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A PREDICTION METHOD FOR LONG-TERM SETTLEMENT OF HIGLY ORGANIC SOFT SOIL

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ABSTRACT: One of the prediction method of the long-term settlement of soft clay is to predict it by defining the linear slope of the latter half of the s-log t curve, as the rate of secondary consolidation. This method has some disadvantages, because the slope of the straight line is depending on how to set the origin of elapsed logarithmic time, and how to determine the initial thickness of soil layer, and so on. The author carried out a series of laboratory experiments using oedometer apparatus against some kinds of highly organic soil and one silty clay which were sampled in Japan. From the experimental results, the author proposed a prediction method for long-term settlement of highly organic soil based on the isotache theory using natural strain which can be used conveniently by eliminating previous problems. To confirm the applicability of the proposed prediction method, some field measurement data were used, constructed in Japan. They were good correlations, and the applicability of proposed method was proved in this study.

Keywords: Highly organic soil, long-term settlement, Isotache method, Natural strain, Strain rate

1. INTRODUCTION

Highly organic soil is known for its high compressibility, high water-contents and low unconfined compression strength [1], [2], [3]. For geotechnical engineers, highly organic soil is treated as a problematic soil for design and construction of buildings. Especially, large settlement occurs not only during construction but also after construction period.

Research was conducted by Ohira et al [4], [5], Matsuo et al. [6] and Kogure [7] regarding long-term settlement prediction methods, which is the subject of the present paper; the hyperbolic method, √t hyperbolic method, s-log t method, etc. have been proposed and are currently used in design practice. In Hokkaido, a long-term settlement prediction method based on the in-situ measurement data of local peaty ground was proposed and is used in practice [8], [9], [10].

Research on the applicability of the isotache model to highly organic soil has been conducted. The isotache model is a time-dependent compression model in which the time and settlement curves trace the same curve regardless of clay layer thickness and hysteresis of consolidation pressure in the case of soil of the same nature; it has previously been reported on by Suklje [11], Imai [12], Matsuo [13] and Den Haan [14].

Imai [12] conducted a step loading test with separate-type-oedometer, experimentally explained the isotache model in clayey soil, and discovered the uniqueness of the relationship between the state index and natural strain rate.

Matsuo [13] conducted laboratory experiments on highly organic soil and explained the isotache model in normally consolidated highly organic soil. It was reported that when focusing on the relationship between the unique void ratio of highly organic soil and consolidation pressure and applying the isotache model to highly organic soil, it is desirable to apply the isotache model by paying attention to the linearity of the relationship between the specific volume and consolidation pressure rather than the relationship between the void ratio and consolidation pressure.

Den Haan [14] proposed an a-b-c model that predicts the long-term settlement of highly organic soil by using natural strain to focus on the state curved surface constructed by natural strain, consolidation pressure, and natural strain rate.

Tanaka et al. [15] investigated the dependency of the isotache model in the peaty ground widely distributed in Hokkaido area using a laboratory test and reported that peat has higher strain rate dependency than clayey soil.

Long-term settlement occurring over a long period in highly organic soil is a major problem, but one of the long-term settlement prediction methods is a method of calculation by utilizing the rate of secondary consolidation defined by the gradient of the latter half of the linear part of the s-log t curve, on which the consolidation time is displayed on the logarithmic scale, and this method is widely used in practice (Kamao et-al. [16], [17]).

However, the conventional method has a disadvantage regarding the fact that depending on where the consolidation time reference point (origin of time) is selected when plotting the settlement amount on a semi-logarithmic scale, the gradient of the latter half of the linear part of the s-log t curve differs. When calculating the settlement amount by defining the gradient of the latter half of the linear part of the s-log t curve with rate of secondary consolidation, it is necessary to always clarify where the reference point of time was selected. It is indicated by Imai [12] that attention should be paid to the method of selection of the reference point of consolidation time.

The author has conducted experimental research based on the isotache concept regarding the fact that the relationship between consolidation pressure and strain is uniquely determined by the value of strain rate as a method of establishing the settlement prediction method, which can eliminate this problem and uniformly express settlement behaviors. The author proposed a long settlement prediction method using natural strain and natural strain rate, verified it using in situ measurement data, and demonstrated the utility of the proposed prediction method.

The present paper is a summary of these research results.

In this study, natural strain (ε^H) is adopted as a representation method of strain occurring under a consolidation pressure. The strain rate is also expressed by the natural strain rate (ε^H).

