Modeling and Implementation of the Isotache Concept for Long-Term Consolidation Behavior

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Modeling and Implementation of the Isotache Concept for Long-Term Consolidation Behavior

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Abstract: A practical use of the isotache concept in creep settlement prediction is newly introduced in this study. The isotache concept introduces a unique relationship between the strain and the consolidation pressure corresponding to the strain rate in association with viscosity. The authors have proposed a method to simply introduce the isotache concept, which uses a compression curve normalized by preconsolidation pressure $[\varepsilon - \log(\sigma'/\sigma'_p)]$ and a strain rate dependency relationship between the preconsolidation pressure (σ'_p) and strain rate ($\dot{\varepsilon} = d\varepsilon/dt$). The strain rate dependency relationship is modeled as an equation based on power law. According to the authors' method, the slope of the strain rate dependency relationship ($\log\sigma'_p - \log\dot{\varepsilon}$), which coincides with $C_{\alpha e}/C_c$, can be calculated as a function of strain rate, showing that $C_{\alpha e}/C_c$ is not constant but decreases with decreasing strain rate. In engineering practice, consolidation settlement is generally estimated based on the compression curve obtained from the 24-h incremental loading oedometer test, which corresponds to a strain rate of about $1 \times 10^{-7}\ \mathrm{s}^{-1}$. Using the compression index C_c at the consolidation pressure and initial void ratio e_0, creep settlement can be easily calculated as a function of $C_c/(1+e_0)$ and in situ strain rate (several orders of magnitude smaller than $1 \times 10^{-7}\ \mathrm{s}^{-1}$). **DOI: 10.1061/(ASCE)GM.1943-5622.0000270.**

Author keywords: Long-term consolidation; Secondary consolidation; Viscosity; Isotache; Strain rate.

Introduction

The consolidation test for soft clays is generally conducted using a specimen with small dimensions, e.g., thickness of 20 mm and diameter of 60 mm. The test results are then used to predict the in situ consolidation settlement of thick clay deposits. The scale–effect relationship between the consolidation behaviors observed in the field and the laboratory is still argued by some engineers. Ladd et al. (1977) and Jamiolkowski et al. (1985) consider the two hypotheses shown in Fig. 1.

If viscosity governs the consolidation behavior, resistance (i.e., consolidation pressure) decreases with decreasing strain rate. In Hypothesis A, the creep compression occurs only after the end of primary consolidation (EOP), i.e., viscosity appears only during secondary consolidation. Therefore, the law of squared H on the scale effect is applicable, resulting in the same value of the compressive strain at EOP in both the field and the laboratory. In contrast, in Hypothesis B, creep compression occurs even during the dissipation of excess pore water pressure and is governed by structural viscosity, i.e., viscosity appears in the whole consolidation behavior from primary to secondary consolidation, resulting in a large compressive strain with the thickness. The scale effect on the consolidation behavior has not yet been clarified.

The two main approaches for the evaluation of the consolidation settlement can be described as follows:

1. The constant $C_{\alpha e}/C_c$ (ratio of secondary compression index $C_{\alpha e}$ to the compression index C_c) concept proposed by Mesri and Castro (1987) with the same strain concept at the EOP proposed by Mesri and Choi (1985). The coupling method of Terzaghi's one-dimensional consolidation theory and constant $C_{\alpha e}$ concept is classified into this. The constant $C_{\alpha e}/C_c$ concept can support both hypotheses A and B, but the same strain concept at the EOP supports only Hypothesis A. Although the constant $C_{\alpha e}$ concept is often used, it is well known that a consolidation curve ($\varepsilon - \log t$) in the secondary consolidation stage is not linear, but convex downward, i.e., $C_{\alpha e}$ decreases with logarithmic time. This approach results in infinite settlement at infinite elapsed time. The constant $C_{\alpha e}/C_c$ concept can model the secondary consolidation curve being convex downward, if the compression curve is convex downward; however, it still results in infinite settlement in an infinite elapsed time.
2. The isotache concept initially proposed by Šuklje (1957), in which a unique relationship between the strain and the consolidation pressure is introduced corresponding to the strain rate in association with the viscosity. Note here that the term isotache means iso- (equal) + rate (speed). According to this concept, a series of compression curves are drawn corresponding to the strain rates. In this concept, $C_{\alpha e}/C_c$ is not necessarily a constant, and it can decrease when the strain rate decreases with time. The isotache concept supports only Hypothesis B, because the viscosity effect appears from primary to secondary consolidation.

Here, $C_{\alpha e}$ denotes the coefficient of secondary consolidation in void ratio $= \Delta e/\Delta \log t$.

Approach 1 is a clear-cut concept, which is easily applicable in practice. From the EOP compression curves, Mesri and Choi (1985) empirically determined that the preconsolidation pressures obtained in the laboratory and in the field are identical. The constant $C_{\alpha e}/C_c$

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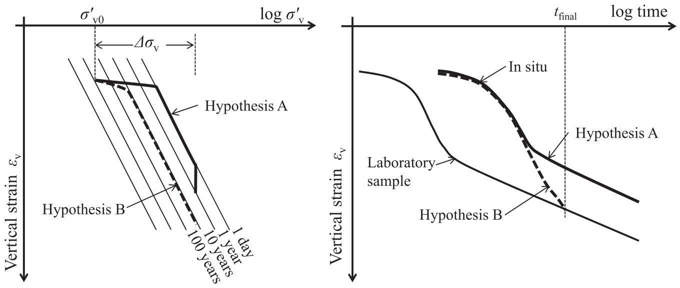

Fig. 1. Comparison between consolidation curves of a thin specimen and a thick specimen/in situ deposit

concept proposed by Mesri and Castro (1987) is useful to explain the secondary consolidation with regard to the delayed creep consolidation (Bjerrum 1967). The constant $C_{\alpha e}/C_c$ concept is consistent with the isotache during secondary consolidation; however, its application is limited because secondary consolidation would continue infinitely against logarithmic time, i.e., the strain increases to infinity at infinite time.

