QUASI-PRECONSOLIDATION EFFECTS DEVELOPED IN NORMALLY CONSOLIDATED CLAYS

YUKITOSHI MURAKAMI¹⁾

ABSTRACT

When a load is applied to a normally consolidated clay which has experienced secondary compression, the skeleton of soil particles can sustain a part of the load increment, before sliding of particles will be initiated at a certain pressure. This is referred to a quasi-preconsolidation effect. The quasi-preconsolidation effect can be mostly explained by Bjerrum's concept concerning the delayed compression of a clay. However, in general, there exists some difference between the observed and the estimated values of quasi-preconsolidation pressure.

In the present Note, the degree of the difference and its characteristics are examined through consolidation tests on various clayey soils. As a result of these tests, it is found that the degree of difference is unchanged by consolidation pressure, but is influenced by the duration of sustained loading at a previous stage and has some relation with the properties of a clay.

Key words: cohesive soil, consolidation, secondary compression, time effect, unconfined compression test (IGC: D5)

INTRODUCTION

When the excess pore-water pressure has substantially dissipated from a normally consolidated clay and a period of time elapses during which the applied stresses are constant, soil particles continue to slowly shift into the most efficient arrangement possible. This process brings about some compression of soil and is called secondary or delayed compression. In the meanwhile the bond of soil particles develops more fully at the contact points among them, thereby increasing the bond strength of soil structure. Accordingly, when a further load increment is applied on such a clay, the skeleton of soil particles can sustain a

part of the load increment, before sliding of particles will again be initiated at a certain pressure. This pressure is apparently equivalent to the preconsolidation pressure which represents a yield stress that separates small strains from large strains, and therefore is referred to as "quasi-preconsolidation pressure". An example of its development is shown in Fig. 1. The preconsolidation pressure of soft clays is one of the important mechanical characteristics for predicting consolidation rate or settlement of a structure. There are some reports which suggest that the quasi-preconsolidation pressure depends upon the previous effective overburden pressure, the magnitude of a load increment, the rate of

¹⁾ Associate Professor, Department of Civil and Environmental Engineering, Yamanashi University, Takeda, Kofu, Yamanashi, 400.

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Fig. 1. Development of quasi-preconsolidation pressure

loading and previous loading duration (Narain et al., 1969).

The present study is based on the consolidation of thin specimens of artificially sedimented clayey soils, and examines the characteristics of quasi-preconsolidation effects by taking the properties of the soils into consideration.

REVIEW OF PREVIOUS STUDIES

When estimating the consolidation which occurs in an actual clay deposit with considerable thickness, it is of major importance to know whether the quasi-preconsolidation effect in a clay element is dependent upon the distance from a drainage boundary. Some investigators have presented their views of this subject. For instance, Berre and Iversen (1972) have indicated from their experimental results that the development of quasi-preconsolidation pressure is considerably different according to the distance from a drainage boundary. On the other hand, Bjerrum (1973) has suggested that the quasi-preconsolidation effect develops as a result of delayed compression and the ratio of the quasi-preconsolidation pressure to the effective overburden p'_c/p'_0 is consequently constant with depth in a homogeneous clay deposit for a given time of

loading. This suggestion means that the developed value of p'_c increases with depth and the quasi-preconsolidation pressure is almost unaffected by the drainage length, and might be justified by some field observations such as shown in Fig. 2. Besides, Bjerrum (1983) has insisted that the value of p'_c/p'_0 increases with the plasticity of clays when their ages are the same. The assertion is contradictory to each other in the former two studies. This discrepancy may be due to the difference between consolidation rates in a laboratory and in a field, although further research should be made to clarify the causes.

Based on many experimental data which have been accumulated up to this time, it is reasonable to infer that the quasi-preconsolidation effect results from the delayed or secondary compression in a previous loading. Primary consolidation and secondary compression occur simultaneously in a clay deposit. The state path for a clay element may depend on clay thickness, as illustrated in Fig. 3 (Imai et al., 1986). However, it may be reasonable to consider that the value of quasi-preconsolidation pressure p'_c developed in a clay is almost the same even though a state path for an element is somewhat different, when the thickness of the clay is relatively small. The

