IOP Conf. Series: Materials Science and Engineering **250** (2017) 012042 doi:10.1088/1757-899X/250/1/012042

The Quasi-static Properties of Natural Marine Clay under Tidal Low Frequency Cyclic Loading in Yangtze Estuary, China

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Abstract. The enclosure engineering of tidal flats behind Changxing Island is taken as the research background. In order to explore the undrained cyclic response of natural marine clay on tidal level periodic changing, the stress-controlled low frequency cyclic tri-axial tests and static creep tests are conducted on natural K0-consolidated Shanghai clay. In the series I tests, samples are cyclically sheared by low-frequency cyclic loading until stability or failure, the accumulative behavior and reversible strain are studied. The effects of confining pressure and stress ratio are also investigated. Significantly, loading frequency is a key factor in controlling the cyclic behavior. In the series II tests, special attention is given to the low frequency cyclic vibration effect on the undrained cyclic tests by comparison with the static creep tests. The critical stress ratio of low frequency cyclic behavior is less than static creep strength.

1. Introduction

In the marine environment, soil foundations are subject to cyclic loads generally induced by waves, tides or vibrations of super structures over a long period of time (Ling et al., 2002). Accordingly, seabed soils are expected to experience cyclic stresses of different amplitudes and frequencies, which will lead the soils to residual settlements and result in a decrease in strength or even damage (Fan et al., 2017).

As for the response of soft clay under cyclic loading, investigations on clay behavior under cyclic loading have been done by many researchers (Matsui et al.,1992; Yasuhara et al.,1994; Soroush et al.,2009). These excellent works provide fundamental tools for further understanding of the cyclic behavior of clays, which is of significance in practical design methods for the stability of nearshore and off-shore structures. In addition to experimental studies, some researchers have evaluated the undrained cyclic behavior of clays using elastic-plastic models (Karim et al.,2013; Graham et al.,2015).

At present, contraposing the mechanics properties of soft clay under the wave loading, which is a kind of alternating load of low amplitude and long period(Zhu et al.,2006), many researchers have constantly deepened the study, and also have applied the theory research to practice. However, the above researches of the soft clay are almost aimed at the high frequency cyclic loading experiment, and few involved the dynamic cyclic creep characteristics of low frequency cyclic loading. There are many common types of low frequency cyclic loading in practical engineering, such as underground water level cyclic change, the load change caused by the amount of storage in tanks or granary, the periodic ballast of tidal level fluctuation on marine soil and so on (Boulanger et al.,2007).The role of low frequency cyclic loading on the foundation soil can be regarded as a long period process of compression, resilience and re-compression(Chu et al.,2008).As everybody known, the tidal period is so long (normally for 12 hours) ,as well as the tidal cyclic loading so weak, that the tidal cyclic loading on the soil can be treated as a kind of quasi-static loading(Graham et al.,2015).

In order to study the dynamic cyclic effect of the rise and fall of tidal level on natural marine soil of Yangtze Estuary, applying the Britain's GDS static tri-axial apparatus, two series of undrained triaxial tests are carried out to study the low frequency cyclic behavior and the effect of the confining pressure, cyclic stress ratio and loading frequency on K0-consolidated natural marine clay. Firstly, based on the natural clay cyclic test results, the constitution of typical low frequency cyclic curve is discussed, and the accumulative deformation and reversible strain are also analyzed in detail. Secondly, the low frequency cyclic behavior is investigated deeply by altering variables, and it is observed that the loading frequency is a key factor in controlling the undrained low frequency cyclic behavior. Thirdly, the special attention is given to the low frequency cyclic vibration effect on the basis of the undrained static creep tests. Compared with static loading tests, the quasi-static properties under low frequency cyclic loading are studied.

