Dilatancy Behaviour in Standard and Constant Strain Rate of Consolidation Test

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ABSTRACT

Embankment requires relatively good soil bed as bearer, where the soil consolidation can subside due to excessive loading. Two problems are usually encountered in the consolidation process, i.e., magnitude of the subsidence and time interval required to reach maximum subsidence. One of the promising methods in soil consolidation test is constant strain rate consolidation (CSRC) test. Although CSRC assures rapid consolidation test, the time dependence on the response of stress-strain such as secondary compaction has not been properly understood. An experiment was conducted in order to study the behavior of the time dependency. Based on the remolding of young clay soil, the test indicated a considerable time dependency behavior as shown in standard consolidation (SC) and CSRC. The behavior was systematically explained with simple assumption of dilatancy time dependency. In the early stage of SC test, each addition of load resulted in small dilatancy and increased several minutes after the loading step. At the end of each loading step, dilatancy occurred proportionally with the addition of logarithm time, which can be observed as secondary compaction. In the CSRC test, some period of time after the stress condition entered the normally consolidation area, the dilatancy tended to occur rapidly with the addition of stress ratio. Since most of the dilatancies had taken place at the earlier stage of consolidation, only small dilatancy occurred at the latter stage of CSRC process. This tendency made the specimen more rigid with time, and made the vertical stress and pore stress increase significantly at the end of the CSRC process. The behavior could be effectively explained on the result of the CSRC test.

Keywords: Clay, consolidation test, dilatancy, secondary compression, time effect

1. INTRODUCTION

The knowledge gathered in studying of the consolidation behaviour of agricultural soils has consequently paved the way for the application of the critical state theory to the analysis of agricultural soil behavior (Kurtay and Reece, 1970; Reece, 1977; Hettiarachi and O'Callaghan, 1980; Hettiarachi, 1987). Critical state theory is described elsewhere (Wulfsohn, 1994). Application of this theory in analyzing agricultural soil behavior was based on the total stress approach (Kirby, 1989; 1991). Laboratory experimental test performed conventional procedure on heavy agriculture clay using soil from Quebec province (Eastern Canada). The tests performed were one-dimensional compression of standard consolidation SC test, isotropic compression and K_0 (Eko, 2004).

The constant strain rate consolidation (CSRC) test appears to be one of the most promising types of rapid consolidation test, because of its simplicity manipulation and reliability. A lot of studies have enabled one to get the void ratio-vertical effective stress relationship, coefficient of volume compressibility and coefficient of consolidation by using CSRC test results (e.g. Crawford, 1964, Smith and Wahls, 1969, Wissa et al., 1971, and Janbu et al., 1981).

This study was divided broadly into two categories, according to whether the study assumes the linear elastic behavior of soils or not. The large strain effect has been considered also by some researchers (e.g. Lee, 1981 and Znidarcic et al., 1986). However, the time dependency in stress-strain response such as the secondary compression has not been sufficiently clarified yet in CSRC test. Although Leroueil et al (1985) and Yin and Graham (1988) carried out various types of consolidometer tests including CSRC test and proposed a unique stress-strain rate relationship, the rheological for CSRC process itself was not explained in detail. Sompie et al. (2001) showed that both many time effects observed in triaxial test and the secondary compression in standard consolidation test were realistically simulated by a numerical procedure based on a simple postulate concerning the time dependency of dilatancy.

This research applied the numerical procedure to CSRC test, and aims to clarify the time dependent behavior of soft clay in CSRC test. As the initial step of the study, concern was restricted only to the stress-strain-time behavior observed in remolded young clay soil, and the infinitesimal strain theory was used.

2. PRELIMINARY DEFINITION

2.1 Fundamental Parameters

For the K_0-consolidation process, a stress state is described by means of effective stress p'^n and stress difference q^n:

$$p'^n = \left(\sigma'^n_v + 2\sigma'^n_h\right)/3\ ,\ q^n = \sigma'^n_v - \sigma'^n_h \qquad (1)$$

and the corresponding strains are

$$v^n = \varepsilon^n_v\ ,\ \varepsilon^n = 2\varepsilon^n_v/3 \qquad (2)$$

where σ'^n_v, σ'^n_h: vertical and horizontal stresses, ε^n_v: vertical strain, and n: a discretized time step number. Hereafter, normal stresses are regarded as effective stresses unless otherwise defined. The term q^n/p'^n is referred to as 'stress ratio'.

2.2 Time Dependency of Dilatancy

When neglecting time dependency, volumetric strain due to dilatancy v^n_d is represented as (see Shibata, 1963, and Otha, 1971)

$$v^n_d = Dq^n/p'^n\ ,$$
$$D = (\lambda - \kappa)/(1 + e_0)M \qquad (3)$$

in which D is dilatancy coefficient, $\lambda = 0.434C_c$ (C_c is compression index), $\kappa = 0.434C_s$ (C_s is swelling index), e_0 is initial void ratio, and M is slope of critical state line. When the stress state within clay specimen changes with the passage of time, it is assumed that volumetric strain due to dilatancy v_d^n takes place as

$$\Delta v_d^n = \left(Dq^n / p'^n - v_d^{n-1} \right) L^n \quad (4)$$

in which

$$L^n = \ln \Delta t^n / \ln T \quad \text{when the stress ratio increases} \quad (5a)$$

$$= \Delta \ln t_1^n / \left(\ln T - \ln t_1^{n-1} \right) \quad \text{for other cases} \quad (5b)$$

where Δt^n is length of discretized time step, t_1^n is elapsed time after stopping the increase in the stress ratio, T is time length required to make dilatancy take place completely, and Δ is increment of succeeding physical quantity. The physical meaning of Eqs. (4) and (5) is given by Arai (1994). Eq. (4) is not sufficient to duplicate the dilatancy behavior for a sudden increase in shear stress. When a shearing process originates in almost static state where the stresses and strain are approximately constant with the passage of time, for instance in the final stage of consolidation, it is assumed that little dilatancy is generated at the early stage of shear until the value of v_d^n calculated by Eq. (4) exceeds a certain prescribed value v_d^*. The value of v_d^* is easily determined by using the effective stress path in conventional triaxial test (Arai, 1985). The early stage of shear, when little dilatancy takes place, is called 'quasi-elastic state'. Summarizing the above assumption, the time dependency of dilatancy is illustrated schematically as in Fig. 1.

2.3 Elastic and Plastic Strain

To be the volumetric strain given by Eq. (4) is assumed perfectly plastic. Incremental volumetric strain due to consolidation Δv_c^n is supposed to be the sum of elastic component Δv_{ce}^n and plastic component Δv_{cp}^n, which are assumed to be time independent.

$$\Delta v_c^n = \Delta v_{ce}^n + \Delta v_{cp}^n \quad (6)$$

$$\Delta v_{ce}^n = \frac{\kappa}{1+e_0} \cdot \frac{\Delta p'^n}{p'^n} \quad (7)$$

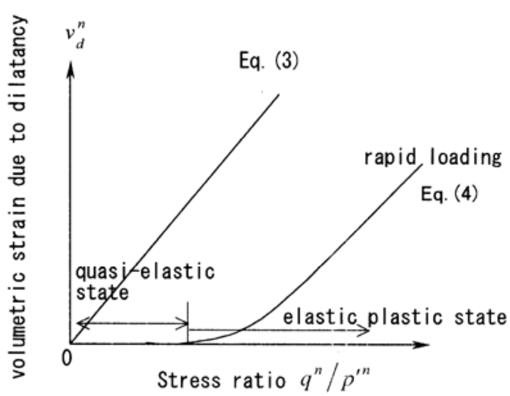

Figure 1. Dilatancy characteristics

$$\Delta v_{cp}^{n} = \frac{(\lambda - \kappa)}{1 - e_0} \cdot \frac{\Delta p'^{n}}{p'^{n}} \qquad (8)$$

Although incremental shear strain, $\Delta\varepsilon^{n}$, consists of elastic and plastic components, $\Delta\varepsilon^{n}$ is specified by Equation (10) for the K_0-consolidation process without defining these components.