Fig. 2. Observed quasi-preconsolidation pressure

Fig. 3. State path followed by element of clay

value of p'_c can be estimated on the basis of Bjerrum's ageing model. Murakami (1979) has suggested the following equation which could evaluate the quasi-preconsolidation pressure p'_c :

$$p'_c/p'_0 = (t_c/t_{100})^{C_\alpha/(C_c - C_{cq})} \quad (1)$$

where t_c is the duration of loading, t_{100} is the duration of primary consolidation, C_α the coefficient of secondary compression which is defined by $C_\alpha = -\Delta e / \Delta \log t$, C_c the compression index and C_{cq} the quasi-compression index. In general, C_{cq} is fairly small compared with C_c and therefore the above equation can be reformed (Mesri and Choi, 1979):

$$p'_c/p'_0 = (t_c/t_{100})^{C_\alpha/C_c} \quad (2)$$

From Eqs. (1) and (2), it is obvious that the quasi-preconsolidation pressure p'_c is directly affected by the magnitude and the duration of effective overburden pressure.

However, it is well-known from consolidation tests that the observed quasi-preconsolidation pressure is somewhat greater than predicted by the above equations or by Bjerrum's model (Leonards and Ramiah, 1960, see Fig. 4). The ratio of the observed to the theoretical value could be expressed by the coefficient of β , and Murakami (1980) suggested the modified equation.

$$p'_c/p'_0 = \beta \cdot (t_c/t_{100})^{C_\alpha/(C_c - C_{cq})} \quad (\beta \geq 1) \quad (3)$$

The variations in both the quasi-preconsolidation

Fig. 4. Experimental result of compression curve (after Leonards and Ramiah, 1960)

tion pressure p'_c and the coefficient β under various conditions should be examined through experimental procedures.

EXPERIMENTAL WORK

Experimental work was carried out on several kinds of clayey soils. The main properties of the soils employed are shown in Fig. 5 and Table 1. Herein, the indices related to the

Fig. 5. Consistency of soil samples employed

Table 1. Properties of soil samples

	Kawasaki Clay A	Yokohama Clay	Kawasaki Clay B	Yatsugatake Loam	Kofu Clay
w_0 :%	88	99	62	61	58
G_s	2.70	2.71	2.68	2.66	2.64
w_L :%	95	91	70	58	61
I_p	50	45	39	21	15
C_{cq}	0.057	0.066	0.022	0.023	0.071
C_c	0.640	0.619	0.419	0.319	0.522
$*C_\alpha$	0.036	0.033	0.012	0.006	0.010
C_α/C_c	0.056	0.053	0.029	0.019	0.019
$C_\alpha/(C_c - C_{cq})$	0.062	0.060	0.030	0.020	0.022
$\times t_{100}$:min	30	90	90	30	15

*the value for $p'_0 = 76.4 \text{ kN/m}^2$

$\times$ the value for $p' = 38.0 \text{ kN/m}^2$ to 76.4 kN/m^2

w_0 : Initial Water Content

G_s : Specific Gravity of Soil Particles

w_L : Liquid Limit

I_p : Plasticity Index

C_{cq} : Quasi-compression Index

C_c : Compression Index

C_α : Coefficient of Secondary Compression ($= -\Delta e / \Delta \log t$)

t_{100} : Time for Primary Consolidation

compressibility of soils C_c , C_{cq} and C_α were preliminarily estimated from the standard consolidation tests. Particularly, the coefficient of secondary compression defined by $C_\alpha = -\Delta e / \Delta \log t$, was appraised from secondary compression which occurred after primary consolidation. A series of typical consolidation tests was conducted to examine the characteristics of quasi-preconsolidation effects developed in normally consolidated clays. The specimens were about 1 cm thick and 6 cm in diameter and were enclosed inside a polished stainless steel ring, only with a porous stone at the top. The consolidometer was placed inside a cylindrical chamber such as employed in a triaxial test. The specimen was subjected to a back pressure by the application of pressure to the fluid in the chamber. The fluid consisted of the water and the lubricating oil which occupy the lower part and the upper part of the chamber respectively. The oil was used for the sake of decreasing the friction between a vertical loading ram and a lid of the cell as much as possible. The specimens of artificially sedimented soils which had consolidated to the pressure of 39.2 kN/m^2 were exclusively employed in the tests. The total pressure of a soil mass and the induced pore-water pressure were separately measured on the bottom of a specimen throughout the consolidation tests, in which