2. Experiment Program

2.1 Test Instrument and Soil Sample

This research adopts the high precision static tri-axial apparatus produced by GDS company for creep tests. The system is mainly composed of triaxis pressure chamber, the axial deformation measurement system, the axial force loading system, data acquisition unit and computer, which can monitor the whole process of tests, conduct the high-speed data acquisition and data storage. All the pressures are exerted by stress controllers, and axial displacements are measured by a GDS axial actuator. Excess pore pressure is measured at the center of the bottom of the specimens.

The soil samples used for tests are soft clay of marine origin, taken from Changxing Island shallow waters in China, which is typical saturated soft soil in Shanghai area with high water content, high sensitivity, large void ratio, high compressibility, low strength and relatively uniform, including visible number of detrital mica and shells, as well as the thixotropic and creep characteristics. The in-situ soft clays are normally consolidated in general, and exhibit obvious viscosity, initial stress-induced anisotropy and some degree of soil structure. All of the samples are quite homogeneous and the index properties are shown in table 1.

Table.1. Basic physical and mechanical parameters of Shanghai marine soft clay

W_0/ %	ρ_0/ (g/cm^3)	G	S_r/%	e_0	W_L/ %	W_P/ %	$a_{0.1\text{-}0.2}$/ Mpa^{-1}	$E_{s0.1\text{-}0.2}$/ Mpa^{-1}
32.0~ 52.1	1.69~1. 88	2.71~ 2.75	94.2~98 .8	0.917~ 1.475	34.5~ 46.7	20.2~ 26.0	0.41~ 1.25	1.92~ 4.67

2.2 Test Scheme and Procedure

To simulate the impact of the tidal level lifting on the creep characteristics of soft soil foundation, long period of low-frequency cyclic creep tests were conducted, started with the soil sample under K0-consolidated state more than 24 hours so as to restore the initial stress state of the soil.

Block samples were taken with thin-walled cubic stainless steel boxes from about 9.0m below the original ground level and were then trimmed for the tri-axial tests. Detailed test steps are described as follows. The specimens are nominally 3.91cm in diameter by 8cm in height and trimmed with their axes of symmetry coincident with the in-situ vertical direction. All specimens were firstly vacuum saturated, and B-values of more than 0.95 were observed. Then, each specimen was consolidated for 24 h under the K0-consolidated condition. The final effective axial stress of consolidation was set to 89kPa according to the in-situ depth, and the radial stress during K0-consolidation was automatically controlled by GDS system. After consolidation, the average value of K0 was 0.55, and each specimen was in normally consolidated state in which the initial mean effective stress and the initial deviator stress.

After K0-consolidation, two kinds of tri-axial tests with load control were performed under undrained conditions. According to the characteristics of the common low frequency cyclic loading, a sinusoidal wave cyclic load was applied in the vertical direction while the cell pressure was in constant. Then the series I low frequency cyclic deformation tests and series II static creep tri-axial tests were both conducted.

In the Series I tests, a cyclic deviator stress σ_d was obtained by calculating the weight of water which is caused by the tide range, shown as Figure.1. Afterwards, the cyclic deviator stress was applied under stress-controlled conditions until the normally K0-consolidated sample failed, ruled as to strain change less than 0.05%, or be loaded into the strain damage, with the standard of destroy 15%. Then the accumulative shear strain and excess pore pressure behavior are investigated. To study the effect of loading frequency on cyclic behavior, the loading period chosen in the tests were 0.5 h, 1 h and 2 h for each given cyclic deviator stress. The loading history curve is shown in Figure.2. The series II undrained static creep tests were conducted on normally K0-consolidated specimens with corresponding strain rate until a shear strain of 15% or more was reached.

