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NORMALIZATION OF STRESS-STRAIN CURVES FROM CRS CONSOLIDATION TEST AND ITS APPLICATION TO CONSOLIDATION ANALYSIS

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ABSTRACT: The results of Constant Rate of Strain (CRS) consolidation test carried out at 0.02 %/min are normalized in order to produce stress-strain curves corresponding to strain rates slower than 0.02%/min. The normalizing procedure consists of two steps: 1) define the curve corresponding to OCR=1, and 2) normalize the difference between the curves defined in the first step and that directly obtained from CRS test. The resulting stress-strain curves are applied to the consolidation analysis of a marine clay deposit loaded by a test embankment. The comparison between the observed field behavior and the consolidation analysis presented here suggests that the normalizing procedure demonstrated the usefulness of CRS consolidation test in consolidation analysis.

Keywords: Constant rate of strain consolidation test, stress-strain curve, normalization, consolidation analysis

INTRODUCTION

Suzuki and Yasuhara, (2003) reported that Constant Rate of Strain (CRS) consolidation test carried out at a strain rate of 0.02 %/min can well explain consolidation settlement of soft marine clays improved by vertical drain method. The spacing between the vertical drains is designed to terminate consolidation settlement within, usually, several months. On the contrary, without vertical drain, consolidation takes from years to a couple of decades to finish, which means that settlement speed is about 1/10 slower than that observed in the ground improved by vertical drain. Stress-strain curves obtained from CRS consolidation test change as a strain rate used for the test changes. When the ground is not improved by vertical drain method, CRS test with a strain rate slower than 0.02 %/min seems preferable to consolidation analysis.

CRS test was proposed several decades ago by Crawford (1964) to evaluate stress-strain curves of clays within a short time. A strain rate of 0.02 %/min can give test specimens near 30 % of compression strain through a 24-hour loading. When much slower strain rate is used, one of the advantages of CRS test, fast operational speed, will disappear. If a stress-strain curve corresponding to a slow strain rate can be deduced from a CRS curve at a fast strain rate, comprehensive use of CRS test can be achieved, without losing its advantage, to analyze consolidation problems with or without vertical drain.

This paper first describes the normalization of CRS curves reported by Leroueil et al. (1985), and a modification to make it more convenient for consolidation analysis. Then, stress-strain curves obtained for a marine clay through the normalization are examined by comparing the results of one-dimensional consolidation analysis with monitored behavior of the ground under a test embankment.

Over consolidation ratio OCR is an important parameter for the normalization described in this paper. Naturally deposited Holocene clays are usually in overconsolidated state induced by aging effects such as chemical bonding and secondary compression, in spite of that they are not subjected to release of overburden stress (Hanzawa, 1983). The term OCR originally means the ratio between effective overburden stress currently bearing in the field and the maximum one in the past. However, this definition is not useful for Holocene clays due to the reason mentioned above. Therefore, Eq. (1) is employed in this paper to define OCR.

$$OCR = \frac{\sigma'_y}{\sigma'_{v0}} \tag{1}$$

where σ'_{v0} is the current value of effective overburden stress and σ'_y is consolidation yield stress.

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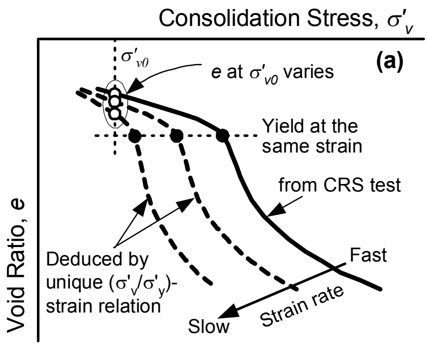
Note: Discussion on this paper is open until December 2005



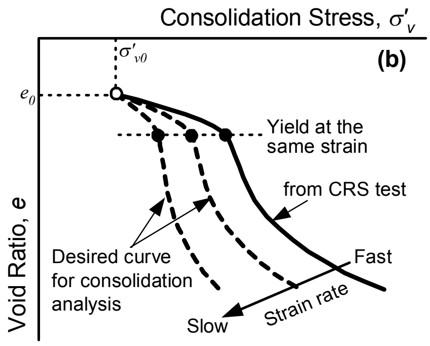


Fig. 1 (a) Strain rate effect on stress-strain relation for laboratory specimen; and (b) expected for clay in-situ

NORMALIZATION OF STRESS-STRAIN CURVES

According to Leroueil et al. (1985), a unique stress-strain relation can be determined from CRS test carried out at various strain rates, when consolidation stresses σ'_v are normalized by consolidation yield stress σ'_y. This means that a CRS curve at a certain strain rate can give another curve at another strain rate, provided that the relation between strain rates and σ'_y is known.

Figure 1(a) schematically shows a CRS curve directly obtained from the test and curves corresponding to strain rates slower than that of the test deduced from the CRS curve by the uniqueness of (σ'_v/σ'_y)-strain relation. As demonstrated in the figure, each curve has its own value of void ratio at $\sigma'_v=\sigma'_{v0}$. This would make the consolidation analysis inconvenient, because an actual ground has only one combination of σ'_{v0} and initial void ratio e_0 at a depth, from which different stress-strain curves start according to the strain rate as illustrated in Fig. 1(b).

For the consolidation analysis of a soft ground with vertical drain, a curve corresponding to a fast strain rate should be used. While for the consolidation analysis without vertical drain, a curve at a slow strain rate is appropriate. But the initial state of the ground expressed by the combination of σ'_{v0} and e_0 should be the same in both cases as shown in Fig. 1(b). In this regard, the normalization based on the uniqueness of (σ'_v/σ'_y)-strain relation cannot be applied directly to the consolidation analysis for actual clay deposits.

