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VARIATION OF PORE WATER PRESSURE IN OVER-CONSOLIDATED CLAY UNDER CYCLIC LOADING: EXPERIMENTAL INVESTIGATION

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Abstract: Under cyclic loading, the cyclical effect of external load during loading time will result in multiple rearrangement of soil particles, and thus causing the particles to arrange more closely together than un static loading. As the soil volume decreases with increase in the number of loading cycles, the accumulated excess pore water pressure dissipates through draining of the soil. This study presented results of prediction the behavior of clay in partially drained cyclic plane test. The results from cyclic triaxial test on a highly plastic marine clay were formulated to predict the time dependent variations of excess pore pressure and axial strains during partially drain cyclic loading. The study further revealed that when saturated clay is exposed to cyclic loading, the reduction in effective stress due to the generation of excess pore water pressure leads to a decrease in soil strength. Over the long term, the accumulation of pore water pressure in saturated clay is influenced by various factors, including the magnitude of the applied load, its frequency, and the intrinsic properties of the soil.

Keywords: Soft Clay, Consolidation, Cyclic Loading, Excess Pore Water Pressure

ИЗМЕНЕНИЕ ДАВЛЕНИЯ ПОРОВОЙ ВОДЫ В ПЕРЕУПЛОТНЕННОЙ ГЛИНЕ ПРИ ЦИКЛИЧЕСКОМ НАГРУЖЕНИИ: ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ

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Аннотация: При циклическом нагружении циклическое воздействие внешней нагрузки в течение времени нагружения приводит к многократной перегруппировке частиц грунта, в результате чего частицы располагаются более плотно друг к другу, чем при статическом нагружении. Поскольку объем грунта уменьшается с увеличением количества циклов нагружения, накопленное избыточное давление поровой воды рассеивается за счет дренирования грунта. В данном исследовании представлены результаты прогнозирования поведения глины в частично дренированном циклическом плоском испытании. Результаты циклических трехосных испытаний высокопластичной морской глины были использованы для прогнозирования зависящих от времени изменений избыточного порового давления и осевых деформаций при циклическом нагружении с частичным дренированием. Исследование показало, что, когда насыщенная глина подвергается циклическому нагружению, снижение эффективного напряжения из-за создания избыточного давления поровой воды приводит к снижению прочности грунта. В долгосрочной перспективе на накопление давления поровой воды в насыщенной глине влияют различные факторы, включая величину приложенной нагрузки, ее частоту и собственные свойства грунта.

Ключевые слова: Мягкая глина, консолидация, циклическое нагружение, избыточное давление поровой воды

1. INTRODUCTION

The classic theory of consolidation was developed by Terzaghi (1943) [1]. This is still today the foundation of one-dimensional (1-D) consolidation theory. This theory, developed for the prediction of long term settlement of soil, uses the rate of seepage of pore water under the action of external load to determine the deformation of a layer of saturated soil. Conventional consolidation analysis based on Terzaghi's one-dimensional theory overlooks the non-linear characteristics of soil. Davis and Raymond (1965) [2] introduced a non-linear theory of soil consolidation. Wilson et al. (1974) [3], through theoretical analysis, noted that consolidation under cyclic loading progresses more slowly than under an equivalent sustained load, making it impossible to achieve 100% consolidation with cyclic loading. Baligh et al. (1978) [4] proposed a straightforward method for predicting the behavior of an inelastic clay layer initially in a normally consolidated state and subjected to cyclic loading. Favaretti et al. (1995) [5] developed a simplified solution to predict consolidation under cyclic loading for non-dimensional time intervals.

When the load is first applied the total stress increases but, as shown above for 1-D conditions, there can be no instantaneous change in vertical effective stress, implying that the pore-pressure must increase by exactly the same amount as the increase in total stress. Subsequently, there will be flow from regions of higher excess pore pressure to regions of lower excess pore-pressure, and the excess pore pressures will dissipate leading to change in effective stress and the soil will deform (consolidate) with time [6-8].

When soft clay soils are exposed to time-dependent cyclic loading, excess pore water pressure gradually builds up. After a certain number of cycles, this pore water pressure begins to dissipate, leading to progressive deformation over time often significantly greater than that caused by static loading. Common examples of cyclic loads include earthquakes, ocean waves, high-intensity traffic, seasonal fluctuations in groundwater levels, and changing fuel levels in oil tanks. Long-term cyclic loads, can sometimes induce consolidation of the underlying soil.