Approach 2 is a concept initially proposed by Šuklje (1957), which involves viscosity and introduces a unique relationship between the strain and the preconsolidation pressure corresponding to the strain rate. This concept, which focuses on the strain rate effect, has attracted a lot of attention in recent research on consolidation. The isotache concept was proposed more than 50 years ago; however, it continues to be studied in academia. There have been many studies on long-term consolidation with regard to viscosity (e.g., Leroueil et al. 1986, 1988; Yin et al. 1994; Adachi et al. 1996; Kim and Leroueil 2001; Hawlader et al. 2003; Imai et al. 2005; Tanaka et al. 2006; Watabe et al. 2008, 2012; Qu et al. 2010; Degago et al. 2011).

In this paper, some arguments on long-term consolidation prediction, particularly on the generality of the constant $C_{\alpha e}/C_c$ concept and the isotache concept, are discussed first. Then the authors' simplified method of the isotache concept, which has been proposed earlier (Watabe et al. 2008, 2012), is introduced, and a practical use of the method in creep settlement prediction is newly described.

Availability of Constant $C_{\alpha e}/C_c$ Concept

An example of constant $C_{\alpha e}/C_c$ for two eastern Canada clays (Mesri et al. 1995) is shown in Fig. 2. An interesting aspect is that $C_{\alpha e}/C_c$ remains within a narrow range for each soil type; it is typically equal to 0.04 in inorganic clays and has larger values for organic soils and lower values for granular soils.

On the other hand, there is evidence that denies the generality of the constant $C_{\alpha e}/C_c$ concept. Fig. 3 shows a normalized stress–strain rate relationship for Canadian and Swedish clays from Leroueil et al. (1988) with an interpretation after Leroueil (2006). The slope α, which is defined as $\Delta\log\sigma'_p/\Delta\log\dot{\varepsilon}$ and is equal to $C_{\alpha e}/C_c$, tends to decrease when $\dot{\varepsilon}$ decreases to a small value. This trend supports the isotache concept. As will be discussed later in this paper, Watabe et al. (2008, 2012) have shown that these results can be generalized in a simplified model with the isotache concept proposed by the authors. If $C_{\alpha e}/C_c$ decreases with time with an asymptotic value of zero, it is very logical because the secondary consolidation finally stops at infinite time.

Modeling of Isotache Concept

The simple equations proposed by Leroueil et al. (1985) are used here but are applied to the viscoplastic strain rather than total strain.

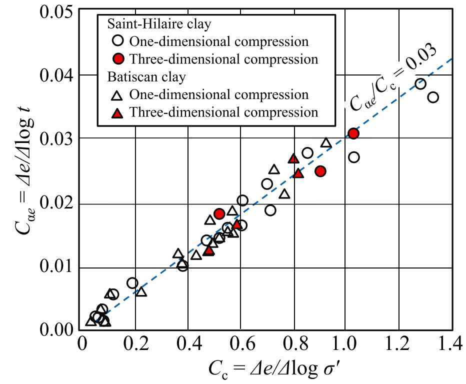

Fig. 2. Relationship between secondary compression index $C_{\alpha e}$ and compression index C_c (data from Mesri et al. 1995)

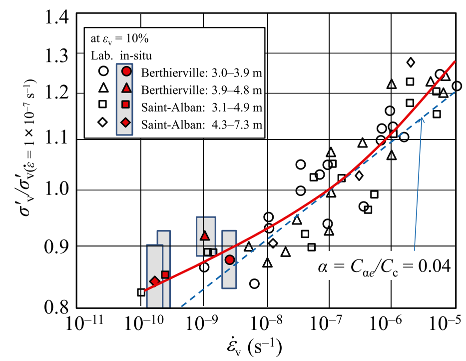

Fig. 3. Normalized stress–strain rate relationship for Canadian and Swedish clays (data from Leroueil et al. 1988 with interpretation from Leroueil 2006)

For clarity, the authors use the ε_{vp}–log σ'_v relationship, where ε_{vp} is the viscoplastic strain, defined as the difference between the total strain ε obtained from the consolidation test and the elastic strain ε_e. Then Eqs. (1)–(3) are used, as follows:

$$\varepsilon_{vp} = \varepsilon - \varepsilon_e \tag{1}$$

$$\frac{\sigma'_v}{\sigma'_p} = f(\varepsilon_{vp}) \tag{2}$$

$$\sigma'_p = g(\dot{\varepsilon}_{vp}) \tag{3}$$

where σ'_v = vertical effective consolidation pressure; σ'_p = preconsolidation pressure (consolidation yield stress p'_c); $\dot{\varepsilon}_{vp}$ = plastic strain rate defined as $d\varepsilon_{vp}/dt$; and f and g express a function of the following parameter(s). To obtain the relationships expressed by Eqs. (2) and (3), a constant rate of strain consolidation (CRS) tests and long-term consolidation (LT) tests are required to be performed. The details have been described in Watabe et al. (2008, 2012).

The parameter ε_e is defined as the strain expressed by the straight line passing through the points $(\sigma'_v, \varepsilon) = (1\text{ kPa}, 0)$ and $(\sigma'_{v0}, \varepsilon_0)$ on the ε–log σ'_v curve, as illustrated in Fig. 4(a). Here, σ'_{v0} denotes the overburden effective stress and ε_0 denotes the strain at $\sigma'_v = \sigma'_{v0}$. The curve expressed by Eq. (2) is illustrated in Fig. 4(b) and named the reference compression curve hereafter.