The comparison between Fig. 1(a) and (b) implies that the normalization should not be applied to the entire stress-strain curve, but only to the portion where σ'_v is equal to or greater than σ'_{v0}. For this purpose, Eq. (2) is the simplest way to normalize a CRS curve, in which $f(\varepsilon)$ is a normalization function and ε is given by $(e_0-e)/(1+e_0)$.

$$\frac{\sigma'_v-\sigma'_{v0}}{\sigma'_y-\sigma'_{v0}}=f(\varepsilon) \tag{2}$$

Equation (2) can be transformed to Eq. (3) as follows:

$$\begin{aligned}\sigma'_v &= \sigma'_{v0}+(\sigma'_y-\sigma'_{v0})f(\varepsilon)\\ &= \sigma'_{v0}+\sigma'_{v0}(OCR-1)f(\varepsilon)\end{aligned} \tag{3}$$

Leroueil et al. (1988) reported the results of CRS test performed for an overconsolidated Canadian clay with a variety of strain rates. They showed that a CRS curve at a very slow strain rate produced a σ'_y value equal to σ'_{v0}. Equation (3) is not valid for such a case, because it would result to $\sigma'_v = \sigma'_{v0}$ when OCR is equal to 1, and thus would no longer produce stress-strain curves as a function of ε. Therefore, Eq. (2) is not appropriate as a normalizing equation.

In order to produce stress-strain curves corresponding to different strain rates as shown in Fig. 1(b), a normalizing technique that can include the case where OCR=1 should be developed. From this viewpoint, stress-strain curves are normalized through the proposed procedures given below. Figure 2 illustrates the proposed procedures applied to the result of CRS test performed on an undisturbed Ariake clay sample.

1) Draw a stress-strain curve that corresponds to OCR=1 (Curve 1) from the curve obtained from CRS test at a strain rate of 0.02 %/min (Curve 2) with the use of Eq. (4) derived from the uniqueness of (σ'_v/σ'_y)-strain relation (Leroueil at al. 1985) as given below:

$$\sigma'_{v(1)} = \frac{\sigma'_{v(2)}}{\sigma'_{y(2)}} \sigma'_{v0} \tag{4}$$

where, $\sigma'_{y(2)}$ is the yielding stress appears on Curve 2, $\sigma'_{v(2)}$ is effective stress of Curve 2 at a certain strain, and $\sigma'_{v(1)}$ is effective stress of Curve 1 at the same strain.

2) Mark a point on Curve 2 corresponding to (σ'_{v0}, e_0) (Point A in Fig. 2).
3) Connect Point A and Curve 1 smoothly by a straight line in e-log σ'_v space as shown in Fig. 2. The inclination of the line depends on the position of Point A and the shape of Curve 1.
4) Assume the curve from points A to B to C as the stress-strain curve corresponding to OCR=1. Then, normalize the curve A-B-C and the hatched area in Fig. 2 by the following equations.

Curve A-B-C:

$$\sigma'_{norm1} = \frac{\sigma'_{v(ABC)} - \sigma'_{v0}}{\sigma'_{v0}} = f_{(1)}(\varepsilon) \tag{5}$$

Hatched area:

$$\sigma'_{norm2} = \frac{\sigma'_{v(2)} - \sigma'_{v(ABC)}}{\sigma'_{y(2)} - \sigma'_{v0}} = f_{(2)}(\varepsilon) \tag{6}$$

where, $\sigma'_{v(ABC)}$ represents the curve from A to B to C.

5) Draw a stress-strain curve corresponding to a given OCR with Eq. (7) derived from Eqs. (5) and (6), as given below:

$$\begin{aligned} \sigma'_v &= \sigma'_{v(ABC)} + (\sigma'_{y(2)} - \sigma'_{v0}) f_{(2)}(\varepsilon) \\ &= \sigma'_{v0} + \sigma'_{v0} f_{(1)}(\varepsilon) + (\sigma'_{y(2)} - \sigma'_{v0}) f_{(2)}(\varepsilon) \\ &= \sigma'_{v0} \left\{1 + f_{(1)}(\varepsilon) + (OCR - 1) f_{(2)}(\varepsilon)\right\} \end{aligned} \tag{7}$$

Figure 3 demonstrates normalized stress-strain curves obtained from Eqs. (5) and (6) applied to the CRS test result shown in Fig. 2. When ε is greater than that at point B in Fig. 2, the value of $\sigma'_{v(ABC)}$ in Eq. (5) is equal to $\sigma'_{v(1)}$. Then, Eqs. (4) to (6) yield Eqs. (8a) to (8c). Since Eq. (8b) is the same as the normalization described in Leroueil et al. (1985), it is evident that the curves of σ'_{norm1} and σ'_{norm2} in Fig. 3 move leftward when the compressibility of clay is low.

$$\sigma'_{norm1} = \frac{\sigma'_{v(1)} - \sigma'_{v0}}{\sigma'_{v0}} = \frac{\sigma'_{v(1)}}{\sigma'_{v0}} - 1 \tag{8a}$$

