COMPRRESSIVE BEHAVIOR DURING THE TRANSITION OF STRAIN RATES

AYATO TSUTSUMI and HIROYUKI TANAKA

ABSTRACT

The application of a strain-rate-dependent model, for example, an isotache model, is very useful and highly effective for predicting the settlement due to consolidation, including secondary consolidation. In the isotache model, compression curves are not only determined by pressure, but also by strain rate. The validity of this model has been experimentally confirmed by many researchers using different types of oedometer tests, such as constant rate of strain (CRS) tests, incremental loading (IL) tests, etc. However, considerable scatter has been observed in the test results, which show the effects of the strain rate, and questions arise as to whether such scatter is caused by the heterogeneity of the soil samples or by the incompleteness of the model. To avoid the heterogeneity of the tested samples, special CRS tests, in which the strain rate is not kept constant but is varied during the tests, were carried out on intact and reconstituted Osaka clay samples. The effects of the strain rate on the compressive behavior of these clays were carefully evaluated in terms of visco-plastic strain, assuming that the total strain consists of visco-plastic strain and elastic strain. It was confirmed that the stress and the visco-plastic strain relation of clay samples strongly depends on the visco-plastic strain rate. However, the effects of the strain rate, under a given constant visco-plastic strain rate, do not become constant when the visco-plastic strain rate becomes very small. The reason is assumed to be due to the development of structures under a constant small visco-plastic strain rate. The development of structures may restrict the applicability of the isotache model to the compressive behavior of clay.

Key words: clay, elastic strain, isotache, one-dimensional consolidation, strain-rate effect (IGC: D5)

INTRODUCTION

Settlement due to consolidation is one of the most important issues among geotechnical problems. In practice, the prediction of settlement is conducted based on Terzaghi's consolidation theory; changes in volume are only caused by changes in effective pressure. However, from consolidation tests, it is well known that even after the dissipation of excess pore water pressure, a large amount of settlement, called secondary consolidation, is observed. It is considered that changes in volume under a constant effective stress are caused by the viscous behavior of the clay skeleton. According to many studies, it has been confirmed that such a viscous creep deformation not only takes place during secondary consolidation, but also during primary consolidation, i.e., when the effective stress levels are changing (see Leroueil et al., 1985, 1988; Imai and Tang, 1992; Imai et al., 2003; Tanaka, 2005b; Leroueil, 2006). To describe this viscous behavior, a strain-rate-dependent model, called the isotache model (Šuklje, 1957), is used. In this model, the relationship between the effective stress and the strain or the void ratio is determined by the strain rate. In other words, as shown in Fig. 1, the stress and strain relation consists of a family of Equi-Strain Rate Lines (ESRLs), which are determined by the order of the strain rate. Kobayashi et al. (2005) reported that this isotache model was able to yield a fair prediction of the settlement for the Pleistocene clay layers at Kansai International Airport, Japan.

Many researchers have succeeded in obtaining a unified explanation for settlement from different types of oedometer tests, such as constant rate of strain (CRS), incremental loading (IL), controlled gradient and relaxation tests, taking into account the effect of the strain rate (for the CRS tests and the controlled gradient tests, see Leroueil et al., 1985; for the IL tests, see Tanaka, 2005a; for the relaxation tests, see Tanaka et al., 2006). When their test results are carefully examined, however, considerable scatter can be observed in their relations. Questions arise as to whether the scatter is caused by the heterogeneity in the tested samples or because the isotache model is not able to perfectly describe the settlement behavior. Heterogeneity is an unavoidable problem in geotechnical engineering, especially when an intact sample is tested in the laboratory. Tanaka et al. (2003) performed Cone Penetration Tests (CPTs) at the Kansai International Airport construction site, to a maximum depth of 250 m, and indicated that the point resistance of the CPTs va-
ried considerably within the Pleistocene clay layers, even for small variations in depth.

To overcome the problem of heterogeneity in the tested specimens, special CRS tests were carried out in this study by changing the strain rate during the tests. This testing method is quite useful for removing the effect of the sample’s heterogeneity, since only one specimen is required to obtain the stress and strain relation under various strain rates. In addition, there is another advantage to measuring the strain-rate dependency at very small strain rates. For example, the IL tests require 0.5 years to attain a strain rate of $10^{-9} \text{s}^{-1}$, (see Tanaka, 2005a) and CRS tests under a strain rate of $10^{-9} \text{s}^{-1}$ take 20 months to generate a strain of 5%. Although some researchers have employed this testing method (Leroueil et al., 1985; Deng and Tatsuoka, 2005), their studies mainly focus on the behavior under a constant strain rate, not during changes in the strain rate, i.e., the transit phases of the strain rate. According to the isotache model shown in Fig. 1, if the strain rate changes, the stress and strain relation will immediately shift to the ESRL corresponding to the new strain rate. However, as will be discussed in more detail, a certain strain is required to shift to this new ESRL. To observe this behavior precisely and to find rules for the transition, a special loading device has been developed, in which the displacement of the CRS is provided by a step drive motor controlled by a computer.

