Integrated interpretation with isotache concept of long-term consolidation behaviour for worldwide clays

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ABSTRACT
The authors proposed a simplified method based on the isotache concept by using a compression curve and relationship between the consolidation yield stress (preconsolidation pressure) and the strain rate. The latter is expressed by an equation with three isotache parameters. The isotache parameters commonly determined for the Osaka Bay clays retrieved from various depths up to 300 m below the seabed are applicable to worldwide clays with various characteristics.

RÉSUMÉ
Les auteurs ont proposé une méthode simplifiée fondée sur le concept isotache en utilisant une courbe de compression et la relation entre la pression de préconsolidation et la vitesse de déformation. Celui-ci est exprimée par une équation à trois paramètres isotache. Les paramètres isotache souvent déterminée pour la baie d'Osaka argiles extraites de différentes profondeurs allant jusqu'à 300 m sous le fond marin sont applicables aux argiles à travers le monde avec des caractéristiques différentes.

1 INTRODUCTION

The consolidation characteristics of clay interpreted with isotache concept in which the effect of the strain rate on the compression characteristics is considered have been studied by many researchers including the authors. Most of these studies are aimed at calculating the secondary consolidation in consideration of the strain rate effect (e.g., Leroueil et al., 1985; Yin et al., 1994; Adachi et al., 1996; Kim and Leroueil, 2001; Imai et al., 2005; Tanaka et al., 2006; Watabe et al., 2008; Qu et al., 2010).

The isotache concept was proposed by Šuklje (1957), which involves viscosity and introduces a unique relationship between the strain and the consolidation pressure corresponding to the strain rate in association with the viscosity. This concept, which focuses on the strain rate effect, has attracted a lot of attention in recent researches on consolidation. Recently, the authors (Watabe et al., 2008) proposed a simplified method with the isotache concept using a reference compression curve and a function of strain rate dependency of consolidation yield stress (preconsolidation pressure) obtained from both the constant rate of strain one-dimensional consolidation test (CRS test) and long-term consolidation test under constant applied stress (LT test). It is noteworthy that the isotache parameters used in this method can be commonly determined for the Osaka Bay clays retrieved from various depths up to 300 m below the seabed at the Kansai International Airport, indicating that this method is very useful in practice because we do not need to determine the parameters at each depth.

This study aims at investigating the applicability of the proposed method with the common isotache parameters to worldwide clays with various characteristics.

2 PROPOSED METHOD

The authors use the very simple equations proposed by Leroueil et al. (1985); but applied to the visco-plastic deformation only. For clarity, we employ the ε_{vp} – log p' relationship, where ε_{vp} is the visco-plastic strain, which is defined as the difference between the total strain ε obtained from the consolidation test and the elastic strain ε_e. We then use Equations 1, 2, and 3.

$$\varepsilon_{vp} = \varepsilon - \varepsilon_e \quad [1]$$

$$\frac{p'}{p'_c} = f(\varepsilon_{vp}) \quad [2]$$

$$p'_c = g(\dot{\varepsilon}_{vp}) \quad [3]$$

Here, p' is the vertical effective consolidation pressure (σ'_v), p'_c is the consolidation yield stress (pre consolidation pressure σ'_p) and $\dot{\varepsilon}_{vp}$ is the strain rate defined as $d\varepsilon_{vp}/dt$. In order to obtain the relationships expressed by Equations 2 and 3, the CRS and LT tests are required to be performed. The details will be described later.

Table 1. Physical properties of the Osaka Bay clay samples.

Layer	Ma13	Ma12	Ma11	Ma10	Ma9	Ma8	Ma7a	Ma7b	Ma3	Ma4	Ma13Re
Undisturbed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Reconstituted	No	No	No	No	No	No	No	No	No	No	Yes
Depth (C.D.L.–m)	39	61	109	161	195	208	223	271	325	264	30–40
Overburden effective stress σ'_{v0} (kPa)	88	286	619	1014	1262	1348	1457	1839	2278	1802	(98)
Consolidation yield stress p'_c (kPa)	122	439	737	1357	1719	1698	1887	1991	3016	2512	134
Overconsolidation ratio *OCR*	1.39	1.53	1.19	1.34	1.36	1.26	1.30	1.08	1.32	1.39	(1.37)
Soil particle density ρ_s (g/cm^3)	2.66	2.66	2.67	2.69	2.72	2.72	2.70	2.71	2.61	2.67	2.70
Liquid limit w_L (%)	75.1	102.6	88.9	94.5	87.6	91.8	100.4	97.0	119.3	93.6	91.3
Plastic limit w_p (%)	31.9	40.8	34.4	35.8	33.3	35.8	37.8	38.6	41.7	35.3	30.3
Plasticity index I_p	43.2	61.8	54.5	58.7	54.3	56.0	62.6	58.4	77.6	58.3	61.0
Natural water content w_n (%)	62.0	83.8	55.4	52.6	52.2	49.9	49.0	52.9	52.3	50.6	71.5

The parameter ε_e is defined as the strain expressed by the straight line passing through the points (p', ε) = (1 kPa, 0) and (σ'_{v0}, ε_0) on the ε – log p' curve. The value ε_e that corresponds to p' is denoted as $\varepsilon_e(p')$. Here, σ'_{v0} denotes the overburden effective stress and ε_0 denotes the strain at $p' = \sigma'_{v0}$ (see Figure 2 in Watabe et al., 2008). From the ε – log p' curve obtained from the CRS test, ε_{vp} is calculated as the difference between ε and ε_e; the ε_{vp} – log p' curve is then obtained. The parameter p' is normalized by the value of the consolidation yield stress (preconsolidation pressure) p'_c read from the ε_{vp} – log p' curve, and subsequently the ε_{vp} – log p'/p'_c curve that corresponds to Equation 2 is obtained. Hereafter, this curve is called the "reference compression curve."