Yin et. al (1989) [9, 10] reported a case study on settlement of a road in "Jie Pu highway, in Guangdong province, China", built on a low bank road embankment on typical soft alluvial clay. It settled substantially after opening to traffic, which was nearly 2m over a length of 1700m. Xie et al. (2006) [11] reported a case study on long term settlement of break water constructed at the port of Tianjin in China due to static and wave-induced cyclic loads.

Chen et al. (2005) [12] predicted that pore water pressure increases during loading and decreases during unloading under low frequency cyclic loading with different boundary conditions.

Guo-Wei Li and Hu [13-15] studied the effect of dynamic cyclic loading and surcharge preloading method on the settlement of low embankments and showed that the settlement increases with increasing amplitude of cyclic load and the effectiveness of surcharge preloading depends on the difference between the magnitude of surcharge and amplitude of the cyclic load. This study presents selected results of the effects of the frequency on the post-construction settlement of low embankments subjected to cyclic loading and showed that under drained condition the variation of pore water pressure is compatible with the axial creep strain of soft clay in the over-consolidated state. The measured pore water pressure values can be used to assess the long-term settlement of the soft ground after construction.

When a clay sample is suddenly loaded in the oedometer test its void ratio or compression decreases with time. The consolidation process is traditionally divided into primary and secondary consolidation phases. During the primary consolidation phase settlement is controlled by the dissipation of excess pore pressures and Darcy's law. Whereas during secondary consolidation the rate of settlement is controlled by soil viscosity, Leroueil (1996)

[16]. However, settlement requires a hydraulic gradient, i.e. excess pore pressure exists at that stage. Secondary consolidation or creep is characterized by the slope of the consolidation/compression curve.

Soft soil is widely distributed over coastal and riverside regions, where the embankment loads are sensitive for differential settlement. In a marine environment, cyclic loading forms a significant proportion of the loading and this decides the safety of many structures founded on the ocean bed. By and large, marine structures subjected to cyclic loading are offshore petroleum production platforms, offshore pipelines, storm surge barriers and harbor structures [17]. The foundations of these structures truly transmit the cyclic loads to the soil below in one form or another. Rail track subgrade is very important for railway stability and therefore the behaviour of soft soil subgrade under cyclic loading is of paramount significance in railway engineering. Most of rail tracks travel through coastal areas comprising of soft soils and highly compressible marine deposits. Load cycles from moving trains rapidly generate high excess pore pressures. In the absence of good drainage conditions, cyclic pore pressure will dramatically reduce the effective load bearing capacity of the soft formation [18].

Zhu et al. 2005 [19] presented a study on the deformation behavior of a saturated soft clay under cyclic loading. Considering the intrinsic anisotropy of the soil, a soil specimen was initially restored to the in-situ stress state under K_0 consolidation in a triaxial cell, and the specimen was then sheared in the same triaxial cell under axial cyclic loading and tested under a drained or undrained creep condition. The test results show that the increase of excess pore water pressure initially lagged behind that of stress. The stable excess pore pressure was about 50% of the stress amplitude for an drained specimen. However the residual excess pore water pressure was approximately 20% of stress amplitude for a drained specimen.

When a pressure is applied to a saturated soil and drainage is allowed, the gradient of the excess pore pressure causes flow of water out of the soil, Prediction the dissipation of pore water pressure is important to understanding the behaviour of soils under cyclic loading and also for estimation of their effective stresses. In the proposed paper, an analytical solution for one-dimensional consolidation of soft cohesive soil under cyclic loading has been developed based on the formulations given by Thang.,.N.N. (2023) [20] and a hyperbolic relationship for generation of pore water pressure under drained condition. The model successfully explained the generation and dissipation of pore water pressure during consolidation under cyclic loading.

2. MODEL OF CYCLIC TRAFFIC LOAD

2.1 Numerical Model of Traffic Load Form

A method for analyzing the behavior of clay under long-term cyclic loading has been proposed by Hyodo and Yasuhara, in which Terzaghi's consolidation equation is proposed for calculating the settlement of low embankment subjected to the traffic load [21, 22]. Hyodo and Yasuhara used a 10-ton truck moving at different speeds of 0km/h, 10km/h, 20km/h, 30km/h, and 35km/h to simulate vehicular load and investigated the vertical stresses acting on top of a subgrade and at different depths of a low embankment. On the subgrade, the vertical stress waveform at some points, shown in Fig. 1, described as sine curve.

