Effect of confining pressure and loading frequency on dynamic characteristics of Batu Pahat marine clay

S Saleh[1, 2*], N Z Mohd Yunus[3], K Ahmad[3], K N Mat Said[3]

[1]PhD Student, School of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia
[2]Lecturer, Department of Civil Engineering, Hassan Usman Katsina Polytechnic, Katsina, Nigeria
[3]Lecturer, School of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia

* Corresponding author email: samailasaleh@graduate.utm.my

Abstract. This paper presents the laboratory study on the dynamic characteristics of marine clay subject to cyclic load over a long period of time. Remoulded marine clay samples were used to conduct the experiments using a dynamic triaxial machine. Confining pressure and loading frequency were varied while pore pressure development, resilient strains and plastic strain resulting from the application of cyclic loading were observed. The results acquired from this study revealed that as soon as the cyclic loading was introduced, it induced pore pressure that triggered the rapid accumulation of permanent strain and gradual increase in resilient strain. However, after the strain reached a stable value, the rate of accumulation of the permanent deformation started decreasing. The results also showed that an increase in confining pressure improved the marine clay resistance to cyclic loading. Similarly, when the loading frequency increased, it caused a decrease in strain generation and vice versa.

Keywords: Marine clay; cyclic loading; confining pressure; frequency

1. Introduction

The dynamic characteristics of soil are its mannerisms when subjected to cyclic loading. Cyclic loads are triggered by earthquakes, waves, vehicular movements and machinery operations and cause a decrease in soil strength [1] and bearing capacity [2], unpredictable settlement and other geotechnical problems [3]. Wang *et al*. [4] investigated the deformation behaviour of natural soft clay that was subjected to cyclic loading and reported that the hysteretic loop of the stress-strain, pore pressure and dynamic modulus of the trials are considerably reliant on the confining pressure and the cyclic stress ratio. As the confining pressure and the cyclic stress ratio increase, the degradation index value becomes higher. The sample threshold limit in terms of cyclic stress ratio was 0.255. Similarly, Cai *et al*. [5] and Gu *et al*. [6] had studied the undrained dynamic behaviour of saturated clays under variable confining pressure. Cai *et al*. [5] reported that in simulating the in-situ loading conditions of traffic loading, variable confining pressure (VCP) tests are more appropriate than constant confining pressure (CCP) tests because the coupling effects of the variable deviator stress can be simulated in a VCP test. Moreover, VCP stress paths have a strong influence on excess pore water pressure (epwp) development. Furthermore, the permanent axial strain in the CCP tests is a little higher than that in the

VCP tests. Test results by Gu *et al*. [6] reaffirmed that cyclic confining pressure has significant influence on the development of cyclic strain, stress paths and cyclic epwp, while residual epwp development has little impact. Tang *et al*. [7] uses the shakedown concept with fully loaded trucks and determined the influence of traffic load on the clayey subsoil. The three influencing factors identified are: (a) the threshold depth, beyond which the traffic load has a negligible dynamic effect; (b) the depth of plastic shakedown limit, in which visible continuous deformation is experienced in the subsoil; (c) the depth of critical failure, in which failure occurs in the soil due to excessive strain. The findings revealed that the threshold cyclic stress ratio (CSR_t) is 0.03, the cyclic stress ratio at the plastic shakedown limit (CSR_p) is 0.33 and the critical cyclic stress ratio (CSR_c) is 0.44. The plastic shakedown limit depth is 7.0 m. Despite the importance of studying dynamic loading, particularly in a rapidly developing area such as Batu Pahat Johor, attention has not been paid to their dynamic behaviour.

2. Materials

The material used for this research was a disturbed sample of marine clay collected from the campus of Universiti Tun Hussein Onn Malaysia. The sampling site had a flat topography with abundant watercourses. The surface condition of the region was damp, with low permeation of approximately 0.188 mm/min [8]. About 1.5 m of topsoil was removed before sampling the marine clay. The collected sample was air-dried, pulverised and stored in plastic containers for storage, as shown in Figure 1

Figure 1 Dried and pulverised marine clay sample

The engineering properties of the marine clay have been reported in previous research [9–11]. The summary of the properties is presented in Table 1.