2. THE PREDICTION METHOD OF LONG-TERM SETTLEMENT USING NATURAL STRAIN

The strains dealt with in this paper are linear strain (ε^C) and natural strain (ε^H), which are defined as Eq. (1) and Eq. (2), respectively. Fig. 1 shows a symbolic description of linear strain (ε^C) and natural strain (ε^H). From this figure, the linear strain ε^C is obtained by dividing the strain amount Δl by the initial sample height l_0 (soil layer thickness), and is defined by the Eq. (1).

$$\varepsilon^C = \frac{l_0 - l}{l_0} = \frac{\Delta l}{l_0} \tag{1}$$

$$\varepsilon^H = -\int_{l_0}^{l} \frac{dl}{l} = -\ln\frac{l}{l_0} = -\ln\left(1-\varepsilon^C\right) \tag{2}$$

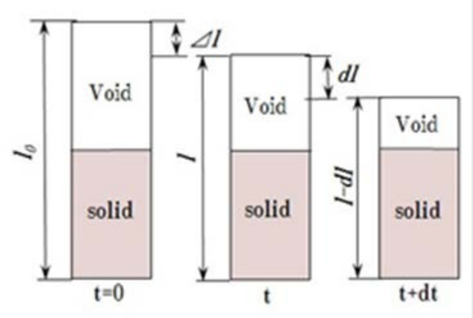


Fig. 1 A symbolic description of linear strain (ε^C) and natural strain (ε^H)

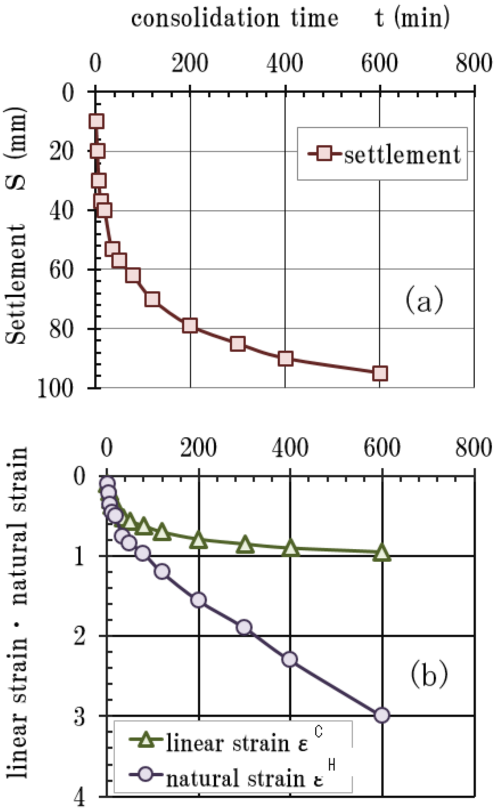


Fig. 2 Relationship between settlement, linear strain and natural strain

Fig. 2 (a) and (b) shows the ε^C and the ε^H values with respect to the settlement of the simulated specimen.

Fig.3(a) shows settlement of a specimen in a simulated manner assuming initial specimen height (L) is 100 mm. Fig.3(b) shows a value of linear strain and natural strain at this time, respectively. From these figures, the maximum ε^C was calculated less than 1.0, but calculated ε^H exceed 1.0, and reach 2 or even 3, because it is calculated by using the specimen height as a reference which may change from moment to moment.

For highly organic soil, it is more advantageous to use natural strain, which the values of natural strain become larger than the linear strain closing to 1.0 as the settlement increases. This paper summarizes the prediction method of highly organic soil using natural strain and natural strain rate.

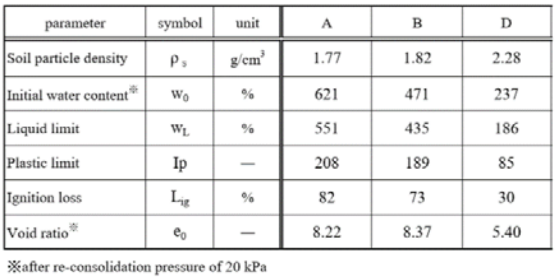
There are few studies about the prediction method of long-term settlement of highly organic soil using natural strain and its rate. Therefore, the author would like to propose a new long-term settlement prediction approach by conducting the conventional oedometer test apparatus with constant incremental loading tests standardized by JIS A 1217 and a long-term consolidation test as well as interpreting test results.

3. USED SOILS AND TEST PROGRAMS

Table 1 shows the typical properties of used five soils. The soil A, B, C and D are highly organic soil sampled in Hokkaido, Japan. The soil E is silty clay sampled in Tokyo.