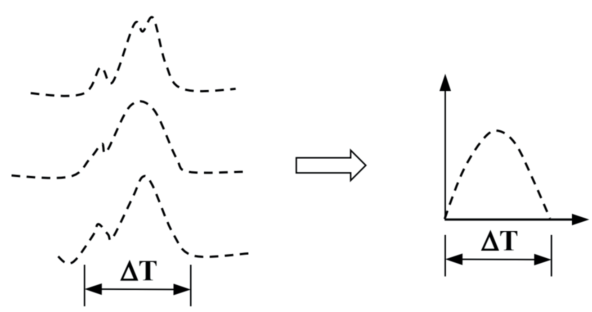


Figure 1. Vertical pressure waveform [21]

Based on the multi-layer elastic theory, Ling and Shoji [23, 24] conducted research on the residual deformation of saturated clay subgrade under vehicular load, analyzing the impact of vehicle speed and loading time without considering the influence of inertia and viscosity on the loading time. Different vehicle speeds of 40km/h, 60km/h, 80km/h, and 100km/h were used to establish an asphalt pavement structure. The loading time at any point on top of the subgrade is 0.7205s, 0.4805s, 0.3605s and 0.2885s, respectively. The relationship between vehicle speed and loading time is shown in Figure 2.

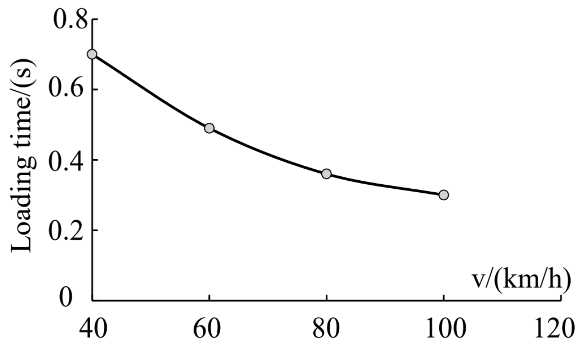


Figure 2. Vehicle speed - Loading time [23, 24]

As shown in Figure 3, the triangular waveform load simulates the vertical stress distribution on top of the subgrade for a typical pavement structure, with a correlation coefficient greater than 0.9. Therefore, the waveform load can be used to simulate the effect of traffic loads on top of the subgrade. In this Figure, the dotted line represents the surface of the subgrade at any point; the solid line is the vertical stress distribution caused by traffic load that affects the surface of the subgrade; the dashed line is the triangular waveform load simulating variation of vertical stresses.

XIE et al. (2006) [26] presented the variations of excess pore water pressure with dimensionless depth z/H, in case of trapezoidal cyclic loading. They presented a nonlinear analytical solution for the 1-D consolidation of soft soil under cyclic loading. A soil stratum with thickness H, vertical permeability coefficient k_υ, volume compressibility coefficient m_υ, and consolidation coefficient C_υ is shown in Fig. 4.

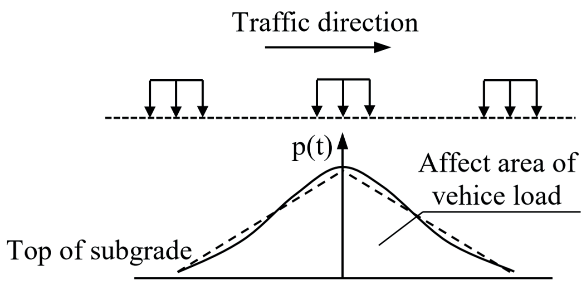


Figure 3. Vertical stress distribution on top of subgrade under vehicular load [25]

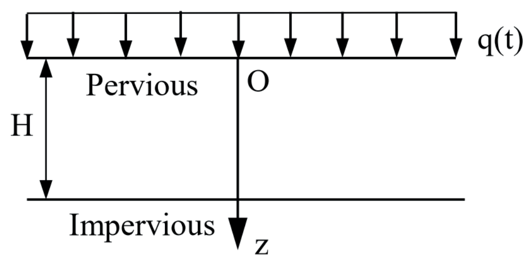


Figure 4. Model of clay layer under cyclic loading [26]

It shown that the greater the value of z/H, the greater the excess pore water pressure, indicating that the effective stress σ' and excess pore water pressure u vary with depth. In this state the pore water pressures and the effective stresses have final or equilibrium values; this is a steady state condition under cyclic loading.