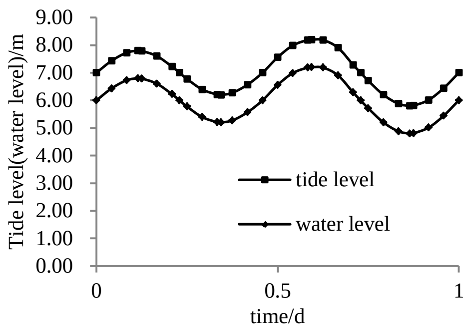

Figure 1 Tide level and water level monitoring curves

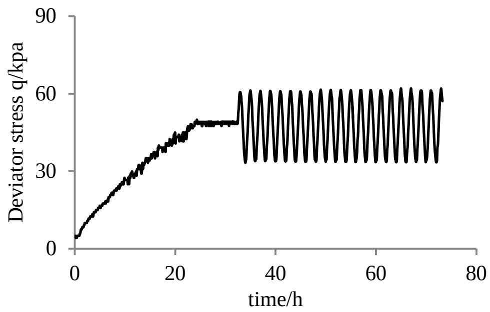

Figure 2 Loading history curve

3. Analysis of Series I and II Test Results

3.1 The Constitution of Typical Low Frequency Cyclic Curve

Due to the specimens with K0-conslidated, special attention was paid to the accumulative behavior of Shanghai clay during undrained low-frequency cyclic shearing. It can be noted that, for a given loading frequency, the development of single amplitude accumulative shear strain is highly dependent on the magnitude of the applied cyclic stress. When the cyclic stress ratio is small, the development of shear strain has the similar creep growing trend, extremely slowly, in an extreme small amount of accumulative strain, which leads the specimen to get into the creep decay stage in a certain cycles, and stabilizes at a small value. A trend of cyclic failure is not observed. However, when the cyclic deviator stress is larger, the creep deformation curve has a relatively large value in a few cycles, and gets into the collapse stage absent of the creep decay stage. There is an inflexion on each accumulative shear strain amplitude curve if the cyclic stress ratio is large enough to induce cyclic failure. If the stress ratio is large to a certain degree, the strain will develop in a sharp trend, which leads the sample to collapse abruptly. The undisturbed clay samples always collapse abruptly in a relatively short period once the shear strain amplitude is larger than that corresponding to the inflexion of the strain curve.

For example, the parameters for the experiment specimen were set as T=1h, σ_c=50kpa, σ_d=$15kpa$. According to the measured results, the strain curve can be geared to the decay creep type. As shown in Figure.3, which are creep strain curves of the initial three cycle curve and the last three cycle curve, it can be seen that the increasing rate of strain slows down with loading time, the initial three cycle made the 0.54% of strain amount. While in the last loading period, creep curve keeps stable, with a little strain increasing, and the strain amplitude kept on about 0.3%.

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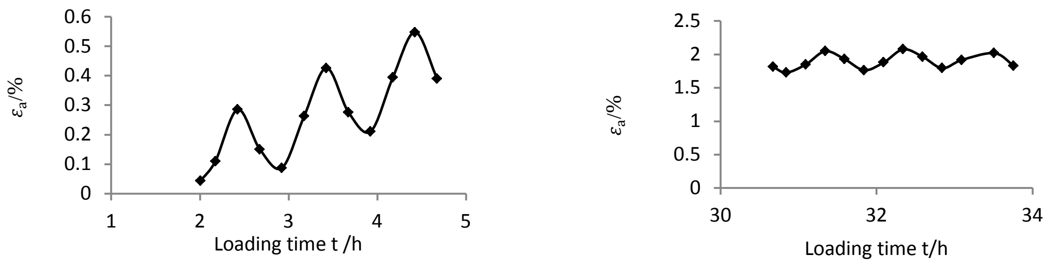


(a) Initial stage curve (b) Final stage curve

Figure 3 Initial stage and final stage of the decay creep cyclic curves

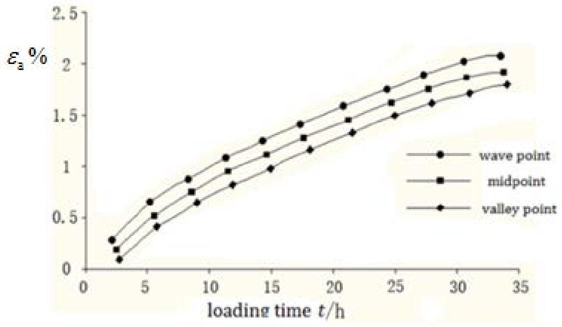


Figure 4 Wave crest curve, wave valley curve and wave midpoint curve (T=1h, σ_c=50*kpa*, σ_d=15*kpa*)

