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Time Effects on One-dimensional Consolidation Analysis

by

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Abstract

Two secondary compression models are examined by analysis and one-dimensional consolidation test in clays of different drainage distances. Scale effects on one-dimensional consolidation taking account of secondary compression are influenced by the increase in effective stress during consolidation. Observed consolidation time curves agree with calculated results of the secondary compression model expressed by the function of consolidation elapsed time and the effective stress.

Keywords: *One-dimensional consolidation, Constitutive model, Scale effect, Difference method, Secondary compression*

1. Introduction

Terzaghi's consolidation theory assumes a linear stress strain relationship. Consequently, the theory is unable to explain secondary compression that continues even after the degree of consolidation has reached 100 percent. Since secondary compression settlement is observed with almost all types of cohesive soil, many theories of one-dimensional consolidation including secondary compression have been put forward since soon after Terzaghi published his consolidation theory[1)]. In practice, however, designers seldom take secondary compression into account[2)]. The reason for this is generally thought to be that secondary compression is observed only in laboratory tests in which the maximum drainage distance is short; at a site where the maximum drainage distance is long, primary consolidation occurring over a long period of time includes secondary compression. Current design practice poses many questions yet to be answered concerning secondary compression, such as why the consolidation observed in standard consolidation tests in which loads are applied at one-day intervals tend to agree with field measurement results and whether or not the influence of secondary compression may be ignored in the coefficient of consolidation[2)].

In one-dimensional consolidation analysis that takes secondary compression into account, determination of the method by which to process. There is a significant difference in the consolidation settlement evaluate similarity in the rate of one-dimensional consolidation (scale effect) is an important consideration. Experimental research[3),4)] and the results of field measurements of long-term settlement[5)] revealed that secondary compression begins to occur while primary consolidation is still in progress, and that the amount of secondary compression, when it occurs over a long period of time, is roughly proportional to the logarithm of time. Although the assumption concerning secondary compression that the amount of one-dimensional consolidation, that is, a decrease in the void ratio of saturated clay continues infinitely in proportion to the logarithm of time is not ideal, it is generally recognized as practical and rational[6)-11)]. As for scale effect, it is generally said that no definitive conclusion can be drawn because verifying scale effect experimentally is a very onerous and time-consuming task[12),13)].

In many of the constitutive equations for secondary compression that have been proposed thus far, secondary compression is expressed as a function of time only[9),14)-17)] based on the concept of isotaches[18)]. Akai and Adachi[19)], however, pointed out that secondary compression is caused by dilatancy and that the mechanism of one-dimensional consolidation needs to be considered in terms of the applied effective stress field. Since the reason that volumetric strains at different points in the consolidating layer have to converge to constant values in the process of secondary compression is not clear, there is room for reconsidering the simplification based on the isotaches theory.

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In this paper, the effect of assumptions made concerning the amount of secondary compression in an analysis of one-dimensional consolidation including secondary compression on the consolidation -time curves for clays with different drainage distances is investigated. Numerical analyses were conducted assuming that secondary compression is a function of time and effective stress, and the analysis method was compared with the conventional method that regards secondary compression as a function of time only. One-dimensional consolidation tests on clay samples with different maximum drainage distances were also conducted to investigate time effect and scale effect on one-dimensional consolidation.

2. One-dimensional consolidation analysis

2.1 Constitutive equation for one-dimensional consolidation including secondary compression

In one-dimensional consolidation, changes in the void ratio e of normally consolidated saturated soil due to effective stress σ' can be expressed as follows[6,20,21];

$$e = e_0 - C_c \log(\sigma'/\sigma_0) - C_\alpha \log(t/t_i) \tag{1}$$

where $C_c = (de/d\log\sigma')$ is compression index; $C_\alpha = (de/d\log t)$, the coefficient of secondary compression; t, the time elapsed after the start of consolidation at a point in the consolidating layer; and t_i, the time at which secondary compression begins. The subscript "0" appended to the effective stress and the void ratio represents the initial state before consolidation.

The total differential of the void ratio is given as

$$de = de_p + de_s \tag{2}$$

The terms on the right-hand side of Eq. (2) can be expressed as

$$de_p = \left(\frac{\partial e}{\partial \sigma'}\right)_t d\sigma' = -\frac{0.434C_c}{\sigma'}d\sigma' = m_p d\sigma' \tag{3}$$

$$de_s = \left(\frac{\partial e}{\partial t}\right)_{\sigma'} dt = -\frac{0.434C_\alpha}{t}dt = m_s dt \tag{4}$$

In this paper, de_p due to a change in effective stress defined by Eq. 3 is called the amount of primary consolidation, de_s due to a change in time defined by Eq. 4 is called the amount of secondary compression. In Eq. 3, m_p is equivalent to the coefficient of volume compressibility.