3. TEST PROCEDURE

The soil used for the consolidation tests was the remolded Ota clay from Fukui Prefecture, Japan, which had the following index properties: specific gravity, 2.67; liquid limit, 53.2%; plastic limit, 25.4%; clay fraction, 60%; silt fraction, 36.7%; and fine sand fraction, 3.3%. The clay was mixed with water into slurry (moisture content = 72 %) and consolidated under the pre-consolidation pressure of 98 kPa in a consolidometer. After being stored for more than 2 weeks, a test specimen with 20 mm in height and 60 mm in diameter was carefully trimmed from the pre-consolidated cake which was fully saturated. Subsequently two types of consolidation test were performed separately, i.e. the standard consolidation and CSRC tests. The standard consolidation test was carried out according to the Japanese Industrial Standard A1217-2000.

The loading pressures were applied step-by-step as 9.8-19.6-39.2-78.4-156.8-313.6-627.2-1254.4 kPa, each loading pressure was maintained constant for 24 hours. CSRC test was carried out under the specified strain rates of 0.1, 0.05 and 0.01 %/min. CSRC test was performed by the equipment shown in Fig. 2. During CSRC process no control on the strain rate was done except for the deformation rate. The upper and lower surfaces of specimen were the permeable and impermeable boundaries respectively. Pore water pressure was monitored at the bottom of the specimen. After setting the test specimen into consolidometer and after introducing the back pressure of 98 kPa, the specimen was consolidated by vertical constant pressure of 9.8 kPa for 24 hours under anisotropic K_0-condition. This pre-consolidation process seems essential for bringing the test specimen into complete contact with the loading plate (Sompie et al , 2001 and 2006).

4. NUMERICAL ANALYSIS

4.1 Discretization Technique

In addition to the laboratory testing described above, a finite element technique as developed by Akai and Tamura (1978) was employed for two-dimensional consolidation analysis. Using this technique a consolidation test specimen subjected to analysis was subdivided into rectangular finite elements as shown in Fig. 3. The rectangular element was considered to be composed of four triangular elements. and The stresses, strains and pore water pressure were assumed to be constant throughout each rectangular element.

4.2 Nonlinear Stress-Strain Analysis

The aim here was to solve the following two equations as one simultaneous equation, without using the plastic flow rule. One was the equation for specifying a volumetric strain due to consolidation and dilatancy (Eq. 9), the other was the equation which specifies a shear strain (Eq.

10). Assuming that $\Delta p'^{n}$ and Δq^{n} were given at a time step, the volumetric strain was calculated as the sum of the components due to consolidation and dilatancy (Otha, 1971) as follows:

$$\begin{aligned}\Delta v^{n} &= \Delta v_{ce}^{n} && \text{over-consolidated} \\ &= \Delta v_{ce}^{n} + \Delta v_{cp}^{n} + \Delta v_{d}^{n} && \text{normally consolidated}\end{aligned} \qquad (9)$$

For the K_0-consolidation process, the shear strain was given as

$$\Delta \varepsilon^{n} = 2\Delta \varepsilon_{v}^{n}/3 = 2\Delta v^{n}/3 \qquad (10)$$

Using Δv^{n} and $\Delta \varepsilon^{n}$, hypothetical bulk modulus K^{n} and shear rigidity G^{n} were calculated as

$$\Delta p'^{n} = K^{n}\Delta v^{n},\ \Delta q^{n} = 3G^{n}\Delta \varepsilon^{n} \qquad (11)$$

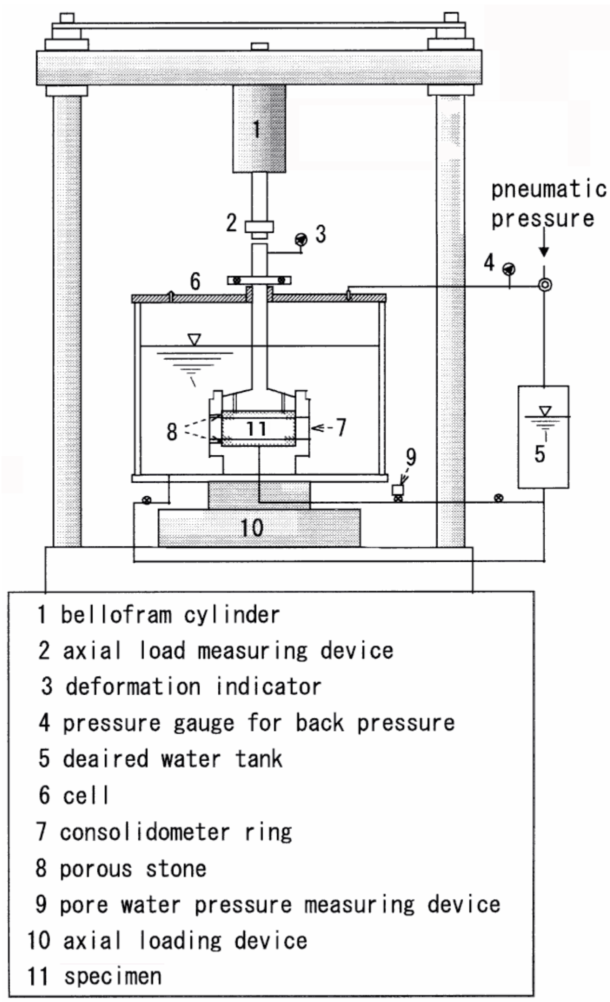

Figure 2. Equipment of CSRC test

Based on K^n and G^n, the hypothetical Young's modulus E^n and Poisson's ratio υ^n were

$$E^n = 9K^nG^n \big/ \left(3K^n + G^n\right),$$

$$\upsilon^n = \left(3K^n - 2G^n\right) \big/ \left(6K^n + 2G^n\right) \qquad (12)$$

The detailed derivation of the equations is given by Arai (1994). These hypothetical elastic constants made it possible to connect all the stress components to strain component respectively without using the plastic flow rule.

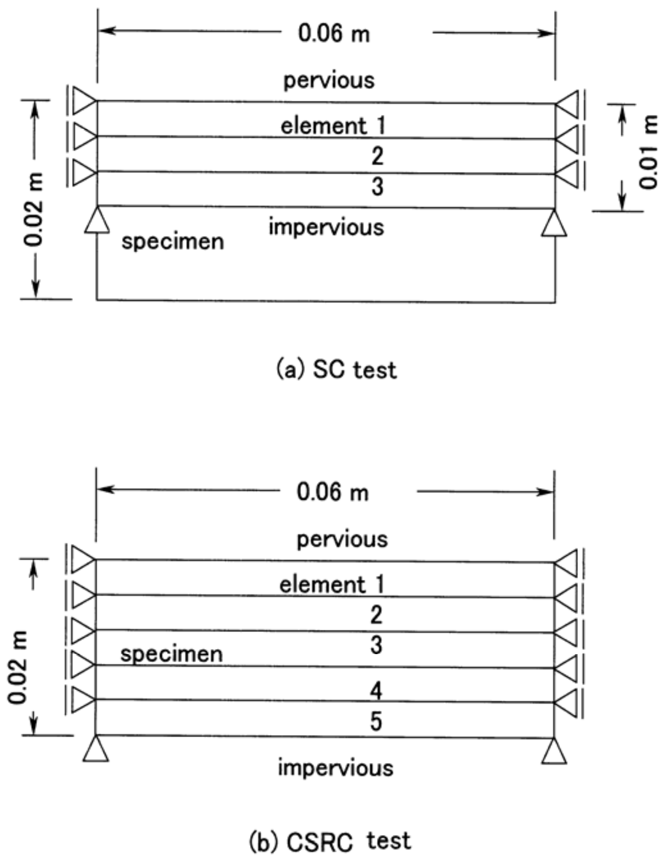

Figure 3. FE mesh of test specimen

4.3 Numerical Procedure

The following procedure was used:

1) Assuming the trial values of hypothetical Young's modulus E^n and Poisson's ratio υ^n.