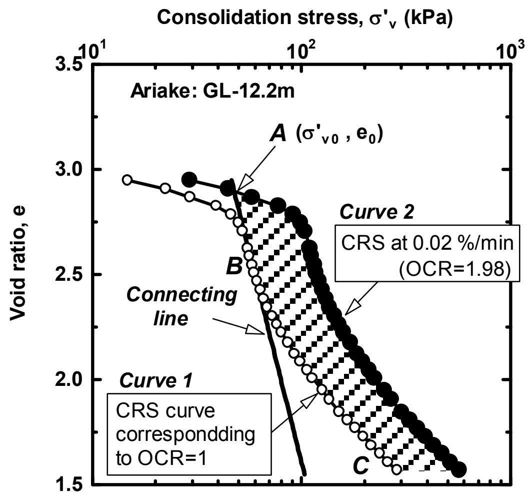


Fig. 2 Normalizing procedure applied for undisturbed

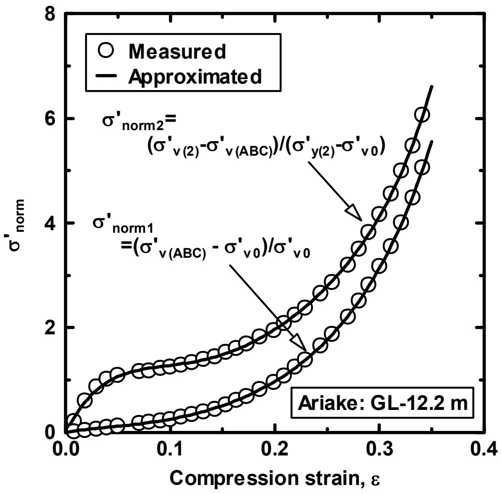


Fig. 3 Normalized curves obtained for undisturbed Ariake clay sample

$$\begin{aligned} \sigma'_{norm2} &= \frac{\sigma'_{v(2)} - \sigma'_{v(1)}}{\sigma'_{y(2)} - \sigma'_{v0}} \\ &= \frac{\sigma'_{v(2)} - (\sigma'_{v(2)} / \sigma'_{y(2)}) \sigma'_{v0}}{\sigma'_{y(2)} - \sigma'_{v0}} = \frac{\sigma'_{v(2)}}{\sigma'_{y(2)}} \end{aligned} \tag{8b}$$

$$\sigma'_{norm2} - \sigma'_{norm1} = 1 \tag{8c}$$

In order to produce stress-strain curves from Eq. (7), it is necessary to define $f_{(1)}(\varepsilon)$ and $f_{(2)}(\varepsilon)$. The two functions were defined in this paper by the same manner as Okumura and Suzuki (1991) who used a polynomial equation as expressed by Eq. (9) to approximate stress-strain curves.

$$\sigma'_v = A\varepsilon^5 + B\varepsilon^4 + C\varepsilon^3 + D\varepsilon^2 + E\varepsilon + F \quad (9)$$

where A to F are constants.

Equations (10) and (11) are the approximations of the two curves in Fig. 3. The constants in the equations were determined by the method of least squares applied to each curve. Ariake clay has high compressibility and so the approximation of the normalized curves using polynomial expression such as Eq. (9) can also be used for other clays. Once the functions of $f_{(1)}(\varepsilon)$ and $f_{(2)}(\varepsilon)$ are defined, stress-strain curves for different values of OCR can be given from the CRS test performed at 0.02 %/min as presented in Fig. 4.

$$\sigma'_{norm1} = f_{(1)}(\varepsilon) = 2024\varepsilon^5 - 1197\varepsilon^4 + 374.5\varepsilon^3 - 35.44\varepsilon^2 + 3.312\varepsilon \quad (10)$$

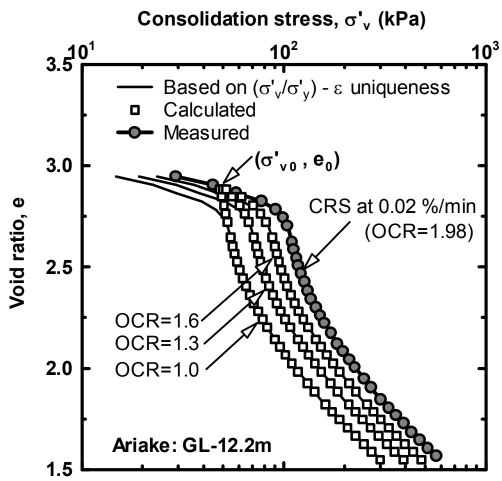


Fig. 4 e-log σ'v curves calculated from Eq. (7) for undisturbed Ariake clay sample

$$\sigma'_{norm2} = f_{(2)}(\varepsilon) = 8990\varepsilon^5 - 8222\varepsilon^4 + 3029\varepsilon^3 - 497.5\varepsilon^2 + 39.58\varepsilon \quad (11)$$

The proposed procedure assumes that the value of e_0 is on the CRS curve obtained from a strain rate of 0.02 %/min. This assumption presented reasonable performances in predicting actual settlement behavior of clays as reported by Okumura and Suzuki (1991) and Suzuki and Yasuhara (2003).

NORMALIZED CURVES OBTAINED FOR SOME CLAYS

The normalizing technique described in the previous section is applied to the stress-strain curves obtained from CRS tests for undisturbed samples taken from soft clay deposits found in Japan and Southeast Asia. All of the CRS tests were carried out at a strain rate of 0.02 %/min for the specimens with 60 mm diameter and 20 mm height. Plasticity index I_p and OCR of the clays are listed in Table 1. The normalized curves obtained for the clays in Table 1 are presented in Fig. 5, where the curves of σ'_{norm1} are in the left and σ'_{norm2} in the right. As can be seen in the figure, the normalized curves occupy very limited range and can be grouped into two or three for respective clays, with some exceptional curves. For Ariake, Isogo and Osaka-Bay clays, although some exceptional data exist, the normalized curves may be represented by a set of σ'_{norm1} and σ'_{norm2} curves to express an average stress-strain relation for each clay. The curves for Kuwana clay clearly can be divided into two groups. While for Yanai, Banjarmasin and Cebu clays, concentration of the curves is not clear, but seems to be represented by a few sets of curves.