As strain-rate dependency is caused by the viscous behavior of clayey soils, it is believed that the isotache model can only be applied to a visco-plastic strain component. In other words, if we assume that the total strain consists of elastic and visco-plastic strain, the strain corresponding to the strain-rate dependency should be reduced by the elastic strain. In CRS or IL tests, the elastic strain is small enough to assume that the isotache model can be applied to the total strain or the visco-plastic strain, especially under a normally consolidated (NC) state. However, when it is necessary to interpret the behavior during the strain rate transit, the magnitude of elastic strain becomes important, because the total strain itself is quite small during the change in strain rate, as will be shown later. In this study, the elastic strain was precisely measured by unloading tests, and using this data, the strain-rate dependency, including the applicability of the isotache model, is carefully examined and discussed.

SAMPLES AND TESTING METHOD

Tested Samples

Two Osaka clay samples, OsakaMa12 and OsakaMa13Re, were obtained from the Kansai International Airport construction site in Osaka Bay, Japan and used in this study. Their main geotechnical properties are shown in Table 1, where $\rho$, $w_s$, $w_l$, $w_p$, $I_p$ and $e_0$ are the density of the soil particles, the natural water content, the liquid limit, the plastic limit, the plasticity index and the initial void ratio, respectively. OsakaMa12 and OsakaMa13Re were recovered from Pleistocene Ma12 and Holocene Ma13 clay layers, respectively. OsakaMa12 is an intact clay sample, whereas OsakaMa13Re is a reconstituted clay sample, which was consolidated in an acryl cylinder under a consolidation pressure of 100 kPa after thoroughly remolding it with a soil mixer at a water content of about two times $w_l$.

Testing Apparatus

CRS tests were carried out following the Japanese Industrial Standard (JIS A 1227); the specimen was 60 mm in diameter and 20 mm in initial height. A consolidation cell allowed hydraulic pressure to be applied as back pressure in order to obtain high saturation. The bottom part of the specimen was undrained and connected to a hydraulic pressure transducer to measure the pore water pressure $u$. The upper part of the specimen was drained. The load generated by applying a constant strain was measured by a load cell. A back pressure ($u_b$) of 100 kPa was applied during the test. The effective vertical pressure ($p'$) was calculated assuming that the excess pore water pressure in the specimen was distributed in a parabolic manner by Eq. (1), following the Japanese Industrial Standard:

$$p' = \sigma - \frac{2}{3} \Delta u$$

where $\sigma$ is the total pressure calculated from the measured load and corrected for the uplift force caused by back pressure, and $\Delta u$ is the excess pore water pressure obtained by subtracting $u$ from $u_b$.

![Schematic view of isotache model](image)

**Fig. 1.** Schematic view of isotache model

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Condition</th>
<th>Depth (m)</th>
<th>$\rho$ (g/cm³)</th>
<th>$w_s$ (%)</th>
<th>$w_l$ (%)</th>
<th>$w_p$ (%)</th>
<th>$I_p$</th>
<th>$e_0$</th>
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<td>OsakaMa12</td>
<td>intact</td>
<td>67.4</td>
<td>2.675</td>
<td>61.2</td>
<td>92</td>
<td>38</td>
<td>54</td>
<td>1.624</td>
</tr>
<tr>
<td>OsakaMa13Re</td>
<td>reconstituted</td>
<td>2.693</td>
<td>70.7</td>
<td>91</td>
<td>38</td>
<td>53</td>
<td>1.896</td>
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</tr>
</tbody>
</table>