The preconsolidation pressure is found to vary with strain rate as per the following model curve of $\log \sigma'_p$–$\log \dot{\varepsilon}_{vp}$, which was proposed by Watabe et al. (2008)

$$\ln \frac{\sigma'_p - \sigma'_{pL}}{\sigma'_{pL}} = c_1 + c_2 \ln \dot{\varepsilon}_{vp} \tag{4}$$

where c_1 and c_2 = constants representing the value and slope of the preconsolidation pressure at a large strain rate ($\dot{\varepsilon} = 1$) and σ'_{pL} = lower limit of σ'_p at infinitesimal strain rate ($\dot{\varepsilon} = 0$). When $\dot{\varepsilon}_{vp}$ decreases toward zero in Eq. (4), σ'_p converges toward σ'_{pL}. The authors call these three parameters isotache parameters. This equation is consistent with Leroueil (2006) and Fig. 3, in which it was emphasized that the slope α decreases when $\dot{\varepsilon}_{vp}$ decreases to very small values for in situ data (indicated as a solid line), whereas the slope α is apparently constant for most of the laboratory data in a range of large strain rates from 10^{-8} to $10^{-5}\ \mathrm{s}^{-1}$ (indicated as a dotted line). Note here that Eq. (4) is essentially the same as that proposed by Qu et al. (2010), which was directly derived from Norton's power law (Norton 1929) in conjunction with overstress viscoplastic theory (Perzyna 1963). Actually, Eq. (4) can be transformed to Eq. (5)

$$\dot{\varepsilon}_{vp} = c_3 \left(\frac{\sigma'_p - \sigma'_{pL}}{\sigma'_{pL}} \right)^{c_4} \tag{5}$$

where c_3 and $c_4 = \exp(-c_1/c_2)$ and $1/c_2$, respectively.

The parameter c_1 is equal to $\ln\{(\sigma'_p - \sigma'_{pL})/\sigma'_{pL}\}$ at $\dot{\varepsilon}_{vp} = 1$, i.e., it represents the relative position of the $\log \sigma'_p$–$\log \dot{\varepsilon}_{vp}$ curve. The parameter c_2 represents the level of strain rate dependency. The compressibility of the soil is represented by the reference compression curve expressed by Eq. (2). Consequently, the reference compression curve and three isotache parameters (σ'_{pL}, c_1, and c_2) are required to describe clay compressibility in the proposed method. In the relationship expressed by Eq. (4), if it is assumed that the curve passes by a given point, the parameter c_2 is automatically calculated as a dependent variable of σ'_{pL} and c_1 (or the parameter c_1 is automatically calculated as a dependent variable of σ'_{pL} and c_2).

The preconsolidation pressure σ'_p is obtained as a function of $\dot{\varepsilon}_{vp}$ from the reference compression curve $\{\varepsilon_{vp} - \log[\sigma'_v/\sigma'_p(\dot{\varepsilon}_{vp})]\}$ by using the data set of σ'_v and ε_{vp}. The procedure to obtain the $\log \sigma'_p$–$\log \dot{\varepsilon}_{vp}$ relationship from results of one CRS and one LT test is illustrated in Fig. 5.

The slope (α) of the $\log(\sigma'_p/\sigma'_{p0})$–$\log \dot{\varepsilon}_{vp}$ relationship at a given strain rate corresponds to the ratio of secondary compression index $C_{\alpha e}$ to the compression index C_c as expressed in Eq. (6)

$$\alpha = \frac{\Delta \log(\sigma_p/\sigma'_{p0})}{\Delta \log \dot{\varepsilon}_{vp}} = \frac{\Delta \log \sigma_p}{\Delta \log \dot{\varepsilon}_{vp}} = \frac{C_{\alpha e}}{C_c} \tag{6}$$

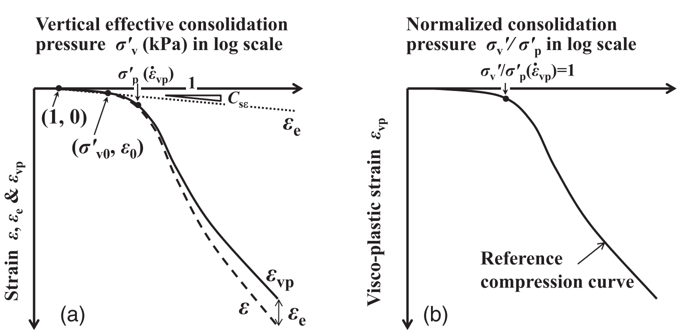

Fig. 4. Compression curve (ε–$\log \sigma'_v$ curve): (a) definition of ε_e and ε_{vp}; (b) reference compression curve

Discussion of the Model

Experimental Evidence

In Watabe et al. (2008), a series of CRS tests and LT tests were carried out for Osaka Bay clays collected up to 300 m below the seabed under the construction site of the Kansai International Airport, Izumisano, Osaka, Japan, and the proposed method was first applied to these test results. It was determined that the isotache parameters for Osaka Bay clays at various depths were $\sigma'_{pL}/\sigma'_{p0} = 0.70$ and $c_1 = 0.935$. Here, σ'_{p0} is defined as the σ'_p corresponding to an $\dot{\varepsilon}_{vp}$ value of $1.0 \times 10^{-7}\ \mathrm{s}^{-1}$, which is close to the average strain rate obtained in 24-h incremental loading consolidation tests. Because the curve passes the point of σ'_{p0} at $\dot{\varepsilon}_{vp}$ of $1.0 \times 10^{-7}\ \mathrm{s}^{-1}$, c_2 is automatically calculated as 0.107 with the parameters $\sigma'_{pL}/\sigma'_{p0} = 0.70$ and $c_1 = 0.935$. The best-fitting curve with these isotache parameters commonly determined for all the soil layers is named the integrated fitting curve, whereas the fitting curve for each soil layer is called simply the fitting curve. In Watabe et al. (2012), a series of CRS and LT tests were carried out for mostly inorganic worldwide clays with various characteristics in plasticity, mineralogy, microstructure, fabric, overconsolidation, etc., and the proposed method was applied to those test results. It was found that the common isotache parameters determined for the Osaka Bay clays are applicable to all clays worldwide, even to the Mexico City clay whose characteristics are exceptional compared with usual soils (Díaz-Rodríguez 2003), with water content w almost equal to 400% (in a range of 200–400% at the sampling site near the Mexico City International Airport, Mexico City, Mexico).