2.2 Cyclic Loading Test Model

Based on the results of previous experimental studies and combining the actual conditions of the vehicular traffic flow and loading characteristics of laboratory equipment, a continuous half-sinusoidal dynamic load waveform is chosen for this study. This takes into consideration a non-continuous load distribution and thus accounts for the distance between vehicles.

The dynamic load waveform is illustrated in Figure 5, where T_1, t_0 are the continuous and interrupted duration of traffic load, respectively.

T_1 is the period of time that the dynamic load acted on the soft ground in one cycle. In this model, traffic loads are simulated as a half-sine wave cyclic load. For each test group, the cyclic load frequency, *f*, is constant in order to minimize the differences between the various types of vehicular traffic and their speeds and also to reduce the impact of varying distances between vehicles. P is the sum of vehicle weight and overburden pressure of the embankment; σ_{dmax} is the amplitude of traffic load. The same values of σ_{dmax} are used for a group test, irrespective of the impact of varying sizes of the vehicles.

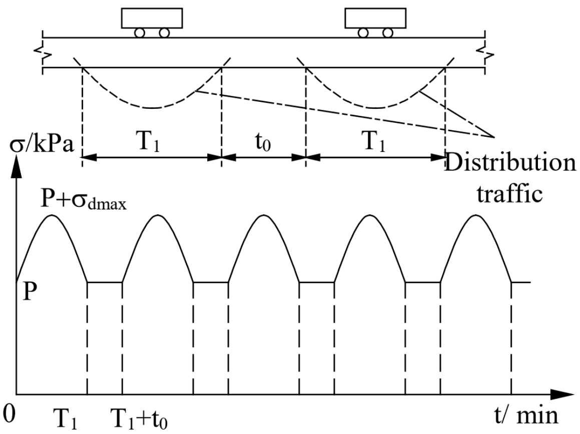


Figure 5. Simulation of the effect of traffic loading

Fujiwara et al. 1990 [27] conducted experimental study on the shear characteristics of clays with respect to cyclic stress-strain history and its corresponding pore pressures. The results of the study clarified the effect of load frequency, effective confining pressure, cyclic stress level and over-consolidation ratio on the excess pore pressure during cyclic loading.

Nash (2001) [28] also explained the physical process of consolidation under cyclic loading. When the load is applied for the first application, the entire load is carried by the water in the pores as excess pore pressure; the gradient of the excess pore pressure causes drainage and part of the load is transferred to the soil structure with an increase in the effective stress. When the load is removed, stress is reduced, the soil tries to rebound; these negative pore pressures cause water to flow into the soil, which causes a reduction in effective stress. When loaded again, a part of the load is carried by the residaal effective stress and the rest is carried by the water as excess pore pressure.

3. LABORATORY STUDIES

3.1. Sample and specimen

Soil samples were taken from a soft clay deposit located beneath the embankment. The test was conducted on a group of specimens; that had 2 cm and 30 cm2 height and cross-sectional area, respectively. The main physico-mechanical properties determined from the samples according to standard procedures are shown in Table 1.

Table 1. Physico-mechanical properties of soil samples

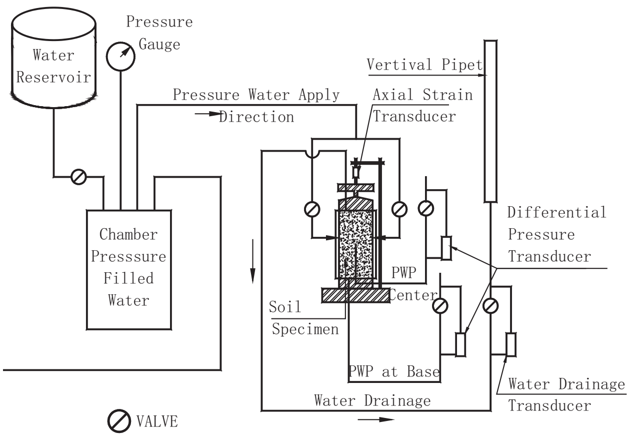
Physico-mechanical properties		Value
Density *ρ* *(g/cm³)*		1.595
Water Content *ω (%)*		61.61
Specific Gravity G_s		2.70
Void Ratio *e*		1.736
Liquid Limit w_l *(%)*		57
Plastic Limit w_p *(%)*		32
Plasticity Index I_p		25
Liquidity Index I_L		1.178
Degree of Saturation S_r *(%)*		98.9
Compression Factor $\alpha_{0.1\text{-}0.2}$ (MPa^{-1})		1.372
Compression Modulus E_s *(MPa)*		1.356
Coefficient of	C_{v100}	0.391
consolidation	C_{v200}	0.487

