Consolidation behavior of Shanghai clay under cyclic loading

Comportement de consolidation de l'argile de Shanghai sous chargement cyclique

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ABSTRACT: In this paper the experiments of the primary and secondary consolidation behavior of Shanghai clay under the cyclic loading with period of several minutes, simulating the characteristics of yearly periodical fluctuation of the water level, are conducted. The factors such as the loading wave shape, cyclic loading parameters, loading order, consolidation state, existence of secondary consolidation before cyclic loading, are investigated. The superposition theorem between the accumulated deformation and secondary consolidation is verified. The pore pressure development is also measured in some cases. The test results provide the model and the nonlinear soil parameters for the computation of land subsidence, and also serves the basis of measures for slowing down the subsidence rate.

RESUME: Dans ce papier les résultats expérimentaux sur les consolidations primaires et secondaires sur l'argile de Shanghai, sous le cycle de chargement avec une période de minutes réelles, sont conduites pour simuler les caractéristiques d'une période annuelle de fluctuation du niveau de l'eau. Les facteurs telles que le chargement de la forme de l'onde, le cycle de chargement des paramètres, l'ordre de chargement, l'état de consolidation, l'existence de consolidation secondaire avant le cycle chargement, ont été étudiés. Le théorème de superposition entre la déformation accumulée et la consolidation secondaire est vérifié. Le développement de la pression du pore est aussi mesuré dans quelques cas. Les tests résultats produisent le modèle et les paramètres terriens non linéaire pour le calcul de l'affaissement du terrain et servent aussi pour la mesure basic de la descente lente du taux d'affaissement.

1 INTRODUCTION

The primary consolidation theory has been applied rather successfully for computatiion of land subsidence due to water withdrawal in Shanghai for quite a number of years (Tsien & Gu 1981). However,since 1981 some divergency appears between the computation resuults and the observed data, especially for the areas where the clay layers above the acquifer (Figure 1) possess the rheological properties. Thus the effect of the secondary consolidation should also be considered in computation(Gu et al 1991).

The groundwater level of the acquifer, which causes the land subsidence in Shanghai, has the characteristics of yearly periodical fluctuation(Figure 2). According to the water level change, the stress-strain diagram can be drawn as shown in Figure 3. In order to verify the computation model and obtain the soil parameters, the experiments for studying the primary and secondary consolidation behavior of Shanghai clay under the cyclic loading simulating the above characteristics, are conducted.

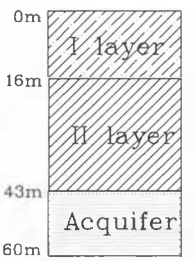

Figure 1. Soil profile

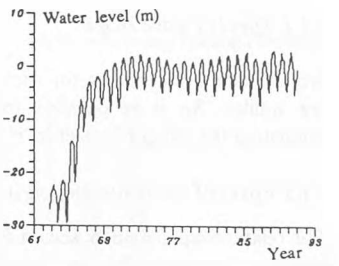

Figure 2. Water level change

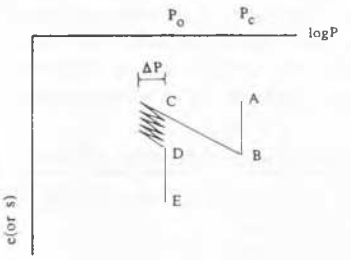

Figure 3. Stress-strain diagram due to water pumpage

2 TEST PROCEDURE

Because of the rationality of one-dimensional problem of land subsidence in Shanghai, the experiments are conducted in oedometers. Before applying the cyclic loading samples are subjected to initial pressure P_0, and after the cyclic stage the secondary consolidation is investigated for two weeks.The laboratory temperature is maintained constant with errors ±0.5°C.

In order to obtain the soil parameters which reflect the real situation, the following factors are investigated:

1. Shape of loading wave

The sinusoidal wave shape is closer to the actual water level fluctuation. However, the rectangular wave shape can be operated more easily and has the advantage of obtaining the coefficients of consolidation for compression and rebound conditions. So tests with these two wave shapes are compared.

2. Parameters of cyclic loading

The increment ΔP, period T of cyclic loading, and nuumber of cycles N are involved herein. ΔP is determined by the actual water level change. The order of T is from one to several minutes.

3. Loading order

Usually cyclic tests are conducted under the loading-unloading pattern. However, from Figure 3, the unloading-loading pattern seems more suitable. Therefore,tests with both two patterns are investigated.

4. Overconsolidation state

Since the previous water level has been lower than the current one, the lower part of the second compressible layer, locating

near the acquifer, becomes slightly overconsolidated, OCR of which equals 1.5. The difference between the consolidation behavior of normally consolidated and overconsolidated soil under cyclic loading is investigated.