2) Using the assumed E^n and υ^n and known permeability k^n, the elastic consolidation analysis

was performed at a discretized time step. In the consolidation analysis, the displacements were specified for CSRC test and the loads were given for the standard consolidation test at the prescribed boundaries.

3) Employing the incremental stresses obtained by the consolidation analysis, the incremental volumetric and shear strains were calculated respectively from Eqs. (9) and (10).

4) Based on these strains, the hypothetical elastic constants were found using Eqs. (11) and (12).

5) Replacing the trial values of E^n and υ^n with those found at step 4), the consolidation analysis was repeated until convergence of the elastic constant was obtained. This iterative procedure was carried out for each discretized time step.

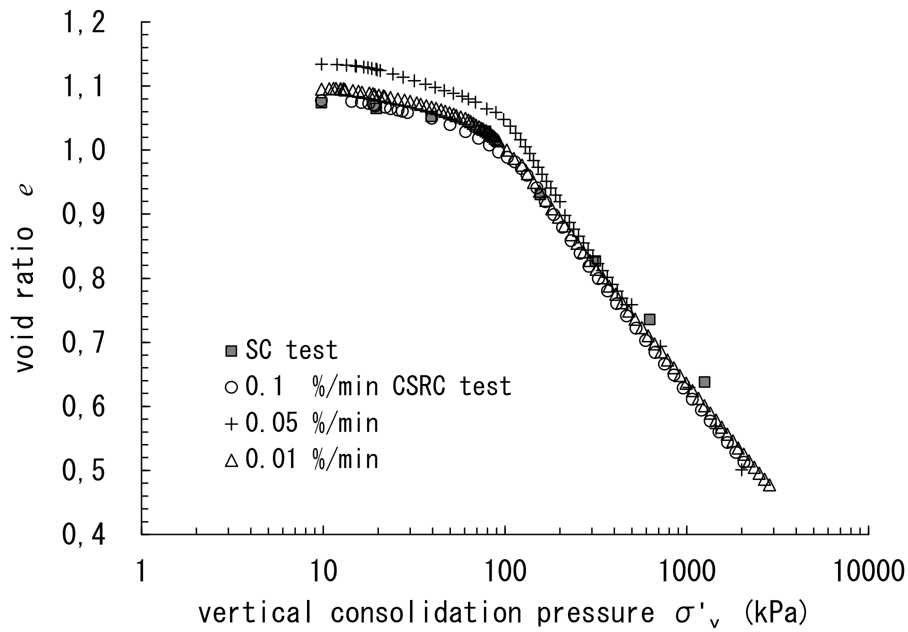

Figure 4. $e-\log\sigma_v'$ relationship observed

5. EXPERIMENTAL AND NUMERICAL RESULTS

5.1 Material Parameters

In the standard consolidation and CSRC tests, void ratio e, effective and vertical consolidation pressure σ_v', coefficient of volume compressibility m_v and coefficient of consolidation c_v were calculated according to JIS (Japanese Industrial Standard) A1217-2000 and JSF (Japanese Soil and Foundation) T412-1993. Fig. 4 shows the $e-\log\sigma_v'$ relationship obtained by these two types of consolidation test, in which the consolidation yield stress is affected in some degree by the strain rate.

Fig. 5 shows m_v and c_v obtained by both types of consolidation test which appear to provide similar tendency. Fig. 6 illustrates the relationship between e and permeability k (cm/s) which is calculated from c_v and m_v.

As shown in Fig. 6, both consolidation tests seem to give a similar $e-\log k$ relationship. Except for exceedingly loose state, the relationship is approximately represented as:

$$e-0.67=0.445\left\{\log_{10}k-\log_{10}\left(8\times10^{-9}\right)\right\} \qquad (13)$$

Although it is not easy to find the correct permeability of cohesive soil due to many factors affecting the permeability (e.g. Murakami, 1987 and Nagaraj et al, 1994), the above relationship provides reasonable numerical results is given later. The consolidation yield stress is regarded as $p_c=(98+2K_0 98)/3=63$ kPa, where K_0-value is taken as 0.464, which was obtain from K_0-consolidation tests using triaxial equipment at the normally consolidated region (Arai, 1994).

Based on these results, the material parameters required for numerical analysis are determined as λ= 0.16, κ =0.033, M=1.13, D=0.056, T= 14 days, v_d^*= 0.004, e_0= 1.04, and Eq.(13). The value of κ , M, and v_d^* are the same as those used by Arai (1994) which were determined by triaxial compression tests performed separately.

5.2 Initial State

The numerical analysis employed here treated the stress-strain response after placing the test specimen into consolidometer. It was difficult to estimate the residual effective stresses or negative pore water pressure within the specimen, since it was not easy to specify the stress history of the specimen until the specimen was placed into consolidometer. Preliminary Analysis showed that the residual stresses may not significantly affect the numerical results, when the residual stresses were represented only by the mean effective stress, and when the mean effective stress was between 20 and 60 % of the mean pre-consolidation pressure.

It was assumed that 40 % of the mean effective stress in the consolidometer remained isotropic within the specimen before starting the consolidation test together with constant value of negative pore water pressure. It was also difficult to estimate the history of dilatancy before placing the test specimen into the consolidometer, because it was not easy to evaluate the dilatancy amount of the slurry sample in consolidometer. Furthermore, the consolidated sample expanded both vertically and laterally when it was taken out of the consolidometer.

As first approximation on the analogy of the residual effective stresses described above, the dilatancy estimated by Eq. (3) was assumed to take place almost entirely in the consolidometer, and 40 % of dilatancy amount remained within the test specimen in the consolidometer. This rough approximation provided fairly good numerical results, and that the numerical results were not so sensitive to the dilatancy amount before placing the specimen into the consolidometer (Kita et al, 1998).