Figure 5 implies that the normalization makes it easy to determine representative stress-strain curves for consolidation analysis. In the succeeding section, consolidation of Yanai clay is analyzed. Three groups of normalized curves are extracted from CRS test.

Table 1 The values of I_p and OCR obtained for clays in Japan and the Southeast Asia

Region	Name of clay	Location	Thickness	I_p	OCR
Japan	Ariake	Saga Pref.	18m	28 – 116	1.5 – 3.5
	Isogo	Kanagawa Pref.	30m	24 – 60	2.1 – 4.3
	Kuwana	Mie Pref.	20m	30 – 60	1.0 – 1.8
	Osaka-bay	Osaka Pref.	20m	45 – 80	1.4 – 2.5
	Yanai	Yamaguchi Pref.	13m	21 – 45	1.1 – 1.6
SE Asia	Banjarmasin	Indonesia	33m	47 – 111	1.6 – 2.9
	Cebu	Philippines	21m	19 – 89	1.3 – 3.5

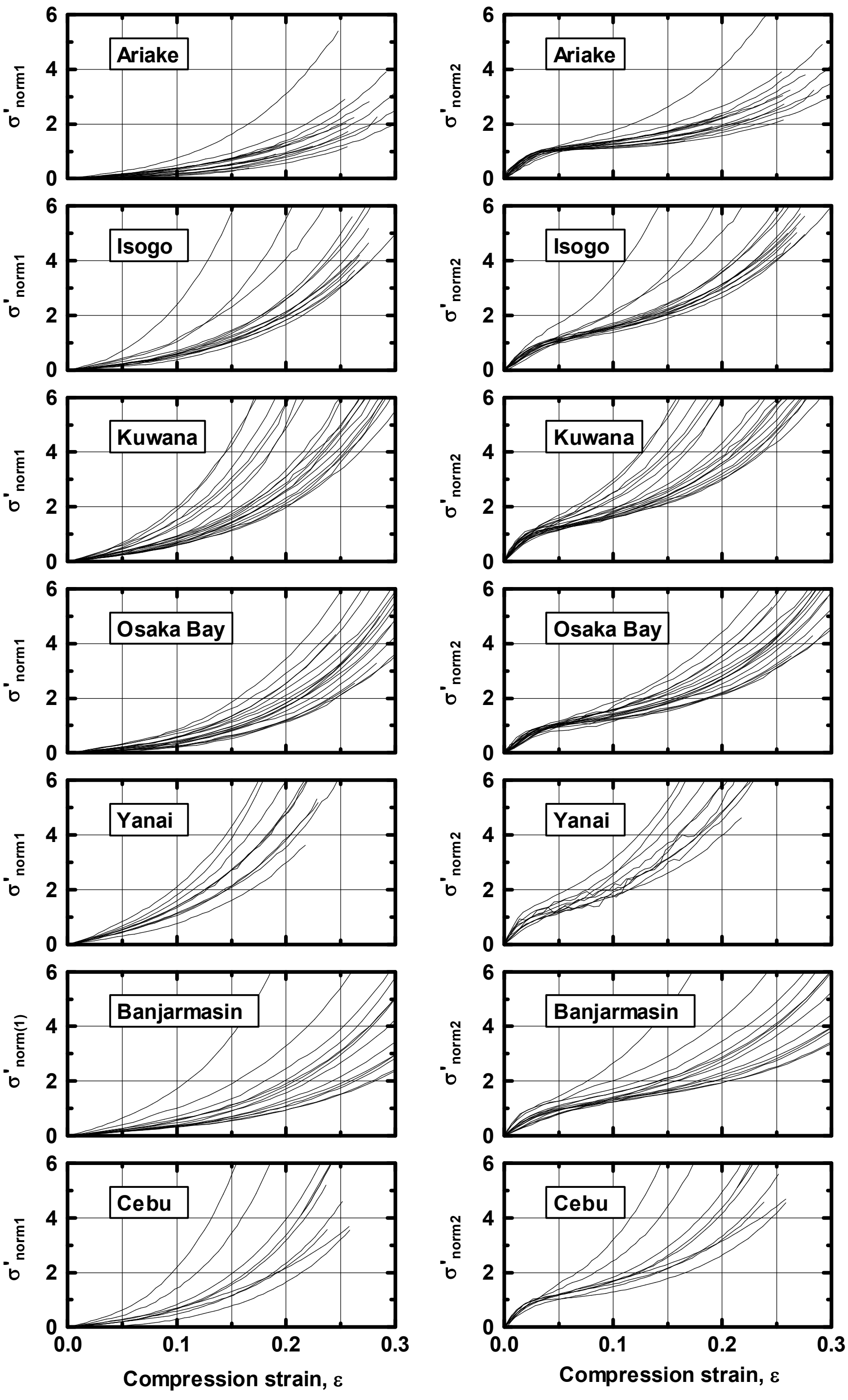


Fig. 5 Normalized curves obtained for clays found in Japan and the Southeast Asia

ANALYSIS OF A TEST EMBANKMENT WITH NORMALIZED CURVES

Test Embankment and Instrumentation

The test embankment described here was constructed in the coastal area of Yanai City, Yamaguchi Prefecture, Japan. The site was reclaimed six years before the construction of the embankment. Under the reclaimed fill, the clay deposit with the thickness of 13.5m was found. The embankment has a 40 m length and a 30 m width at the top. Its height is 5.5m with slopes of 1 : 1.8 and 1 : 2.0. According to the field density test results, the wet density of the embankment material is 20 kN/m^3. The soil deposit was instrumented by extensometers and pore pressure gauges. The shape of the embankment and the instrumentation for monitoring are summarized in Fig. 6. There are two points where the monitoring was made. Geotextile was laid at the bottom of the embankment at Point 1.