Substituting Eq. 2 in Eq. 5 (i.e., one-dimensional consolidation equation) gives Eq. 6. In Eq. 6, the applied load during consolidation is assumed to be constant.

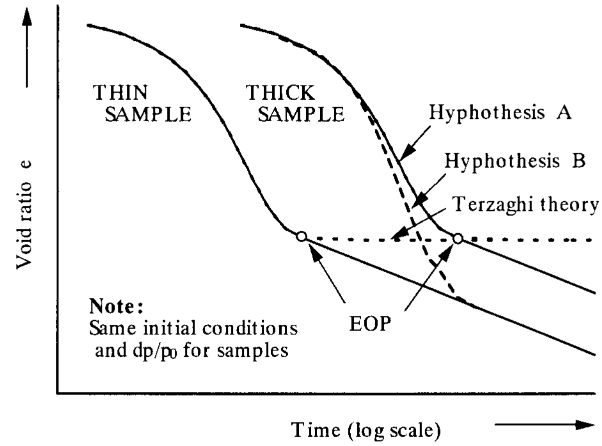

Fig.1 Illustration of Hypotheses A and B for the void ratio and time curves of normally consolidation clay[12)]

$$\frac{1}{1+e_0}\frac{\partial e}{\partial t} = \frac{k}{\gamma_w}\frac{\partial^2 u}{\partial y^2} \tag{5}$$

$$\left(\frac{\partial e}{\partial \sigma'}\right)_t \frac{\partial u}{\partial t} = -\frac{k(1+e_0)}{\gamma_w}\frac{\partial^2 u}{\partial y^2} + \left(\frac{\partial e}{\partial t}\right)_{\sigma'} \tag{6}$$

where k is the coefficient of permeability; γ_ω, the unit weight of water; u, excess pore water pressure; and y, the distance in the consolidating layer.

As shown in Fig. 1, there are two one-dimensional consolidation hypotheses about the consolidation-time relationships for cohesive soils with different maximum drainage distances[12)]. Hypothesis A postulates that creep strain does not occur during primary consolidation. According to this hypothesis, consolidation time is proportional to the square of the maximum drainage distance H, and void ratio-time curves are of parallel type, as shown with solid lines[20)]. Hypothesis B postulates that creep strains that occur during primary consolidation cause overlapping in the secondary compression region and create an "isotaches" condition, as shown with a broken line[14,16)]. With respect to these theoretical postulations concerning similarity of one-dimensional consolidation, Aboshi[13)], as a result of experimental verification, reports that consolidation-time relationships involving different maximum drainage distances are located somewhere between Hypothesis A and Hypothesis B.

The review by Ladd[12)] does not present a conclusion about the validity of the "parallel" or the "isotaches" classification. The hypothesis that secondary compression does not begin until primary consolidation ends (Hypothesis A) is not considered in this study, because the rationale behind the hypothesis

Table 1 Soil constants and consolidation conditions for the calculation.

Compression index C_c	1.0
Coefficient of secondary consolidation C_α	0.04
Initial void ratio e_0	2.0
Coefficient of consolidation c_v (cm^2/min)	0.1
Intial consolidation pressure σ'_0 (kPa)	98.1
Incremental applied load $d\sigma'$ (kPa)	98.1

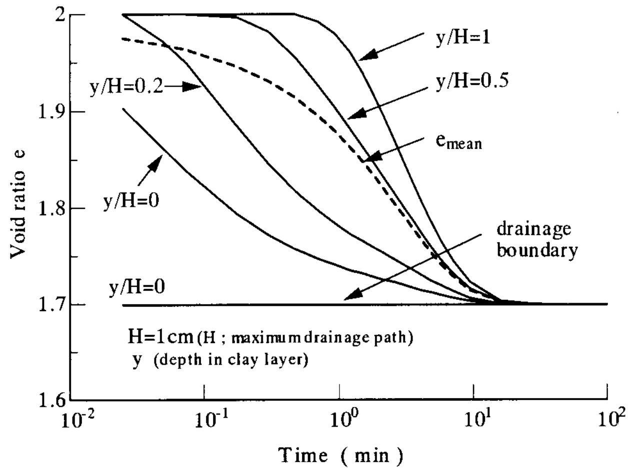

Fig.2 Calculated void ratio-time curves (C_α =0).

