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One-dimensional cyclic loading tests on saturated and unsaturated sand-clay mixtures

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Abstract. A series of one-dimensional cyclic loading tests are carried out on three different proportions of Sydney sand – kaolin mixtures, at various initial degrees of saturation. The settlement of the samples throughout the tests is accurately monitored. The effects of the degree of saturation and frequency of the cyclic load on the evolution of the settlement during the tests are thoroughly investigated for each mixture. The settlement patterns are compared to those of saturated samples to highlight the effect of soil suction on the behaviour. The results show that soil settlement decreases while the time required for the completion of the primary consolidation increases with the decrease in the degree of saturation of the soil. This trend is more pronounced in soils with higher kaolin content. The loading frequency, however, seems to have negligible effects on the settlement behaviour of unsaturated soils under cyclic loading. The result of the study provides valuable data for future simulations and validations of various constitutive models.

1 Introduction

For saturated soils, the theory of soil consolidation is well studied and developed; however, in most practical cases, at least part of the soil subjected to loading is in an unsaturated state, for which the process of consolidation is more complex. The study of the problem becomes even more complex when an unsaturated soil is subjected to cyclic loading due to the complicated interactions between the water and air phases.

In the literature, research on the consolidation of unsaturated soils is mainly focused on numerical simulations and modelling (e.g., [1-6]), with only a few experimental studies. Usaborisut et al. [7] were among the first to conduct tests on unsaturated soils under cyclic loading. This was followed by a few studies on the liquefication of unsaturated soils under cyclic loading [8,9]. Unno et al. [10] investigated the liquefication of unsaturated soils through performing cyclic tests on unsaturated soil samples. Their results showed that both pore water and pore air pressures could increase with the increase of cyclic load, with the possibility that the effective stress reduces to zero, resulting in liquefaction. Kaya and Erken [11] studied the behaviour of different unsaturated soils under cyclic seismic load. The pore water pressure, axial strain and dynamic strength were monitored during the tests, and their relationships to soil plasticity and fine content were analysed. However, the tests were performed only up to 20 cycles since they followed their cyclic tests with post-cyclic monotonic tests, hence the steady state of pore water pressure and axial strain were not achieved in cyclic loading. Cary and Zapata [12] conducted triaxial tests on six different clayey sand samples under cyclic load. Pore water pressure response subjected to cyclic loading was obtained in the tests for both saturated and unsaturated soils. Comparisons were made between saturated soil specimens and unsaturated soil specimens. The results showed that the void ratio and hydraulic conductivity greatly impact the dissipation duration and peak value of pore pressures. Also, it was found that in some unsaturated soil specimens, the excess pore pressures generated were higher than those generated in saturated specimens, which is contradictory to many other experimental data in the literature. They attributed this to the pressurised air pores exerting pressure on the pore water, but no further evidence was given in this regard.

Overall, limited data is available in the literature on the generation and dissipation of pore pressure under cyclic loadings. Furthermore, loading tests for the same soil at different degrees of saturation are rarely seen in the literature. As a result, it is difficult to find sufficient data for simulations when validating constitutive models. To address this deficiency, in this study, several sets of one-dimensional cyclic consolidation tests are performed on three Sydney sand – kaolin mixtures to 1) obtain data of pore water pressure over time to investigate the generation and dissipation behaviour under different cyclic loading frequencies for saturated soils, and 2) investigate the effect of soil types and degree of saturation on settlement of the test soils when the samples are in an unsaturated state.

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2 Experimental program

2.1 Test materials

Three types of Kaolin and Sydney sand mixtures with different proportions are used in this research. They are mixed at 75% Sydney sand - 25% Kaolin, 50% Sydney sand - 50% Kaolin, and 25% Sydney sand - 75% Kaolin, which are referred to as 75S25K, 50S50K, and 25S75K, respectively. The index properties of these soils are provided in Table 1.

Table 1. Properties of different soil mixtures used in this study.