Fig. 6 shows superimposed reference compression curves for the worldwide clay samples examined in Watabe et al. (2008, 2012), and

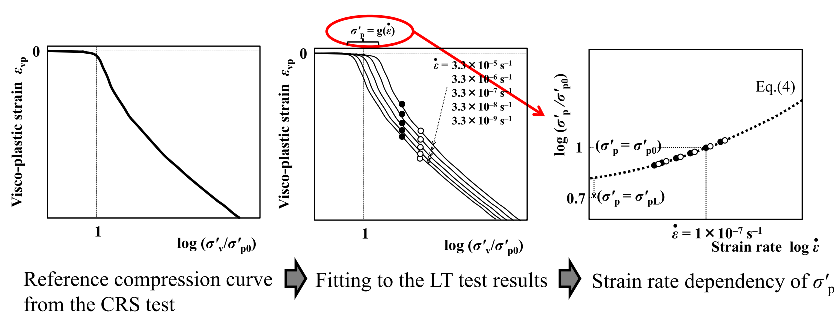

Fig. 5. Illustration of the method to evaluate the strain rate dependency of σ'_p from the CRS and LT test results

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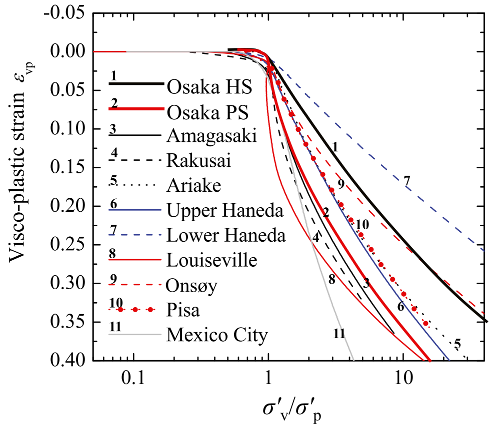

Fig. 6. Superimposed reference compression curves for the worldwide clays examined in Watabe et al. (2008, 2012)

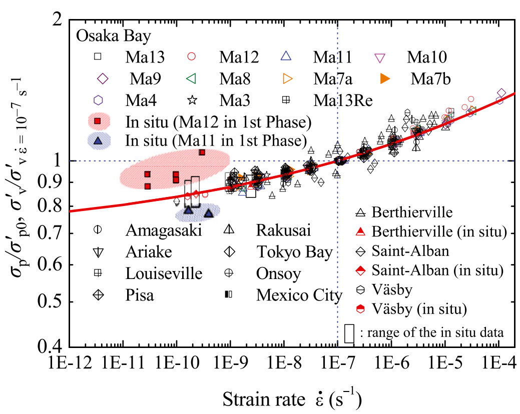

Fig. 7. The $\log \sigma'_p/\sigma'_{p0}$—$\log \dot{\varepsilon}_{vp}$ [or $\log \sigma'_v/\sigma'_v(\dot{\varepsilon}_{vp} = 10^{-7}\ \mathrm{s}^{-1})$—$\log \dot{\varepsilon}$ for Canadian and Swedish clays] relationship for all the worldwide clays studied in Watabe et al. (2008, 2012), as well as Leroueil et al. (1988) with interpretation from Leroueil (2006), compared with the integrated fitting curve with the common isotache parameters determined for the Osaka Bay clays

Fig. 7 shows the $\log \sigma'_p/\sigma'_{p0}$—$\log \dot{\varepsilon}_{vp}$ relationship for all the worldwide clays examined, including the Osaka Bay clays (Watabe et al. 2008, 2012), as well as Canadian (Berthierville and Saint-Alban) and Swedish (Väsby) clays [from Leroueil et al. (1988) with an interpretation after Leroueil (2006)]. On vertical axis σ'_p is normalized by σ'_{p0} and, consequently, all the test results pass through $\sigma'_p/\sigma'_{p0} = 1$ at $\dot{\varepsilon}_{vp} = 1.0 \times 10^{-7}\ \mathrm{s}^{-1}$. Fig. 7 shows the integrated fitting curve with the common isotache parameters determined for the Osaka Bay clays ($\sigma'_{pL}/\sigma'_{p0} = 0.70$ and $c_1 = 0.935$) superimposed. The test results and the integrated fitting curve have good agreement in value and tendency. It can be quantitatively said that squared correlation coefficient (R^2) for the Osaka Bay clays from various layers was 0.978 and that for all the worldwide clays examined was 0.936. Note that because the results are for natural clays including both laboratory and field data, some variability is inevitable. The integrated fitting curve is useful to conduct a calculation for the secondary consolidation behavior.

Discussion

Mesri and Castro (1987) proposed a practical concept in which $C_{\alpha e}/C_c$ [i.e., α in Eq. (6)] would be constant. For inorganic clays, this ratio is typically equal to 0.04 ± 0.01 (Mesri et al. 1995). Fig. 8 shows a comparison of the integrated fitting curve with the constant $C_{\alpha e}/C_c$ concept with $\alpha = 0.04$ [Fig. 8(a)] and the relationship between α and strain rate calculated from the integrated fitting curve [Fig. 8(b)]. As seen in Fig. 8(b), $\alpha = C_{\alpha e}/C_c$ is not a constant and decreases when $\dot{\varepsilon}_{vp}$ decreases. This is consistent with the emphasis in Leroueil (2006) on the data for the Canadian and Swedish clays (see Fig. 3) and confirmed with the Osaka Bay clays (Watabe et al. 2008) as well as the worldwide clays (Watabe et al. 2012). For the integrated fitting curve, the value of α is between 0.03 and 0.05 for strain rates between 2.6×10^{-8} and $3.4 \times 10^{-5}\ \mathrm{s}^{-1}$, i.e., strain rates usually encountered in the laboratory. Then the value of σ'_p/σ'_{p0} converges to 0.7 for the integrated fitting curve. This tendency is consistent with the comments in Leroueil (2006) and quantitatively clarified by the integrated fitting curve. It appears that $C_{\alpha e}/C_c = 0.04 \pm 0.01$ is essentially valid for strain rates generally observed in the laboratory, which explains the observation made by Mesri et al. (1995). The integrated fitting curve [Eq. (4) with the common isotache parameters] is obtained for mostly inorganic clays; however, it would be interesting to define the asymptotic value using Eq. (6) of σ'_p/σ'_{p0} to have $C_{\alpha e}/C_c = 0.02$ (cohesionless soils), 0.05 (organic clays), and 0.06 (peat) (Mesri et al. 1995). Because data for these