C_{v100} $(10^{-3}cm^2/s)$ and C_{v200} $10^{-3}cm^2/s$: correspond with the pre-consolidation stresses of 100kPa and 200kPa, respectively.

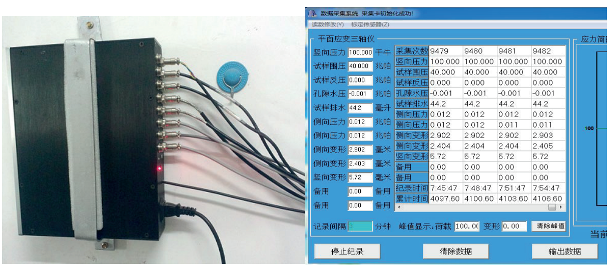
A series of creep tests were carried out by using the plane strain creep apparatus for both normally and over-consolidated clay. In the initial loading step, the specimens were consolidated under a sustained load (σ_x - σ_z) of (25 - 25) kPa for 24 hours in order to eliminate the differences of various soil specimens, such as the differences in the initial pre-compression, the physical properties and the non-uniform dispersion of the clay particles. In the next steps, the specimens were subjected to vertical consolidation stresses, σ_z values of 75, 100, 150 kPa for cyclic loading tests. The loading scheme of cyclic test scheme is summarized in Table 2.

3.2. Test procedure

A test equipment for creep under plain strain condition due to Li et al., [29- 31], Yuzhou et al., [32] and Thang., N. N [33, 34] was developed as illustrated principle sketch of the apparatus in Figure 6a. The test was developed based on the principle of conventional triaxial testing, featuring both the loading system of the former and air pressure controlling system of the latter. A data acquisition system, is connected to the computer shown in Figure 6b.



(a) Sketch of the apparatus



(b) Data acquisition system

Figure 6. Principle schematic sketch of cyclic test [29]

Table 2. Loading scheme of cyclic tests

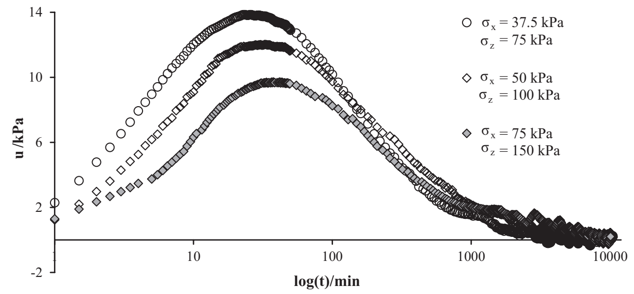
Nº	State	Static Loading		Cyclic Loading	
		σ_x/ kPa	σ_z/ kPa	σ_d/ kPa	f/ Hz
Nº-1	Normal consolidation	25	25	-	-
		37.5	75	20	0.05
		50	100	20	0.05
		75	150	20	0.05
		25	25	-	-
Nº-2	Over consoli-dation	37.5	75	20	0.05
		50	100	20	0.05
		75	150	20	0.05

4. TEST RESULTS AND ANALYSIS

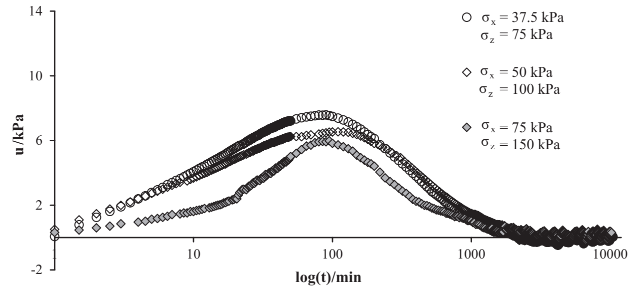
4.1. Excess Pore Water Pressure

Figure 7 shows the excess pore water pressure histories for both normally and over-consolidated soil specimens under cyclic loading for plane strain tests scheme shown in Table 3 with cyclic load amplitude of 20 kPa and frequency of 0.05Hz. The excess pore pressure due to effect of cyclic loading developed and increased rapidly to reach the peak value and then dissipated gradually to the stable equilibrium value in creep deformation process. The results are similar to that of static load condition in [34].