Soil Mixture	75S25K	50S50K	25S75K
Specific Gravity (Gs)	2.596	2.686	2.733
Liquid Limit	32.7%	43.2%	60.3%
Classification (USCS)	SM	ML	ML

2.2 Sample preparation

The moist tamping method was used to prepare samples for both saturated and unsaturated tests. First, the appropriate amount of dry sand and kaolin mixture was placed into a mixing pan, then de-aired water was gradually added to the target moisture content (around 1.1 times the liquid limit) and then mixed thoroughly until the sample took on a paste-like consistency. The initial moisture contents was selected higher than the liquid limit of the soil for the ease of sample preparation. The sample was then put in a sealed container and wrapped with plastic film for at least 24h to let water distribute homogeneously throughout the soil. After 24 hours, the soil paste was transferred from the container to the CRS retaining ring (50mm in diameter and 22mm in height). The retaining ring was constantly tapped in the process of transferring to ensure an even spread of the paste inside the ring and to remove trapped air bubbles in the sample. The surface of the soil inside the ring was then evened by a spatula. Filter papers were put on both sides of the ring to prevent the porous disks from being blocked by the movement of fine soil solids which can disrupt the drainage path between the sample and the porous disks during the tests.

2.3 Characterisation tests

2.3.1 Pressure plate tests

A set of pressure plate tests were first performed (according to ASTM D6836-02 and considering the recommendations in [13]) on the samples to obtain their soil water retention curves (SWRC). The SWRCs obtained for the soil samples, along with the estimated air entry value (AEV) for each soil mixture, are presented in Fig. 1. The void ratio of the samples at the start of the SWRC tests were 0.78, 1.04 and 1.57 for the 75S25K, 50S50K and 25S75K samples, respectively. The AEVs have been obtained by fitting the Brooks and Corey equation [14] to the experimental data.

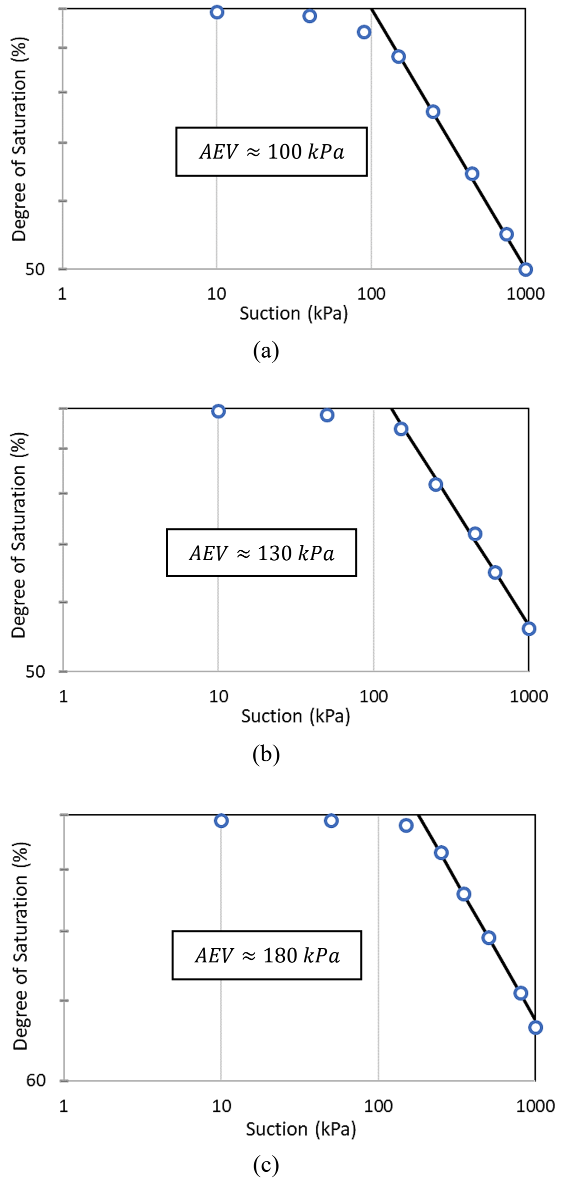

Fig. 1. SWRCs of the samples along with their estimated air entry values: (a)75S25K; (b)50S50K; (c)25S75K.

