after 1000 seconds (N=2000).

Within the limit of this study, it is found that regardless of the effective confining pressure, the frequency (0.5 and 1.0 Hz) did not have a significant effect on the deformation behavior of the untreated marine clay. Putting 10% as the limiting strain, untreated marine clay failed within less than 20 seconds upon subjected to cyclic deviator stress of 90% of the maximum static stress of the soil. Hence, the marine clay needs to be treated to withstand the cyclic loadings of wind, earthquake and traffic. For marine clay treated with optimum recycled tiles and 2% cement, the cyclic loading tests at 28 days curing period showed a significant frequency effect to the deformation of the treated soil. However, the deformation is much smaller than the untreated marine clay especially at high effective confining pressure. In general, the increased in frequency decreased the axial strain occurred. The time required to achieve the limiting strain of 10% is decreased as the frequency increased. At each frequency, the time required to reach 10% strain increased with the increased effective confining pressure. From the three frequencies investigated in this study, 0.5 Hz shows the most damaging effect to the treated soil. It shows that the treated soil failed within 40 seconds (for 50 kPa effective confining pressure) to about 500 seconds (for 200 kPa effective confining pressure) upon subjected to cyclic deviator stress of less than 31% of the maximum static stress of the soil. The development of lower axial strain during the cyclic loading tests using higher frequency is due to the insufficiency of the time for the soil to develop new structure. When the frequency is low and the soil structure is destroyed during the cyclic loading, the structure partially recovers during the vibrational unloading, but the recovered structure is damaged again during the next loading cycle to higher deformation. Therefore, the strain developed in treated soil tested under 2.0 Hz is lower than that of 1.0 Hz and those results are in a good agreement with those of Kucharczyk *et al.* (2018).

For treated soil which has undergone the completion of pozzolanic reaction, the same cyclic loading did not significantly affect the treated soil. At 2.0 Hz frequency, the treated sample cured at 90 days had less than 1% of axial strain after undergoing 1000 seconds (N=2000) of cyclic loading at all effective confining pressures. For 28 days curing period, the sample achieved 10% axial strain at about 400 seconds (N=800) at 50 kPa effective confining pressure while at 100 and 200 kPa effective confining pressures, the treated samples showed less than 7% axial strain at 1000 seconds (N=2000) of cyclic loading.

Liu *et al.* (2016) investigated the effect of 0.1, 0.2, and 0.5 Hz loading frequency on cyclic loading of soft clay in China. The authors found 0.2 Hz as the critical frequency at which higher deformation occurred. In this study, the minimum frequency used was 0.5 Hz. From all the analyzed results, it could be summarized that this smallest frequency used gave the most detrimental effect to both the untreated and treated marine clay. However, since smaller frequencies were not used, this 0.5 Hz could not be validly concluded as the critical frequency.

5. Conclusions

This experimental study aimed to provide an understanding of the cyclic behavior of untreated and treated marine clay. To accomplish this, a series of undrained triaxial cyclic tests was conducted using different frequencies and effective confining pressures on untreated and treated marine clay in order to identify its behavior under cyclic loading. The interpretation of the tests data resulted in determining the cyclic strength, excess pore water pressure and axial strain. The following conclusions can be drawn:

- The results of the cyclic undrained triaxial tests conducted on untreated marine clay samples and RT-cement treated marine clay samples showed that the cyclic strength of marine clay increased with the increased effective confining pressure. The axial strain was increased with cycle time and number of cycles. However, the effect of the effective confining pressure on treated samples cured for 90 days was not significant. Untreated marine clay could not even stand few cycles whereas the treated marine clay samples were able to stand a high number of cycles, up to 2000 cycles.
- The development of axial strain in the untreated samples was very fast and reached the limiting strain (10%) after a short period of time (~20 seconds). On the other hand, the strain development in the treated samples was minimal even after a long period of cycle time (1000 seconds). This situation is obvious for samples cured for 90 days which is due to the cementitious compounds formed during the curing time of the stabilization process that was completed after 90 days of curing time. Besides, the increase of the CSR resulted in an increase in the deformation behavior of all tested samples except the ones cured for 90 days.
- The effect of different loading frequencies (0.5, 1.0, and 2.0 Hz) on both untreated marine clay and treated marine clay with optimum RT and 2% cement was not significant. Although the highest deformation was observed for untreated and treated marine clay samples tested at 0.5 Hz frequency, it cannot be concluded as a critical frequency since smaller frequencies were not used. With the increase of frequency, its effect on both untreated and treated marine clay samples was reduced. Hence, when considering the effect of loading frequency only, the lowest deformation was observed for samples tested under 2.0 Hz.
- The development of the excess pore water pressure was dependent on the effective confining pressure and the number of cycles to failure, especially for the treated samples. The higher number of cycles to failure, the better stabilization for the pore water pressure. Besides, the effect of loading frequency was minimal, and the development of excess pore water pressure was found to be a time-based phenomenon.

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