Table 1. Geotechnical properties of clay samples
The strain (ε) described in this study is not the natural strain, but the nominal strain, because the strain rate is easily controlled. To generate a stable and extremely slow strain rate, a special loading apparatus was employed, consisting of a Step Motor System whose resolution is as accurate as 2,621,440 pulses per revolution, the movements of which can be controlled by a personal computer (see Tsutsumi et al., 2010). Strain rates (ε) faster than 5 × 10^{-6} s^{-1} were provided by the continuous rotation of the motor, while ε slower than 5 × 10^{-9} s^{-1} could not be obtained by continuous rotation, but by discontinuous rotation, i.e., the displacement was created by several steps, as shown in Fig. 2. Furthermore, the displacement was not measured by a conventional dial gauge, but by directly counting the revolutions of the step motor. It was found from the loading tests without a specimen that the deformation was mainly caused by the stiffness of the load cell and its amount was more than 80% of the total deformation. Therefore, the displacement derived from the step motor during the test was corrected only by the deformation of the load cell. Figure 3 compares the relationship between ε and the time (t) measured by the CRS tests in this study and that measured by the conventional CRS test apparatus, where the displacement was generated by a conventional motor and the rotation speed was reduced by several gear boxes. In this figure, ε and ε̇ are calculated assuming that the specimen height is 20 mm. It can be seen in the figure that even at an extremely slow ε of 3 × 10^{-10} s^{-1}, the movement created by the new loading apparatus is quite smooth and is considered to run at quasi-continuous loading. This apparatus gives us useful and precise measurements even during the transition to different ε.

**Evaluation of Strain-rate Dependency**

In the isotache model, a family of ESRLs is drawn in parallel in the ε and log p' space, and these ESRLs horizontally shift by the order of ε̇, as shown in Fig. 1 (these ESRLs are not necessarily linear to log p'). Hereafter, ESRLs will be used to describe the ideal relations in the isotache model; i.e., when ε is changed during the CRS tests, the ε-log p' relation should follow an ESRL at a new ε̇ after changing ε. The strain-rate dependency in this paper is presented by R, which is the stress ratio of the reference ESRL (ESRL₀) to a new ESRL after changing ε at the same ε, and the order of ε̇ for ESRL₀ is 3 × 10^{-6} s^{-1}. As shown in Fig. 1, log R corresponds to the horizontal distance of the new ESRL from ESRL₀. During the secondary compression in the IL tests, the ε-log p' relation in Fig. 1 can be expressed by a vertical line as the excess pore water pressure is completely dissipated and the consolidation pressure (p') is constant. From the IL tests, the coefficient of secondary consolidation (Cₘ) is usually defined as a change in the void ratio (Δε) in logarithmic elapsed time (Δ log t). Then, R and Cₘ can be correlated by the following equation:

\[
\log R = \frac{Cₘ}{C_c} \log \dot{\varepsilon} \tag{2}
\]

where C_c is the compression index defined as the slope of the ε-log p' relationship in the NC state. If the ratio between C_c and Cₘ is constant for a given clay, as reported by Mesri and Castro (1987), then log R decreases or increases linearly with log ε.

**Testing Procedure**

The testing procedure used in this study is shown in Fig. 4. A specimen was consolidated under ε₀ of 3 × 10^{-6} s^{-1} to attain ε of 8%, resulting in an NC state. At ε of 8%, ε̇ was instantly changed from ε₀ to 3 × 10^{-7} s^{-1} (ε₀/10) and compression was continued to reach an additional ε of 3%. Once more, ε̇ was reduced to 3 × 10^{-8} s^{-1} (ε₀/100) from ε₀/10 until a total ε of 13% was achieved. Furthermore, ε̇ was instantly increased to ε₀ from ε₀/100 until a certain ε was attained. Finally, to obtain the elastic
strain, unloading tests were carried out under a constant $\dot{\varepsilon}_0$.

$\text{ESRL}_0$, which is the $\varepsilon$-$\log p'$ relation that a specimen may follow if $\dot{\varepsilon}$ is not changed, is a very important line for evaluating the strain-rate dependency, i.e., $R$. Assuming that $\text{ESRL}_0$ at the NC state can be expressed by a linear relation in $\varepsilon$ and $\log p'$ space, $\text{ESRL}_0$ can be drawn by extrapolating the first part of the $\varepsilon$-$\log p'$ relation under $\dot{\varepsilon}_0$ to the $\varepsilon$-$\log p'$ relation when the strain rate is changed from $\dot{\varepsilon}_0/100$ to the original $\dot{\varepsilon}_0$. As can be seen in Fig. 4, however, this extrapolated line does not sufficiently match the experimental results. It is well known that the $\varepsilon$-$\log p'$ relation is not linear even after the stress conditions enter the NC state; i.e., the value of $C_c$ decreases with an increase in $p'$, especially for highly structured intact clay samples such as OsakaMa12. Even reconstituted clay samples, such as OsakaMa13Re, show slight non-linearity, as shown in Fig. 4(b). Instead of adopting a linear relation, $\text{ESRL}_0$ can be expressed by the third degree polynomial equation, shown in Eq. (3).