2.3.2 Oedometer tests on saturated samples

A set of static consolidation tests were conducted on the samples to determine the consolidation indices of the soil. The test results are shown in Fig. 2. Also included in Fig. 2 are the best estimations of the normally consolidation line for each sample.

2.4 Dynamic consolidation tests

A constant rate of strain (CRS) oedometer apparatus, designed by GDS Instrument Ltd., was used in this study to perform the tests. The equipment is capable of controlling suction through the axis translation technique, and is capable of applying both static and dynamic loads on soil samples. A photo of the equipment used in this study is provided in Fig. 3.

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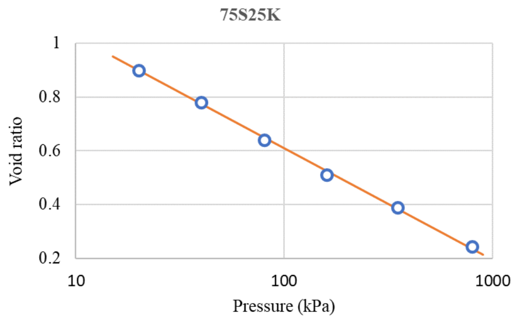

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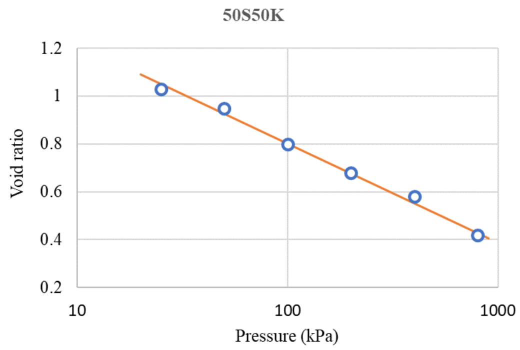

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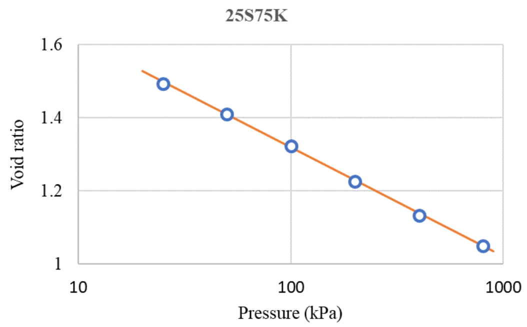

(c)

Fig. 2. Consolidation curves for different soils: (a)75S25K; (b)50S50K; (c)25S75K.

Tests on fully saturated samples were performed on the samples after they were saturated in the CRS cell, and consolidated under $25kPa$ normal load. For saturating the samples, the back pressure technique was used according to the method recommended in ASTMD4186/D4186M- 2014. For the unsaturated tests, after the sample was fully saturated, the water in the cell was removed and the target suction was applied to the sample to ensure that the hydraulic state of the sample is on the drying path. A vertical stress of $\sigma = 25kPa$ was applied to the samples during unsaturation to ensure the samples remain docked during suction application. To avoid application of a sudden net stress to the samples, the target suctions were applied by first increasing both the pore air and water pressures, and then (once equilibrium was reached decided by monitoring the vertical displacement of the sample) reducing the pore water pressure to induce the target suction (pore air pressure was remained constant).