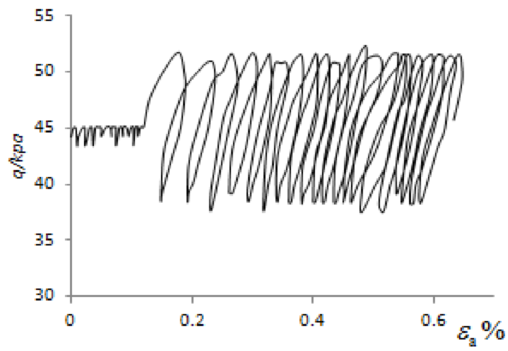


Figure 5 Deviator stress-strain cyclic curve (T=1h, σ_c=50*kpa*, σ_d=15*kpa*)

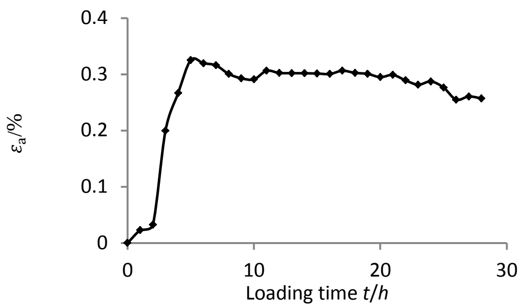


Figure 6 Reversible strain history curve of decay type
(T=1h, σ_c=50*kpa*, σ_d=15*kpa*)

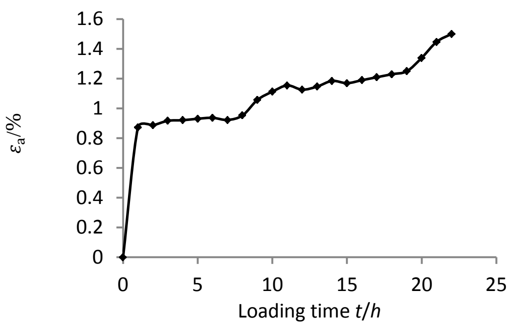


Figure 7 Reversible strain history curve of damage type (*T*=1*h*, σ_c=50*kpa*, σ_d=20*kpa*)
(T=1h, σ_c=50*kpa*, σ_d=15*kpa*)

If the wave crest points, wave valley points and the intermediate points of value ε_0, corresponding to the definition $\varepsilon_0 = 1/2(\varepsilon_a + \varepsilon_b)$ are joined in smooth curves respectively, these three curves are shown in Figure.4. They keep in similar trend of decreasing slope with loading cycles increasing, demonstrating the soil samples keep in stable creep development.

Figure.5 shows the deviator stress-strain variation curve, displayed as nonlinear hysteresis loops, which elapse towards the right more intensely. This phenomenon which is similar to the high frequency cyclic curve (Guo et al., 2013) demonstrates that plastic strain happened and accumulated in the cyclic process with the decrease of the accumulative rate.

In addition, the reversible strain (denoted as $\varepsilon_e = \varepsilon_{max} - \varepsilon_{min}$) increases rapidly during the initial of loading, then declines slowly to stability (illustrated in Figure.6) which is identical with the typical cyclic loading results (Guo et al., 2013).

With regard to the destructive type curve, the reversible strain of experiment specimen set as σ_d=20kpa (other parameters same as above) can be taken as the example, shown in Figure.7. On the contrary, reversible strain increases with the number of cycles till the specimen destroyed.