Inclinometers were also installed at the toe and the shoulder of the slope (Miki et al., 1994). But they are omitted from the figure, because the consolidation of the clay is analyzed one-dimensionally in this paper, and only vertical settlement and excess pore water pressure are evaluated.

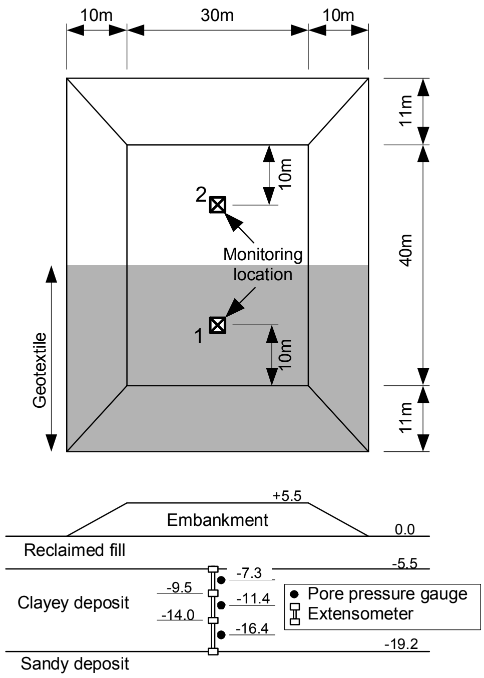


Fig. 6 Plan and cross section of test embankment and instrumentation

Profile and Properties of the Clay Deposit

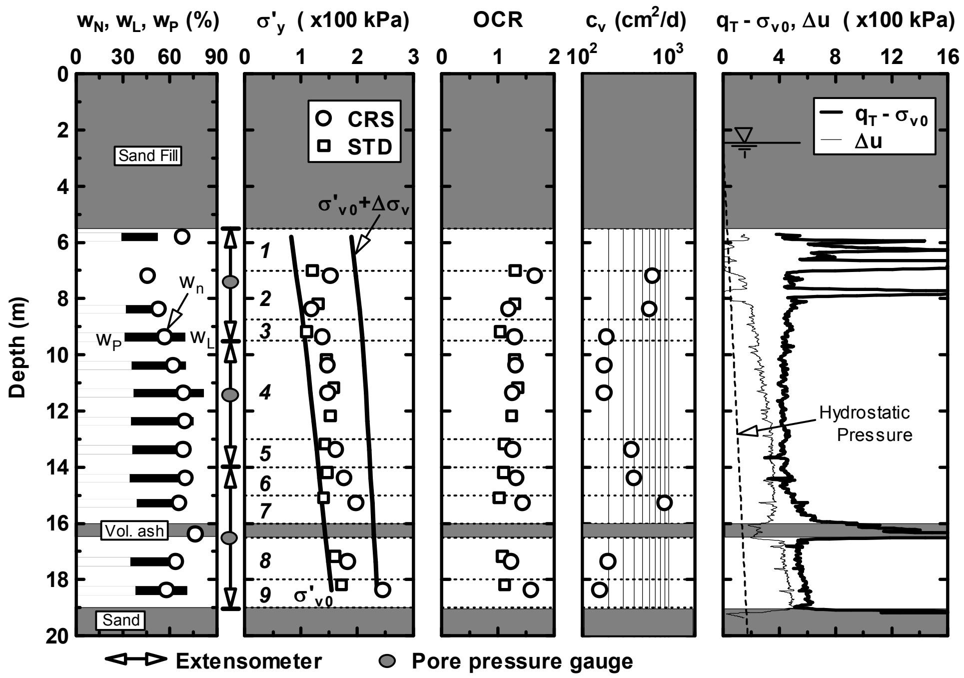


Fig. 7 Profile of Yanai clay

Geotechnical investigation at the site was conducted before the start of the embankment construction. Figure 7 demonstrates the results of CRS test at 0.02 %/min, standard (STD) consolidation test and cone penetration test CPT together with natural water content w_n and Atterberg limits w_L and w_P. According to CRS test results, the values of σ'_y are larger than σ'_{v0} and OCR varies from 1.19 to 1.66 with an average of 1.3. Since the reclaimed fill under the embankment was spread only six years before the soil investigation, the clay is supposed to be normally consolidated and have OCR being equal to 1. Therefore, σ'_y values in the figure seem overestimated. STD test yields smaller values of σ'_y than CRS test, and OCR ranges from 1.02 to 1.35, which still seems overestimated. The values of coefficient of consolidation c_v in the figure are those in normally consolidated state determined by CRS test. Entire profiles of c_v through loading are presented in Fig. 8.

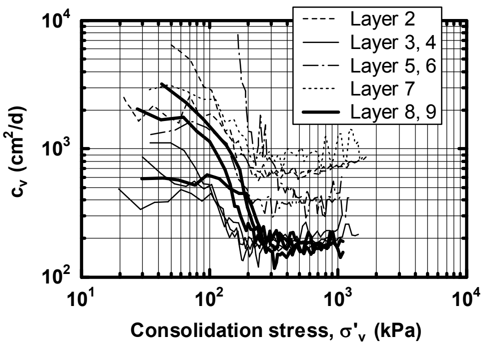


Fig. 8 Coefficient of consolidation c_v determined by CRS test at 0.02 %/min

Point resistance and pore water pressure during penetration of CPT presented in Fig. 7 suggest that the nature of the deposit at the top is silty or sandy and very diverse. A sandy sediment with about 0.5 m thickness is also found at the depth of 16 m. This sediment is volcano ash fallen 6,300 years ago (Endo, et al. 1995). As indicated in Fig. 7, a pressure gauge is located immediately below this sediment. Generation of excess pore water pressure measured by this gauge suggested that this volcano ash sediment would not function as a drainage layer.