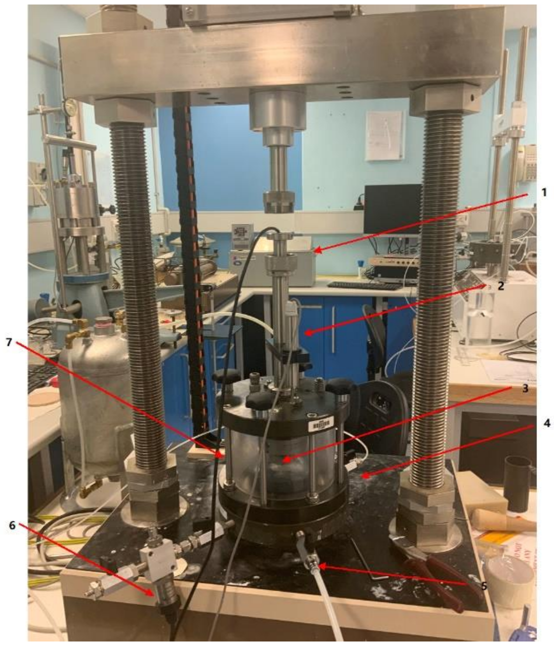

Fig. 3. Dynamic CRS equipment used in this study. Parts shown in the photo are: 1) Loading ram; 2) Axial displacement transducer; 3) Load cell; 4) Back pressure valve; 5) Cell pressure valve; 6) Pore water pressure transducer; 7) CRS cell.

All the tests were conducted on a sample configuration with permeable top and impermeable bottom, and started with a seating load of $25kPa$. Considering that in geotechnical applications mostly compression loading is considered, the haversine form of loading was applied to the samples, as follows,

$$L(t) = q sin^2(\pi t f) \quad (1)$$

where q is the load amplitude, t is time, and f is the load frequency. The tests in this study were performed with q=200kPa.

2.4.1 Saturated samples

In total, 9 cyclic consolidation tests were performed on saturated samples at three frequencies of 0.01, 0.02 and 0.04Hz. The initial void ratio of the samples were 0.78, 1.04 and 1.57 for the 75S25K, 50S50K and 25S75K samples, respectively. The variations in the pore water pressure (PWP) normalised against the load amplitude (i.e., u/q), and settlement normalised against the initial height of the sample (i.e., s/h) during the tests are presented in Figs. 4 to 6. The results are presented in terms of the dimensionless time factor (T_v) as follows,

$$T_v = \frac{c_v \, . \, t}{h^2} \quad (2)$$

where c_v is the average coefficient of consolidation (obtained from consolidation tests on each sample), and h is the sample height.

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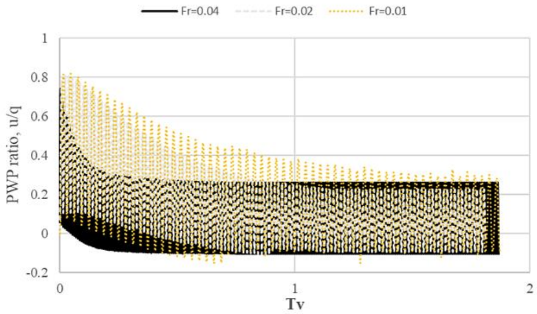

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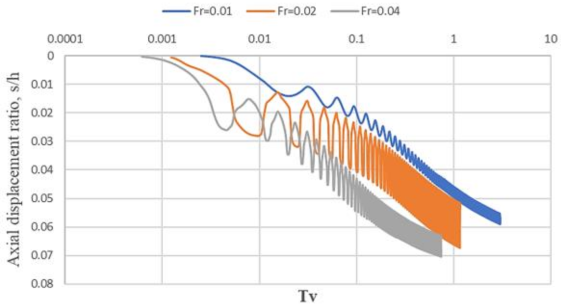
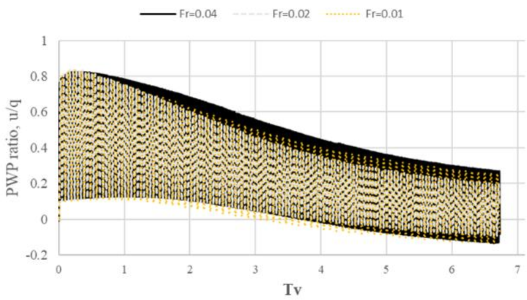


(b)

Fig. 4. The response of the saturated 75S25K soil under cyclic CRS tests (a) variation of pore water pressure; (b) settlement variations.