is unclear and is not consistent with recent research findings$^{2,4,21)}$. It should be noted, however, that Hypothesis B also is unclear in many aspects. For example, it is unclear about when secondary compression begins during primary consolidation and whether or not secondary compression occurring time during primary consolidation differs from that occurring after primary consolidation has ended. Imai and Tang$^{4)}$ and Oka$^{22)}$ showed that consolidation analysis using constitutive equations of isotaches type can be made to support either of the two hypotheses (A, B) by taking into consideration differences in the initial conditions of samples, such as the void ratio before consolidation and the rate of strain (rate of secondary compression). Aboshi's experimental results were attributed to differences in the initial conditions of samples.

In Eq. 4, secondary compression occurs whether or not effective stress increases even if the time of the start of secondary compression, t_i, in Eq. 1 is assumed to be earlier than the end of primary consolidation (EOP). It is widely known that secondary compression in anisotropic consolidation is affected by effective stress$^{11,23)}$, and it is quite possibly that secondary compression in primary consolidation is affected by effective stress.

Secondary compression of clay in natural ground occurs under constant effective stress over a period of several hundred to several thousand years. The rate of secondary compression over so long a period of time is quite difficult to determine$^{7)}$. In engineering practice, secondary compression over the first several tens of years is an important consideration.

The authors, therefore, think that secondary compression occurs in proportion to the increase in effective stress if the influence of secondary compression before consolidation does not take into consideration and the initial conditions of clay are identical. Thus, the authors use to an equation for normally consolidated clay that can be used in place of Eq. 4$^{8,17,20)}$;

$$de_s = \left(\frac{\partial e}{\partial t}\right)_{\sigma'} U_y dt = -\frac{0.434C_\alpha}{t} U_y dt = m_s U_y dt \qquad (7)$$

Secondary compression at a point, y, in the consolidating layer calculated using Eq. 7, which is obtained by multiplying Eq. 4 by the degree of consolidation U_y , increases with effective stress during consolidation. For the purposes of calculation, the time of the start, t_i, of secondary compression is assumed to be the same as the start of consolidation (time of the occurrence of an increase in effective stress) at each points in the consolidating layer.

2.2 Effect of the amount of secondary compression on consolidation-time curve

Examples of calculation to clarify differences between a secondary compression analysis using Eq. 4 and one using Eq. 7 are shown below. Finite difference approximation for Governing Eq. (6) is as follows:

$$\begin{aligned} u_{y,t+dt} &= u_{y,t} + \alpha(u_{y+dy,t} - 2u_{y,t} + u_{y-dy,t}) \\ &\quad + m_s dt / m_p \end{aligned} \qquad (8)$$

where $\alpha = c_v \cdot dt/dy^2 \le 0.5$ and $c_v (= k(1+e_0)/\gamma_\omega / m_p)$ is coefficient of consolidation. Equation 8 is solved by the following initial and boundary conditions. The initial conditions and boundary conditions for comparative study based on difference calculation are shown below. The soil constants used in the calculation are shown in Table 1.

$$\begin{aligned} & y = 0 \ , t \ge 0 \ : \ u = 0 \\ & y > 0 \ , t = 0 \ : \ u(y) = \Delta\sigma \\ & y = H \qquad : \ \frac{\partial u}{\partial y} = 0 \end{aligned} \qquad (9)$$

where H is the maximum drainage distance in the consolidating layer; and $\Delta\sigma'$, an incremental consolidation load.

Figure 2 shows void ratio-time curves at different points, in the consolidating layer at a coefficient of