The clay deposit is divided into 9 sub-layers, for the purpose of the consolidation analysis, corresponding to the change of soil properties and the arrangement of settlement and pore pressure gauges. Consolidation properties of Layer 1 were investigated by CRS test, but the result was discarded because high quality undisturbed sample was not expected from sandy or silty sediment, and the trimming of the sample for this sediment most likely resulted to sample disturbance.

Normalized Stress-Strain Curves

The process of the normalization for representative samples are demonstrated in Fig. 9, in which CRS curves directly obtained from the test at 0.02 %/min (Curve 2), those corresponding to OCR=1 (Curve 1) and the connecting lines are presented. Because the values of OCR for GL-8.4m and GL-11.4m are relatively close to

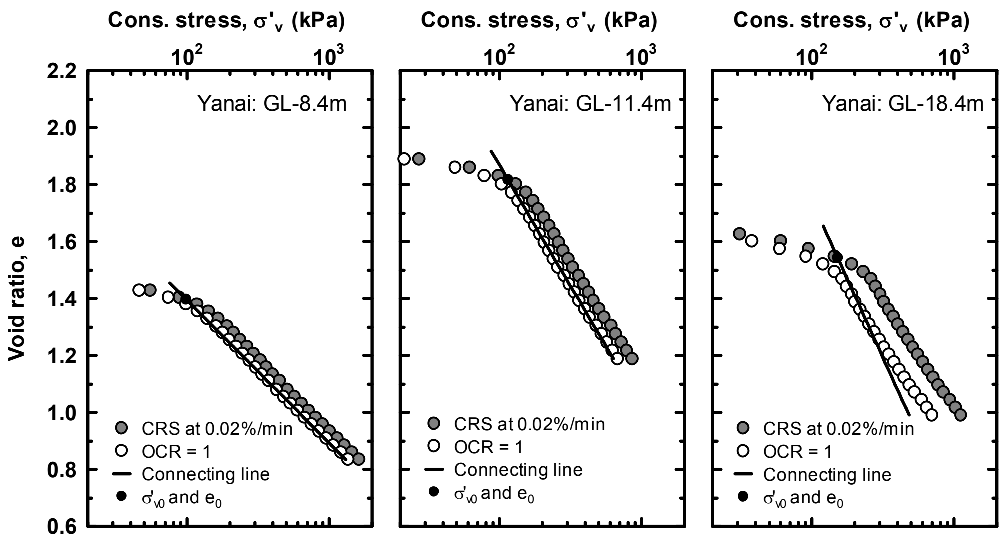


Fig. 9 CRS curves corresponding to 0.02 %/min and OCR=1, and connecting line obtained for some Yanai clay samples

1.0 as indicated in Fig. 7, there is no marked difference between Curve 1 and Curve 2. While for GL-18.4m, where OCR is larger than 1.5, there is a clear difference between the two curves. All of the normalized curves for Yanai clay determined through the process as demonstrated in Fig. 9 are already presented in Fig. 5.

It is necessary for consolidation analysis to approximate the normalized curves, which can be divided into three groups as shown in Fig. 10. The first group (top part) includes two curves from Layer 2. In the consolidation analysis mentioned later, a representative stress-strain curve for Layer 1 is assumed to be the same as Layer 2. The second part (middle part) is composed of Layer 3 to 8, including seven curves. The third (bottom part) corresponds to Layer 9, and has only one curve. Figure 10 shows that the stress-strain curves can be approximated well by the polynomial expression such as Eqs. (10) and (11).

Consolidation Analysis

Once the equations to approximate the normalized curves are defined, a representative stress-strain curve for the analysis can be calculated for each sub-layer with its σ'_{v0}, OCR and Eq. (7). As mentioned earlier, the values of OCR in Fig. 7 seem overestimated. Furthermore, since the clay was not improved by vertical drain method, the settlement speed is less than that expected for the ground improved by vertical drain method, where CRS test at 0.02%/min worked well to predict consolidation settlement as reported by Okumura and Suzuki (1991) and Suzuki and Yasuhara (2003). Therefore, direct application of CRS test results would not likely make an accurate prediction of the settlement behavior of the clay due to the embankment construction in Yanai site. In this regard, the following two cases were chosen to be analyzed:

Case 1: An average OCR of 1.3 is applied for the entire deposit.
Case 2: OCR=1.0 is assumed for the entire deposit.

In both cases, drainage ability and compressibility of volcano ash were ignored. Although the problem is three-dimensional, the analysis was carried out with Mikasa's one-dimensional consolidation equation as given by Eq. (12) that allows using non-linear stress-strain relation. A computer program based on the finite difference method was employed to perform the analysis.

$$\frac{\partial \varepsilon}{\partial t} = c_v \frac{\partial^2 \varepsilon}{\partial z^2} \tag{12}$$

where, c_v is coefficient of consolidation, t is time and z is depth, ε is compression strain.