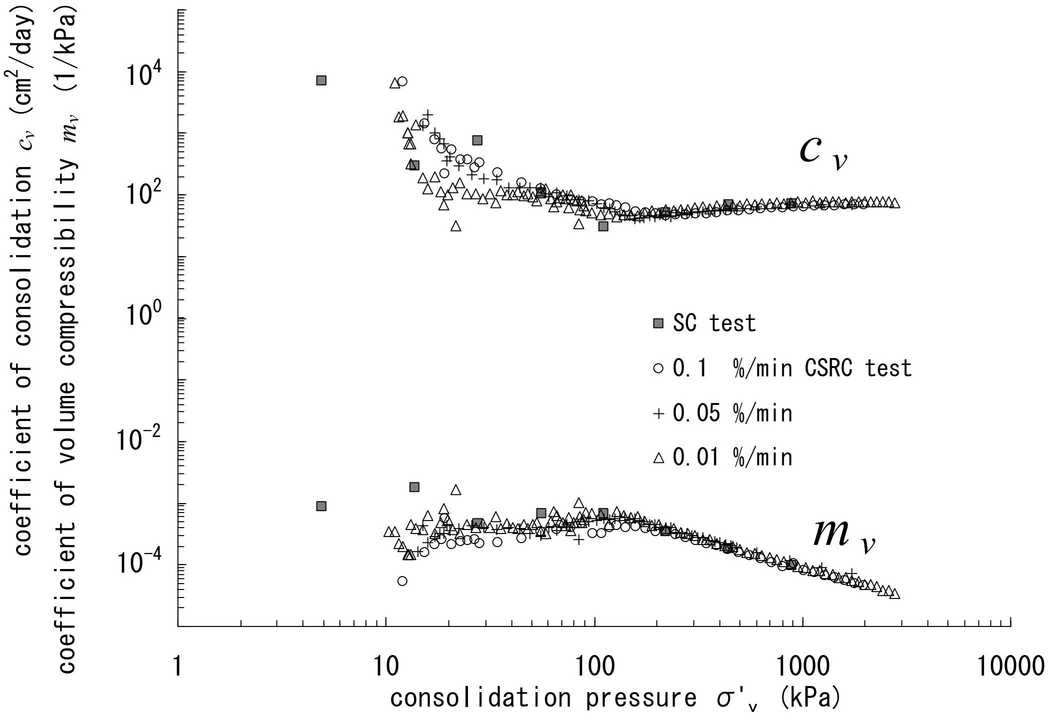

Figure 5. m_v and c_v observed

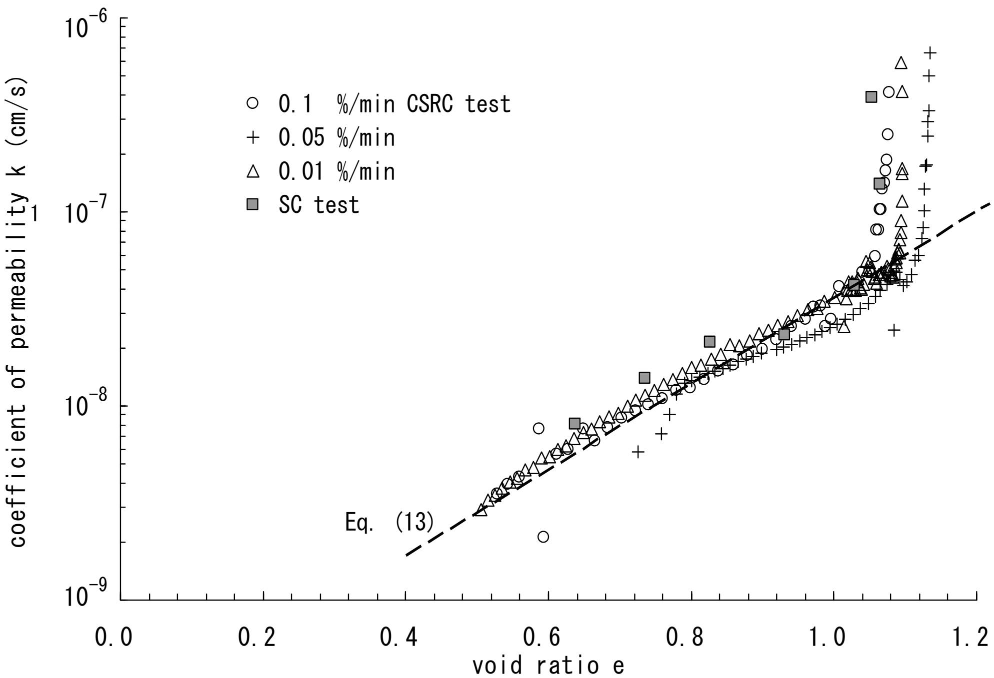

Figure 6. Observed $e - \log k$ relationship

5.3 Standard Consolidation Test

Fig. 7 compares the experimental and numerical results of time-settlement relationship in the standard consolidation test. The numerical result appears to agree fairly well with the experimental one, except for the loading pressure of 78.4 kPa assuming that no plastic component of volumetric strain takes place at the over-consolidated state. The stress ratio, volumetric strain and hypothetical elastic constant (E^n) and Poisson's ratio (υ^n) during consolidation are illustrated in Figures. 8 through 10 for comparison with the result of the CSRC test.

In Figures. 8 through 10 and Figs. 12 through 17, B_i denotes the point at which the stress state moves to the normally consolidated region, and C_i is designated as the point at which dilatancy begins to occur both in finite element i. As seen in Fig. 9, at the first stage of each loading step, the state of the specimen enters the quasi-elastic state as illustrated in Fig. 1 where no dilatancy takes place. A little while after each loading step, the volumetric strain due to dilatancy begins to occur.

Although the stress ratio becomes almost constant at the latter stage of each loading step as shown in Fig. 8, the ratio continues to increase very slightly with the passage of time. Referring to Figs. 7 through 9, the secondary compression observed at the latter stage of standard consolidation test is represented by the dilatancy occurrence according to nearly constant stress ratio, which takes place proportionally with the logarithm of elapsed time. Figs. 9 and 10 indicate the following tendency of hypothetical Young's modulus E^n.

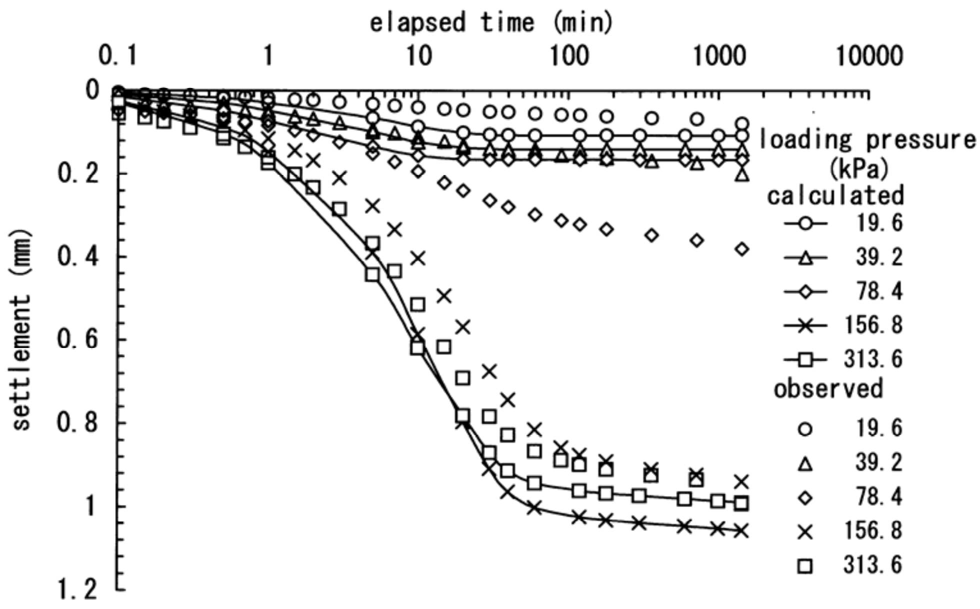

Figure 7. Settlement curve (SC test)

After the stress state moves to normal consolidated region, E^n decreases suddenly due to the occurrence of v_{cp}^n. Subsequently E^n increases gradually with the progress of consolidation. The occurrence of dilatancy reduces E^n substantially because the volumetric strain due to the dilatancy increases whereas the effective vertical stress increases slightly at the latter stage of each stage of each loading step.

Whether or not dilatancy occurs, E^n approaches 0 at the final stage of each loading step because the effective stresses reach the constant values in spite of the slight increase in volumetric strain. Hypothetical Poisson's ratio, υ^n, is hold constant throughout the consolidation process as shown in Fig. 10.