Because the pore water pressure u is generally not measured in the LT test, the effective consolidation pressure p' cannot be evaluated during primary consolidation. However, during the secondary consolidation stage, the excess pore water pressure is essentially zero ($\Delta u = 0$), i.e., p' is equivalent to p that is constant. Therefore, $\dot{\varepsilon}$ essentially coincides with $\dot{\varepsilon}_{vp}$.

The parameter $\dot{\varepsilon}_{vp}$ is calculated from the secondary consolidation section (after the end of primary consolidation (EOP)) of the ε – log t curve (consolidation curve) observed in the LT test under a constant consolidation pressure of p'; $\dot{\varepsilon}_{vp}$ is then obtained as a function of ε_{vp}. The quantity p'/p'_c is obtained as a function of ε_{vp} from the reference compression curve (ε_{vp} – log p'/p'_c curve); p'_c is then calculated from p' and $p'/p'_c(\dot{\varepsilon}_{vp})$. This procedure is repeated for some $\dot{\varepsilon}_{vp}$ values, and then the (p'_c, $\dot{\varepsilon}_{vp}$) data set that corresponds to Equation 3 are obtained.

The model equation of the strain rate dependency used in this proposed method, i.e., p'_c – $\dot{\varepsilon}_{vp}$ relationship in Equation 3, is as follows. Watabe et al. (2008) proposed Equation 4:

$$\ln \frac{p'_c - p'_{cL}}{p'_{cL}} = c_1 + c_2 \ln \dot{\varepsilon}_{vp} \qquad [4]$$

Here, c_1 and c_2 are constants and p'_{cL} is the lower limit of p'_c. When $\dot{\varepsilon}_{vp}$ decreases to zero in Equation 4, p'_c converges to p'_{cL}. Note here that Equation 4 is essentially the same as that proposed by Qu et al. (2010), in which it was directly derived from Norton's power law (Norton, 1929) in conjunction with overstress viscoplastic theory (Perzyna, 1963).

The parameter c_1 is equal to $\ln\{(p'_c - p'_{cL})/p'_{cL}\}$ at $\dot{\varepsilon}_{vp} = 1$, i.e., it represents the relative position of the log p'_c – log $\dot{\varepsilon}_{vp}$ curve. The parameter c_2 represents the level of strain rate dependency. The compressibility of the soil which reflects the level of developed skeletal structure is represented by the reference compression curve expressed by Equation 2. Consequently the reference compression curve and three isotache parameters (p'_{cL}, c_1 and c_2) are required in the proposed method. In the relationship expressed by Equation 4, if it is assumed that the curve passes on certain point, the parameter c_2 is automatically calculated as a dependent variable of p'_{cL} and c_1 (or the parameter c_1 is automatically calculated as a dependent variable of p'_{cL} and c_2). The details will be described later.

3 TESTING PROCEDURE

3.1 Constant rate of strain consolidation test (CRS test)

CRS tests were conducted on specimens with a diameter of 60 mm and a height of 20 mm. The cell was filled with deaired water; a hydraulic pressure of 98 (or 196) kPa was applied as backpressure. The specimen was compressed at a constant $\dot{\varepsilon}_{vp}$ of 0.02%/min (= 3.3 × 10^{-6} s^{-1}).

3.2 Long-term consolidation test (LT test)

An oedometer was assembled with a specimen with a diameter of 60 mm and a height of 20 mm. A consolidation pressure equivalent to σ'_{v0} was applied for 24 h or seven days. Subsequently, a target pressure was applied for the long-term consolidation until $\dot{\varepsilon}_{vp}$ decreased to 3.3 × 10^{-9} s^{-1}. Target pressures in the range of σ'_{v0} to 1.5–3.5 times of p'_c were specified for each sample.

Table 2. The LT test conditions for the Osaka Bay clays.