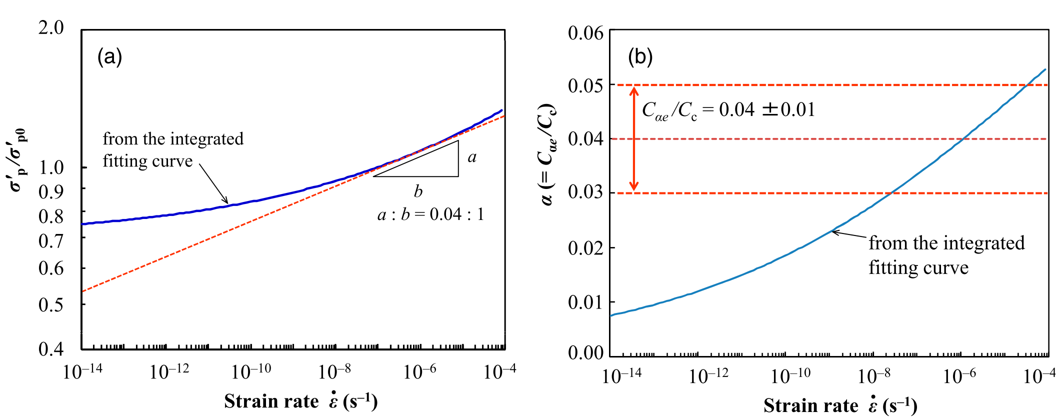

Fig. 8. Comparison of the integrated fitting curve with the constant $C_{\alpha e}/C_c$ concept: (a) relationship between σ'_p/σ'_{p0} and strain rate; (b) relationship between α (=$C_{\alpha e}/C_c$) and strain rate $\dot{\varepsilon}$ (data from Watabe et al. 2012)

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other classes of materials are not available, this behavior cannot be extrapolated to smaller strain rates that generally characterize clay deposits under embankments.

According to the isotache model, the vertical effective stress–strain curve followed in situ should be below the EOP compression curve obtained in the laboratory, as schematized in Fig. 9. This implies that, at the same strain in the laboratory and in situ, the field pore pressure (SF in Fig. 9) is larger than the one predicted from laboratory test results (LF in Fig. 9). This also implies that at the EOP, the in situ strain (ε_{ff} in Fig. 9) is larger than the laboratory one (ε_{fc} in Fig. 9).

There is much evidence for the viscosity effect during the primary consolidation in situ, i.e., isotache concept, and some of this evidence is shown subsequently.

The compression curves observed for Ma12 layer under Kansai International Airport Phase 1 together with the isotache model deduced from 24-h incremental loading oedometer tests with the integrated fitting curve are shown in Fig. 10. The marine clay layers in Osaka basin are numbered from Ma1 at the bottom to Ma13 at the surface. Ma13 is the Holocene clay layer, and Ma12 to Ma1 are Pleistocene clay layers. Note that the sites for the field data and the laboratory data were about 500 m apart. The oedometer tests were performed on samples taken at a different location from the site of sublayer measurements under Kansai International Airport Phase 1. Here, the reference compression curve is an average of five test results at different depths at 2-m intervals. It can be seen that the effective stresses of the first set are larger than those of the second set for the same strain and strain rate. However, the data show that the slope of the in situ compression curve associated with decreasing strain rates is much steeper than the slope of the isotaches deduced from laboratory tests. This behavior is consistent with the isotache model.

Fig. 11 shows the stress–strain relationship observed in situ compared with a compression curve obtained in the laboratory for Väsby clay in Sweden (Kabbaj et al. 1988). The vertical effective stress–strain curve followed in situ is below the EOP compression curve obtained in the laboratory, and this relationship is consistent with the behavior illustrated in Fig. 9.

It is notable that sample quality is very important in predicting the field behavior based on the laboratory test result. Fig. 12 shows a difference between compression curves for high-quality and poor-quality samples. Two types of samplers, the 200-mm Laval sampler and the 50-mm Swedish piston sampler, were used to collect undisturbed samples for Väsby clay, in Sweden. As seen in Fig. 12, the compression curve for the specimen taken with the Laval sampler shows clearer yielding than that with the Swedish sampler. This fact

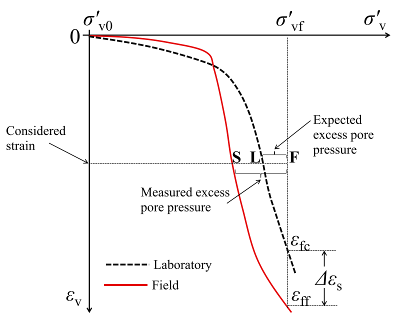

Fig. 9. Schematic interpretation of compression curves in situ and in the laboratory (adapted from Leroueil 2006)