All specimens are used as remolded conditions under re-consolidation pressure of 20 kPa. They are prepared as follows; the water content of the disturbed sample is first adjusted to be twice as liquid limit (L.L.) and then consolidated under the re-consolidation pressure of 20kPa for about two weeks. Re-consolidation apparatus is shown in Fig. 3. A series of laboratory test using conventional standard oedometer test apparatus standardized by JIS A 1214 were done against four Japanese highly organic soils and one Japanese marine silty clay.

Table 1 Typical soil properties



parameter	symbol	unit	A	B	D
Soil particle density	ρ_s	g/cm^3	1.77	1.82	2.28
Initial water content※	w_0	%	621	471	237
Liquid limit	w_L	%	551	435	186
Plastic limit	Ip	—	208	189	85
Ignition loss	L_{ig}	%	82	73	30
Void ratio※	e_0	—	8.22	8.37	5.40

※after re-consolidation pressure of 20 kPa

4. EXPERIMENTAL RESULTS

Oedometer tests were done against 5 soil（4 highly organic soil and 1 silty clay）. While the linear gradient of the curve's latter part is what is conventionally called as the rate of secondary consolidation, we call it as the rate of long-term settlement for distinguishing from those and obtained each value by defining formulas (3) to (6) since results are interpreted here by using natural strain. The rate of long-term settlement (C^{Ht}) in

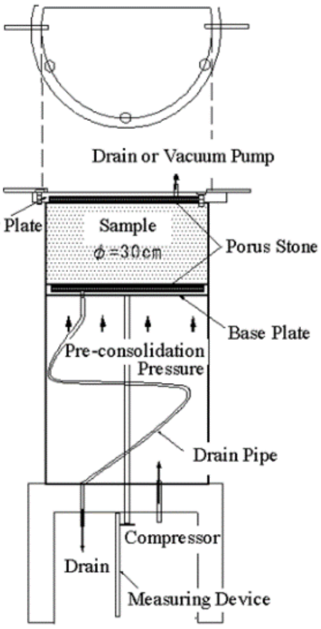


Fig. 3 Re-consolidation apparatus

$$C^{Ht} = \Delta\varepsilon^{H} / \Delta\log t \quad (3)$$

$$C^{HH'} = \Delta\varepsilon^{H} / \Delta\log \dot{\varepsilon}^{H} \quad (4)$$

$$C^{Ct} = \Delta\varepsilon^{C} / \Delta\log t \quad (5)$$

$$C^{CC'} = \Delta\varepsilon^{C} / \Delta\log \dot{\varepsilon}^{C} \quad (6)$$

Eq. (3) is expressed by displaying log t on the horizontal axis and natural strain on the vertical axis, depicting natural strain - log t curve, and showing linear gradient of the curve's latter part. The rate of long-term settlement ($C^{HH'}$) in Eq. (4) is expressed by displaying natural strain on the horizontal axis and natural strain rate ($\dot{\varepsilon}^{H}$) on the vertical axis, depicting natural strain - natural strain rate curve, and showing a gradient of the curve's latter linear part.

The rate of long-term settlement (C^{Ct}) in Eq. (5) is expressed by conventional linear strain, depicting linear strain - log t curve, and showing a linear gradient of the curve's latter part in order to compare with those in Eqs. (4) and (5) based on natural strain. Similar to Eq. (6), the rate of long-term settlement ($C^{CC'}$) is also expressed by depicting linear strain - linear strain rate curve and showing a linear gradient of the curve's latter part.

Fig. 4 shows the relationship between natural strain and consolidation time of soil A and B, respectively. Natural strain was chosen, instead of linear strain. Fig. 5 shows relationship between natural strain and natural strain rate（$C^{HH'}$）. Those using linear strain used so far are shown in Figs. 6 and 7 for reference.

From Fig. 4, it can be seen that an inverted S-shaped curves are drawn for A soil, and the curve in the latter half linearly advances with respect to elapsed consolidation time. It can be seen that the linear gradient of this part has almost the same slope during the normally consolidated region.

Figure 5 shows the natural strain rate ($\dot{\varepsilon}^{H}$) on the horizontal axis instead of consolidation time in Fig. 4. The similar trend can be seen from Fig. 5. (inverted S-shaped curves and same gradient during normally consolidated region, and so on) Figs. 6 and 7 are shown using linear strain (ε^{C}) and its rate ($\dot{\varepsilon}^{C}$) by comparison with Figs. 4 and 5. The values of the rate of secondary consolidation and the rate of long-term settlement for other soils, are almost same tendency as soil A, even silty clay also. The linear gradients in the latter half of Figs. 4 to 7 were calculated for each loading step and are summarized in Tables 2, 3 and 4.