3.2 Influence of Confining Pressure, Cyclic Stress Ratio

Taking the structural yielding stress range value as the reference basis, for a given cyclic period of one hour per cycle, different cyclic creep tests under different cyclic stress ratios were conducted under two different confining pressure, to explore the soil structural effects on the cyclic creep characteristics. Partial experimental results are demonstrated in the following analysis.

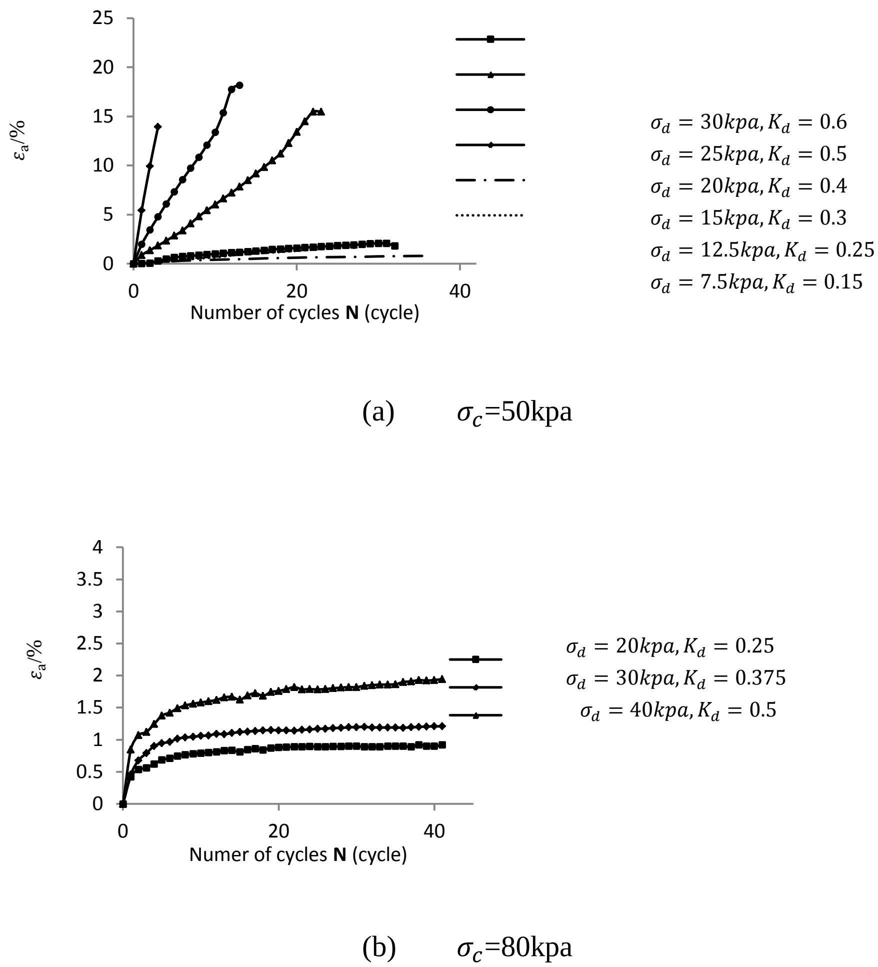


Figure 8 Low frequency cyclic creep curves under different confining pressure

Figure.8 (a) illustrates cyclic creep curves of different cyclic stress amplitude under condition of 50*kpa* K0-consolidated, denoted as the variable named cyclic stress ratio with the definition of