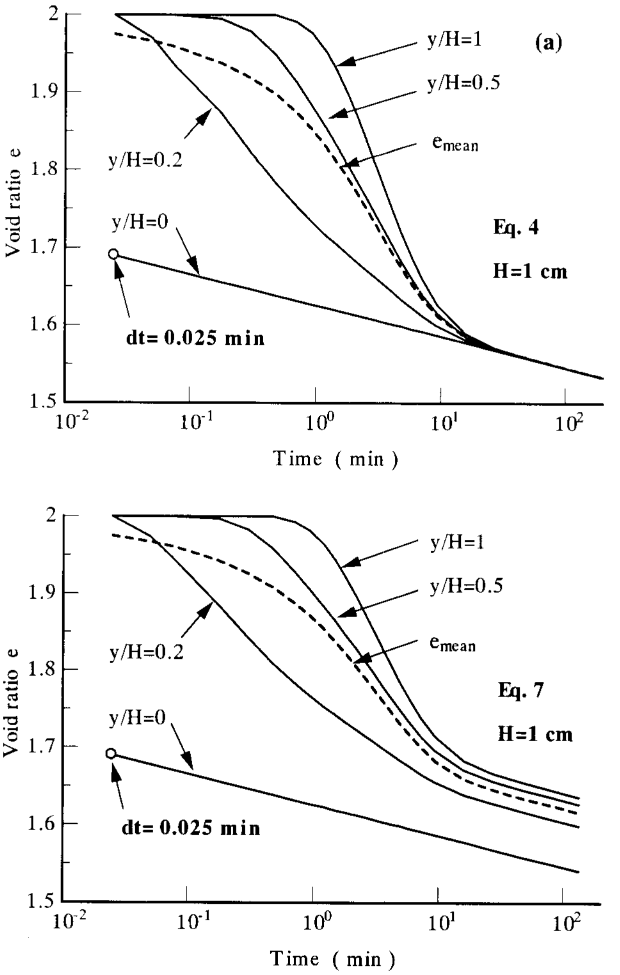

Fig.3 Comparison of calculated void ratio-time curves (C_α =0.04): (a) using the Eq. 4 and (b) using the Eq. 7.

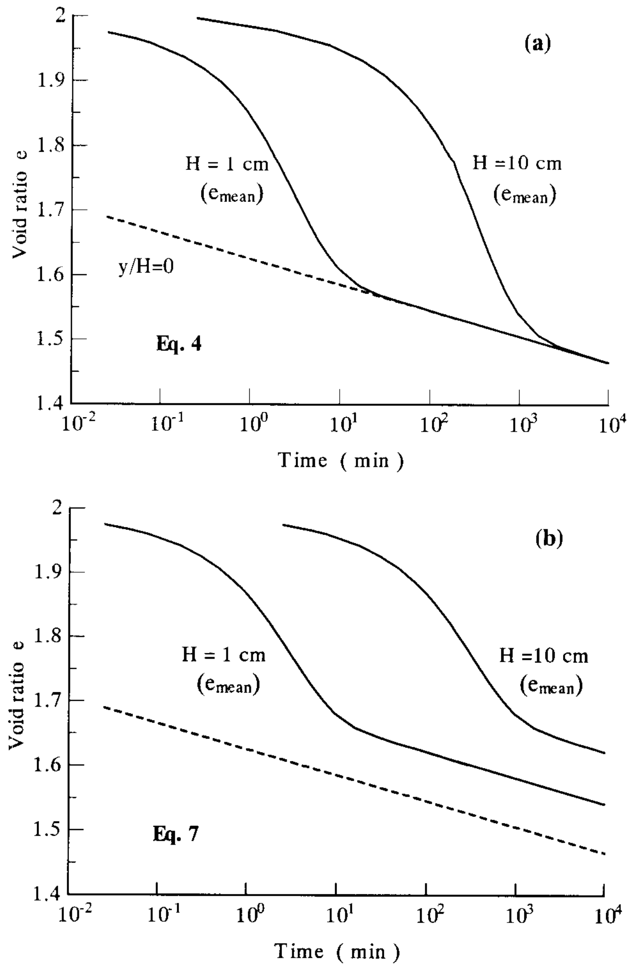

Fig.4 Calculated void ratio-time curves for clay with different drainage distances: (a) using the Eq. 4 and (b) using the Eq. 7.

Table 2 Physical properties of the alluvial clays.

sample	ρ_s (g/cm^3)	ω_L (%)	ω_P (%)	Grading (%)		
				clay	silt	sand
1	2.644	112.0	50.5	47	38	15
2	2.642	82.6	20.8	54	41	5
3	2.356	73.3	50.7	40	38	22

secondary compression of $C\alpha$ =0, obtained from calculations performed partly for the purpose of verifying the difference calculation software used. The mean void ratio e_{mean} shown with a broken line corresponds to the calculations based on the Terzaghi theory.