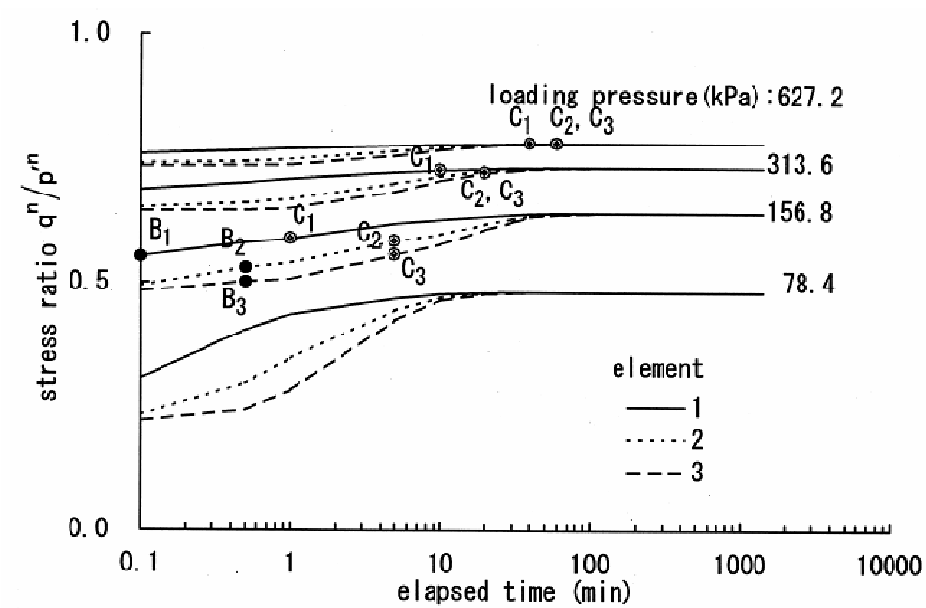

Figure 8. Stress ratio (SC test)

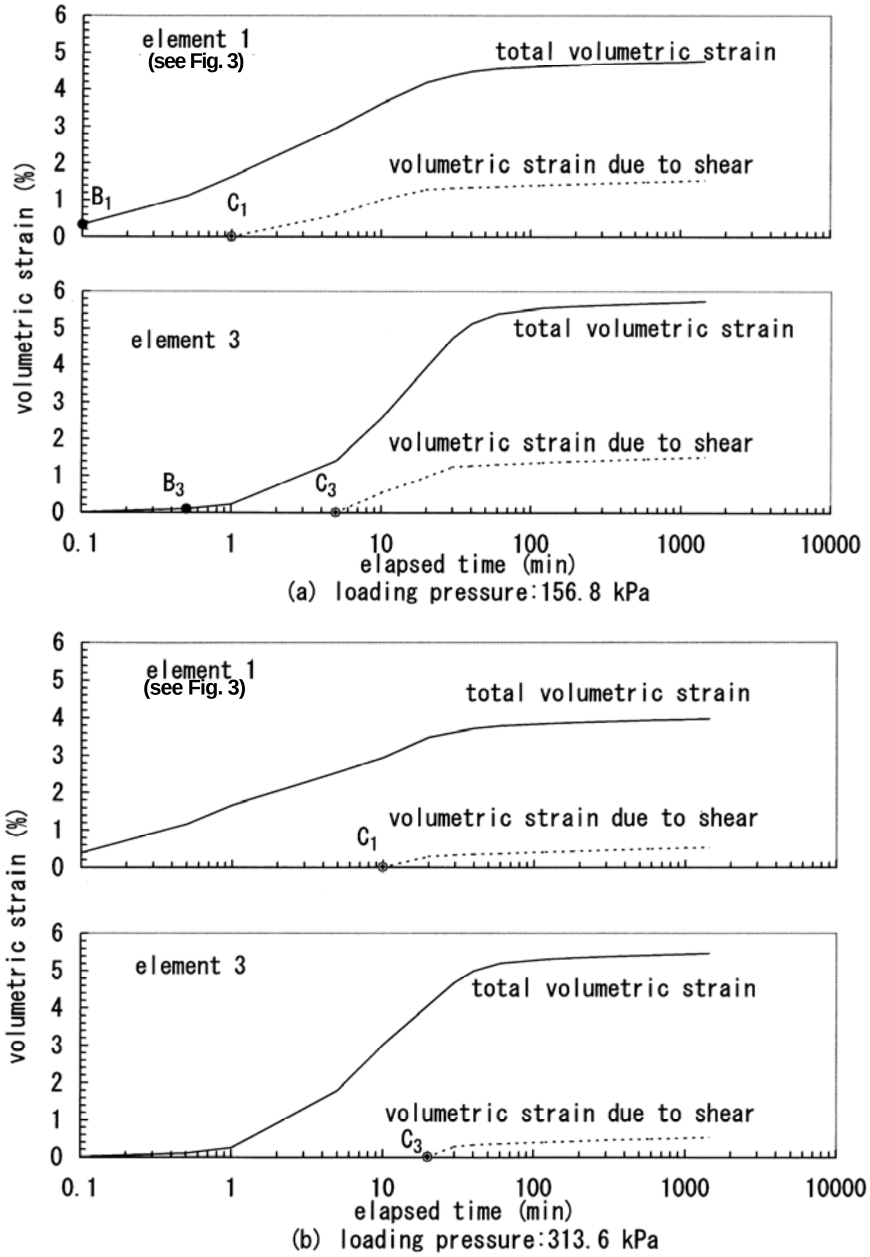

Figure 9. Components of volumetric strain (SC test)

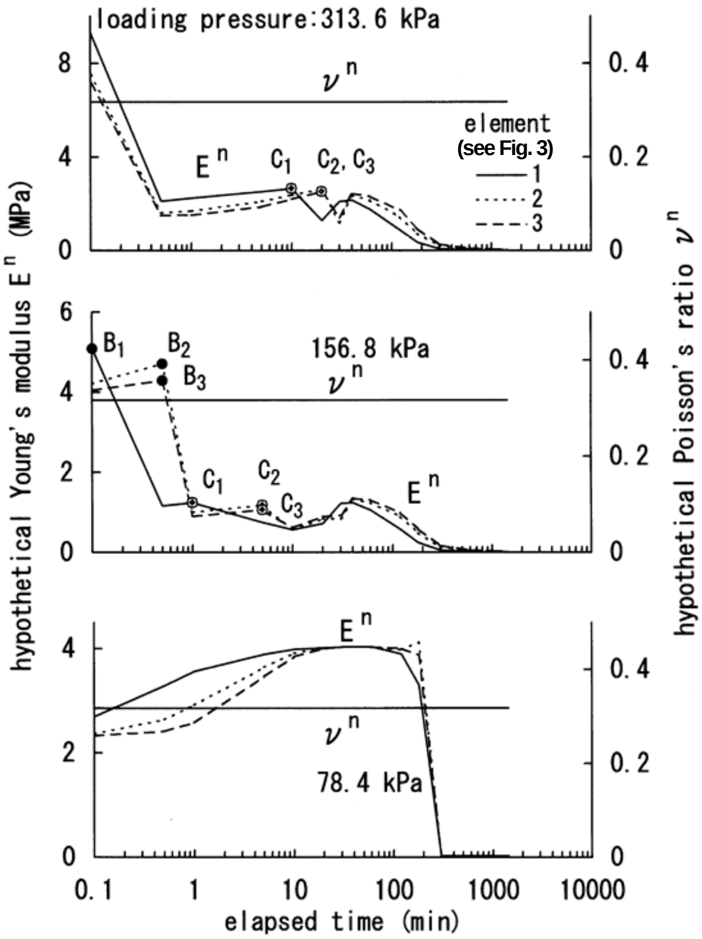

Figure 10. Hypothetical elastic constants (SC test)

5.4 Constant Strain Rate Consolidation (CSRC) test

After setting a test specimen into the consolidometer, the specimen was consolidated by the total vertical pressure of 9.8 kPa for 24 hours under K_0-condition. Following this pre-consolidation process, CSRC test was carried out under a certain strain rate of 0.1, 0.05 and 0.01 %. Thus, numerical analysis was performed by two separate stages, i.e., the pre-consolidation process for which the pre-consolidation pressure of 9.8 kPa was specified, and CSRC process for which a displacement was prescribed at the upper surface of specimen at each discretized time step. The initial state for pre-consolidation process was the same as the initial state for the standard consolidation test described previously. The final state for pre-consolidation process corresponded to the initial state for CSRC process. Note that at the final state of the pre-consolidation process, vertical stress σ_v' (= 9.8 kPa) was less than lateral stress σ_h' (= 18.03 kPa) due to the isotropic initial stresses of 24 kPa for the pre-consolidation process. Fig. 11 compares the calculated and monitored quantities for CSRC process, for different strain rate. As seen in Fig. 11, the prescribed and monitored displacements at the upper surface of the specimen are slightly different from each other due to the limitation of displacement control system. In the numerical analysis, the monitored displacement is given at each discretized time step. Thus the fluctuation from prescribed displacement causes the fluctuation of physical quantities calculated by the proposed procedure (for instance, see Figs. 11, 12, 14, 15 and 16 given later). As shown in Fig. 11 both the calculated loading pressure, displacement and pore water pressure, appear to be consistent with the monitored results. Figs. 12 through 17 illustrate some of the detailed numerical results upon which the calculated results shown in Fig. 11 are based. Though it is not possible to compare directly these detailed numerical results with monitored ones, these numerical results enable one to interpret the soft clay behavior during CSRC process, which is described as follows. In Figs. 14 through 17, vertical stress σ_v' is less than lateral stress σ_h' until point A_i, where suffix i denotes finite element number.