Table 3 provides a summary of the average excess pore pressure values observed in cyclic loading tests. The results indicate that as the level of cyclic loading increases, the peak values of excess pore pressure, u_{max}, decrease in both normally consolidated and over-consolidated states. Moreover, the values of u_{max} for over-consolidated state are much smaller in comparison with those in normally consolidated state at the same value of external load. The results also show that u_{max} decrease with increasing external load under cyclic loading.



(a) Normal consolidation



(b) Over consolidation

Figure 7. Variation of excess pore water pressure due to cyclic load

Table 3. Summary of excess pore water pressure generation in plane strain tests under cyclic loading condition

Stress (σ_x, σ_z)/kPa \ Consoidation state	Normally Consolidation		Over Consolidation	
	Peak PWP/ kPa	Peak Time /mins	Peak PWP/ kPa	Peak Time/ mins
37.5, 75 (σ_d = 20)	14.4	25	7.6	90
50, 100 (σ_d = 20)	11.2	35	6.5	110
75, 150 (σ_d = 20)	9.7	38	5.9	95

Note: PWP = Pore water pressure, σ_d = 20kPa, f = 0.05Hz

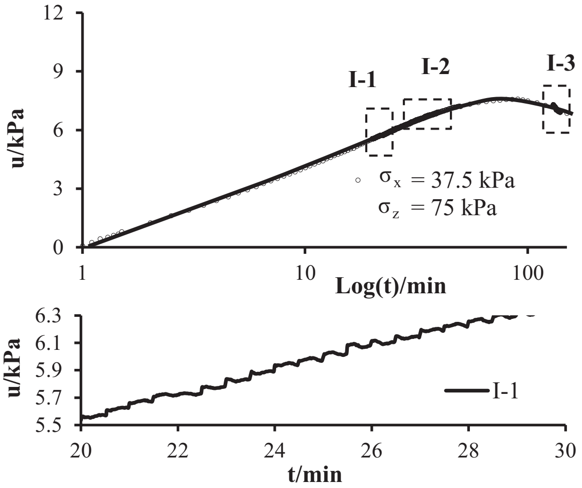
Actually, the generation and dissipation of excess pore water pressure depend on the pores spaces and contact interaction between the soil particles. Immediately after the load application, deformation occurs throughout the soil skeleton which produces the excess pore pressure while sliding at some of the grain contacts produces non-recoverable strains. As a result of sliding at contacts which have failed, permanent deformation occurs.

Since the pore water is resisting the particle rearrangement, the pore water pressure is added above the static value and immediately the increase in total stress takes place to reach a maximum value. Due to the water draining out during loading, however, soil particle rearrangement and pore pressure starts to decrease again. Thus, in the end of the loading process, excess pore pressure dissipates to a stable equilibrium value, corresponding with the soil particles being in a state of high stability and the void ratio of soil sample decreases significantly.

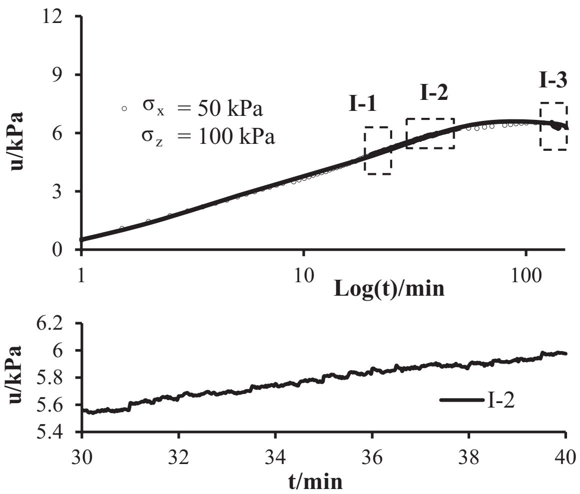
Figure 8(a-c) show the excess pore pressure histories of over-consolidation samples for a time period of 10 minutes at different times corresponding to the various loading stages, (σ_x, σ_z), of (37.5, 75), (50, 100) and (75, 150) kPa.