Sample	Pressures for preliminary consolidation (kPa)		Pressures for long-term consolidation (kPa)
	24 hours (or 2 hours) incremental loading	24 hours (or 7 days) loading at σ'_{v0}	
Ma13	10→29→	88 (7 days)→	98, 137, 206, 235, 353 and 412
Ma12	39→79→157→	294 (7 days) →	333, 373, 412, 451, 490, 529, 608, 686, 882 and 1370
Ma11	39 (2 hours)→	628 →	647, 667, 686, 706, 726, 745, 1000 and 1569
Ma10	157→314→627 →	1014→	2275 and 2903
Ma9	157→314→627→	1262→	2511 and 3295
Ma8	39 (2 hours)→	1373 →	1412, 1471, 1530, 1589, 1648, 1726, 1785 and 2040
Ma7a	39 (2 hours)→	1491 →	1549, 1608, 1667, 1726, 1785, 1844, 1922 and 2177
Ma7b	157→314→627→1255→	1843→	2991
Ma4	39 (2 hours)→	1863 →	1902, 1961, 2059, 2157, 2256, 2354, 2452 and 3138
Ma3	157→314→627→1255 →	2275→	4521
Ma13Re	10→29→	88 →	118, 137, 206, 275, 343 and 412

4 COMPRESSIBILITY OF THE OSAKA BAY CLAYS

4.1 Clay samples

The Osaka Bay clay samples were retrieved from geotechnical investigation sites of the second-phase project of the Kansai International Airport. Approximately 20 m of the thick surface layer is composed of Holocene clay deposits called Ma13. Below this layer is a very thick layer of Pleistocene deposits that comprised alternating clay and sand layers. Marine clays are numbered starting from Ma13 and the numbering decreases with depth. The reconstituted Ma13, which was remoulded and preliminarily consolidated under 98 kPa and named Ma13Re, was also tested. The data for Ma13, Ma12, Ma11, Ma8, Ma7, Ma4 and Ma13Re have already been presented in Watabe et al. (2008). The data for Ma10 and Ma9 are updated in this study. The data for Ma7 at different depth (previous Ma7 is renamed Ma7a and the new Ma7 is named Ma7b) and Ma3 are newly obtained. The physical properties of the clay samples are listed in Table 1.

4.2 Test results

All the reference compression curves are shown in Figure 1. The curve for Ma13Re shows a bi-linear relationship pattern, which yields at p'_c. This pattern is typically observed for non-structured clays. The Ma13 curve is also similar to this. A unique reference curve is formed by the Ma12 to Ma3 curves, and it exhibits overshooting around p'_c and a concave shape in the normal consolidation range.

The test conditions for LT tests are listed in Table 2. The consolidation curves (ε – log *t* curves) obtained from the LT tests for Ma10 is shown in Figure 2 as an example. The parameter ε is calculated using the initial specimen height (= 20 mm) and it is offset by the strain after the preliminary consolidation under σ'_{v0}. Thus, all the consolidation curves start from zero strain.

The EOP appears after the inflection point between

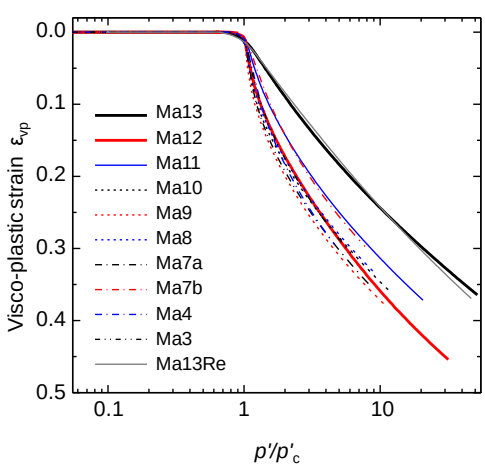

Figure 1. Superimposed reference compression curves for the Osaka Bay clays.

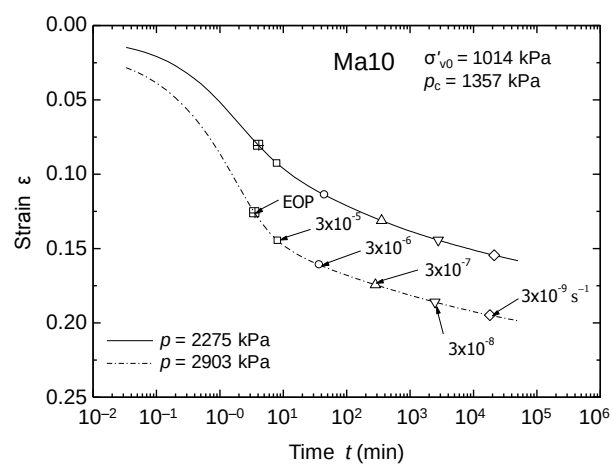

Figure 2. Consolidation curves (ε – log *t* curves) observed in the LT tests for Ma10.

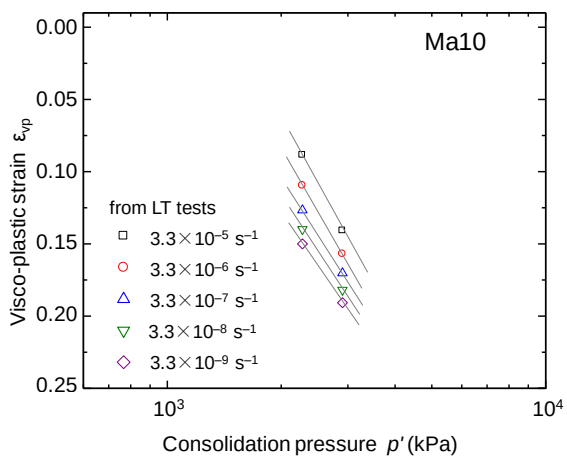

Figure 3. Strain rate dependency in ε_{vp} – log p' relationship obtained from the LT tests for Ma10.