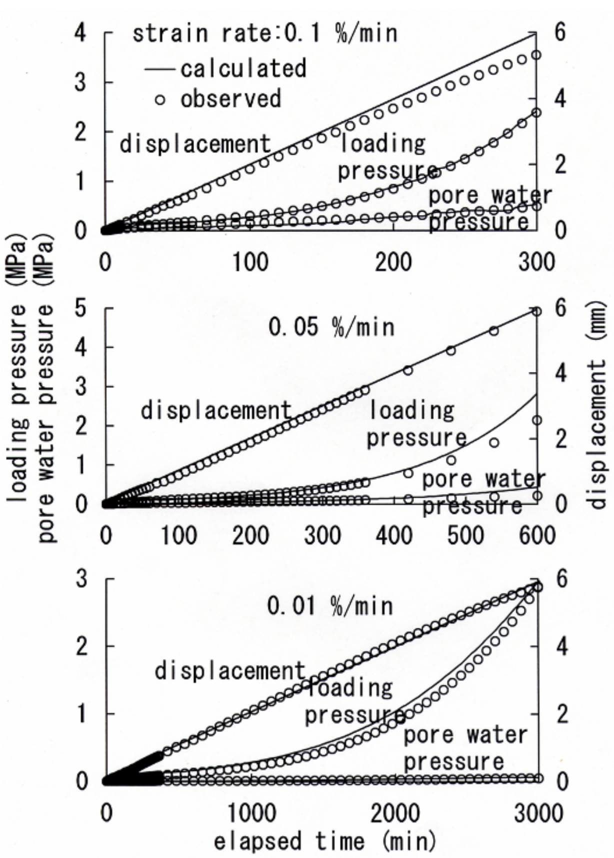

Figure 11. Comparison between calculated and monitored results (CSRC)Test

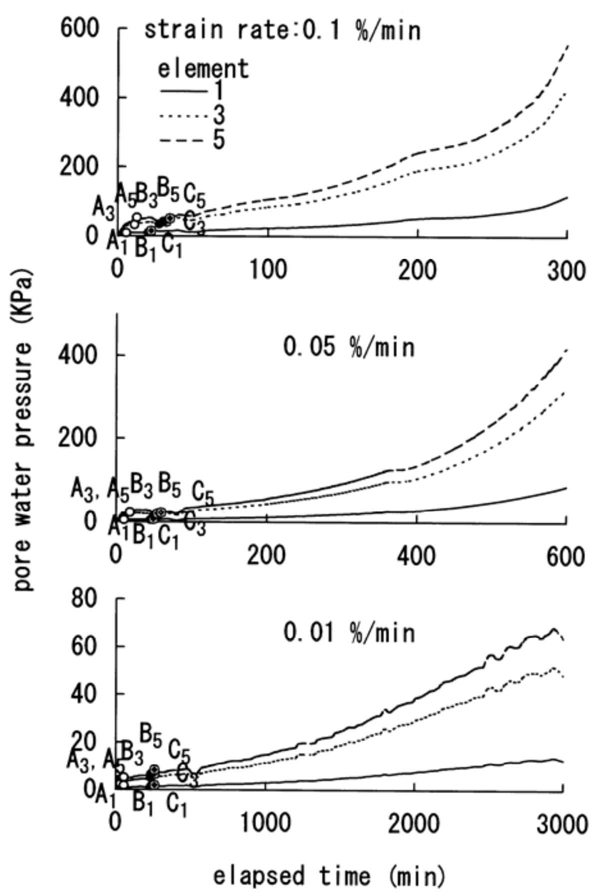

Figure 12. Pore water pressure

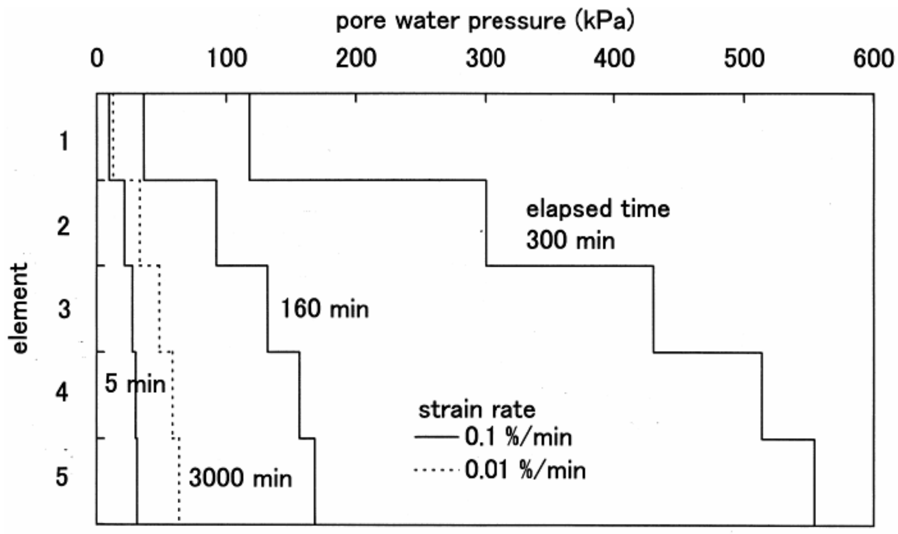

Figure 13. Distribution of pore water pressure in CSRC test

From the initial state to point A $_i$, q^n increases as shown in Fig. 17 because σ'_v approaches gradually σ'_h, resulting in the increase of q^n/p'^n as shown in Fig. 14. At this state, the Poisson's ratio is kept constant and E^n increases slightly with the progress of consolidation. The ratio of $\Delta q^n/\Delta p'^n$ is whole constant throughout the CSRC process as illustrated in Fig. 17. This makes q^n, σ'_v and E^n increase as shown in Fig. 16 because of the small total volumetric strain which consists of only v^n_{ce}.

Note that the constant value of $\Delta q^n/\Delta p'^n$ provides constant Poisson's ratio of 0.317 after passing point A $_i$ as shown in Fig. 16. Although $\Delta q^n/\Delta p'^n$ is constant for CSRC process, stress ratio q^n/p'^n varies as illustrated in Fig. 17, and approaches to the following value as shown in Eq. 14.

$$\left(q^n/p'^n\right)^{\infty} = \left(\sigma'_v - \sigma'_v K_0\right)/\left(\sigma'_v + 2\sigma'_v K_0\right)/3 = 0.834 \qquad (14)$$

In Figs. 12 through 17, at point B $_i$, the stress of element i moves to the normally consolidation region. Immediately after passing point B $_i$, the state enters the quasi-elastic state at which v^n_{ce} and v^n_{cp} take place. This transition causes the reduction of E^n as in Fig. 16 because of the considerable increase in volumetric strain, which restrain the increase q^n or stress ratio q^n/p'^n as shown in Fig. 14.