Table 1 Properties of marine clay (sources: [9–11])

Parameters	Results
Natural moisture content	67 %

Liquid limit (*LL*)	65 %
Plastic limit (*PL*)	26 %
Fine particles (silt+ clay) ≤ 63μm	98 %
Optimum moisture content (*OMC*)	25 %
Maximum dry density (*MDD*)	1440 kg/m^3
Specific gravity (G_s)	2.56
pH	3.25
Classification	CH
Unconfined compressive strength	66 kPa
Compression indexes C_c	0.268
Swelling indexes C_s	0.005

3. Methodology

Consolidated undrained cyclic triaxial tests were conducted on the marine clay samples based on ASTM standard procedure [12,13] using GDS cyclic triaxial apparatus. The cyclic triaxial device has a controller that automates the applied pressure and volume to the cell. The inbuilt linear displacement transducer measures the axial deformation of the test specimen. The device also has 2 MP built-in pore water pressure (pwp) sensor and 5 kN submersible load cell sited inside the pressure cell, as shown in Figure 2. Data were recorded automatically using high precision real-time data acquisition function.

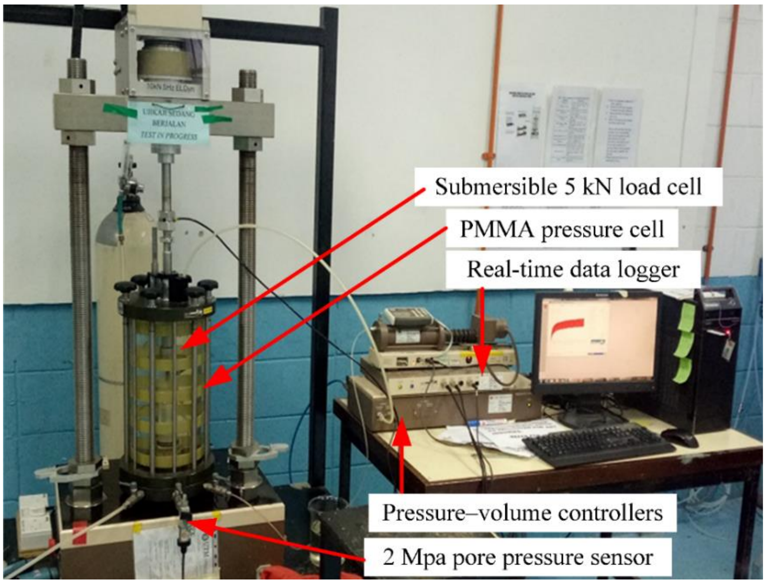

Figure 2 Cyclic triaxial test apparatus

The cylindrical specimen of size 38 mm in diameter and 76 mm in height were also prepared from remoulded marine clay mixed with OMC, as shown in Figure 3. Side drain surrounding the specimen was also fixed to enhance the saturation and consolidation processes. The sample was mounted on the base of the equipment, then saturated under 100 kPa cell pressure with ten kPa backpressure difference. The B check was performed automatically and gradually increased the cell pressure by 100 kPa until a B check of 0.95 was achieved. Subsequently, the specimen was consolidated under different effective stresses of 100 kPa, 200 kPa and 300 kPa [14]. Finally, cyclic triaxial tests were conducted on the marine clay using the varying frequencies of 0.5 Hz, 1 Hz and 2 Hz [14].