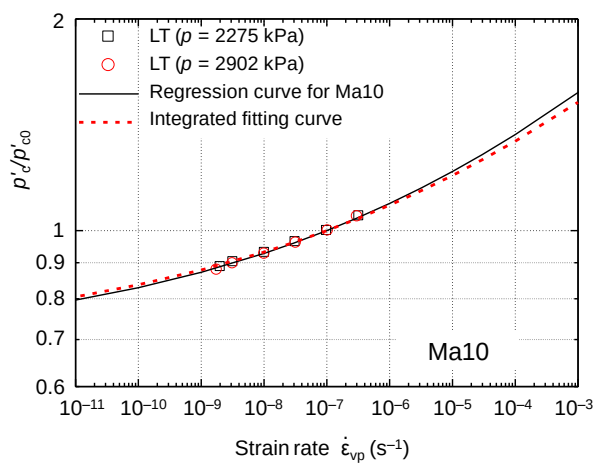

Figure 4. The log p'_c/p'_{c0} – log $\dot{\varepsilon}_{vp}$ relationships and the fitting with Equation 4 for Ma10.

the convex and the concave parts of the curve. The points corresponding to the $\dot{\varepsilon}_{vp}$ values of 3.3 × 10^{-5}, 3.3 × 10^{-6}, 3.3 × 10^{-7}, 3.3 × 10^{-8}, and 3.3 × 10^{-9} s^{-1} are shown on the curves. The relationships between the consolidation pressure p', i.e., the long-term consolidation pressure, and ε_{vp} corresponding to these $\dot{\varepsilon}_{vp}$ values are plotted in Figure 3. We can clearly identify the compression line in normal consolidation range corresponding to each strain rate. This strain rate dependency is consistent with the isotache concept.

The consolidation yield stress p'_c is obtained as a function of $\dot{\varepsilon}_{vp}$ from the reference compression curve (ε_{vp} – log($p'/p'_c(\dot{\varepsilon}_{vp})$)) by using the data set of p' and ε_{vp} (Figure 3), and the relationship is plotted in Figure 4 for Ma10. The isotache parameters p'_{cL}, c_1 and c_2 in Equation 4 are adjusted by fitting to this log p'_c – log $\dot{\varepsilon}_{vp}$ relationship. The fitting is performed by the least square method for c_1 and c_2 for various p'_{cL} values. The vertical axis representing p'_c for the fitting curve is normalized by p'_{c0}. Here, p'_{c0} is defined as the p'_c corresponding to an $\dot{\varepsilon}_{vp}$ value of 1.0 × 10^{-7} s^{-1}.

Table 3. The isotache parameters obtained by the fitting with Equation 4 and p'_{cL} = 0.70 × p'_{c0}.

Sample	σ'_{v0} (kPa)	p'_{c0} (kPa)	p'_{cL} (kPa)	p'_{cL}/p'_{c0}	c_1	c_2
Ma13	88	112.8	79.0	0.70	1.13	0.119
Ma12	286	378.4	264.8	0.70	1.13	0.119
Ma11	619	686.3	480.4	0.70	1.17	0.121
Ma10	1014	1296	907.0	0.70	1.05	0.114
Ma9	1087	1577	1104	0.70	0.56	0.084
Ma8	1348	1469	1029	0.70	1.11	0.118
Ma7a	1457	1540	1078	0.70	1.06	0.115
Ma7b	1839	1834	1283	0.70	0.41	0.075
Ma4	1802	2054	1438	0.70	1.08	0.116
Ma3	2278	2666	1866	0.70	0.56	0.085
Ma13Re	–	128.3	89.8	0.70	1.03	0.113

In Watabe et al. (2008), the consolidation yield stress corresponding to a $\dot{\varepsilon}_{vp}$ value of 3.3 × 10^{-6} s^{-1}, which is the strain rate in CRS test, was denoted as p'_{c0}. In the present study, however, the consolidation yield stress corresponding to a $\dot{\varepsilon}_{vp}$ value of 1.0 × 10^{-7} s^{-1}, which is close to the average strain rate corresponding to 24 h incremental loading consolidation test, is denoted as p'_{c0}. This strain rate value was obtained for the series of 24 h incremental loading oedometer tests in practice for the Kansai International Airport project. It is also consistent with the data for Canadian clays shown in Leroueil (2006). We believe that this modification makes its definition much clear in the essential meaning of p'_{c0} in engineering practice.