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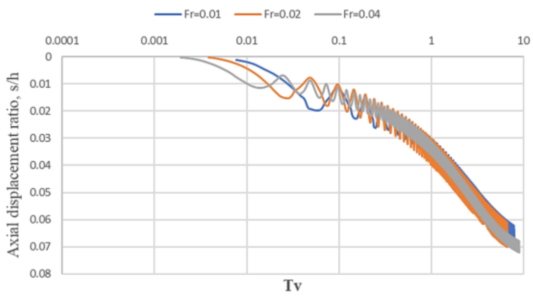
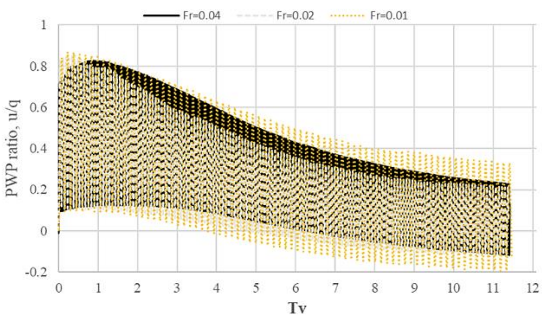


(b)

Fig. 5. The response of the saturated 50S50K soil under cyclic CRS tests (a) variation of pore water pressure; (b) settlement variations.



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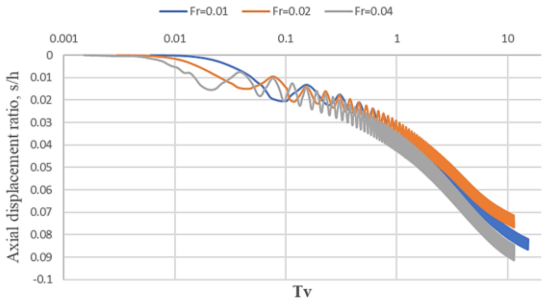


(b)

Fig. 6. The response of the saturated 25S75K soil under cyclic CRS tests (a) variation of pore water pressure; (b) settlement variations.

The test results on saturated samples show that the excess pore water pressure for all the samples dissipates and decreases to zero after a number of cycles (frequency dependent), and then oscillates around 0.1q with an amplitude value of around 0.2q, which seems to be independent of the soil type and loading frequency of the sample. The results also show that the effect of the load frequency on the excess pore water pressure dissipation rate decreases significantly as the fine content of the soil increases. For sandy soils with a high permeability, the dissipation duration of pore water pressure is highly related to the frequency of loading. The lower the load frequency, the longer it takes for the pore water pressure to dissipate. However, for samples with higher kaolin content, the excess pore water changes are almost independent of the load frequency.
The effect of load frequency on settlement is also more obvious for saturated sandy soils. In agreement with the observed variations of pore water pressure, for samples with kaolin over 50%, load frequency has almost no effect on the settlement of the soil, neither on the final value of the settlement nor on the time to complete the primary consolidation.

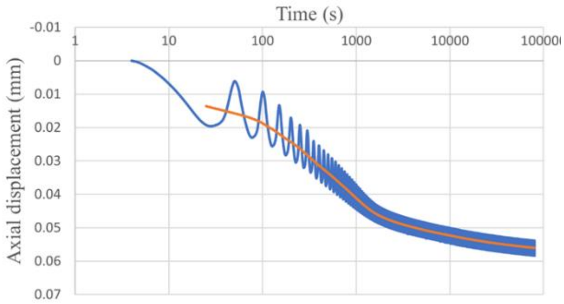
2.4.2 Unsaturated samples

A total of 15 tests were conducted on unsaturated samples of 75S25K and 25S75K, at initial degrees of saturation of Sr=70%, 80% and 90%. The initial void ratio of the samples prior to the application of cyclic loading are presented in Table 2. Two loading frequencies of 0.01Hz and 0.04Hz were used for the 75S25K samples. However, the test results showed that the frequency does not have a noticeable effect on the test results, hence, only one loading frequency (i.e., 0.01Hz) was used for the subsequent tests on the 25S75K samples. Only the test data related to this load frequency are presented in this paper.

Table 2. Initial void ratio of the unsaturated soil samples.