$$p'(\varepsilon)_{\text{ESRL}_0} = a + b\varepsilon + c\varepsilon^2 + d\varepsilon^3 \quad (3)$$

where $a$, $b$, $c$ and $d$ are constants. To obtain constants $a$, $b$, $c$ and $d$, fitting was carried out by the least squares method for the $p'$-$\varepsilon$ relation. It should be noted that these constants are used to show a portion of the $p'$-$\varepsilon$ relation during the changing strain rates, although they may be related to the conventional $\varepsilon$-$\log p'$ curve at the normally consolidated state. Figure 5 shows the observed $p'$-$\varepsilon$ relation for OsakaMa12 and OsakaMa13Re, and the data used for the fitting are plotted as circular points. The first
part to obtain the ESRL₀ is 2% of the \( p' - \varepsilon \) relation smaller than \( p'_1 \), which is the effective stress just before \( \varepsilon_0 \) is changed to \( \varepsilon_0/10 \). The second part is 2% of the \( p' - \varepsilon \) relation larger than the \( p' \) level, about 1.5 times \( p'_1 \), which is the effective stress just before \( \varepsilon \) is changed back to \( \varepsilon_0 \) from \( \varepsilon_0/100 \). It can be seen in Fig. 5 that the experimental \( p' - \varepsilon \) relation slightly exceeds the predicted \( \text{ESRL}_0 \) when the strain rate is changed from \( \varepsilon_0/100 \) to \( \varepsilon_0 \). Such an overshooting should be avoided in order to fit the \( \text{ESRL}_0 \) such that the experimental data are obtained at 1.5 times \( p'_1 \). The \( \text{ESRL}_0 \) calculated from Eq. (3) is also drawn in Fig. 5, where it can be seen that the third degree polynomial line follows the experimental \( p' - \varepsilon \) relation as a whole, and the \( \text{ESRL}_0 \) can be estimated when the order of \( \dot{\varepsilon} \) is changed.

Constants \( a, b, c \), and \( d \) of the third degree polynomial line, shown in Eq. (3), are given in Table 2.

### TEST RESULTS

**Total Strain Test Results**

Figure 6 shows the changes in the stress-strain relation due to changes in \( \dot{\varepsilon} \), along with the \( \text{ESRL}_0 \), where the \( p' \) is normalized by \( p'_1 \) and \( \Delta \varepsilon \) is the incremental strain from \( \varepsilon \) at \( p'_1 \). It is confirmed from Figs. 6(a) and (b) that the \( \Delta \varepsilon = \log (p'/p'_1) \) relation is influenced by the strain rate, seen by the shift with changes in \( \dot{\varepsilon} \). In these figures, the relationship between the excess pore water pressure ratio \( (\Delta u/\sigma) \) and \( p'/p'_1 \) is also shown. It can be seen that changes in \( \Delta u \), caused by the reduction in \( \dot{\varepsilon} \), are quite small against \( \sigma \). This indicates that changes in the \( \Delta \varepsilon = \log (p'/p'_1) \) relation are not caused by an increase or a decrease in the effective stress due to changes in \( \Delta u \), but that they reflect strain-rate dependency, in other words, viscous behavior. Additionally, the \( \Delta \varepsilon = \log (p'/p'_1) \) relations at \( \varepsilon_0/10 \) or \( \varepsilon_0/100 \) are not parallel to \( \text{ESRL}_0 \). This can especially be noticed when \( \dot{\varepsilon} \) is returned to \( \dot{\varepsilon}_0 \), where the \( \Delta \varepsilon = \log (p'/p'_1) \) relation exceeds \( \text{ESRL}_0 \) considerably. This overshooting is more prominent in OsakaMa13Re (Fig. 6(b)) than in OsakaMa12 (Fig. 6(a)). Akai et al. (1984) confirmed similar trends after long-time creep deformation (70 days) in IL tests with small loading steps.

**Visco-plastic and Elastic Strain**

To verify the isotache model, particularly for the interpretation of the compressive behavior during changes in \( \dot{\varepsilon} \), the amount of elastic strain becomes important. Based on previous studies (Nash, 2001; Den Haan and Kamao, 2003), the isotache model can only be applied to the visco-plastic strain, not to the total strain. If the total strain (\( \varepsilon^T \)) is assumed to consist of the elastic strain (\( \varepsilon^e \)) and the visco-plastic strain (\( \varepsilon^{vp} \)), as indicated in Eq. (4), then \( \varepsilon^e \) should be measured by other tests to obtain \( \varepsilon^{vp} \).

\[
\varepsilon^T = \varepsilon^{vp} + \varepsilon^e
\]  

(4)

Hereafter, in order to precisely distinguish the strain, \( \varepsilon^T \) will be used to represent nominal strain \( \varepsilon \). In most constitutive models, it is considered that the elastic component of strain increases linearly with an increase in stress on the logarithmic scale.
Fig. 7. $e$-$\log p'$ relation obtained from unloading and reloading CRS tests on OsakaMa12