$K_d = \sigma_d/\sigma_3$. Due to the different effects caused by different cyclic stress ratios on soft clay, the soil samples present different creep characteristics. It can be seen that at the outset of the cyclic loading, axial strain of soil rapidly grows with the increase of cyclic stress amplitude in a very short time. When the stress level is low, with the increase of loading cycles, creep curve is gradually leveling off after reaching a certain number of cycles. The instantaneous deformation is small, although creep deformation increases with loading time increasing, in which only the attenuation creep stage is presented. For the confining pressure is 50kpa, the multiple sets of soil samples (the stress amplitude 7.5kpa, 12.5kpa, 15kpa, 20kpa, 25kpa, 30kpa) appear attenuation creep characteristic. As the stress level increases, the deformation of soft clay increases sharply. When the stress level has reached a certain degree, damage occurs in a very short time, such as the value of cyclic stress amplitude set as 20kpa, 25kpa, 30kpa, the loading curve quickly entered the stage of accelerated creep and damage stage. By comparison of the curves in Figure.8 (a), it can be found that the greater cyclic stress ratio is, the greater the total creep deformation is, and the more obvious creep deformation behavior is.

As shown in the Figure.8 (b), the specimens with confining pressure 80kpa are used to conduct the tests in the same conditions as above. Obviously, the specimens only go through the creep stage to reach stability. With the confining pressure increasing, the structure of the soil is more powerful, and there will be less possibility to get the specimen to be disruptive.

The results of excess pore pressure of specimens with period 1h are selected to analyze, as shown in Figure.9. It could be seen that the pore pressure rises to a certain value after reaching a stable equilibrium no matter how much the cyclic loading. In the early loading cycles, we find that if the cyclic stress amplitude is greater, the pore pressure rise faster and the peak of the pore pressure is higher. Simultaneously, the curve with the greater stress level achieves stabilization in less cycles, and quickly enters the decay stage. In conclusion, the pore pressure law is consistent with the high frequency dynamic experiment results (Wu et al., 2015).

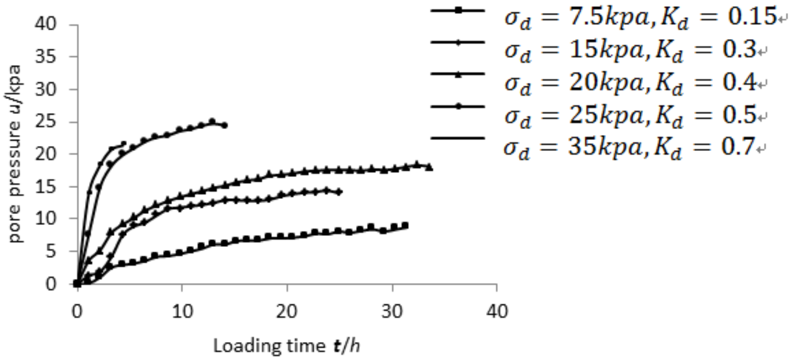
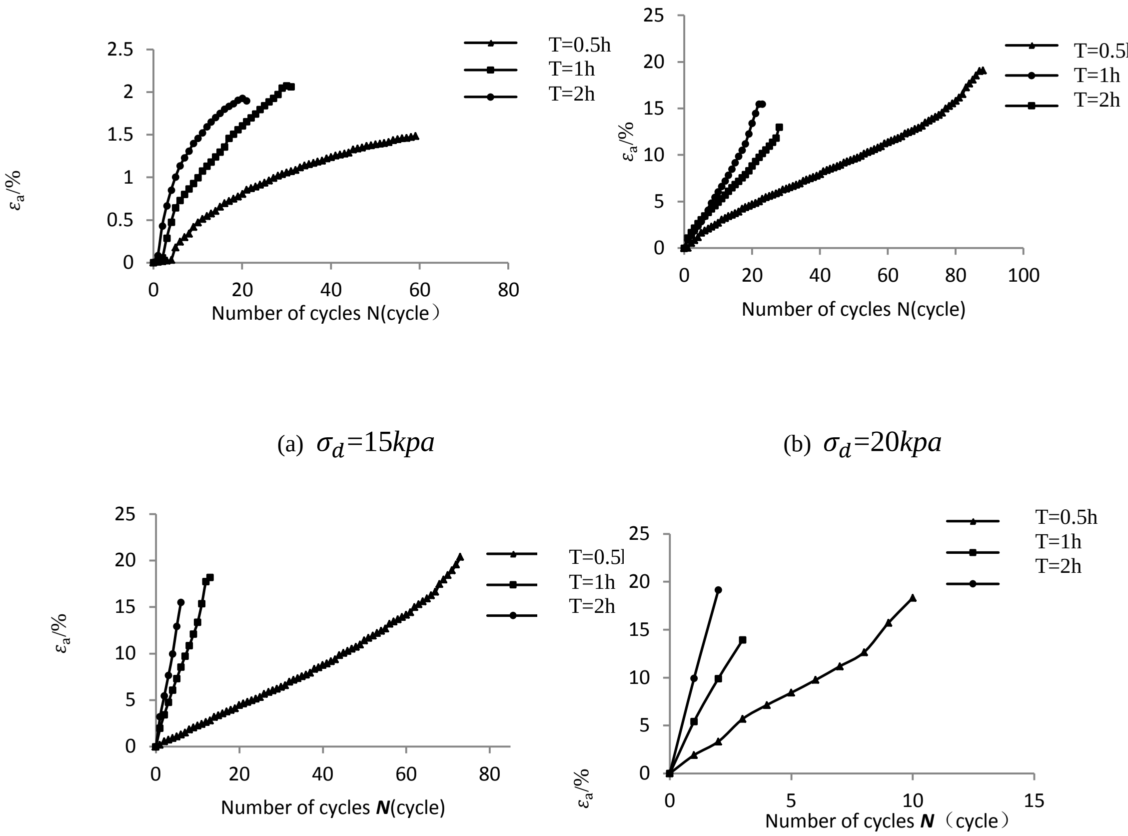