Figs. 3 (a) and (b) show void ratio-time curves from Eq. 4 and Eq. 7 taking secondary compression into consideration. If the amount of secondary compression is assumed to be a function of time only as indicated by Eq. 4, void ratios at different points in the consolidating layer overlap one another after the end of primary consolidation, as shown in Fig. 3(a).

Calculation using the proposed Eq. 7, however, gives parallel void ratio-time curves at different points in the layer corresponding to different degrees of delay due to increases in effective stress. Fig. 4(a) and (b) show void ratio-time curves for different maximum drainage distances, calculated from Eq. 4 and Eq. 7.

In the results obtained from Eq. 4, void ratio-time curves for different maximum drainage distances overlap one another, showing agreement with the Hypothesis B pattern (isotaches) shown in Fig. 1. The results obtained from Eq. 7 run parallel and do not overlap. These calculation results, however, differ from Hypothesis A in that it is assumed that secondary compression begins to occur while primary consolidation is still in progress. The void ratio-time curves for different maximum drainage distances based on the assumptions made for Eq. 7 are of parallel type and differ from the consolidation test results obtained by Aboshi$^{13)}$. To reproduce Aboshi's consolidation test results, it is necessary to make other assumptions concerning calculation conditions such as the initial conditions of samples (e.g., void ratio, strain rate)$^{21\text{-}25)}$.

Table 3 Test conditions.

TEST	sample	H (cm)	D (cm)	σ'_0 (kPa)	$d\sigma'$ (kPa)
A	*1, 2*	1,3.5,6	6,20,40	9.8	29.4
B	*2*	6	6	9.8	29.4
C	*3*	2,3,4,8	6	39.2	78.5

3. One-dimensional consolidation test under different maximum drainage distance

In this section, differences in void ratio-time curves at different points in the consolidating layer are discussed in view of the results of one-dimensional consolidation tests involving different maximum drainage distances conducted using inter-connected oedometers.

3.1 Sample and test method

Table 2 shows the physical properties of the alluvial clay used in a one-dimensional oedometer. Clay samples were thoroughly mixed at water contents exceeding the liquid limit. Three tests were designed so as to satisfy the assumption for calculation that the initial conditions of all samples are identical and the normally consolidated condition. All test conditions is shown in Table 3.

Test A: Uniformly mixed samples were set in one-dimensional oedometers of three different sizes (diameter D=6cm, 20cm, 40cm). After a load of 4.9kPa was applied for one day, a preload of 9.8kPa was applied. Preloading periods of 1 day, 13days and 36 days were used for ring diameters D of 6cm, 20cm and 40cm, respectively. In deciding the preloading periods, the period of 1 day for D=6cm was used as the basis, and the 13 days and 36 days for D=20cm and D=40cm were chosen as periods proportional to the square of the maximum drainage distance. After preloading, the uppermost part of each sample was trimmed so that the ratio of the diameter D to the maximum drainage distance H (D/H) became about 3. The heights of test specimens thus prepared were 2cm, 7cm and 12cm. After a load of 9.8kPa was applied for another day, the applied load was increased by an increment of $d\sigma'$=29.4kPa, and changes over time in the amount of settlement were measured. Samples *1* and *2* were used.

Test B: Test B and test C were conducted to investigate the secondary compression behavior of the inner part of a sample. Sample *2* preloaded under the same conditions as Test A (D=6cm, H=2cm) was set in a inter-connected oedometer equipped with a ring of corresponding diameter. Three oedometers were connected in series, and preloading was continued for 36days with single drainage. After that, an incremental consolidation load of $d\sigma'$=29.4kPa was applied, and settlement was measured.

Test C: Sample *3* and *4* was put into a one-dimensional oedometer 25cm in diameter and 30cm in height, and a preload of 24.5kPa was applied to the sample for three weeks. Specimens were cut off from the sample block, and each sample was set in a inter-connected oedometer. Maximum drainage distances H of 2, 3, 4 and 8cm were reproduced by connecting two to four oedometers containing a 1cm high specimen and four oedometers containing a 2cm high specimen. To make initial conditions for different samples identical, the following method was used. A preload of 39.2kPa was applied with a back pressure of 147.2kPa for two days. The oedometers had not yet been connected and had been drained separately with the aim of making the stress conditions and the secondary compression period identical for all samples.

After the oedometers were connected together, $d\sigma'$=39.2 kPa was applied and changes over time in the amount of settlement and pore water pressure were measured. For the 2cm specimens, a preload of $d\sigma'$=39.2kPa was applied for four days.