Fig. 8. Magnified $\Delta e$-$\log (p'/p'_{\max})$ relations under four different $p'_{\max}$ levels obtained from unloading CRS tests on OsakaMa12

\[
\Delta e' = \frac{C_i}{1 + \varepsilon_0} \Delta \log p'
\]  

where $C_i$ is the swelling index defined as the gradient of the $e$-$\log p'$ relationship measured by unloading tests. However, the $e$-$\log p'$ relation for unloading and reloading does not coincide; instead it shows hysteresis. Figure 7 presents a typical example of the $e$-$\log p'$ relationship for OsakaMa12, for which unloading and reloading tests were carried out under a constant $\varepsilon_0$. In addition to hysteresis, the problem of the non-linearity of the swelling line was also found.

Figure 8 presents the magnification of the unloading process shown in Fig. 7, where the $p'$ is normalized by the effective pressure at the start of the unloading process ($p'_{\max}$). In the vertical axis, the changes in void ratio from the start of the unloading process ($\Delta e$) are plotted. Although unloading tests were carried out at different $p'_{\max}$ values (A to D in Fig. 7), it can be seen that their $\Delta e$-$\log (p'/p'_{\max})$ relation shows almost the same behavior, and that they are not influenced by strain or stress levels. This observation was also reported by Tanaka et al. (2006). As a result, the unloading tests in this study were carried out after a series of tests at different strain rates had been completed, as shown in Fig. 4.

Defining $C_i$ becomes difficult, as the $e$-$\log p'$ relation in the unloading process indicates strong nonlinearity; i.e., the value of $C_i$ increases as $p'/p'_{\max}$ decreases (see Fig. 8). To examine the effects of $C_i$ on $\varepsilon^p$, in order to verify the isotache model, two values for $C_i$ were used, namely, $C_{0.2}$ and $C_{0.8}$. Index $C_{0.2}$ is defined as the slope of a secant line for the $e$-$\log p'$ relation in the unloading process between $p'/p'_{\max}$ values of 1 and 0.2, while $C_{0.8}$ is defined as that between $p'/p'_{\max}$ values of 1 and 0.8. The values obtained for OsakaMa12 and OsakaMa13Re are given in Table 2, together with $C_i$, which is the slope of the $e$-$\log p'$ relation before $\varepsilon_0$ is changed to $\varepsilon_0/10$. In most constitutive models, including the Cam-clay model, the ratio of $C_i$ to $C_C$ ($C_i/C_C$) is an important index, and $C_i/C_C$ for usual clays is reported to be in the range of 0.1 to 0.6 (Iizuka and Ohta, 1987). However, it is confirmed that the values for $C_i/C_C$ in this study (see Table 2) are considerably smaller than those reported. Due to the nonlinearity of the $e$-$\log p'$ relationship in the unloading process, $C_{0.2}/C_C$ is much larger than $C_{0.8}/C_C$. Nevertheless, even the $C_{0.2}/C_C$ measured in this study is far smaller than 0.1, as shown in Table 2. In most studies however, the $C_i/C_C$ ratio is measured by IL tests, not by CRS tests. Thus, this ratio might be influenced by the strain-rate effect.

**Strain-rate Effect during Transition**

Figure 9 shows the relationship between strain rate and strain for OsakaMa12. The horizontal axis in this figure plots both incremental $\Delta e'$ and $\Delta \varepsilon^p$ from $p'$, while the vertical axis plots the strain rates defined by $e$ and $\varepsilon^p$. The transitions are labeled a through g in Figs. 6(a), 9, 10 and 11(a). As shown in Figs. 9 and 6(a), for example, “a-b” and “c-d” describe a process with a decrease in the strain rate, while “e-f” describes a process with an increase in the strain rate. Figure 9(b) shows a magnification of the “a-b-c” transition. Since the CRS tests conducted in this study controlled the total strain rate ($e'$), $\varepsilon^p$ could not instantly change and required a certain strain to obtain a constant $\varepsilon^p$. Moreover, the measured $\varepsilon'$ does not instantly change because of the deformation of the load system, especially the load cell, although the motor was instantly rotated to a rate corresponding to a given $e'$. Therefore, as shown in Fig. 9(b), even in the $\varepsilon'$ and $\Delta e'$ relation, a certain $\Delta e'$ (in this figure, about 0.1%) is required to obtain a constant $\varepsilon'$. The reduction of $\varepsilon'$ causes a decrease in $p'$ by the strain-rate effect so that a negative $\varepsilon'$ is yielded by the reduction of $\varepsilon'$. In other words, the amount of $\varepsilon^p$ becomes larger than that of $\varepsilon'$ in this proc-
Fig. 9. Relationship between strain rate and strain for OsakaMa12: (a) overall view and (b) magnified “a-b-c” process