For all the depths of the Osaka Bay clays, Watabe et al. (2008) concluded that p'_{cL}/p'_{c0} = 0.55 can be commonly used, and then, the other parameters c_1 and c_2 were also commonly determined as 1.08 and 0.101, respectively. Note here that p'_{cL}/p'_{c0} = 0.55 with p'_{c0} corresponding to $\dot{\varepsilon}_{vp}$ = 3.3 × 10^{-6} s^{-1} in Watabe et al. (2008) can be converted to p'_{cL}/p'_{c0} = 0.70 with p'_{c0} corresponding to $\dot{\varepsilon}_{vp}$ = 1.0 × 10^{-7} s^{-1} in the present study. The log p'_c/p'_{c0} – log $\dot{\varepsilon}_{vp}$ relationship evaluated with Equation 4 is indicated by solid line in Figure 4. The isotache parameters were evaluated as, e.g., p'_{cL} = 907.0 (p'_{cL}/p'_0 was assumed to be 0.70), c_1 = 1.05 and c_2 = 0.114 for Ma10. From the definition, the curve passes through p'_c/p'_{c0} = 1 at $\dot{\varepsilon}_{vp}$ = 1.0 × 10^{-7} s^{-1}. The fitting curve and the test results are compared thoroughly.

When we use p'_{cL}/p'_{c0} = 0.70 as the common value for all the Osaka Bay clays examined as concluded by Watabe et al. (2008), the isotache parameters p'_{cL}, c_1 and c_2 are determined by the least square method, and those values are listed in Table 3. Note here that if $p'_c = p'_{c0}$ and $\dot{\varepsilon}_{vp}$ = 1.0 × 10^{-7} s^{-1} are substituted into Equation 4, the parameter c_2 can be expressed as a function of the parameter c_1 as follows:

$$c_2 = \frac{\ln \dfrac{p'_c - p'_{cL}}{p'_{cL}} - c_1}{\ln \dot{\varepsilon}_{vp}} = \frac{\ln \dfrac{1-0.7}{0.7} - c_1}{\ln 1.0\times10^{-7}} = \frac{c_1 + 0.847}{16.12} \quad [5]$$

Therefore, the strain rate dependency of consolidation yield stress can be essentially expressed with two

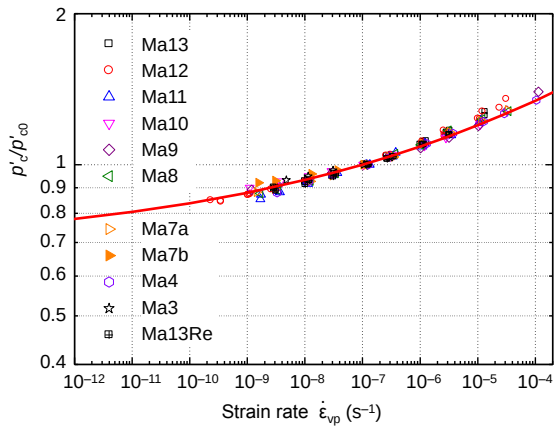

Figure 5. The log p'_c/p'_{c0} – log $\dot{\varepsilon}_{vp}$ relationship for all the Osaka Bay clays comparing to the integrated fitting curve.

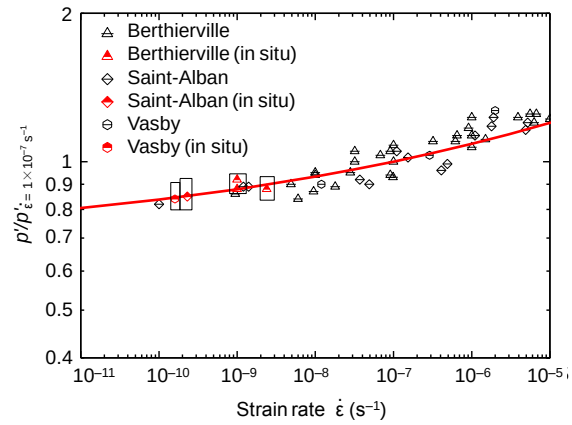

Figure 6. Normalized stress – strain rate relationship for Canadian and Swedish clays (from Leroueil et al. (1988) with an interpretation after Leroueil (2006)) comparing to the integrated fitting curve for the Osaka Bay clays.

isotache parameters of p'_{cL} and c_1, and the other parameter c_2 is automatically deduced by Equation 5.

In Table 3, c_1 and c_2 are evaluated as 0.935 ± 0.279 (COV = 0.298) and 0.107 ± 0.017 (COV = 0.158). Following the conclusions of Watabe et al. (2008), we decided to use all the data sets to determine the common isotache parameters, even though the data variation is larger. Note here that because the results are for natural clays, some variation is inevitable. Consequently, p'_{cL}/p'_{c0} = 0.70 and c_1 = 0.935 are determined as the common isotache parameters for Osaka Bay clays in this study. The fitting curve corresponding to p'_{cL}/p'_{c0} = 0.70 with parameter(s) c_1 = 0.935 (and c_2 = 0.107) is shown by dotted line in Figure 4.

The log p'_c/p'_{c0} – log $\dot{\varepsilon}_{vp}$ relationship for all the Osaka Bay clays are superimposed in Figure 5 comparing to the fitting curve expressed by Equation 4 along with the common isotache parameters (p'_{cL}/p'_{c0} = 0.70 and c_1 = 0.935). The test results and fitting curve are compared thoroughly. This fact indicates that the strain rate dependency can be modeled by this common fitting curve as an integrated interpretation for the Osaka Bay clays.