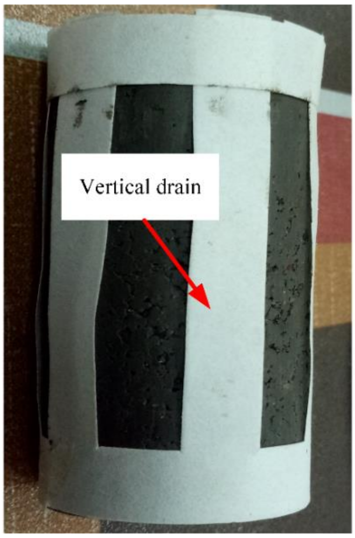

Figure 3 installation of the vertical drain in the test specimen

4. Results and discussion

4.1. Dynamic behaviour of marine clay

Figure 4 shows the response of marine clay subjected to continuing cyclic loading, which includes pore pressure development and axial strain plotted against the number of cycles. The cyclic loading induces total strain, ϵ_t which is the sum of the permanent strain, ϵ_p and resilient strain, ϵ_r [14,15]. Once the cyclic loading was initiated, it induced pore pressure that triggered the rapid accumulation of permanent strain and gradual increase in resilient strain. The strain will build up to a constant value, while the rate of permanent deformation build-up will start decreasing [16]. For example, in Figure 4, during the first 100 cycles of loading, the pore pressure developed rapidly from 420 kPa to 500 kPa. The pwp mobilised the permanent plastic strain and the total strain of the marine clay to increase promptly from 0 to 3 % and 0 to 5.5 %, respectively. Furthermore, from 100 to 1000 cycles, the pore pressure increased gradually from 500 to only 540 kPa and then continued slowly. The resilient stain was then mobilised and continued to increase along with the plastic strain as the loading progress. After 1000 cycles of loading, the resilient strain showed a minimal increase; only the plastic strain continued to increase as the number of loading cycles continued [14]. Marine clay behaviour under long-term dynamic loading was further studied by changing the effective confining pressure and frequency as summarised in **Error! Not a valid bookmark self-reference.**.

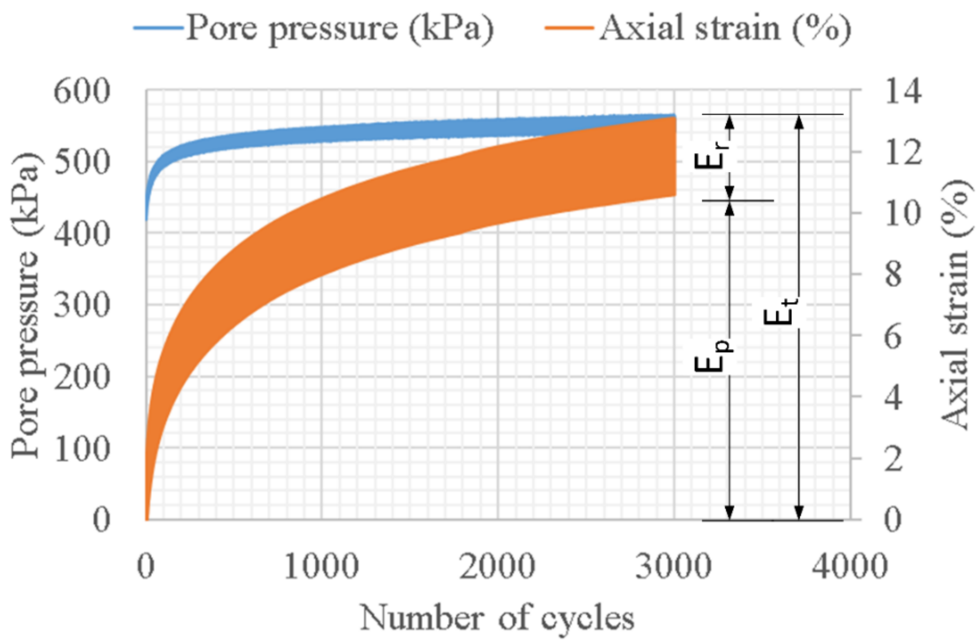

Figure 4 Dynamic behaviour of marine clay under persistent long-term cyclic loading

Table 2 Undrained cyclic triaxial tests summary

Effective confining pressure (kPa)	**Frequency, f (Hz)**	**Amplitude (kN)**	**No. of cycles, N**
100	1.0	0.4	10,000
200	1.0	0.4	10,000
300	1.0	0.4	10,000
200	0.5	0.4	10,000
200	1.0	0.4	10,000
200	2.0	0.4	10,000