In Test A and Test B, different preloading periods were used for different layer thicknesses in an attempt to use the same initial void ratios, but the initial conditions of the samples were not necessarily uniform. Since it is impossible to make pre-consolidation strain rates identical by the Test A method using a remoulded clay, the validity of Test A as a basis for discussing the effect of drainage distance is limited. In contrast, in Test C, it is possible to make the initial conditions before consolidation identical, regardless of drainage distance, by preloading one-centimeter-thick specimens individually. Even in Test C, however, is not without a problem; in the case where four oedometers containing two-centimeter specimens are connected together, strain rates at different points in the specimens that have not yet been loaded vary.

3.2 Test results and discussion

Figure 5(a) and (b) show the results of Test A conducted with three drainage distances. The initial void ratio e_0 and the mean void ratio $e_{0(mean)}$ for all test specimens are shown. As shown clearly in Fig. 5(a) and (b), the void ratio-time curves for specimens with different drainage distance H continue to run almost parallel after primary consolidation ends. Figure 6 shows void ratio-time curves for specimens consisting of connected 2 cm blocks used in Test B. The time at which consolidation begins varies depending on the distance from the drainage surface, and curves do not

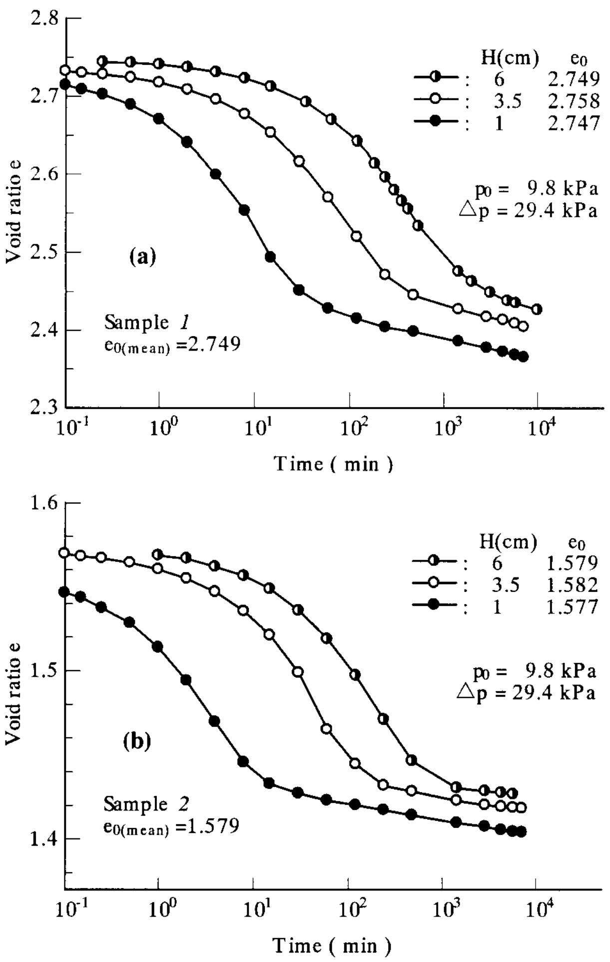

Fig.5 Void ratio-time curves with different drainage distances obtained from Test A: (a) sample 1 and (b) sample 2.

meet even after primary consolidation ends after the elapse of 1000 minutes.

Figure 7 shows the results of an analysis of one-dimensional consolidation including secondary compression, conducted on the basis of the test results (sample *2*) shown in Fig. 5(b). The coefficient of consolidation c_v and the coefficient of secondary compression C_α necessary for the analysis were determined from the void ratio-time curve for H=1cm shown in Fig. 5(b), and secondary compression was calculated using Eq. 7. The calculation results closely reproduce the test results in terms of the amount of consolidation and the parallelism that continues even after the end of primary consolidation.