The reference compression curves of the Holocene clays (Ma13 and Ma13Re) were significantly different from those of the Pleistocene clays (Ma12 and deeper ones). However, it is very interesting that the isotache parameters in the normal consolidation range can be commonly determined for all the specimens of the Osaka Bay clay examined in this study.

5 APPLICATION TO WORLDWIDE CLAYS

5.1 Comparison to previous data sets—motivation of this study

The integrated fitting curve determined for the Osaka Bay clays in this study and test results from Leroueil et al. (1988) with an interpretation after Leroueil (2006) are compared in Figure 6. Here, the parameter representing the vertical axis was obtained as $p'(\dot{\varepsilon})$ at ε = 10% normalized by $p'(\dot{\varepsilon} = 1.0 \times 10^{-7}\ s^{-1})$ at ε = 10%. The integrated fitting curve for the Osaka Bay clays is consistent with the data sets from both laboratory tests and in situ observations for the Canadian and Swedish clays. This fact indicates that the integrated fitting curve determined for the Osaka Bay clays should be available for worldwide clays. In the following part, applicability of the proposed method to worldwide clays with various characteristics is studied.

Table 4. Physical properties of the worldwide clay samples examined in the present study.

Sample	Rakusai	Amaga-saki	Ariake	Upper Haneda	Lower Haneda	Louise-ville	Pisa	Onsøy	Mexico City
Undisturbed	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Reconstituted	No	No	No	No	No	No	No	No	No
Depth (G.L.–m)	24	34	10	10	24	9	17	17	7
Overburden effective stress σ'_{v0} (kPa)	205	257	51	35	127	62	173	106	26
Consolidation yield stress p'_c (kPa)	846	542	57	72	242	190	261	129	43
Overconsolidation ratio OCR	4.13	2.11	1.12	2.07	1.91	3.06	1.51	1.22	1.65
Soil particle density ρ_s (g/cm^3)	2.73	2.69	2.63	2.69	2.66	2.75	2.76	2.77	2.65
Liquid limit w_L (%)	107.7	124.2	107.4	152.5	46.0	78.7	98.8	80.1	414.7
Plastic limit w_p (%)	33.7	44.0	45.4	63.1	21.9	21.6	32.6	24.8	64.2
Plasticity index I_p	74	80.2	62.0	89.4	24.1	57.1	66.2	55.3	350.5
Natural water content w_n (%)	62.8	82.9	139.0	150.6	40.9	74.3	54.9	61.3	395.2

Table 5. The LT test conditions for the worldwide clay samples examined in this study.

Sample	Pressures for preliminary consolidation (kPa)		Pressures for long-term consolidation (kPa)
	24 hours (or 2 hours) incremental loading	7 days (or 24 hours) loading at σ'_{v0}	
Rakusai	39 (2 hours)→	196 (24 hours)→	314, 471, 549, 628, 726, 824 and 941
Amagasaki	39 (2 hours)→	255 (24 hours)→	314, 373, 412, 451, 490 and 608
Ariake	9.8→20→	49→	83, 113 and 172
Upper Haneda	4.9→9.8→20→	35→	93 and 152
Lower Haneda	20→39→	127→	314 and 549
Louiseville	10→29→	59→	137, 196, 275, 373 and 471
Pisa	39→78→	176 (24 hours)→	177, 265 and 530
Onsøy	20→49→	98→	118, 137, 176, 235 and 353
Mexico City	10→20→	29→	69 and 88

5.2 Clay samples

The isotache concept with the integrated fitting curve determined for the Osaka Bay clays is attempted to apply to worldwide clays with various characteristics. The physical properties of the clay samples examined in this section are listed in Table 4. The Amagasaki and Rakusai clays (Tanaka et al., 2002), Ariake clay (e.g., Hanzawa et al., 1990). Haneda clay (Watabe and Noguchi, 2011), Louiseville clay (Leroueil et al.,2003), Pisa clay (Lo Presti et al., 2003), Onsøy clay (Lunne et al., 2003), and Mexico City clay (Díaz-Rodríguez, 2003) are considered in this study.

5.3 Test results

Both CRS and LT tests were conducted for the worldwide clays. The testing procedures are the same as that conducted for the Osaka Bay clays. The test conditions for LT tests are listed in Table 5. The results obtained from these tests are described hereunder.

The reference compression curves of the nine clays are shown in Figure 7. This figure corresponds to Figure 1 for the Osaka Bay clays. The curve for the Lower Haneda clay shows a bi-linear relationship pattern with the smallest change in visco-plastic strain. The curves for the other clays exhibit overshooting around p'_c and a concave shape in the normal consolidation range. This is a typical pattern for structured clays as abovementioned for the Pleistocene Osaka Bay clays. This tendency is the most significant in the Louiseville clay, which shows slight decrease in effective vertical stress because of the excess pore water pressure generated by brittle yielding.

The consolidation curves (ε – log *t* curves) for the Louiseville clay obtained from the LT tests are shown as an example in Figure 8. The tendency seen in these curves is very similar to that seen in the curves obtained for the Osaka Bay clays. The points corresponding to the $\dot{\varepsilon}_{vp}$ of 3.3×10^{-6}, 3.3×10^{-7}, 3.3×10^{-8}, and 3.3×10^{-9} s^{-1} are shown on the curves.