In case 1, the calculation starts with c_v values 10 times as much as that in Fig. 7 because this case assumes the clay is in overconsolidated state, where c_v values are larger than those in normally consolidated state as indicated in Fig. 8. When a layer becomes normally

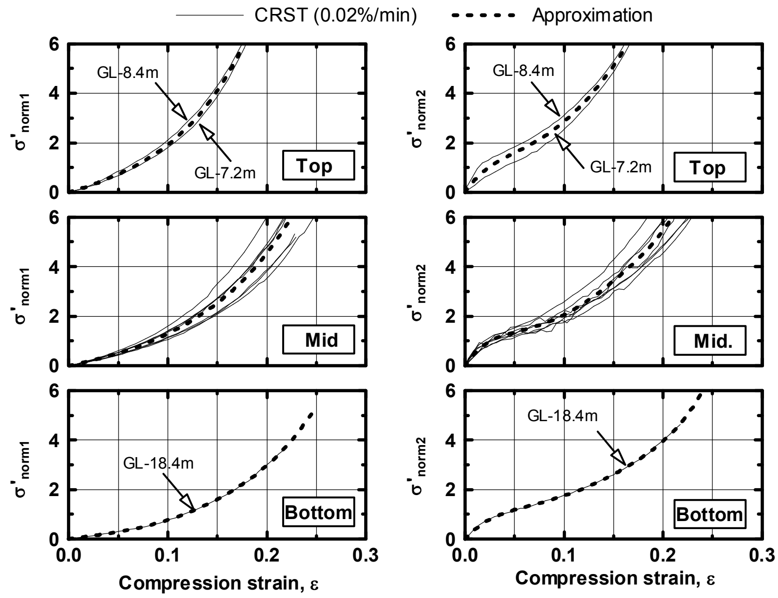


Fig. 10 Normalized CRS results and approximation by polynomial expression

consolidated as the embankment construction progresses, the c_v value is reduced to that in Fig. 7. The value of c_v for Layer 1 is assumed to be 10,000 cm^2/d because it is sandy, regardless the layer is in overconsolidated or normally consolidated state. This value was selected to terminate consolidation of Layer 1 at the end of embankment construction.

The results of the analysis with two-way drainage condition are presented in Fig. 11 for both cases together with the measured settlements and excess pore water pressures. The total settlements obtained from the analysis agree with the measured values up to the end of the embankment construction for both cases. After that, the Case 2 analysis produces better prediction than Case 1, being parallel to the actual settlement with about 10 cm deviation. While, the Case 1 analysis predicts smaller settlement than the actual one as time elapsed.

For Layer 1-3 and Layer 6-9 where pore water flow is relatively one-dimensional, the Case 2 analysis gives the predictions close to the observed settlements. The calculated settlements are slightly larger by a few centimeters in Layer 1-3 and smaller within 10 cm in Layer 6-9. While, the result of Case 2 analysis for Layer 4-5 is very different from the observed one. Three-dimensional effect is the most likely reason for the discrepancy. Case 1 analysis shows good agreement with the observed settlement for Layer 1-3. However, for Layers 4-5 and 6-9, only the initial part of the settlement agrees with the observed one.

Excess pore water pressure generated at GL-7.3m is compared with the calculated values for Layers 1 and 2. The gauge installed in Layer 2 is sandwiched by sandy sediments as observed in CPT result in Fig. 7, but the lower one was not considered in the analysis. Therefore, the calculated pore water pressure for Layer 2 must be larger than the measured values. For the pore water pressure at GL-11.4m (Layer 4), Case 1 calculation is relatively closer to the monitored values than Case 2. Since the pressure gauge at GL-16.4 is located near the boundary between Layers 7 and 8, average values obtained from the calculation for the two layers are compared with the monitored pressure that fallen in between Cases 1 and 2.

Discrepancies between the actual behavior and the calculation were significant at the middle of the deposit that is distant from drainage boundaries and the phenomenon seems three-dimensional. On the other hand, for the top and the bottom parts, because the drainage condition is somewhat close to one-dimensional, the calculation provided better results than for the middle part.

As already mentioned earlier, OCR of the deposit is

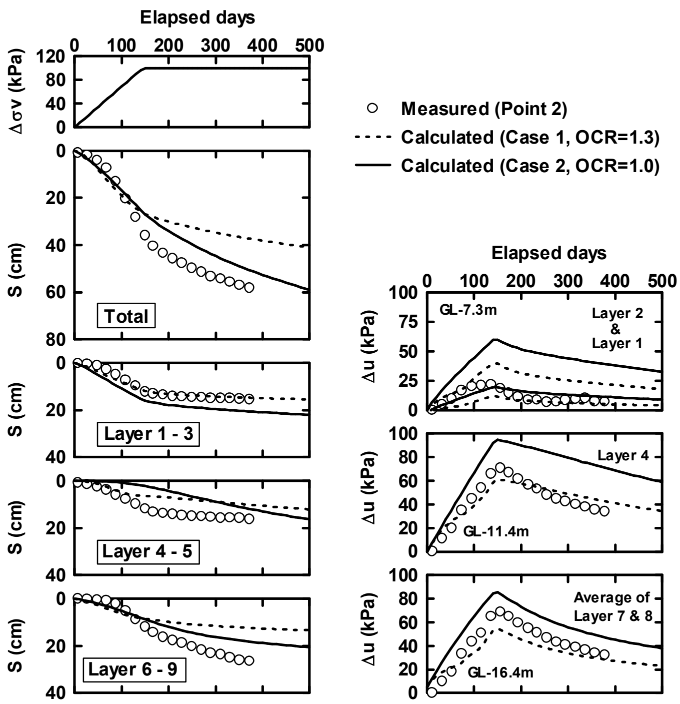


Fig. 11 Comparison of actual consolidation behavior and results of analysis with OCR being 1.3 and 1.0

supposed to be 1.0. The Case 2 analysis, in which OCR=1 is assumed, provided acceptable prediction for the top and the bottom part of the deposit as shown in Fig. 11. While, the Case 1 analysis underestimated the settlement of the ground. The stress-strain curves for the Case 2 analysis were deduced from CRS curves obtained at 0.02 %/min by the normalization technique described in this paper. Therefore, the normalization technique seemed to provide appropriate stress-strain curves for consolidation analysis.