Figure 8 shows water content distributions of sample *3* preloaded for three weeks on a one-dimensional preloading apparatus. The preloaded specimen was about 12cm high. After 1cm pieces were cut off from both ends of the specimen, the trimmed specimen was cut into 10 pieces, and their water content in the vertical direction was measured. Since similar samples were also used for other tests, they were prepared three times (three kinds of symbol in Fig.9)

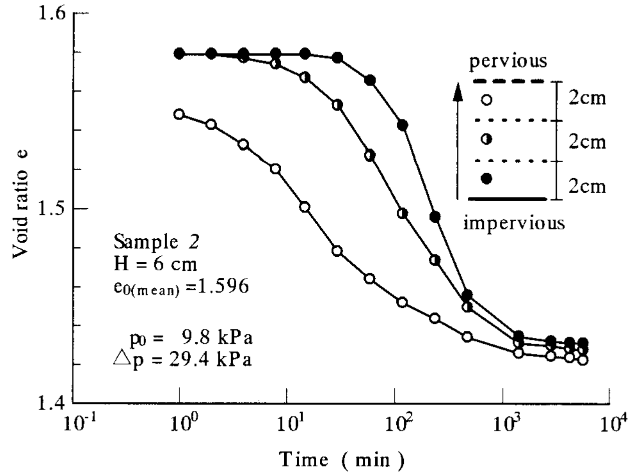

Fig.6 Results of three inter-connected test B; void ratio-time curves of each subspecimen.

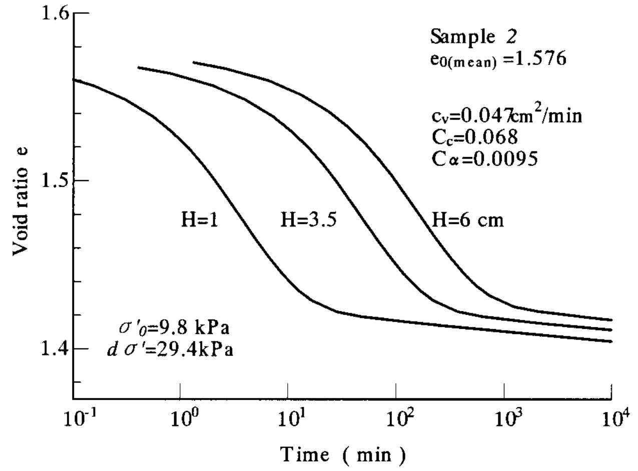

Fig.7 Calculation result of the experimental result shown in Fig. 5(b).

Because the water content of the upper part tended to be lower by 3% to 5% than that of the lower part, relatively homogeneous samples taken from the lower part were used in Test C.

The void ratio-time curves for different layers, obtained for maximum drainage distances of 3 cm and 4 cm from Test C are shown in Fig. 9(a) and (b). The white symbols indicate that the corresponding results were obtained from specimen-by-specimen application of the preload of σ_0' ; while the black symbols represent the results obtained after the specimens were connected together. Since the initial void ratios before preloading were 2.885±0.005 and their changes over time under the influence of the preload were not substantial, the initial conditions of all layers before consolidation under σ'=78.5kPa may be considered identical. The void ratio-time curves for these specimens connected together and compressed ran more or less parallel after the end of primary consolidation, as shown in Fig. 6. Similar tendencies were observed at the maximum drainage distances H of 2cm and 8cm.

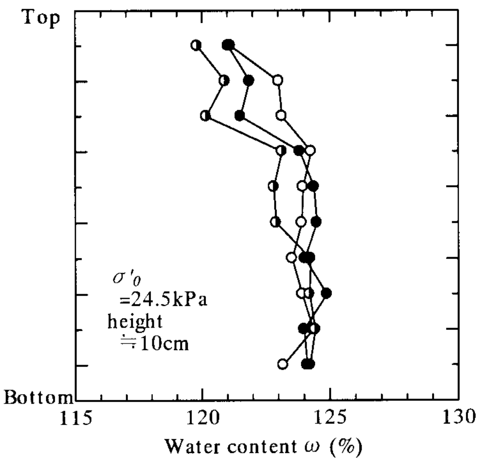

Fig.8 The water content distribution of clayey blocks applied to a preload of 24.5 kPa for three weeks.

Figure 10 shows the relationships between the mean void ratio and time for specimens with different maximum drainage distances. As shown, the curves ran more or less parallel after the end of primary consolidation and did not meet, at least during the measurement period. From the test results described above, it can be said that secondary compression begins while primary consolidation is still in progress and the amount of secondary compression is highly likely to be affected by increases in effective stress at different points in the consolidating layer, as assumed in Eq. 7. In other words, it can be said that for secondary compression in one-dimensional consolidation, the proposed equation, Eq. 7, gives results closer to test results than Eq. 4.

4. Concluding remarks

Judging from the test results obtained in this study as well as previous studies, it will be possible to say that occurrence of secondary compression during the primary consolidation is unquestionable. The question, then, is how it can be formulated so that it can be reflected in numerical analysis.