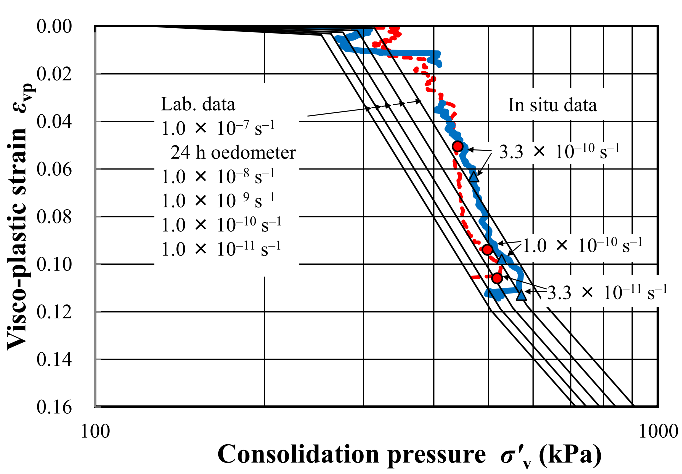

Fig. 10. Compression curves observed for Ma12 under Kansai International Airport Phase 1 together with the isotache model deduced from 24-h incremental loading oedometer tests, corresponding to the strain rates of $1.0 \times 10^{-7}\ s^{-1}$; the oedometer tests were performed on samples taken at a different location from the site of sublayer measurements under Kansai International Airport Phase 1; here, the reference compression curve is an average of five test results at different depths at 2-m intervals (data from Watabe et al. 2012)

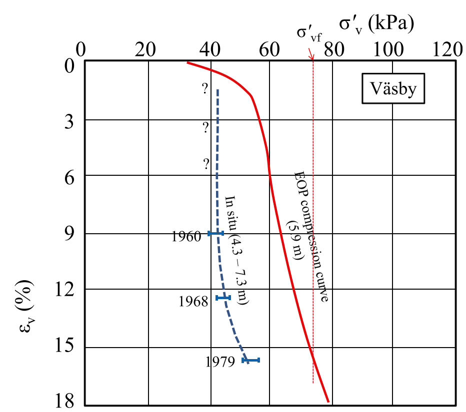

Fig. 11. Comparison between stress–strain relations observed in situ and measured at EOP in laboratory (data from Kabbaj et al. 1988)

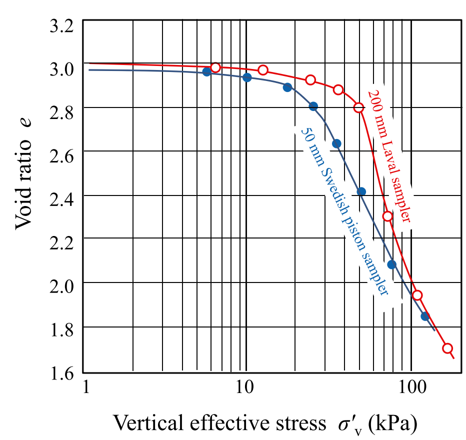

Fig. 12. Typical compression curves for Väsby clay at a depth of 4.0–4.3 m (data from Leroueil and Kabbaj 1987)

indicates that if a poor-quality sample were examined in the laboratory, the compression curve would be below the one for the intact clay. Mesri and Choi (1985) indicated that Hypothesis A was valid, whereas Leroueil (2006) indicated that the use of high-quality samples collected with the Laval sampler (La Rochelle et al. 1981) shows that it is not the case and that the isotache model or Hypothesis B is valid (Leroueil 2006). To discuss this argument, one has to consider the soil quality of Mesri and Choi (1985) and Leroueil (2006).

Prediction Based on the Model

Fig. 13 shows (1) depth profiles of compression indices C_c obtained in the laboratory and the field and (2) temporal variations of excess pore pressure measured in the field and predicted in Changi International Airport, Singapore (Cao et al. 2001). It is noted here that the values showed good agreement between calculated and measured settlement curves. The compression index obtained in the field is larger than that obtained in the laboratory, indicating that this fact is consistent with Fig. 10, in which the field data show a steeper slope than the laboratory data. Excess pore pressure measured in the field was always higher than that predicted. This fact is also consistent with Fig. 9, which shows that the pore pressure in the field is expected to be higher than that predicted based on the compression curve obtained in the laboratory.

In this study, one-dimensional consolidation FEM with the authors' isotache model was newly programmed, and long-term consolidation for Ma12 of Osaka Bay clay was calculated in cases of different thickness: 10 and 100 mm, and 1 and 10 m in single drainage conditions. Detailed parameters are not discussed here, but the integrated fitting curve was used. Consolidation curves (ε–log t curves) obtained by the FEM simulation are drawn in Fig. 14. Because the isotache concept is adopted in this calculation, the results support Hypothesis B, in which the larger strain at EOP was calculated with the larger thickness. In addition, all the consolidation curves converge at last, and the secondary consolidation curves are always convex downward.

Application to Engineering Practice

Shown in Fig. 15 (after Watabe et al. 2012) is a schematic illustration of the compression curve which would be obtained from a LT test in the laboratory (A → C → D → E) and in situ (A → B → E → F) for an incremental loading from the overburden effective stress σ'_{v0} to a vertical pressure σ'_{vf} in the postyield domain. The compression

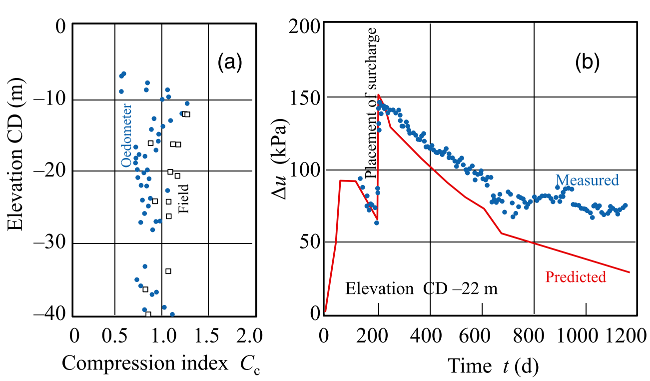

Fig. 13. Evidence of the viscosity effect during the primary consolidation in Changi International Airport, Singapore: (a) depth profiles of compression index C_c; (b) temporal variation of excess pore pressure (data from Cao et al. 2001)

curves corresponding to several strain rates are superimposed. The curve for the infinitesimal strain rate represents the maximum potential compression of the clay. The points D, E, and F correspond to the strain rates of 1.0×10^{-7}, 3.3×10^{-11}, and $1.0 \times 10^{-\infty}$ s^{-1} (infinitesimal strain rate), respectively. From the authors' experience, the minimum strain rates obtained from laboratory tests are generally around 1.0×10^{-9} s^{-1}, and generally do not reach point E. Strain rates obtained from in situ observations at the Kansai International Airport are currently around 3.3×10^{-11} s^{-1} (close to point E), and the clay is still in its primary consolidation stage; they will thus be smaller than this at the EOP. However, point F will never be reached.