5. Effect of secondary consolidation before cyclic loading

In actual condition, it is unknown whether the secondary consolidation has taken place before cyclic loading. Therefore, two series of tests are compared. Series A: Before applying the cyclic loading consolidate the sample under initial pressure Po for 24 hours. Series B: No sooner the primary consolidation under Po has completed, than the cyclic loading is applied, and after cyclic loading the secondary consolidation is observed.

6. Relationship between accumulated deformation under cyclic loading and secondary consolidation

Take three samples for which primary consolidation under Po has completed. To the first one apply static pressure to 2Po and observe secondary consolidation. To the second one apply cyclic loading and obtain the accumulated deformation. To the last one apply both static pressure to 2Po and cyclic loading, then observe secondary consolidation. From the test results find out if the deformation of the third sample equals the sum of the first two's.

7. Pore pressure development

For distinction of primary and secondary consolidation the pore pressure is measured in some samples.

3 TEST RESULTS

3.1 Accumulated deformation caused by cyclic loading Sc

3.1.1 Effect of wave shape

From Table 1 the results for rectangular and sinusoidal wave are similar. So it is possible to use rectangular wave for simulating the effect of water level change.

3.1.2 Effect of cyclic loading parameters

The relationship between accumulated deformation and cyclic laoding increment for five samples from the same layer is shown in Figure 4. Sc increases with the increase of ΔP. It means different cyclic loading increments reflecting the real condition should be applied to samples from different layers. For the first layer, very small increment brings about very small deformation, sometimes even no deformation is observed. While for the second compressible layer, ΔP is relatively large, and Sc is obvious. It implies the periodical fluctuation of water level has significant effect on the II compressible layer, but not on the I layer.

The figures in Table 2 shows that accumulated deformation increases with the increase of period. So T for different clay layer is decided from the following formula:

$$T = T_f H^2 / H_f^2 \quad (1)$$

where H-thichness of the drainage path, subscript f indicates the field condition.

Figure 5 is a typical deformation - cycle number curve. The accumulated deformation increases with the increase of cycle number N, but its increment has the descending tendency. The accumulated deformation is related to the difference of volume compression coefficients under loading and unloading conditions (mvc-mvs). The changes of mvc and mvs with N are shown in Figure 6. mvs basically keeps constant. The relationship between mvc and N depends on loading order, as shown below.

The changes of the consolidation coefficients Cvc and Cvs with N are shown in Figure 7. For first several cycles, Cvc<Cvs, but afterwards Cv stabilizes, i.e. Cvc=Cvs.

Table 1. Accumulated deformation Sc under different wave shapes

Sample No.	Wave shape	Accumulated deformation(mm)
28-3	Sinusoidal	0.048
28-4	Rectangular	0.049
18-5	Sinusoidal	0.004
18-2	Rectangular	0.002
15-2	Sinusoidal	0.130
15-4	Rectangular	0.147

Table 2. Accumulated deformation for different periods

Sample No.	Period (min)	Number of cycles	Accumulated deformation (mm)
28-2	4	20	0.032
28-5	60	20	0.085
7-2	1	20	0.011
7-1	4	20	0.024
36-1	1	20	0.0025
36-3	4	20	0.011