Soil Mixture	75S25K	25S75K
$S_r = 90\%$	0.601	1.147
$S_r = 80\%$	0.586	1.129
$S_r = 70\%$	0.577	1.112

The sample settlements during the cyclic tests are presented in Figs. 7 and 8 for different soil mixtures at different initial degrees of saturation. Also included in these figures are the average values of the cyclic displacements, shown with a solid line passing through the middle of the cyclic settlement data.



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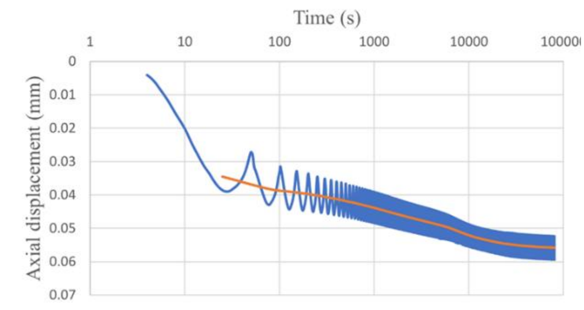

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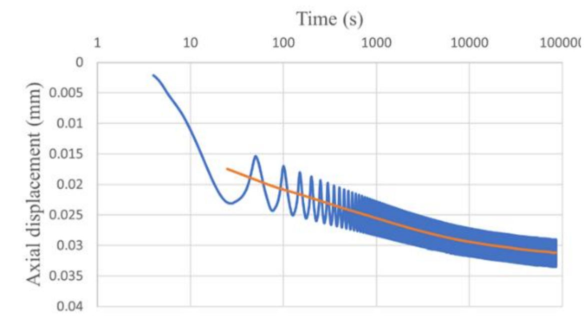
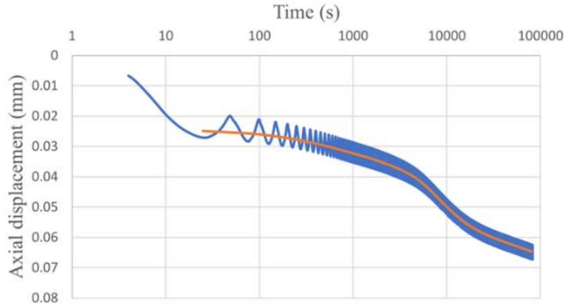


(c)

Fig. 7. Settlement of 75S25K samples under cyclic CRS tests at the initial degree of saturation of (a) $S_r = 90\%$; (b) $S_r = 80\%$; (c) $S_r = 70\%$.

Several observations can be made from the test results. The samples with more kaolin show slightly larger settlement under load at high degree of saturation levels compared to the samples with more sand, perhaps due to their higher initial void ratios and compressibility. However, at lower degrees of saturation, the difference between the settlement values of these two soils diminishes. For each soil mixture, the final sample settlement decreases as the initial degree of saturation decreases, which is expected due to the hardening effects of suction in soils; however, the initial settlements are larger in 75S25K samples with lower degrees of saturation due to the higher contribution of the air phase in the sample settlement when the initial degree of saturation is lower.



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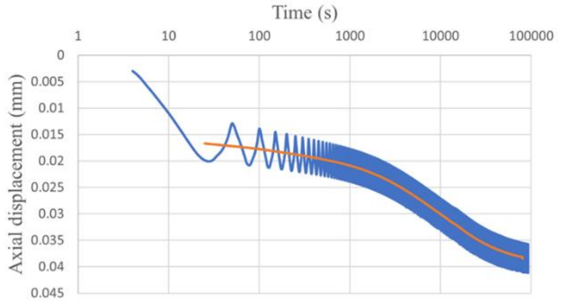

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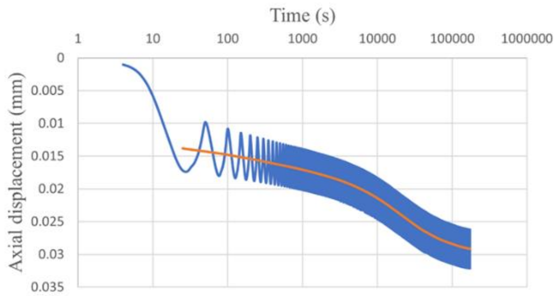

(c)

Fig. 8. Settlement of 25S75K samples under cyclic CRS tests at the initial degree of saturation of (a) $S_r = 90\%$; (b) $S_r = 80\%$; (c) $S_r = 70\%$.