4.2. Effects of confining pressure on the dynamic behaviour of marine clay

Figure 5 shows the effects of confining pressure on the dynamic behaviour of marine clay. The results show that the increase in confining pressure contributes to the improvement of the resistance of marine clay to cyclic loading. The soil subjected to the same loading condition failed (attained total strain of 20%) in less than 100 cycles of cyclic loading when the consolidation pressure was 100 kPa. At the same time, the same soil survived 10, 000 cycles of cyclic loading when the consolidation pressure was increased to 300 kPa. Thus, the rate of development of excess pore pressure due to cyclic loading is high when the confining pressure is low [5] [6]. As the excess pore pressure is increased, it will mobilise the development of the permanent axial strain in the soil, and that will cause the failure of the sample within a few cycles of cyclic loading. [5,6,14–16]. It can also be observed from the result in Figure 5 that the sample failed within the first 100 loading cycles for 100 kPa confining pressure. In contrast, for 300 kPa confining pressure, the specimen experienced only 5 % strain, meaning that the soil is not likely to fail even if the loading cycles are doubled or tripled. However, the sample showed moderate deformation when 200 kPa confining pressure was applied. Thus, 200 kPa confining pressure was used for the remaining tests, where the loading frequency was varied. The empirical formulae for estimating the soft cumulative plastic strain and epwp are given in equations (1) and (2) [5,17,18]. Equations (1) and (2) show that the higher the effective pressure, the lower the permanent axial strain, and this corresponded well to the findings, as shown in Figure 5.

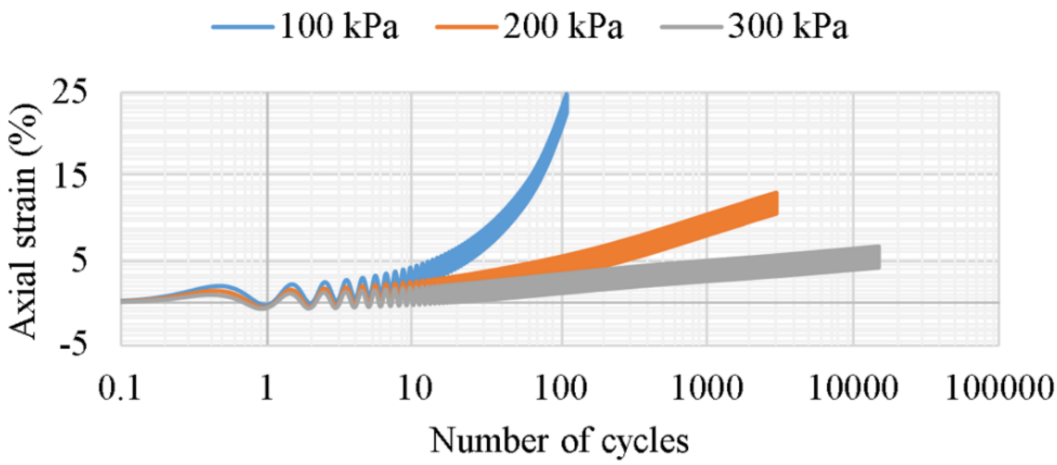

Figure 5 Effects of confining pressure on the dynamic behaviour of marine clay under long-term cyclic loading

$$\varepsilon_a^p = A.\left(q^{ampl}/P_0^1\right)^M (log\,N)^D \quad (1)$$

$$\frac{\Delta\,\cup}{P_0^1} = a.\left(q^{ampl}/P_0^1\right)^m (log\,N)^d \quad (2)$$

Where

$\Delta\,\cup$ = excess pore-water pressure
ε_a^p = permanent axial strain
q^{ampl} = deviatoric stress amplitude
P_0^1 = initial effective pressure
N = number of load cycles
a and A = parameters linked to the soil physical properties
m and M = constants related to the loading intensities;
d and D = constants related to the number of cycles.