As previously mentioned, in order to determine \( \varepsilon^o \), two values of \( \varepsilon^e \) were obtained based on \( C_{s0.8} \) and \( C_{s0.2} \). As shown in Table 2, \( C_{s0.2} \) is approximately three to four times larger than \( C_{s0.8} \); thus, on \( C_{s0.2} \) and \( C_{s0.8} \), the magnitude of \( \varepsilon^e \) varies by three to four times. The change in stress ratio \( R \), due to a change in \( \varepsilon^t \), is at most 0.8 (Fig. 10(a)), so that it may be reasonable to calculate \( \varepsilon^o \) based on \( C_{s0.8} \). Although the relation between \( \Delta \varepsilon^o \) and \( \varepsilon^o \), based on \( C_{s0.2} \), slightly shifts to the right side, as seen in Fig. 9, this difference is relatively small. Therefore, it can be concluded that the stress level for the determination of \( C \) does not greatly affect the relation between \( \Delta \varepsilon^o \) and \( \varepsilon^o \).

Stress ratio \( R \) has already been defined in Fig. 1. However, if we assume that the isochoke model is only valid with \( \varepsilon^o \), and not with \( \varepsilon^t \), then \( R \) should be redefined with \( \varepsilon^o \). To distinguish the previous \( R \), the \( R^o \) is used to correspond with \( \varepsilon^o \). The test results are shown in Figs. 10(a) and (b), where the relation between \( R^o \) and \( \Delta \varepsilon^o \) is calculated based on two \( C \) values, i.e., \( C_{s0.2} \) and \( C_{s0.8} \). To examine the relation at the transit of the strain rate in more detail, the scale of the strain is magnified in Fig. 10(b) for the “a-b-c” process, where the strain rate decreases. It is confirmed from Fig. 10(b) that the value of \( R^o \) is slightly smaller than that of \( R \), and this tendency becomes stronger as a larger value is taken for the magnitude of \( \varepsilon^o \). The strain required to attain the minimal value also increases, if \( \varepsilon^e \) is assumed to be large. After a minimal value is achieved for \( R^o \) or \( R^o \), it gradually increases with an increase in \( \Delta \varepsilon^o \), and it apparently approaches a certain constant value. The same tendency was observed in the “e-f-g” process with an increase in strain rate, although the trend of the direction is opposite to that when the strain rate decreases.

The relationship between \( R^o \) and \( \varepsilon^o \) for the tested clays is shown in Fig. 11, where two values for \( C_i \), i.e., \( C_{s0.8} \) and \( C_{s0.2} \), are used to calculate \( R^o \) and \( \varepsilon^o \). If the relation between \( \varepsilon^t \) and \( R \) is plotted, then the \( \varepsilon^t \) and \( R \) relation can be obtained only in the steady state, such as “b-c” and “d-e”, because \( \varepsilon^t \) is almost instantly changed in the transit process (see Fig. 9(b)). However, for the relation between \( R^o \) and \( \varepsilon^o \), the strain-rate dependency during the transit process as well as in the steady state can be obtained, because \( \varepsilon^o \) changes gradually, even in the
transit process, due to the negative $\varepsilon'$ (see Fig. 9(b)). The features of the $R^w$ vs $\varepsilon^w$ relationship obtained by two different $C_s$ values are summarized as follows:

1) The $R^w$ vs $\varepsilon^w$ relationship for both clays depends on $C_s$, especially in the transit process. This difference, however, is not so significant that the order of $\varepsilon'$ is not critical to obtaining the strain-rate dependency during the transit process.

2) No matter which $C_{0.8}$ or $C_{0.2}$ is used to calculate $R^w$ and $\varepsilon^w$, $R^w$ does not become constant even when $\varepsilon^w$ becomes constant. According to the isotache model, in which the $\varepsilon^w$ vs $\rho'$ relationship is determined by $\varepsilon^w$, $R^w$ should be constant when $\varepsilon^w$ is constant.

3) In the isotache model, as shown in Fig. 1, the unique $R^w$ vs $\varepsilon^w$ relationship must be defined, regardless of the strain-rate history. However, the $R^w$ vs $\varepsilon^w$ relations, with increases and decreases in $\varepsilon^w$, do not coincide with each other.

Watabe et al. (2008) proposed a formulation for strain-rate dependency based on the isotache model, as indicated by Eq. (6). In their formulation, the strain-rate dependency is expressed by the yield consolidation pressure ($p'_c$), instead of $R^w$.