the back pressure of 98 kN/m^2 was constantly applied. In the midst of a consolidation test, the settlement of 90% consolidation w_{90} was estimated from the settlement observed up to about 95% consolidation by adopting the square-root-of-time method and the settlement of 100% consolidation w_{100} was predicted by multiplying w_{90} by 10/9. Then, the time of primary consolidation t_{100} was obtained as the time at which the settlement attained w_{100} and was reconfirmed by the dissipation of excess pore-water pressure measured. Immediately after the finish of primary consolidation had been recognized, the load increment of 39.2 kN/m^2 was additionally applied on the specimen, and both primary consolidation and a certain amount of secondary compression were allowed. Subsequently, small load increments were stepwise applied at the duration which was equivalent to the time for primary consolidation. The volume change of a specimen, and both the pore-water pressure and the total pressure at the bottom of a specimen were continuously measured throughout the series of consolidation tests. The measured value of the total pressure was about 96% to 98% of the applied load, although the ratio of the thickness to the diameter of a specimen was diminished as much as possible. This may be due to the effect of friction. For convenience, the modified

Fig. 6. Void ratio-logarithm of effective pressure curve observed in consolidation test

effective pressure p' is defined by the average of the measured and the applied pressures.

The compression curves obtained from the consolidation tests indicate the existence of a quasi-preconsolidation pressure, as shown in Fig. 6. This is generally larger than the value extrapolated from the initial stage of the test. However, at higher stresses, the compression curve approaches to that observed in the consolidation test which includes only primary consolidation.

TEST RESULTS

Figs. 7 and 8 show the variations in both the quasi-preconsolidation pressure p'_c and the coefficient β with the effective pressure at previous loading p'_0 and the time allowed for secondary compression t_c , respectively. These results, which have been obtained from the consolidation tests on Kofu clay, show that p'_c/p'_0 is considerably influenced by the duration of previous loading t_c , as suggested from the theory, while the coefficient β is not affected by the magnitude of the consolidation pressure. However, the coefficient β is mostly influenced by the time during which secondary compression occurred. The similar characteristics are recognized in the other soils used, although there is a difference in the degree. Fig. 9 and Table 2 illustrate the effect of the

Fig. 7. Effect of consolidation pressure p'_0 on quasi-preconsolidation pressure p'_c and coefficient β

Fig. 8. Effect of loading duration t_c on quasi-preconsolidation pressure p'_c and coefficient β

plasticity of soils on the value of β . Judging from the characteristics of the variation in β , it can be said that the coefficient β is somewhat related to the plasticity of the clayey soils.

It is supposed that the strength of soils increases through the development of secondary compression and is related to the quasi-preconsolidation effect. This was examined by conducting an unconfined compression test on the soils employed in the consolidation tests. The specimens were 10 cm thick and 5 cm in diameter and were different from those used in the consolidation tests. The specimens were

Table 2. Relationship of unconfined compression strength, quasi-preconsolidation pressure and coefficient β

Soils	I_p	$Su(t_c)/Su(t_{100})$	p'_c/p'_0		β
			Observed	Estimated	
Yokohama Clay	44.5	1.28	1.312	1.262	1.04
Kawasaki Clay	39.2	1.21	1.303	1.123	1.16
Yatsugatake Loam	20.6	1.14	1.297	1.081	1.20

$t_c/t_{100}=48$; $p'_0=76.4 \text{ kN/m}^2$

Fig. 9. Relationship between loading duration t_c and coefficient β

prepared by consolidating the soils up to $t=t_{100}$ and $t=t_c > t_{100}$ under the load of 78.4 kN/m^2 . The unconfined compression test was carried out and the unconfined compression strength Su was obtained for each of the soils. The ratio of $Su(t_c > t_{100})$ to $Su(t_{100})$ is shown together with quasi-preconsolidation pressure p'_c for three kinds of cohesive soils in Table 2. It appears that $Su(t_c)/Su(t_{100})$ is nearly proportional to p'_c/p'_0 and the strength increase of soils during secondary compression has some relation to the quasi-preconsolidation effect. However, the coefficient β has no immediate connection with the strength increase during secondary compression.

CONCLUSIONS

The present Note treats the characteristics of quasi-preconsolidation pressure developed

in a clayey soil exhibiting secondary compression under a sustained loading. The coefficient β , that is, the ratio of the observed to the predicted value of quasi-preconsolidation pressure, shows the following nature:

- 1) The value of β is generally greater than unity.
- 2) The coefficient β is considerably affected by the duration of a sustained loading.
- 3) The coefficient β is unaffected by consolidation pressure.
- 4) The coefficient β may be mostly related to the soil properties such as the plasticity but has no immediate connection with the strength increase during secondary compression.

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