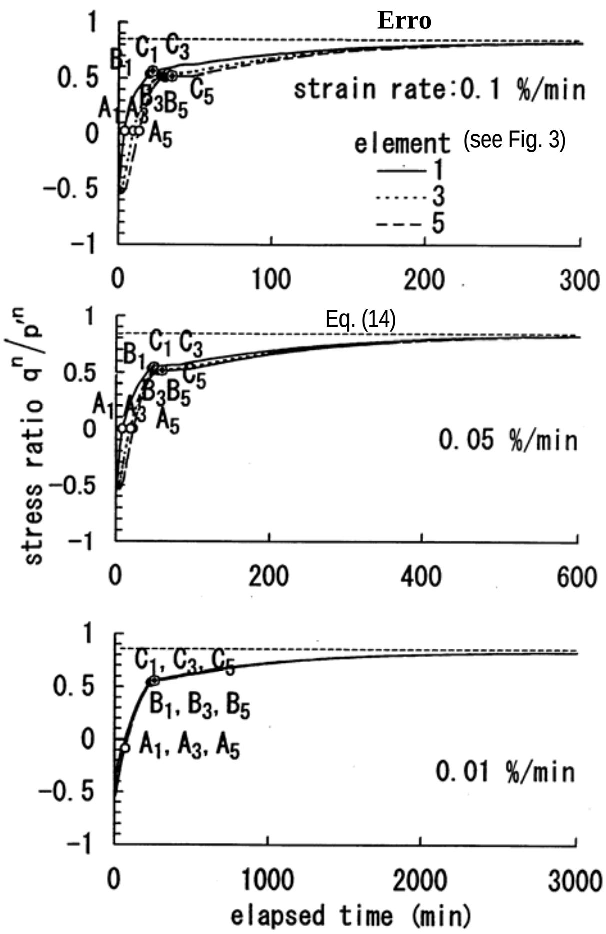

Figure 14. Stress ratio

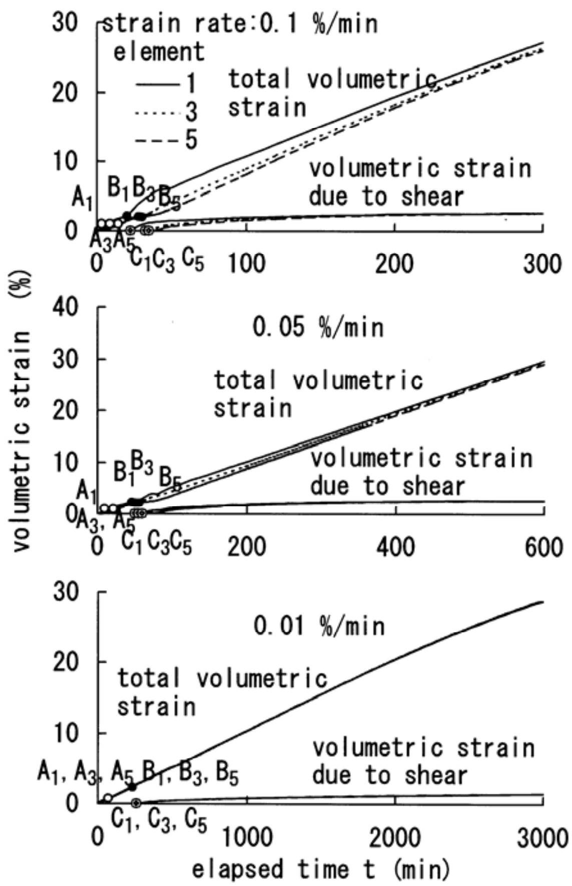

Figure 15. Components of volumetric strain

The duration of quasi-elastic state is short in this case because the stress ratio tends to increase rapidly for CSRC process. Thus, the quasi-elastic state may not give a substantial effect to the global behavior of CSRC specimen. Immediately after the state of specimen has been removed from the quasi-elastic state (point C_i in Figs. 12 through 17), volumetric strain due to dilatancy v_d^n reduces E^n as shown in Fig. 16. Subsequently E^n tends to increase gradually because the occurrence of dilatancy becomes smaller with the passage of time as shown Fig. 15. Note that the total amount of dilatancy is assumed to be limited by Eq. (3) as illustrated in Fig. 15. Since most of the dilatancies has taken place at the earlier stage of consolidation, small dilatancy occurs at the latter stage of CSRC process. This means that the larger effective stresses are required to produce the constant volumetric strain at the latter stage where the volumetric strain consists of almost only v_{ce}^n and v_{cp}^n. This tendency makes the specimen stiffer with time (see Fig. 16) and makes loading pressure and pore water pressure increase substantially as illustrated in Fig. 11.

Being similar with the standard consolidation test, when the increasing rate of stress ratio is less than 10^{-3}/min, Eq. (5b) is employed instead of Eq. (5a). This treatment is applied only to the initial and last stages where dilatancy takes place for strain rate equal to 0.01 %/min, since the loading pressure for stress ratio continues to steadily increase in most stages of CSRC process. In Figs. 12 through 17, the difference of physical quantities in each finite element is remarkable for strain rate equal to 0.1 %/min due to less uniform distribution of pore water pressure within a specimen, while the difference seems almost negligible for 0.01 %/min (see Fig. 13). When the strain rate is too fast, and when the difference of physical quantities within a specimen is larger as seen in Figs. 14, 15, and 16, the overall material parameters obtained from CSRC test which are supposed constant within the test specimen, may tend to fluctuate largely. For instance, Fig. 18 shows the m_v and c_v in each finite element calculated by using hypothetical elastic constants E^n and υ^n. The general agreement between Figs. 18 and Fig. 5 indicates the appropriateness of the proposed procedure. The difference of E^n in each finite element as shown in Fig. 16 appears