In the overconsolidated domain, p = 137 kPa, a significant delayed consolidation was observed during the secondary consolidation stage. This tendency is consistent with the results obtained for eastern Canada clays (Leroueil et al., 1985) and Osaka Bay clays (Watabe et al., 2008). This fact can be clearly explained with the isotache concept. As illustrated in Figure 9, even

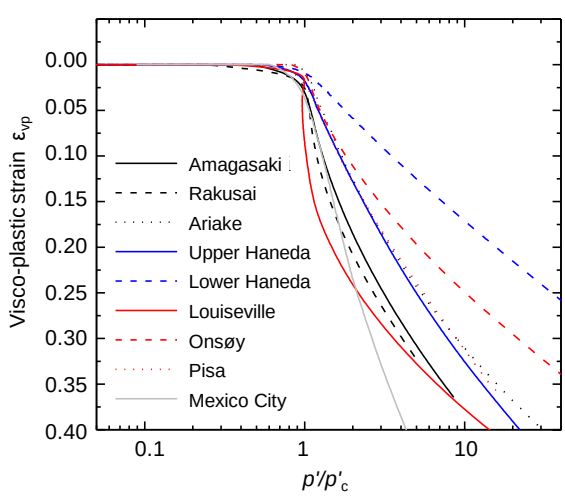

Figure 7. Superimposed reference compression curves for the worldwide clay samples examined in the present study.

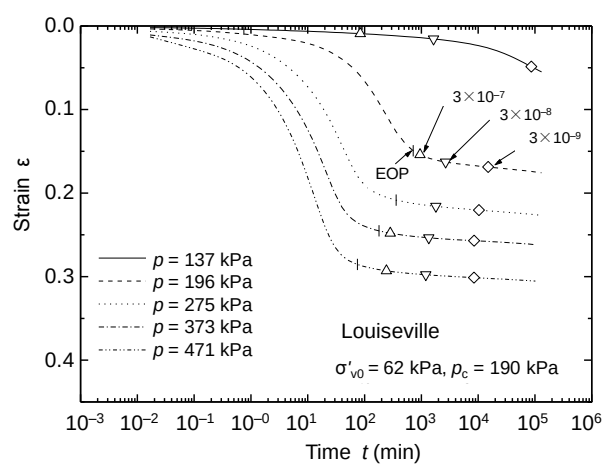

Figure 8. Consolidation curves (ε – log t curves) observed in the LT tests for Louiseville clay.

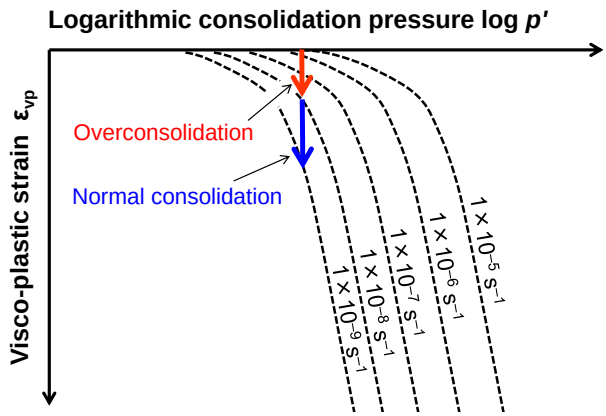

Figure 9. Illustration of transition from overconsolidaiton with a small strain rate to normal consolidation with a high strain rate.

though, the clay was originally in overconsolidation range at a high strain rate, its state becomes beyond the yield stress p'_c when the strain rate decreases to a significantly smaller value during the secondary consolidation stage under a constant effective stress p'.

The values of ε_{vp} corresponding to the $\dot{\varepsilon}_{vp}$ values of 3.3×10^{-6}, 3.3×10^{-7}, 3.3×10^{-8}, and 3.3×10^{-9} s^{-1} are obtained from the LT test results. The consolidation yield stress p'_c is obtained as a function of $\dot{\varepsilon}_{vp}$ from the reference compression curve by using the data set of p' and ε_{vp}. The results are plotted in Figure 10, which corresponds to Figure 5 for the Osaka Bay clays. On vertical axis p'_c is normalized by p'_{c0}, consequently, all the test results passes through $p'_c/p'_{c0} = 1$ at $\dot{\varepsilon}_{vp} = 1.0 \times 10^{-7}$ s^{-1}. The integrated fitting curve with the common isotache parameters determined for the Osaka Bay clays ($p'_{cL}/p'_{c0} = 0.70$ and $c_1 = 0.935$) is superimposed. The trend of the test results, except the Pisa clay, and the integrated fitting curve are compared thoroughly. Note here that because the results are for natural clays, some variation is inevitable. However, the integrated fitting curve is useful as a primary approximation to conduct a rough calculation for the secondary consolidation behaviour, because the difference is not so significant. The model also fits the laboratory results (Figure 6) obtained by Leroueil et al. (1985), indicating that the model is very general for inorganic clays.