In engineering practice, consolidation settlement is generally estimated based on the $e - \log \sigma'_v$ curve obtained from 24-h incremental loading oedometer tests, which corresponds to a strain rate of about 1.0×10^{-7} s^{-1} (point D). Using the compression index C_c at the consolidation pressure σ'_{vf}, the maximum additional settlement $\Delta\varepsilon_{ult}$ (point F) can be estimated as follows from geometric relation (Watabe et al. 2012):

$$\Delta\varepsilon_{ult} = \Delta\varepsilon_{D\rightarrow F} = \frac{C_c}{1+e_0} \log \frac{\sigma'_{p0}}{\sigma'_{pL}} \tag{7}$$

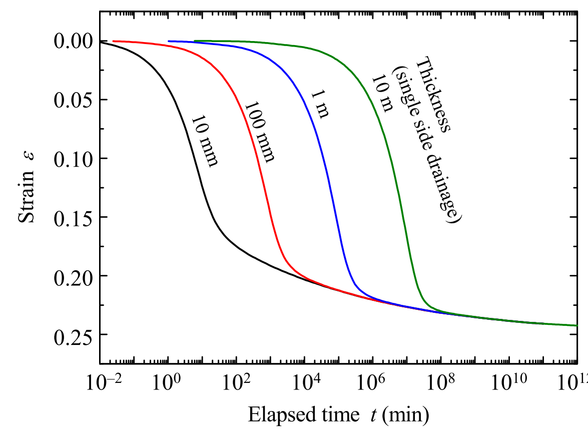

Fig. 14. FEM simulation with the authors' isotache model along with the integrated fitting curve for different thicknesses

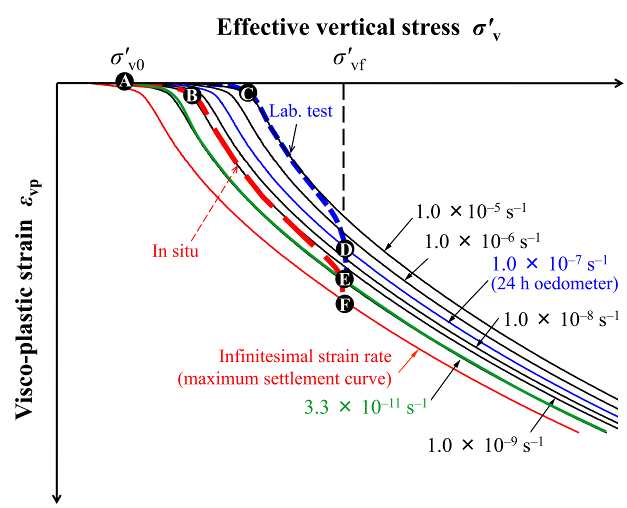

Fig. 15. Schematic illustration of compression paths for LT test in the laboratory and in situ behavior (data from Watabe et al. 2012)

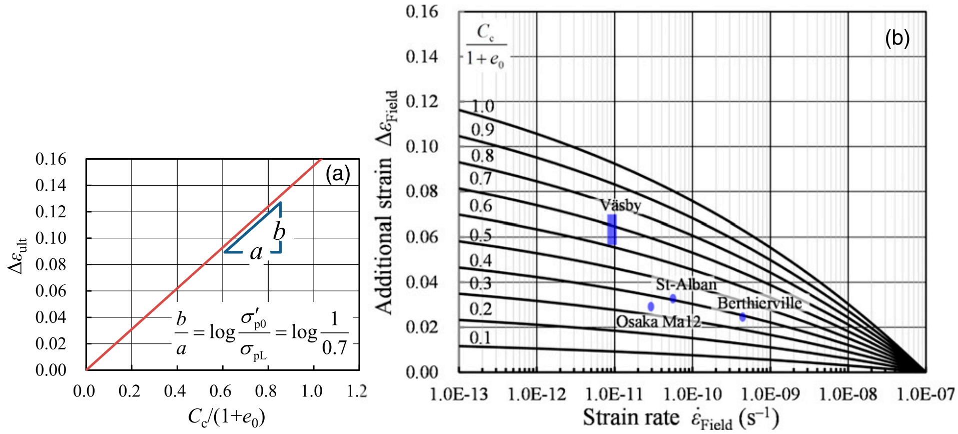

Fig. 16. Additional settlement calculated with isotache concept: (a) maximum additional strain corresponding to an infinitesimal strain rate as a function of $C_c/(1+e_0)$; (b) additional strains in the field calculated as a function of $C_c/(1+e_0)$ and in situ strain rate