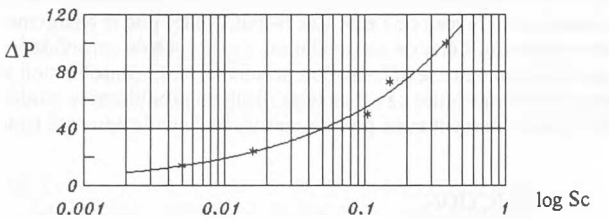

Figure 4. Accumulated deformation- cyclic loading increament curve

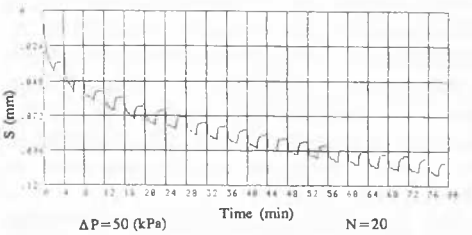

Figure 5. Accumulated deformation S - cycle number N curve

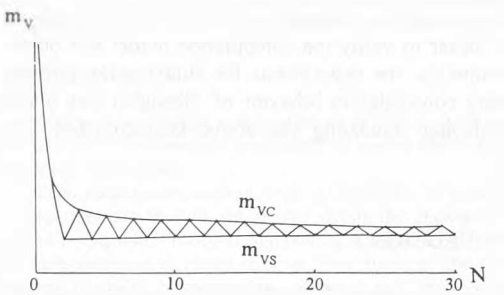

Figure 6. Change of volume compression coefficients with cycle number

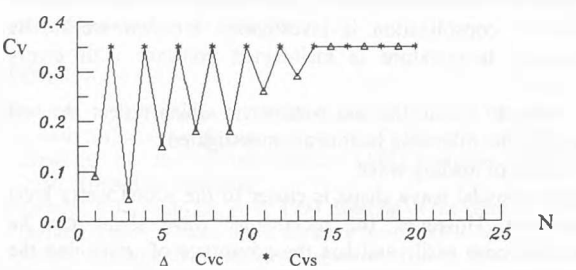

Figure 7. Change of consolidation coefficients with cycle number

3.1.3 Effect of loading order

The amount of accumulated deformation for the loading-unloading pattern is much larger than the one for the unloading-loading pattern under the same cyclic loading parameters. Figure 5 is the test result under loading-unloading condition, and Figure 8 for unloading-loading condition. The S-N relationship under loading-unloading pattern can be fitted by the exponential function:

$$\sum_{i=1}^{N}(m_{vci}-m_{vsi})=BN^{a} \qquad (2)$$

Since mvs is a constant, the following formula can be obtained:

$$m_{vc}=B[N^{a}-(N-1)^{a}]+m_{vs} \qquad (3)$$

When N>10, the fitted results are somehow larger than the experimental data, so then mvc are taken as different constants under different segments of N.

Under unloading-loading pattern, mvc-N relationship has linear character for different segments of N. The curvilinear character can be observed only during first two cycles. So mvc for unloading-loading pattern is represented by several constants.

For unloading-loading pattern, the stabilized Cv is much larger than that for the loading-unloading pattern, see Table 3.

Table 3. Stabilized consolidation coefficient under different loading patterns

Sample No.	Loading order	Consolidation coefficient($10\ m^2/s$)
22-2	L-U	23
22-5	U-L	73
36-2	L-U	161
36-3	U-L	531

L-U: loading-unloading U-L: unloading-loading

3.1.4 Effect of overconsolidation state

The test result for the overconsolidation sample under unloading-loading condition is shown in Figure 9. The sample rebounds under cyclic loading, but the rebounding amount is quite small, and it stabilizes soon.

3.2 Secondary consolidation S_α

3.2.1 Secondary consolidation after cyclic loading

The whole consolidation curve for the unloading-loading condition is shown in Figure 10. The secondary consolidation coefficient doesn't change after the cyclic loading. For the loading-unloading condition, the whole consolidation curve is shown in Figure 11. The accumulated deformation Sc is much larger than the one for unloading-loading condition, C_α after cyclic loading is smaller than that before cyclic loading, and then increases gradually until it becomes the same value as that before cyclic loading. When Sc is even larger, the increasing tendency of C_α will be slower, it does not reach the value of C_α before cyclic loading within two weeks. Therefore, the change of C_α after cyclic loading depends on the loading order as well as the accumulated deformation Sc. When Sc is small, for both two loading patterns C_α doesn't change. When Sc is quite large for the loading-unloading pattern, C_α after cyclic loading is restrained for some time.

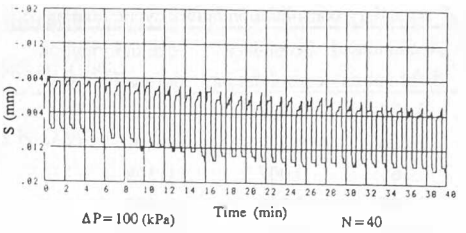

Figure 8. S - N curve under unloading-loading condition

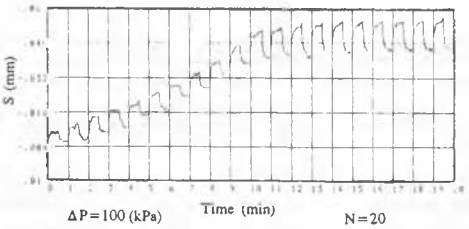

Figure 9. S - N curve of overconsolidated sample

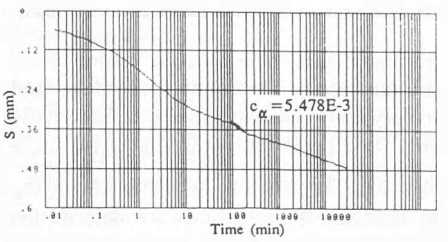

Figure 10. Whole consolidation curve for unloading-loading condition

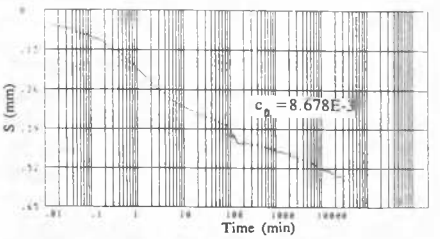

Figure 11. Whole consolidation curve for loading-unloading condition

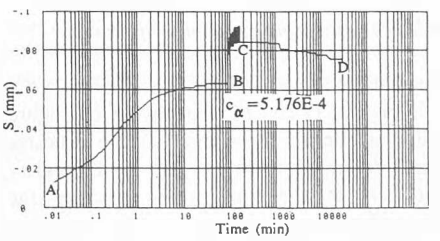

Figure 12. Whole consolidation curve for overconsolidated sample

For investigating the effect of overconsolidation state, apply the cyclic loading after unloading the sample from P_1 to P_0, and then observe the secondary consolidation. The whole consolidation curve of the overconsolidated sample is obtained as shown in Figure 12. CD is the secondary consolidation part. Compare to the normally consolidated sample, C_α for the sample of OCR=1.5 reduces for about three times.