The settlement curves for samples with more kaolin show clear inflection points, particularly when the degree of saturation is lower. The time to reach the steady state for the samples with more kaolin is also larger compared to that for sandy samples. Interestingly, for both soils, there seems to be a critical initial degree of saturation beyond which the degree of saturation has no longer an effect on the time required to reach the steady state, although more test data are required to confirm this observation.

3 Conclusion

This paper presented an experimental study on the behaviour of saturated and unsaturated sand-kaolin mixtures under cyclic loading to investigate the variation of pore water pressure (in saturated soils) and consolidation curves for different loading frequencies and soil types. The results of the study are valuable for development and verification of constitutive models for unsaturated soils.

Tests on saturated samples showed that for samples with a higher sand content (i.e., 75S25K), the rate of pore water pressure dissipation increases with an increase in the loading frequency. However, the loading frequency

effects were almost disappeared after the kaolin content exceeded 50% in this study (and also for unsaturated samples). Also, the time required for the dissipation of the initial excess pore water pressure increased with the increase in the kaolin content. Consistent with the observations on the excess pore water pressure change in the samples, the settlement of sandy soils is also influenced by the loading frequency while this is less evident for soils with higher fine content (and for initially unsaturated samples).
Tests on unsaturated samples showed that the settlement values decrease while the time of primary consolidation (for the backbone curve) increases with the decrease in the initial degree of saturation of the samples. This trend was more pronounced in soils with higher kaolin content. As the initial degree of saturation decreases, the settlement curves for the sandy soils showed a higher initial drop due to the more contribution of the air phase. After this initial drop, the settlement curves for sandy soils followed with a smooth curve, while the curves for the clayey soils showed clear inflection points. The results also showed that the time at which the average settlement reached the steady state increased with the decrease of the initial degree of saturation, although there seems to be a critical degree of saturation below which the changes in the initial degree of saturation no longer influences the time to steady state.

References

1. D. Sheng, S.W. Sloan, A. Gens A, D.W. Smith. Int J Numer Anal Methods Geomech., **27**(9):745-765 (2003).
2. B. Shahbodagh-Khan, N. Khalili, G. A. Esgandani. Comput Geotech; **69**:411-423 (2015).
3. J. Ghorbani, M. Nazem, J. Carter, Comput Geotech; **71**:195-206 (2016).
4. O. Ghaffaripour, G. A. Esgandani, A. Khoshghalb B. Shahbodaghkhan, Int J Numer Anal Methods Geomech., **43**(11): 1919-1955 (2019).
5. A. Khoshghalb, N. Khalili, Int J Numer Anal Methods Geomech, 37(7): 716-743 (2013).
6. L. Ho, B. Fatahi, H. Khabbaz. Int. J. Geomech. **18**(5): 04018029 (2018).
7. P. Usaborisut, M. Koike, B. Bahalayodhin, T. Niyamapa, A. Yoda, J Terramechanics, **38**(2), 71-87 (2001).
8. I. B. Gratchev, K. Sassa, V. I. Osipov, V. N. Sokolov, Eng Geol., **86**(1), 70-84 (2006).
9. H. Bian, I. Shahrour, Soil Dyn. Earthq. Eng., **29**(2), 237-244 (2009).
10. T. Unno, M. Kazama, R. Uzuoka, N. Sento, Soils Found., **48**(1), 87-99 (2008).
11. Z. Kaya, A. Erken, Soil Dyn. Earthq. Eng., **77**, 83-96, (2015).
12. C. E. Cary, C. E. Zapata, Int. J. Geomech., **16**(6), D4016004, (2016).
13. A. Y. Pasha, A. Khoshghalb, N. Khalili, Int. J. Geomech., **16**(6) D4015004, (2016).
14. R.H. Brooks, A.T. Corey, Hydrology papers, Colorado State University (1964).