The additional strain from D to a given strain rate in the field, $\Delta\varepsilon_{\text{Field}}$, is given by the following equation:

$$\Delta\varepsilon_{\text{Field}} = \Delta\varepsilon_{D\to E} = \frac{C_c}{1+e_0}\log\left\{\frac{\sigma'_{p0}}{\sigma'_{pL}}\left[\frac{1}{1+\exp(c_1+c_2\ln\dot{\varepsilon}_{\text{Field}})}\right]\right\} \quad (8)$$

where $\dot{\varepsilon}_{\text{Field}}$ = strain rate considered at the field, e.g., end of primary consolidation in situ. Note here that $\sigma'_{pL}/\sigma'_{p0} = 0.7$, $c_1 = 0.935$ (and automatically $c_2 = 0.107$) can be used for worldwide inorganic clays. In case of Ma12 of the Osaka Bay clay, for example, the initial void ratio e_0 and C_c are typically 2.2 and 1.0 (Watabe et al. 2002), respectively, corresponding to a natural water content of around 100%. Consequently, using Eq. (7), $\Delta\varepsilon_{D\to F}$ can be estimated as 0.048 (4.8%). In addition, because an in situ strain rate for Ma12 at the Kansai International Airport is typically $3.3\times10^{-11}\ \text{s}^{-1}$ as evaluated from the settlement of sublayers, using Eq. (8) [or Eq. (7) by replacing $\sigma'_{pL}/\sigma'_{p0} = 0.7$ by $\sigma'_p\,(\dot{\varepsilon}_{vp} = 3.3\times10^{-11}\ \text{s}^{-1})/\sigma'_{p0} = 0.82$ from the integrated fitting curve], $\Delta\varepsilon_{D\to E}$ can be estimated as 0.025 (2.5%); this is coarsely what has been observed.

For an application of the proposed method to engineering practice, a chart to predict additional strain (creep strain) was newly drawn. Fig. 16(a) shows the maximum additional strain $\Delta\varepsilon_{\text{ult}}$ corresponding to an infinitesimal strain rate, i.e., $\dot{\varepsilon}_{vp}$ approaching 0.0, from a strain rate of $1.0\times10^{-7}\ \text{s}^{-1}$ calculated as a function of $C_c/(1+e_0)$ with Eq. (7). Fig. 16(b) shows additional strains in the field $\Delta\varepsilon_{\text{Field}}$ calculated as a function of $C_c/(1+e_0)$ and in situ strain rate $\dot{\varepsilon}_{\text{Field}}$. Ranges of field data obtained at eastern Canada (Berthierville and Saint-Alban) and Sweden (Väsby) sites as well as the Osaka Bay clay (Ma12) in Japan are marked in the figure. This chart is very simple and useful in applying the isotache concept to engineering practice.

Conclusions

Watabe et al. (2008) proposed a method to simply introduce the isotache concept, which uses a compression curve normalized by preconsolidation pressure [ε–$\log(\sigma'/\sigma'_p)$] and a strain rate dependency relationship between the preconsolidation pressure (σ'_p) and strain rate ($\dot{\varepsilon} = d\varepsilon/dt$). The compression curve and the strain rate dependency relationship are obtained from a CRS test and a LT test, respectively. The strain rate dependency relationship is modeled as an equation based on power law with three parameters that represent a lower limit of preconsolidation pressure at an infinitesimal strain rate ($\dot{\varepsilon} = 0$) and the value and slope of the preconsolidation pressure at a large strain rate ($\dot{\varepsilon} = 1$). The authors call these three parameters isotache parameters. In Watabe et al. (2012), the three parameters [σ'_{pL}, c_1, and c_2 in Eq. (4)] can be commonly determined for Osaka Bay clays as well as worldwide clays with various characteristics, i.e., $\sigma'_{pL}/\sigma'_{p0} = 0.70$, $c_1 = 0.935$, and automatically $c_2 = 0.107$. Here, σ'_{p0} is defined as the preconsolidation pressure corresponding to $\dot{\varepsilon}_{vp} = 1.0\times10^{-7}\ \text{s}^{-1}$, which is close to the strain rate corresponding to 24-h incremental loading oedometer test results. This fitting curve is named the integrated fitting curve.

The slope (denoted α) of the $\log(\sigma'_p/\sigma'_{p0})$–$\log\dot{\varepsilon}_{vp}$ relationship at a given strain rate, which also corresponds to the ratio of the secondary compression index $C_{\alpha e}$ to the compression index C_c, can be calculated from the integrated fitting curve, showing that it is not constant but decreases with decreasing $\dot{\varepsilon}_{vp}$. This tendency is consistent with the comments made by Leroueil (2006) and is quantitatively clarified with Eq. (4) and the common isotache parameters. The main conclusions newly obtained in this study are as follows:

1. Based on the proposed method, the argument on constant $C_{\alpha e}/C_c$ concept versus isotache concept was theoretically discussed, and there is much evidence to support the isotache concept, resulting in Hypothesis B.
2. In engineering practice, consolidation settlement is generally estimated based on the e–$\log\sigma'_v$ curve obtained from 24-h incremental loading oedometer tests, which corresponds to a strain rate of about $1\times10^{-7}\ \text{s}^{-1}$. Using the compression index C_c at the consolidation pressure σ'_v, the maximum additional strain (creep strain) can be estimated by Eq. (7) with $\sigma'_{pL}/\sigma'_{p0} = 0.7$, which can be used for worldwide inorganic clays. Additional strains (creep strains corresponding to a strain smaller than $1\times10^{-7}\ \text{s}^{-7}$) in the field calculated as a function of $C_c/(1+e_0)$ and in situ strain rate can be calculated by Eq. (8) and charted as Fig. 16(b).

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Notation

The following symbols are used in this paper:

C_c = compression index;
$C_{\alpha e}$ = coefficient of secondary consolidation;
c_1, c_2 = constants for Eq. (4);
e_0 = initial void ratio;
t = elapsed time;
α = slope of $\log \sigma'_p - \log \dot{\varepsilon}_{vp}$ relationship ($= C_{\alpha e}/C_c$);
ε = total strain;
ε_e = elastic strain;
$\dot{\varepsilon}_{\text{Field}}$ = viscoplastic strain rate at the field;
ε_{vp} = viscoplastic strain;
$\dot{\varepsilon}_{vp}$ = viscoplastic strain rate;
ε_0 = strain at $\sigma'_v = \sigma'_{v0}$;
σ'_p = preconsolidation pressure (consolidation yield stress p'_c);
σ'_{pL} = lower limit of σ'_p;
σ'_{p0} = σ'_p corresponding to $\dot{\varepsilon}_{vp} = 1.0 \times 10^{-7}\ \text{s}^{-1}$;
σ'_v = vertical effective consolidation pressure; and
σ'_{v0} = overburden effective stress.

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