Fig. 8 shows the relationship between C^{Ht} and p for soils A, B, and D. The value of C^{Ht} is given as a substantially constant value during normally consolidated region (p> 40 kPa). On the other hand, the value of C^{Ct} has peak values around 3 to 6 times the pre-consolidation pressure. This is the same trend as Yasukawa's report (1987).Fig. 10 shows the tendency for the value of C^{HH} ' to be constant with normally consolidated region when using the natural strain rate. It was found that the values of C^{Ct} for each loading step in Fig. 11, are curved shape that is convex upward.

Figure 12 shows the relationship between C^{HH} 'and C^{Ht}. Both parameters tend to be almost the same values from this figure. When the elapsed time is displayed using a logarithmic scale, the gradient of the straight line changes depending on the method of setting the origin of the time. Therefore, in the present paper, the author proposes to use natural strain rate rather than logarithmic time.

In the laboratory experiment, it was found that the rate of long-term settlement (linear gradient) obtained from logarithmic time and the linear gradient obtained from the natural strain rate showed approximately the same values.That is, it is the authors' opinion that when predicting field measurement data from a laboratory experiment, accurate prediction can be made by using natural strain rate instead of logarithmic time.

Fig. 12 shows the rate of long-term settlement ($C^{HH'}$) and water content.

It was shown that according to the quantity of water content, the rate of long-term settlement also became linearly larger, and it can be approximated by Eq. (7).

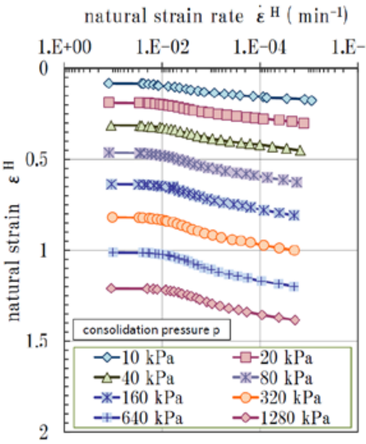


Fig. 4 Relationship between natural strain and consolidation time. (Soil A)

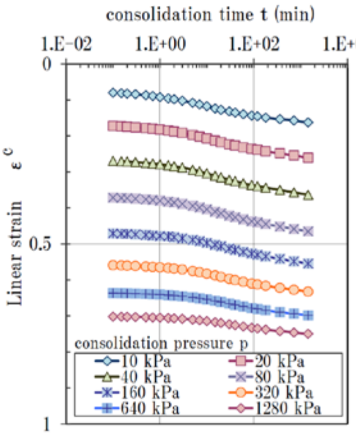


Fig. 5 Relationship between natural strain and its rate. (Soil A)

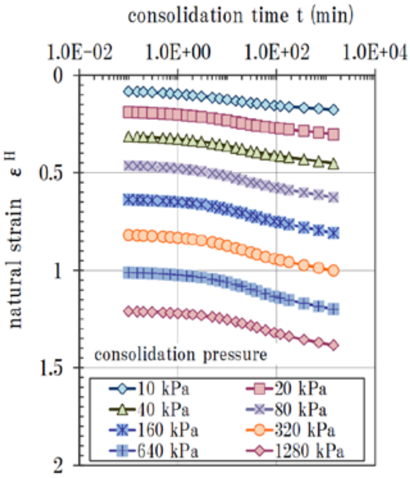
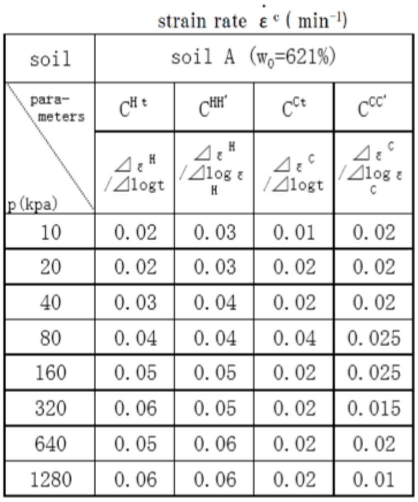


Fig. 6 Relationship between linear strain and consolidation time. (Soil A)