The curves show that the distribution of excess pore pressure with elapsed time during the beginning of loading duration, in which the deformation in rapidly incresing status, has cyclical form with difference frequency and amplitude for different loading stages. The amplitude of pore pressure increased with decreasing magnitude of loading, while the frequency increased with increasing magnitude of external loading.

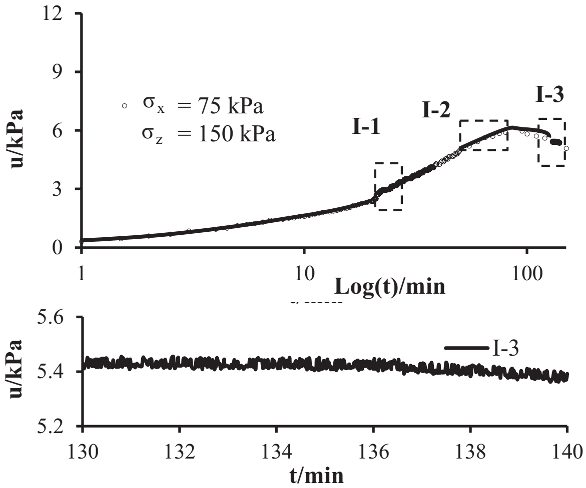
The pore water pressure in a saturated soft cohesive soil may increase with the number of cyclic loadings. At the initial loading stage, pore water pressure is generated and varied under the effect of cyclic load with the cyclical variation. In the short period of time, the changing of pore water pressure in sine form in which the amplitude and frequency are similar to that of the cyclic load, as shown in Fig 9a and Fig 9b for normally and over consolidated, respectively.



(a) (σ_x, σ_z) = (37.5, 75) kPa

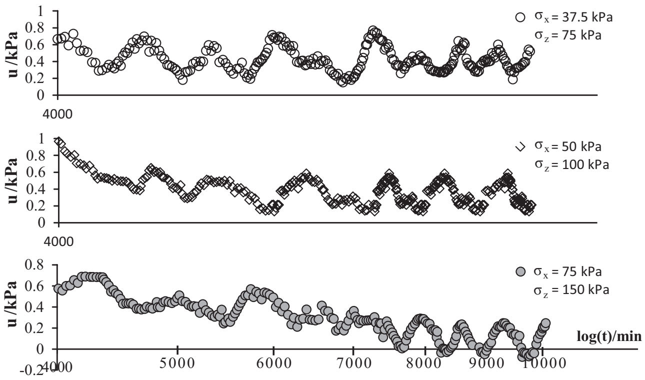


(b) (σ_x, σ_z) = (50, 100) kPa

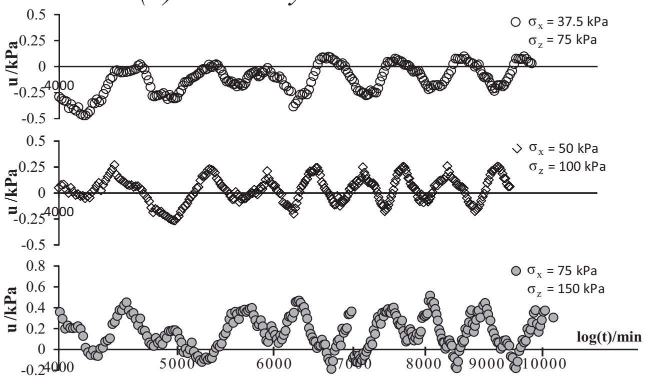


(c) (σ_x, σ_z) = (75, 150) kPa

Figure 8. Variation of excess pore water pressure in shortly time due to cyclic load for over-consolidation samples



(a) Normally consolidated



(b) Over consolidated

Figure 9. Variation of excess pore water pressure due to cyclic loading in creep deformation stage

Figure 9 illustrates the variation of pore pressure versus logarithm of elapsed time, for the started time of t = 4000 minutes and shows that the variation of pore pressure corresponding to the different load levels in the cyclical variation. In this stage, the soil exhibit a tendency for volume reduction when cyclically loaded. In the next stage of loading process when the time is long enough, however, the accumulated pore water pressure decreases by drainage as well as the rate of variation of volumetric strain decreases with increase in number of loading cycles. The values of volumetric strain tend to the constant values, the pore water pressure is approaching a stable equilibrium value approximate of the zero and the volume of the water drained out is almost the constancy. The distribution of pore water pressure in the creep process are illustrated in Figure 9, in which the creep deformation of soil consist of volumetric and axial creep strain at the relatively stable values.