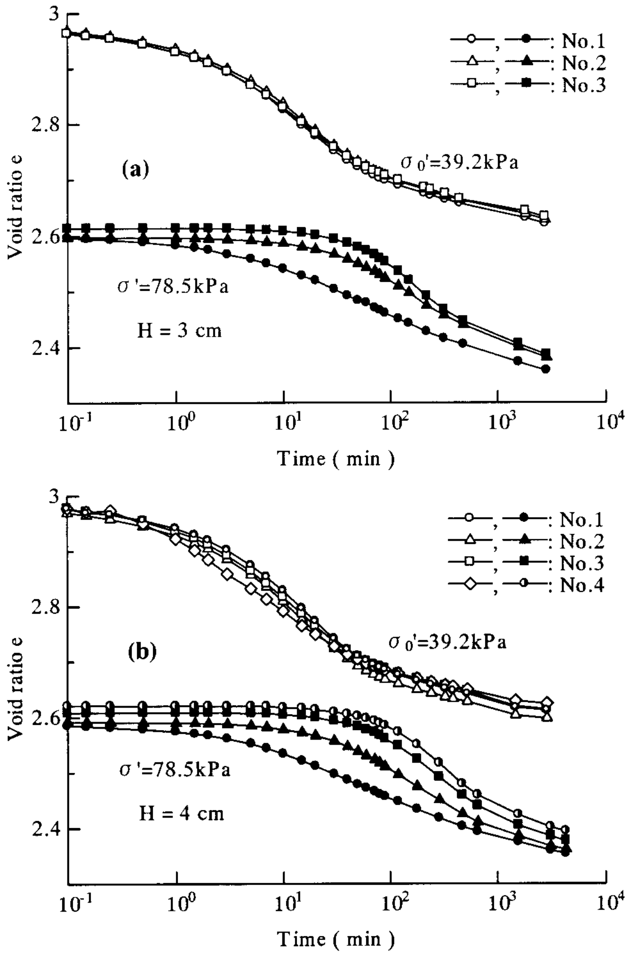

Fig.9 The results of inter-connected test C: (a) H=3cm and (b) H=4cm.

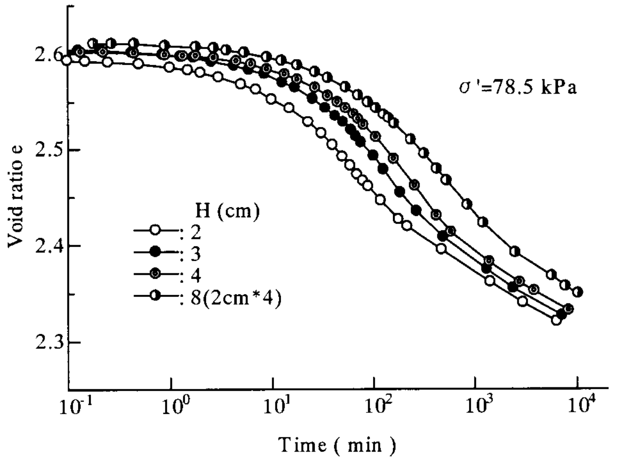

Fig.10 Mean void ratio-time curves with different drainage distances obtained from Test C.

In this paper, an equation (i.e., Eq. 7) based on the assumption that secondary compression is governed by increases in effective stress in the consolidating layer has been proposed, and validity of the proposed equation was evaluated through one-dimensional consolidation tests involving different maximum drainage distances in remoulded normally consolidated clays. Since, however, secondary compression cannot be measured in isolation from primary consolidation in laboratory testing, calculation results obtained by a conventional method, which assumes that secondary compression does not depend on the effective stress, were compared with results obtained by the proposed method, which assumes that it does depend on the effective stress. Calculation results obtained by the two methods, both of which assume that the initial conditions before consolidation are identical, turned out to be isotaches type and parallel type, respectively. The calculation results of parallel category differ from Hypothesis A put forward by Ladd[12] because of the assumption that secondary compression occurs while primary consolidation is still in progress.

The test results obtained from clay samples that were reconstituted in order to make the initial conditions of test specimens identical were parallel type rather than isotaches type. In one-dimensional consolidation tests on remoulded normally consolidated clay samples, however, it is very difficult to make the initial conditions of samples with different drainage distances identical. The further experimental examination is required.

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