4.3. Effects of frequency on the dynamic behaviour of the marine clay

Correspondingly, Figure 6 shows the effects of changes in frequency and amplitude, respectively on the dynamic behaviour of the marine clay subjected to continuing loading. The results revealed that an increase in loading frequency reduces the rate of strain generation. Likewise, a decrease in frequency triggered an increase in the accumulated pwp that causes the accumulation of the permanent axial strain [19]. However, Guo *et al.* [19] revealed that at the start of shaking, the smaller cumulative pwp of about 30 kPa or 40 kPa might be due to low frequency. The effect of frequency changes is similar to the effect of varying cyclic stress ratio (CSR) in various soil types such as peat [15], marine clay[14] and saturated sand [20]. CSR was defined as the ratio of cyclic deviator stress to undrained shear strength [16,20].

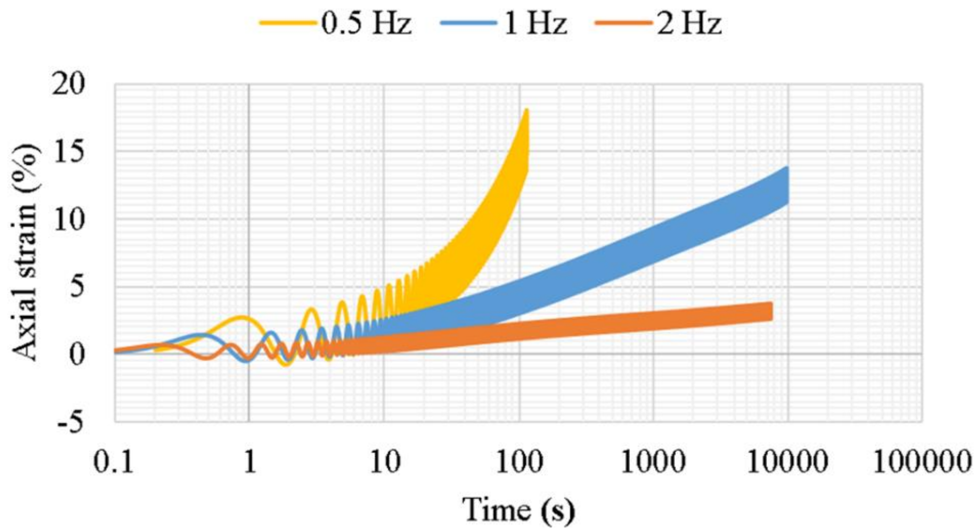

Figure 6 Effects of frequency on the dynamic behaviour of marine clay under long-term cyclic loading

5. Conclusions

Consolidated-undrained cyclic triaxial tests were conducted on marine clay collected from Batu Pahat Malaysia to characterise the dynamic behaviour of the soil. The development of resilient strains and plastic strains due to the application of the cyclic load was observed when the soil was subjected up to 10,000 cycles of cyclic loading at different confining pressures and loading frequencies. The key conclusions from the experimental observations are as follows:

1. The moment the marine clay is subjected to the cyclic loading, pore pressure is induced by the cyclic load, which triggered the rapid accumulation of permanent strain and gradual increase in resilient strain. Then, after strain accumulates to a stable value, the increase of permanent deformation starts decreasing.
2. Increase in confining pressure improves the resistance of the marine clay to cyclic loading.
3. Increase in loading frequency reduces the rate of strain generation. Likewise, a decrease in frequency causes an increase in the accumulated pwp, which in turn leads to the accumulation of the permanent axial strain.

6. References

[1] Li L, Dan H and Wang L 2011 Undrained behavior of natural marine clay under cyclic loading *Ocean Eng.* **38** 1792–805
[2] Wichtmann T, Andersen K H, Sjursen M A and Berre T 2013 Cyclic tests on high-quality undisturbed block samples of soft marine Norwegian clay *Can. Geotech. J.* **50** 400–12
[3] Gu C, Wang J, Cai Y, Yang Z and Gao Y 2012 Undrained cyclic triaxial behavior of saturated clays under variable confining pressure *Soil Dyn. Earthq. Eng.* **40** 118–28
[4] Wang Y, Gao Y, Li B, Fang H, Wang F, Guo L and Zhang F 2017 One-way cyclic deformation behavior of natural soft clay under continuous principal stress rotation *Soils Found.* **57** 1002–13
[5] Cai Y, Gu C, Wang J, Juang C H, Xu C and Hu X 2013 One-Way Cyclic Triaxial Behavior of Saturated Clay: Comparison between Constant and Variable Confining Pressure *J. Geotech. Geoenvironmental Eng.* **139** 797–809
[6] Gu C, Wang J, Cai Y, Sun L, Wang P and Dong Q 2016 Deformation characteristics of overconsolidated clay sheared under constant and variable confining pressure *Soils Found.* **56** 427–39
[7] Tang L, Chen H, Sang H, Zhang S and Zhang J 2015 Determination of traffic-load-influenced depths in clayey subsoil based on the shakedown concept *Soil Dyn. Earthq. Eng.* **77** 182–91