Figure 9 Excess pore pressure time history curves (T=1h,$\sigma_c = 50kpa$)

3.3 Influence of Loading Frequency

Keeping the confining pressure at a fixed value, by altering different cyclic frequencies of cyclic tests, the effect of low frequency cyclic frequency on cyclic creep properties of soft clay can be explored. In this test, the confining pressure is set as 50kpa, and cyclic stress amplitude alters from 15kpa to 32kpa, with the period set as 0.5h, 1h and 2h, the test results are shown in Figure.9. It discovers that the frequency is a significant role on the deformation of low frequency cyclic loading. With regard to the same confining pressure and stress amplitude, the lower the frequency is, the greater the creep deformation is produced.

When σ_d equals to 15kpa and the number of cycles reaches twenty, the creep deformation of period 1h is 2.69 times of that with period 0.5h, which manifests the strong rheological properties of soft soil. In addition, the critical dynamic load range of different period cyclic loading is roughly same, that is 15kpa ~ 20kpa.When the cyclic stress ratio exceeds the critical one, the creep curve changes from decay type into damage type. The accumulative effect of plastic deformation with period 0.5*h* appears more apparent than that with period 1 *h* and 2 *h*, of which the cumulative effect of plastic strain is very weak, only after a few number of cycles the curve reaches damage. For the typical dynamic load (such as earthquake load, traffic load), it's noted that usually the higher the load frequency is, the greater the deformation of soft soil is (Guo et al., 2013; Hosseini et al., 2015). On the contrary, the deformation law under low frequency cyclic load appears significantly different from the law of typical dynamic load type. In addition, under low frequency cyclic load, the experimental results show that the lower the frequency is, the more cumulative effect of plastic deformation is more obvious, and more slowly the soil sample get into the attenuation creep stage and reach stable stage of deformation.