DISCUSSIONS

Tanaka et al. (2000) studied rate effect on σ'_y for 9 clays from Japan, Asia, Europe and North America, and reported that the rate effect defined as the increment ratio of σ'_y for one logarithmic cycle of strain rate is from 1.08 to 1.18. Figure 12 demonstrates the average rate effect on σ'_y for Champlain clays in Canada (Leroueil et al. 1983) and the extrapolation made by the Authors based on the rate effect reported by Tanaka et al. (2000).

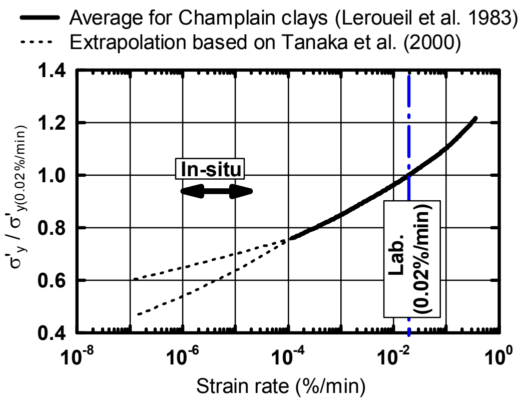


Fig. 12 Rate effect on σ'_y reported by Leroueil et al. (1983) and it extrapolation based on Tanaka et al. (2000)

The Case 2 analysis in the previous section was carried out with stress-strain curves corresponding to OCR=1 deduced from the curves directly obtained from CRS test at 0.02 %/min, which indicated that OCR of the deposit was 1.3 in average. The ratio of OCR is 1.0/1.3=0.77. According to Fig. 12, the ratio of 0.77 corresponds to a strain rate by two orders slower than 0.02 %/min used in CRS test conducted in this study. On the other hand, the in-situ strain rate determined by extensometers falls between 10^{-6} and 2×10^{-5} %/min, which is about three to four orders slower than in CRS test, as shown in Fig. 13. When the line reported by Leroueil et al. (1983) is extrapolated, Fig. 12 implies that the ratio of $\sigma'_y/\sigma'_{y(0.02\%/min)}$ is somewhere between 0.6 and 0.7 when the strain rate is from 10^{-6} to 2×10^{-5} %/min. That means the in-situ value of OCR is less than 1.0. Dissipation test with CPT device performed by Miki et al. (1994) before the embankment construction showed that there was no excess pore water pressure in the clay deposit. Therefore, the consolidation due to reclaimed fill already finished. If in-situ OCR is less than 1.0, the value of OCR contradicts their measurements. The ambiguity described here suggests that the relation in Fig. 12 cannot necessarily give a proper value of OCR that should be used in Eq. (7).

Because the rigid line in Fig. 12 came from different deposits, this kind of relation should be determined for each clay deposit in order to apply the normalization technique. However, its accurate determination requires preparing test specimens taken from exactly the same

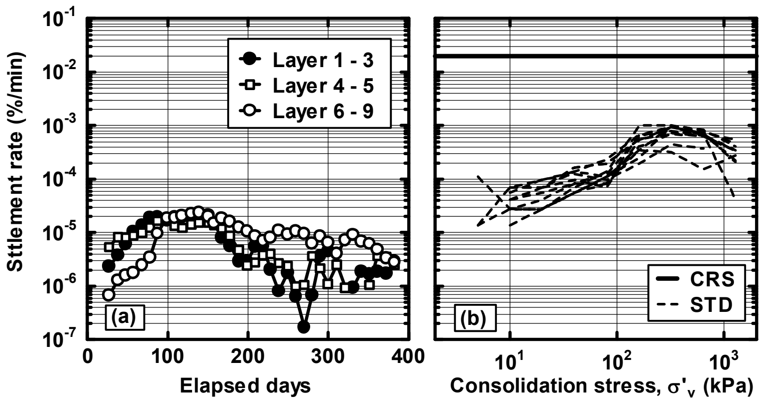


Fig. 13 Settlement rate at the site determined by extensometers (a) and in the laboratory (b)

depth. This is very difficult in routine soil investigation. Therefore, how to use the normalizing procedure practically in consolidation analysis is to produce stress-strain curves corresponding to probable values of OCR, and then, choose the most likely value by comparing the results of analysis with settlement curves obtained from field measurements. Although the application of the normalizing procedure in this study requires the help of field monitoring to determine an appropriate value of OCR, the normalization described here demonstrated the usefulness of CRS consolidation test.

CONCLUSIONS

A normalizing procedure of stress-strain curves obtained from CRS test was examined through the comparison between the actual behavior of a clay deposit under a test embankment and the results of the analysis. The conclusions of this study can be summarized as follows:

1) The normalizing procedure described in this paper can produce stress-strain curves that are convenient for consolidation analysis, because they start from a point that represents σ'_{v0} and e_0.
2) Two or three sets of σ'_{norm1} and σ'_{norm2} curves can represent stress-strain relation of a clay deposit.
3) The applicability of the normalizing procedure was validated in a consolidation analysis of a test embankment constructed on a marine clay sediment.

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