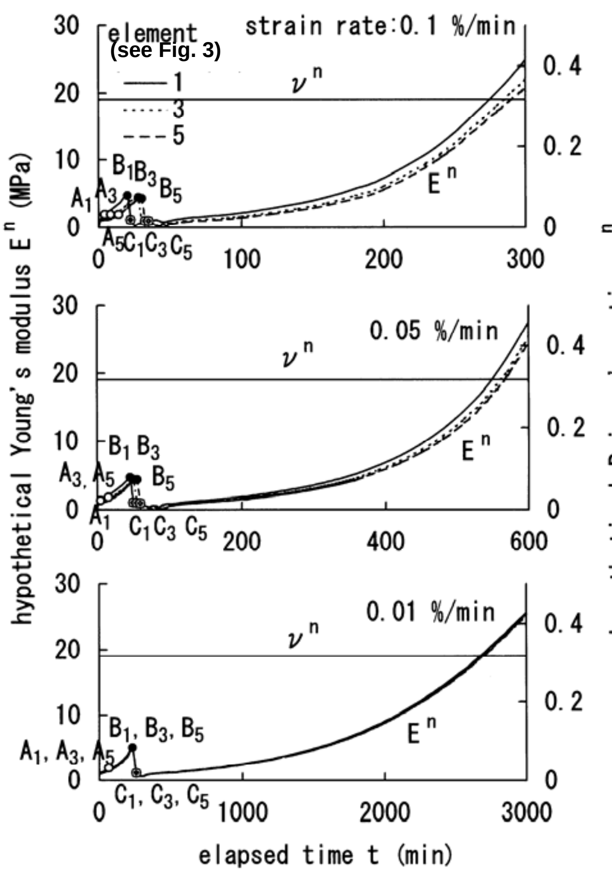

Figure 16. Hypothetical elastic constants

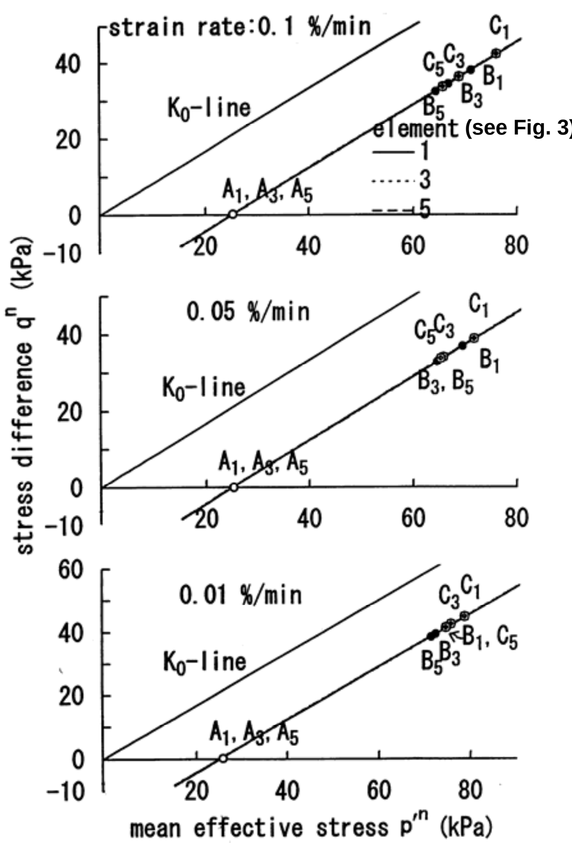

Figure 17. Stress path

to provide the unstable variation of overall m_v and c_v as shown in Fig. 5 which is assumed to be constant within a specimen, especially for the over-consolidated ratio. The secondary compression coefficient is defined for nearly constant stress ratio such as the later stage of each loading step in standard consolidation test as illustrated in Fig. 8. It may be difficult to find directly the secondary compression coefficient by using CSRC process, and because most of the dilatancies has taken place when the stress ratio becomes approximately constant at the last stage of CSRC test as shown in Figs. 14 and 15.

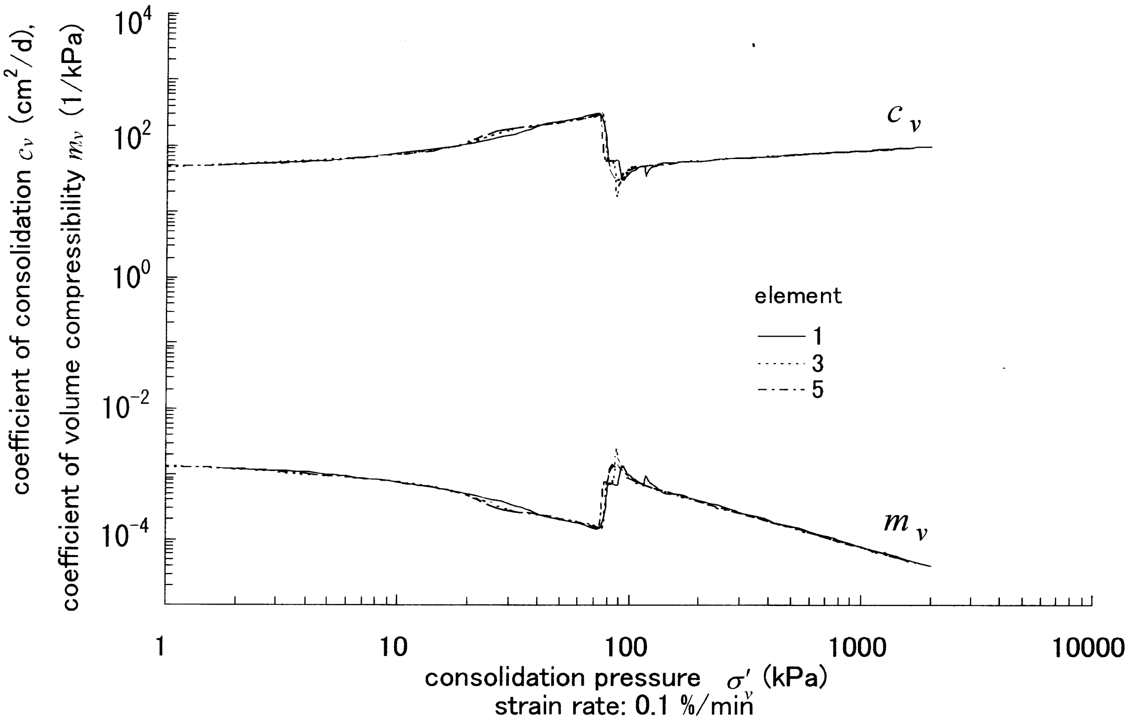

Figure 18. Calculated m_v and c_v

6. CONCLUSIONS

Time dependent behavior in the standard consolidation and CSRC tests using remolded young clay soil was represented by a simple assumption concerning the time dependence of dilatancy. At the first stage of each loading step in the standard test, the state of the specimen was at the quasi-elastic state where no dilatancy takes place. A little time after step loading, dilatancy began to occur. Because the stress ratio became approximately constant at the latter stage of each loading step, dilatancy occurred proportionally with the logarithm of elapsed time, which was observed as the secondary compression.

The dilatancy behavior in CSRC test indicated that when the stress state entered the normal consolidation region, the state moved to the quasi-elastic state. Since the duration of quasi-elastic state was short in CSRC test, the state did not give a dominant effect to the global behavior of test specimen. Some period of time after the stress state had entered the normally consolidated region, dilatancy tended to occur rapidly with the increase in stress ratio. Since most of the dilatancies had taken place at the earlier stage of consolidation, little dilatancy occurred at the latter stage of the CSRC process. This tendency made the specimen stiffer with the passage of time, and made the vertical pressure and pore pressure increase substantially at the last stage of the CSRC process. Considerations to such behavior might be effective to correctly interpret the result of the CSRC test.

The secondary compression coefficient was defined for nearly constant stress ratio such as the latter stage of each loading step in standard consolidation test. It might be difficult to find directly the secondary compression coefficient by means of CSRC test because the stress ratio continued to considerably change throughout the CSRC process; and because most of the dilatancies had taken place when the stress ratio became approximately constant at the last stage of the CSRC test.

The assumption of time dependency of dilatancy enables one to simulate time effects in standard consolidation and CSRC tests. However, by using only this assumption, it might not be possible to simulate the time dependent behavior such as the change of consolidation yield stress according to the loading duration in the standard consolidation test or the strain rate in the CSRC test. Although such behavior may be deeply related to time dependency of dilatancy, it might require another assumption concerning the time dependency of volumetric strain due to isotropic consolidation, which is an important subject to be investigated in the future study.

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NOTATION

Superfix n denotes the discretized time step number, and Δ designates the increment of succeeding physical quantity.

C_c Compression index
C_s Swelling index
c_v Coefficient of consolidation
e_0 Initial void ratio
e Void ratio
E^n Hypothetical Young's modulus
G^n Hypothetical shear rigidity
k^n Coefficient of permeability
K_0 Coefficient of earth pressure at rest
K^n Hypothetical bulk modulus
M Slope of critical state line
m_v Coefficient of volume compressibility
p'^n Mean effective stress
q^n Stress difference
Δt^n Length of discretized time step
t_1^n Elapsed time after stopping the increase in the stress ratio
T Time length required to make dilatancy take place completely
q^n / p'^n Stress ratio
ε^n Shear strain
ε_v^n Vertical strain
v_c^n Volumetric strain due to consolidation
v_{ce}^n Elastic component of volumetric strain due to consolidation
v_{cp}^n Plastic component of volumetric strain due to consolidation
v_d^n Volumetric strain due to dilatancy
v_d^* Parameter which presents the beginning of volumetric strain due to dilatancy
$\kappa = 0.434 C_s$
$\lambda = 0.434 C_c$
υ^n Poisson's ratio
$\sigma_h'^n$ Horizontal effective stress
$\sigma_v'^n$ Vertical effective stress