(a) σ_d=15*kpa* (b) σ_d=20*kpa*

(c) σ_d=25*kpa* (d) σ_d=32.5*kpa*

Figure 10 Comparison chart of creep test curves under different frequencies

3.4 Comparison Between Low Frequency Cyclic Properties and Static Creep Properties

By means of setting the parallel tests, that is the static creep tests under the same test conditions, which can be the effective comparison with low frequency cyclic creep tests, the soft clay creep properties under low frequency cyclic loading can be explored further. Static tri-axial fracture strength 90*kpa* under confining pressure 50*kpa* was obtained by K0-consolidated test. Figure.11 illustrates the creep curves of static loading tests in K0-consolidated conditions. Via stepping loading, the static loading creep curves will be obtained by date handling with the "coordinate translation method". For low level of cyclic stress, such as cyclic stress amplitude of 15*kpa*, static load creep curves keep almost the same trend as low frequency cyclic curves, and appear only the attenuation creep stage, in which the accumulated static creep deformation of soil is 57% of the cyclic deformation with period 0.5 h. Static creep deformation of soil samples can reach stability faster. For example, under static loading condition, the stress level is 15*kpa*, the deformation can achieve stability after about 2*h*. Nevertheless, it gradually achieves deformation stability under low frequency cyclic loading after the 60th cycle, with the time lag of up to 30 times to that of static loading. This phenomenon shows that the impact of loading-unloading reciprocating under low frequency cyclic loading plays a significant role on deformation characteristics of soft clay.

With the increase of stress level, static creep deformation gradually keeps rising. For instance, if the cyclic stress amplitude equals 32.5kpa, creep curve turns into damage type, and failure strain reaches 15% in 3.6 hour, which demonstrates that the static creep damage stress level keeps between 25kpa and 30kpa. However, the critical cyclic stress of low frequency cyclic creep curves is in the range of 15kpa to 20kpa. In conclusion, low frequency cycle vibration intensity is less than the static creep strength of soft soil. The preliminary analysis to this phenomenon can be ascribed to the discharge of pore water in low frequency vibration, and the structure destroying of the soil sample as well (Wu et al., 2015).

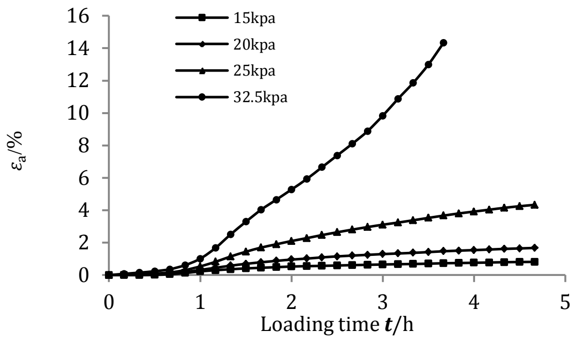


Figure 11 Static load creep curves (T=1h,$\sigma_c = 50kpa$)

4. Conclusion

From the study presented above, the following conclusions can be drawn.

(1) Low frequency cyclic creep curve can be divided into two types: decay type and damage type. The accumulative behavior and reversible strain were studied. The reversible strain of the attenuation curve drops to a stable value after certain cycles. On the contrary, the reversible strain of damage type curve shows the increasing tendency with the increase of cyclic loading time.

(2) The confining pressure and the cyclic stress ratio of low frequency cyclic loading have a significant influence on creep characteristics of soft clay, which reflects the structural influence on its low frequency cyclic creep properties. Tests reveal that the greater the cyclic stress ratio is, the greater the creep deformation of soil is, and the more obvious the creep behavior is;

(3) The cyclic loading frequency is a key factor in controlling the undrained low frequency cyclic behavior .When the number of loading cycles keeps the same, the lower the frequency is, the greater the cumulative plastic deformation is, and the more obvious the cumulative effect is;

(4) The development of the excess pore pressure in low frequency cyclic behavior is similar to the pore pressure properties of typical vibration loading results. The accumulative excess pore pressure can achieve stability after a certain number of cycles, and the cyclic stress ratio makes an effect on stabilizing rate and pore pressure increment;

(5) Comparing the low frequency cyclic loading tests with static creep tests, special attention is given to the low frequency cyclic vibration effect. It has been found that the critical stress ratio of low frequency cyclic behavior is less than static creep strength, the soil samples in low frequency cyclic loading achieve deformation stability more slowly.

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