3.2.2 Effect of secondary consolidation before cyclic loading

Sc and S_α are obtained for two series of tests. Series A:

Table 4. Effect of secondary consolidation before cyclic loading

Sample No.	Kind of test	Accumulated deformation	Secondary consolidation	Total deformation during 24 hours
8-3	B	0.077	0.029	0.106
8-4	A	0.026	0.074	0.100
22-2	B	0.161	0.007	0.168
22-3	A	0.107	0.060	0.167
36-3	B	0.016	0.043	0.059
36-4	A	0.004	0.054	0.058

Table 5. Verification of superposition theorem

Sample No.	Primary consolidation So(mm)	Loading increment	Deformation S(mm)	S/So
18-1	0.599	Po	0.99	1.653
18-2	0.527	$\pm\Delta P$	0.013	0.025
18-3	0.495	$Po\pm\Delta P$	0.86	1.737
29-1	0.379	Po	0.484	1.277
29-2	0.420	$\pm\Delta P$	0.048	0.114
29-3	0.357	$Po\pm\Delta P$	0.493	1.381

Secondary consolidation occurs before cyclic loading, and series B: only primary consolidation occurs before cyclic loading. S_a for series A is smaller than that for series B(see Table 4). While the total deformation, including Sc and S_a, during 24 hours is identical. It implies that the deformation caused by cyclic loading and the secondary consolidation are mutually compensated.

3.2.3 Verification of superposition theorem

The results of the test groups with three parallel samples are shown in Table 5. In order to exclude the effect of sample differences, the amounts of deformation are divided by So, the primary consolidation of this sample under Po. The figures in Table 5 indicate, deformation under both static pressure increment and cyclic loading $(S/So)_3$ equals the sum of that for static pressure increment $(S/So)_1$ and for cyclic loading $(S/So)_2$. Thus the superposition theorem is verified. It means that Sc and S_a are uncoupled.

3.2.4 Relationship between pore pressure and deformation

Pore pressure-deformation curves under static and cyclic loading are shown in Figures 13 and 14 respectively. In Figure 13 the linear part during primary consolidation stage indicates the pore pressure and deformation are one-one correspondent, and the divergent part at the final stage indicates the development of secondary consolidation, i.e. the transition stage of primary and secondary consolidation. In the transition stage the amount of secondary consolidation is a small value compared to primary consolidation. Therefore, from the engineering view, considering secondary consolidation only after pore pressure dissipation will not bring large errors. However, strictly speaking, the occurence of primary and secondary consolidation should not be considered separately. The average curve under cyclic loading (Figure 14) is basically a straight line until pore pressure dissipates to 6 kPa. This kind of relationship is similar to the one under static loading.

Application of the above test results is shown in the paper of Gu et al (1995). The computing model considering the secondary consolidation and the nonlinear parameters are obtained. The agreement between the computation results and observed data is good. Test results of overconsolidated samples

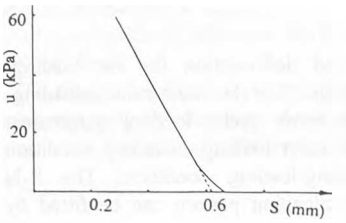

Figure 13. Pore pressure-deformation curve for static loading

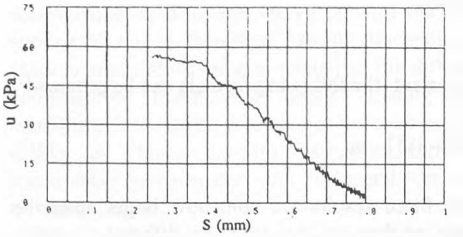

Figure 14. Pore pressure-deformation curve for cyclic loading

also provide the basis of measures for slowing down the subsidence rate.

4 CONCLUSION

In the study of consolidation behavior under cyclic loading simulating the characteristics of the water level change in Shanghai, vast amount of experiments, considering different factors, so as loading wave shape, cyclic loading parameters, loading order, consolidation state, mutual compensation between accumulated deformation and secondary consolidation, pore pressure development etc., have been conducted. The test results provide the model considering the secondary consolidation and soil parameters for the computation of land subsidence, as well as some suggestions for the countermeasures.

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