[8] Musa S, Zakaria N A, Liang L T and Tjahjanto D 2012 Subsurface Conditions with Geo-hydraulic Properties : Empirical Evidence from Parit Raja , Johor *Int. Conf. Civ. Environ. Eng. Sustain. (IConCEES 2011)*

[9] Saleh S, Asmawisham Alel M N, Mohd Yunus N Z, Ahmad K, Ali N, Abang Hasbollah D Z and Asnida Abdullah R 2019 Geochemistry characterisation of marine clay *IOP Conf. Ser. Mater. Sci. Eng.* **527** 012023

[10] Saleh S, Mohd Yunus N Z, Ahmad K, Ali N and Marto A 2020 Micro-Level Analysis of Marine Clay Stabilised with Polyurethane *KSCE J. Civ. Eng.* **24** 807–15

[11] Saleh S, Mohd Yunus N Z, Ahmad K and Ali N 2018 Stabilisation of Marine Clay Soil Using Polyurethane ed Y Haryati, M Y Nor Zurairahetty and I Izni Syahrizal *MATEC Web Conf.* **250** 01004

[12] ASTM:D3999-91 2003 Standard Test Methods for the Determination of the Modulus and Damping Properties of Soils Using the Cyclic Triaxial Apparatus *Am. Soc. Test. Mater.* **91** 1–15

[13] ASTM:D5311-92 2004 Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil *Am. Soc. Test. Mater.* **92** 1–9

[14] Wang J, Guo L, Cai Y, Xu C and Gu C 2013 Strain and pore pressure development on soft marine clay in triaxial tests with a large number of cycles *Ocean Eng.* **74** 125–32

[15] Gao Y, Xiao W, Xu G and Gui Y 2018 Strain behaviour of sapric peat under long-term cyclic loading *Proc. Inst. Civ. Eng. - Geotech. Eng.* **171** 405–21

[16] Zhou J and Tang Y 2018 Practical model of deformation prediction in soft clay after artificial ground freezing under subway low-level cyclic loading *Tunn. Undergr. Sp. Technol.* **76** 30–42

[17] Monismith C L, Ogawa N and Freeme C R 1975 Permanent deformation characteristics of subgrade soils due to repeated loading *54th Annual Meeting of the Transportation Research Board* (Washington D C) pp 1–17

[18] Chai J-C and Miura N 2002 Traffic-Load-Induced Permanent Deformation of Road on Soft Subsoil *J. Geotech. Geoenvironmental Eng.* **128** 907–16

[19] Guo L, Chen J, Wang J, Cai Y and Deng P 2016 Influences of stress magnitude and loading frequency on cyclic behavior of K0-consolidated marine clay involving principal stress rotation *Soil Dyn. Earthq. Eng.* **84** 94–107

[20] Ueno K, Kuroda S, Hori T and Tatsuoka F 2019 Elastic shear modulus variations during undrained cyclic loading and subsequent reconsolidation of saturated sandy soil *Soil Dyn. Earthq. Eng.* **116** 476–89

Acknowledgements

The authors are grateful for the support provided by the research grants of UTMFR Vote No. Q.J130000.2551.21H42 and UTMER Vote No. Q.J130000.2651.18J00 from Universiti Teknologi Malaysia, Johor Bahru, Malaysia. Samaila Saleh is equally grateful for the support provided by the Tertiary Education Trust Fund (TET Fund) Nigeria.