5.4 Discussions

The test results obtained from the series of LT tests with interpretation along with the reference compression curve (CRS test results) for all the worldwide clays examined, including the Osaka Bay clays, are superimposed in Figure 10. The integrated fitting curve determined for the Osaka Bay clays is also superimposed in this figure. In addition, in situ strain rates observed in the Osaka Bay clays are plotted. Here, the parameter representing the vertical axis for the in situ data was obtained as $p'(\dot{\varepsilon})$ at $\varepsilon = 5\%$ normalized by $p'(\dot{\varepsilon} = 1.0 \times 10^{-7}\ s^{-1})$ at $\varepsilon = 5\%$.

These in situ strain rates were calculated from the settlements of sublayers in the first phase island of the Kansai International Airport. The strain rate obtained from the in situ observation ($\dot{\varepsilon}_{vp} = 1 \times 10^{-10}\ s^{-1} - 5 \times 10^{-10}\ s^{-1}$)

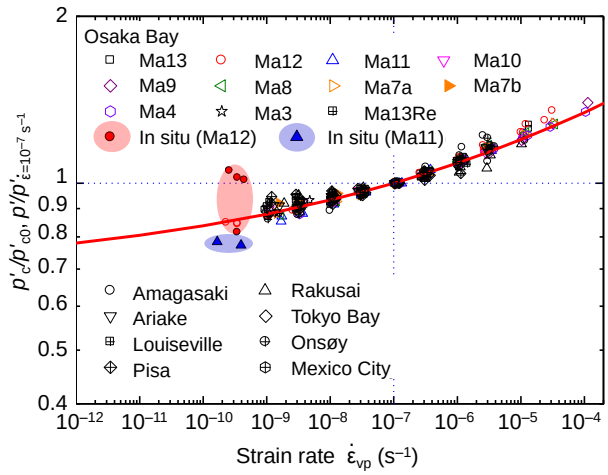

Figure 10. The log p'_c/p'_{c0} – log $\dot{\varepsilon}_{vp}$ relationship for all the worldwide clays examined, including the Osaka Bay clays, comparing to the integrated fitting curve.

is about one order of magnitude smaller than that obtained from LT test in the laboratory ($\dot{\varepsilon}_{vp} = 3.3 \times 10^{-9}$ s^{-1} at the end of LT test). The results from not only the LT tests in the laboratory but also the in situ measurements and the integrated fitting curve determined from the Osaka Bay clay are compared thoroughly.

It is very interesting that the integrated fitting curve with the common isotache parameters determined for the Osaka Bay clays can be applicable for the worldwide clays with various characteristics, even for the Mexico City clay whose characteristics are very exceptional in traditional soil mechanics, e.g., very high water content with cemented structure.

These facts indicate that the integrated fitting curve is very useful in practice. Because the integrated fitting curve is very widely applicable, we do not need in practice to carry out the LT test which requires a very long testing period. Actually, the range of $\dot{\varepsilon}_{vp}$ obtained from LT test is generally limited in the rage from 10^{-9} to 10^{-5} s^{-1}; however, the strain rate observed in situ is much smaller than this. Therefore, we need to extract the fitting curve in settlement prediction in practice. If we have a reference compression curve, which can be easily obtained from CRS test, secondary consolidation can be approximately calculated in consideration of the strain rate dependency, i.e., the isotache concept, represented by the integrated fitting curve. In the proposed method, difference of soil properties such as void ratio, consolidation yield stress (preconsolidation pressure) and compressibility are expressed by the reference compression curve.

6 CONCLUSIONS

Watabe et al. (2008) proposed a simplified method based on the isotache concept by using a compression curve and relationship between the consolidation yield stress (preconsolidation pressure) and the strain rate. The former and the latter are obtained from the constant rate of strain consolidation test (CRS test) test and long-term

consolidation test (LT test), respectively. The latter is expressed by Equation 4 with three isotache parameters (p'_{cL}, c_1 and c_2).

In the present study, additional tests to a series of CRS and LT tests for the clay samples collected at various depths (up to 300 m below the seabed) from the Osaka Bay after Watabe et al. (2008) were carried out to update the data sets of the test results. The isotache parameters can be commonly determined as p'_{cL}/p'_{c0} = 0.70 and c_1 = 0.935 for all the depths of the Osaka Bay clays. Here, p'_{c0} is defined as the consolidation yield stress corresponds to $\dot{\varepsilon}_{vp} = 3.3 \times 10^{-7}\ s^{-1}$, which is close to the average strain rate corresponding to 24 h incremental loading oedometer test. This fitting curve is named the integrated fitting curve. The parameter c_2 is calculated by Equation 5 as a function of parameters p'_{cL}/p'_{c0} and c_1.

A series of CRS tests and LT tests were carried out for worldwide clays with various characteristics in plasticity, minerals, structures, cementations, overconsolidation, etc. and then the proposed method were applied to those test results. It was found out that the long-term consolidation behaviour in not only the laboratory tests but also the in situ observations for the worldwide clays can be well characterized by the proposed method along with the integrated fitting curve (the common values of the isotache parameters).

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