**Table 3. Fitting parameters for Equation (6) after Watabe et al. (2008)**

<table>
<thead>
<tr>
<th>Sample</th>
<th>$c_1$</th>
<th>$c_2$</th>
<th>$p'_c$</th>
<th>$w_L$</th>
<th>$w_p$</th>
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<td>Ma12</td>
<td>1.228</td>
<td>0.1377</td>
<td>280</td>
<td>103</td>
<td>41</td>
</tr>
<tr>
<td>Ma13Re</td>
<td>1.209</td>
<td>0.1467</td>
<td>99</td>
<td>91</td>
<td>30</td>
</tr>
</tbody>
</table>

$$\ln \frac{p'_c - p'_c}{p'_c} = c_1 + c_2 \ln \varepsilon^w$$

(6)

where $p'_c$ is the lower limit of $p'_c$ ($p'_c$ under the infinite slow strain rate), and $c_1$ and $c_2$ are constants. Watabe et al. (2008) have obtained three parameters, $p'_c$, $c_1$ and $c_2$, from long-term consolidation tests for Osaka clay samples recovered from clay layers at Kansai International Airport. These Osaka clays are called Ma12 (intact clay samples) and Ma13Re (reconstituted clay samples), and were recovered from the same clay layer as OsakaMa12 and OsakaMa13Re, having similar physical properties to the samples in this study, as shown in Table 3. Using the fitted parameters obtained for Ma12 and Ma13Re, the strain-rate dependency is calculated from Eq. (6) and compared with the $R^w$ vs $\varepsilon^w$ obtained by this study in Fig. 11. It can be seen in the figure that the $R^w$ vs $\varepsilon^w$ relationship during the transit process for “a-b” and “c-d”, where $\varepsilon^w$ is decreasing, seems to agree with the relation calculated by Eq. (6) for both clays. In particular, the relation based on $C_{0.2}$ (plotted by triangles in Fig. 11) shows a good correlation with Eq. (6). It may be concluded that the $R^w$ vs $\varepsilon^w$ relationship obtained in this study may be partly explained by the isotache model as a general trend, provided that $C_s$ is suitably selected and $\varepsilon'$ (or $\varepsilon^w$) is properly calculated. When $\varepsilon^w$ becomes constant, however, the behavior differs from that expected by the isotache model.

**DISCUSSION OF TEST RESULTS DUE TO STRUCTURING PHENOMENON**

It is confirmed that the behavior observed by the CRS tests in this study does not completely follow the isotache model. That is, $R^w$ is not constant, but changes under a constant $\varepsilon^w$, as shown in the process for “b-c”, “d-e”, and “f-g” in Fig. 11. It seems that soil overreacts against changes in the strain rate and decreases in stress (decreasing $\varepsilon^w$) or increases (increasing $\varepsilon^w$) much more than that expected by the ESRL of the corresponding strain rate. As the strain increases, however, this behavior becomes more moderate and returns to the ESRL expected from the isotache model. Another explanation can be inferred, namely, the behavior just after changing the strain rate is true, and after a certain strain or elapsed time, some unknown phenomenon prevents the deformation caused by the viscous properties of soils.

Leroueil (2006) reported that if the strain rate is below a certain level, the $\varepsilon^w$ vs $\rho'$ relation does not follow the expected strain-rate dependency, which is measured by a series of CRS tests at different $\dot{\varepsilon}$. He insisted that this is due to the effect of structuring, since the structure creat-
ed between soil particles or aggregates resists external deformation under very slow $\varepsilon^t$ conditions. From the viewpoint of structuring, the following explanations may be given to the $R^vp$-log $\varepsilon^p$ relations in Fig. 11(a):
1) In the transit process of “a-b”, $R^vp$ monotonically decreases with a decrease in $\varepsilon^p$. It is inferred that this process is dominated by the viscous effect, which can be simply expressed by the isotache model.

2) In the steady state of “b-c”, $R^vp$ slightly increases at a constant $\varepsilon^p$. It is considered that the effect of structuring is not so dominant, since the order of $\varepsilon^p$ is not slow enough to develop the structure against viscous behavior.

3) In the transit process of “c-d”, $R^vp$ decreases with a decrease in $\varepsilon^p$, but the rate of decrease in $R^vp$ for $\varepsilon^p$ becomes smaller than that in the transit process of “a-b”.

4) Contrary to the steady state of “b-c”, in the steady state of “d-e’’ at $\varepsilon^p$ of $3 \times 10^{-8}$ s$^{-1}$, $R^vp$ increases considerably. This infers that $\varepsilon^p$ is so slow that there are more opportunities to create structures that strongly resist viscous deformation.