4.2. Stabilization State of Soft Clay

The influence of cyclic loads on the generation and dissipation of pore water pressure in the loading stages are different. In the initial phase of each loading step, pore water pressure varies similar to the variation of cyclic load as analysed above. However, after reaching the maximum value, the pore water was discharged out, it decrease and tends to the stable value of zero when the time is long enough. The Table 4 recored the different values of T_s based on the plane strain creep test results, in which T_s are named as the duration time from the initial applying load to the time when variation of the PWP is almost independent with the cyclic load.

Results in Table 4 indicate that the influence of cyclic load to cyclical variation of the pore water pressure is different from the current loading level and consolidation state of soil; the higher in (σ_x, σ_z) values, the bigger in values of T_s. It reflects that in case of the higher current loading level, the longer in effect of cyclic loading on the variation of pore water pressure. They also show that the values of T_s is become smaller when soil changed from normally to over consolidated state at the same external loading level.

Table 4. T_s for the pore water pressure in stabilization state under cyclic loading

Duration time	Consolida-tion state	Current loading (σ_x, σ_z) /kPa		
		(37.5, 75)	(50, 100)	(150, 300)
T_s/ min	Normally	4200	6000	7500
	Over	3800	5500	6000

The minimum value, u_{min}, the maximum value u_{max}, the changed value, Δu, and periodic time, T, of the pore water pressure during creep period are summarized in the Table 5. These resutls indicate that the distribution of pore pressure during creep deformation is independent of loading stages.

Table 5. Excess pore pressure under cyclic loading

Current loading (σ_x, σ_z) /kPa	Consolidation state	u_{min} /Kpa	u_{max} /kPa	Δu /kPa	T /min
37.5, 75	Norm	0.151	0.698	0.547	820
	Over	-0.218	0.095	0.313	950
50, 100	Norm	0.133	0.534	0.401	760
	Over	-0.123	0.181	0.304	930
75, 150	Norm	-0.176	0.286	0.462	670
	Over	-0.182	0.423	0.605	890

Note: u_{min}, u_{max} and Δu = The minimum, maximum and average value of Pore water pressure (kPa), respectively; T = periodic time (min).

Under plane strain conditions with sufficiently long loading duration, changes in pore water pressure are minimal, and it dissipates to a stable equilibrium value close to zero. During the creep deformation stage, the variation in pore water pressure is unaffected by cyclic loading on soft clay. Therefore, calculating long-term soil settlement under cyclic loading can effectively use methods designed for static loading conditions, simplifying the calculations while yielding similar results.

5. CONCLUSION

The results for cyclic loading tests show that the excess pore pressure develops and increases rapidly to reach the peak values as soon as the external loads was applied on the sample, and then decreases gradually to a stable value of zero during creep deformation stage of soil specimen. The peak excess pore pressure in both normally and overconsolidation state increase with increasing magnitude of external loading. However, the rate of distribution of excess pore pressure is much slower when soil samples changed from the normally to over-consolidated state.

On the other hand, due to effect of cyclic loading, the variation of pore water pressure corresponding to the different load levels in both normally and over-consolidated state has cyclical variation. The amplitude of pore pressure increased with decreasing magnitude of loading, while their frequency increased with increasing magnitude of external loading.

When the loading time is long enough, the variation of pore water pressure is relatively small. Pore water pressure dissipated to a stable equiblirium value of approximately zero. The variation of pore water pressure is independent of the effect of cyclic loading on the soft clay during the creep deformation stage. Therefore, in calculating the long-term settlement of soil in case of cyclic loading can deal with the method applied for static loading condition in order to be simply calculation and the results are similar. Subsequent dissipation of the permanent excess pore water pressure results in both axial and volumetric strain. This results in increase in the interaction forces of the soil skeleton, and thus making the structure of soil particle highly stable. Thus in the next loading step, the maximum value of pore pressure does not exceed the value reached in the previous loading step.

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