5) In the transit process of “e-f”, where $\varepsilon^p$ increases from $3 \times 10^{-8}$ to $3 \times 10^{-6}$ s$^{-1}$, $R^vp$ increases with an increase in $\varepsilon^p$ and exceeds 1.0 at $\varepsilon^p$ of $3 \times 10^{-6}$ s$^{-1}$. However, as $\varepsilon^p$ becomes constant in the steady state of “f-g”, $R^vp$ decreases and returns to the original ERSLe. In this process, the structure created by the previous phase under a small $\varepsilon^p$ is broken by a larger $\varepsilon^p$. This phenomenon may correspond to the sudden reduction in $e$ after the $p'_c$ value for highly-structured clays.

The inference of the structure created during the CRS testing seems to provide a reasonable explanation as to why the $R^vp$-log $\varepsilon^p$ relationship does not follow the isotache model. It can be noticed in the relation between $R^vp$ and $\varepsilon^p$ in Fig. 11 that the increase in $R^vp$ at the steady state of “d-e” for OsakaMa13Re is more prominent than that for OsakaMa12. Similarly, after the process of increasing $\varepsilon^p$, a large decrease in $R^vp$ at the steady state of “f-g” is observed for OsakaMa13Re. This indicates that the effect of structuring depends on the properties of the samples. At present, however, it cannot be pointed out which property or properties are responsible for determining this structural effect.

In this paper, the authors have tried to explain the observed deviation from the isotache model in terms of the abstract idea of structuring. The term for the structure is used in the field of compressibility, as well as deformation, including strength, as one of the solutions for the difference between intact and reconstituted soil samples (for example, Leroueil and Hight, 2003), although a precise definition has not been given. However, it is true that the isotache model provides a safe side settlement, since the present isotache model does not consider the structuring effects that resist deformation.

CONCLUSIONS

To avoid the heterogeneity of tested samples, special CRS tests, in which the total strain rate ($\varepsilon^t$) is not constant but varied during the test, were carried out on two types of Osaka clay samples, intact and reconstituted. The strain rate effects of the compressive behavior of these clays were carefully examined by visco-plastic strain assuming that the total strain ($\varepsilon^t$) consisted of visco-plastic strain ($\varepsilon^p$) and elastic strain ($\varepsilon^e$). However, it is difficult to define $\varepsilon^e$, because the e-log $p'$ relation during unloading and reloading tests indicates a strong hysteresis loop and nonlinearity. Therefore, $\varepsilon^p$ is calculated by two orders of swelling indices, $C_{o,2}$ and $C_{o,8}$, at different unloading stress levels. As a result, it is confirmed that even though $\varepsilon^t$ almost immediately changes to a new $\varepsilon^t$, the visco-plastic strain rate ($\varepsilon^p$) gradually changes because of the yielded $\varepsilon^e$, due to the pressure shifting brought about by the strain-rate dependency. The strain-rate dependency was evaluated by stress-changing ratio $R^vp$, which indicated changes in stress with changes in strain rate, and whose strain can be defined by visco-plastic strain, such as $\varepsilon^p$ and $\varepsilon^e$. The following conclusions were obtained:

1) In the transit process where the strain rate is changing, $R^vp$ decreases or increases with a decrease or increase in $\varepsilon^p$. This transit behavior depends on the definition of $\varepsilon^e$. However, the difference is not so significant that the order of $\varepsilon^e$ is not critical to obtaining the strain-rate dependency during the transit process.

2) In the steady state where $\varepsilon^p$ becomes constant, $R^vp$ is not constant, but increases with an increase in strain, while $R^vp$ decreases when the strain rate increases. These trends are observed for both intact and reconstituted clay samples regardless of $C_{o,8}$ and $C_{o,2}$. This result is inconsistent with the isotache model in which the $\varepsilon^p$-log $p'$ relation is determined by $\varepsilon^p$, i.e., $R^vp$ should be constant when $\varepsilon^p$ becomes constant.

3) The reason for 2) is assumed to be due to the effects of structuring, where a structure seems to develop at a slow strain rate. In the steady state under a slow $\varepsilon^p$, $R^vp$ increases as the developed structure resists viscous deformation. When the strain rate is increased to the original strain rate, the specimen behaves as a highly structured clay due to the structure created during the slow strain rate, i.e., the yield consolidation pressure increases and overshooting is observed.

4) In past research works, there has been considerable scatter in the relations showing the validity of the isotache model. This is probably due to the fact that such scatter can be partly attributed to the heterogeneity of the tested samples, and also to the incompleteness of the isotache model brought about by the structuring effects.

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