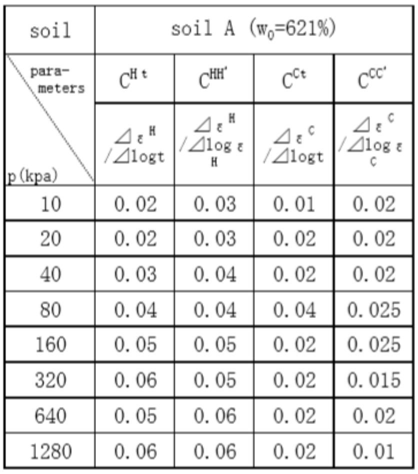


strain rate $\dot{\varepsilon}^{c}$ ($\min^{-1}$)

soil	soil A (w_0=621%)			
para-meters / p (kpa)	$C^{H\,t}$	$C^{HH'}$	C^{Ct}	$C^{CC'}$
	$\Delta\varepsilon^{H}/\Delta\log t$	$\Delta\varepsilon^{H}/\Delta\log\varepsilon_{H}$	$\Delta\varepsilon^{C}/\Delta\log t$	$\Delta\varepsilon^{C}/\Delta\log\varepsilon_{C}$
10	0.02	0.03	0.01	0.02
20	0.02	0.03	0.02	0.02
40	0.03	0.04	0.02	0.02
80	0.04	0.04	0.04	0.025
160	0.05	0.05	0.02	0.025
320	0.06	0.05	0.02	0.015
640	0.05	0.06	0.02	0.02
1280	0.06	0.06	0.02	0.01

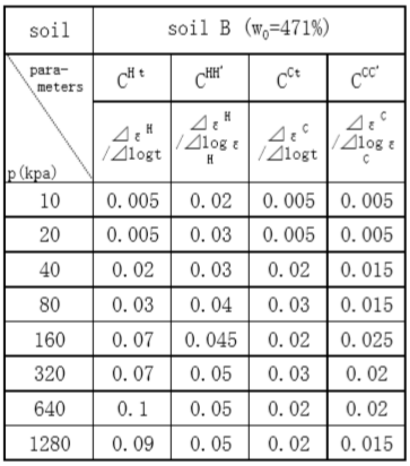
Fig. 7 Relationship between linear strain and its rate. (Soil A)

Table 2 The numbers of calculated $C^{H\,t}$, $C^{HH'}$, $C^{C\,t}$ and $C^{CC'}$ (soil A)



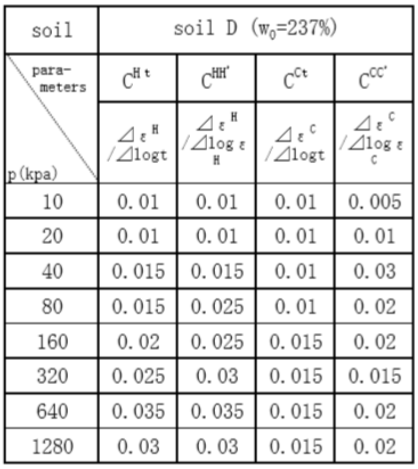
soil	soil A (w_0=621%)			
para-meters / p (kpa)	$C^{H\,t}$	$C^{HH'}$	C^{Ct}	$C^{CC'}$
	$\Delta\varepsilon^{H}/\Delta\log t$	$\Delta\varepsilon^{H}/\Delta\log\varepsilon_{H}$	$\Delta\varepsilon^{C}/\Delta\log t$	$\Delta\varepsilon^{C}/\Delta\log\varepsilon_{C}$
10	0.02	0.03	0.01	0.02
20	0.02	0.03	0.02	0.02
40	0.03	0.04	0.02	0.02
80	0.04	0.04	0.04	0.025
160	0.05	0.05	0.02	0.025
320	0.06	0.05	0.02	0.015
640	0.05	0.06	0.02	0.02
1280	0.06	0.06	0.02	0.01

Table 3 The numbers of calculated $C^{H\,t}$, $C^{HH'}$, $C^{C\,t}$ and $C^{CC'}$ (soil B)



soil	soil B (w_0=471%)			
para-meters / p (kpa)	$C^{H\,t}$	$C^{HH'}$	C^{Ct}	$C^{CC'}$
	$\Delta\varepsilon^{H}/\Delta\log t$	$\Delta\varepsilon^{H}/\Delta\log\varepsilon_{H}$	$\Delta\varepsilon^{C}/\Delta\log t$	$\Delta\varepsilon^{C}/\Delta\log\varepsilon_{C}$
10	0.005	0.02	0.005	0.005
20	0.005	0.03	0.005	0.005
40	0.02	0.03	0.02	0.015
80	0.03	0.04	0.03	0.015
160	0.07	0.045	0.02	0.025
320	0.07	0.05	0.03	0.02
640	0.1	0.05	0.02	0.02
1280	0.09	0.05	0.02	0.015

Table 4 The numbers of calculated $C^{H\,t}$, $C^{HH'}$, $C^{C\,t}$ and $C^{CC'}$ (soil D)



soil	soil D (w_0=237%)			
para-meters / p (kpa)	$C^{H\,t}$	$C^{HH'}$	C^{Ct}	$C^{CC'}$
	$\Delta\varepsilon^{H}/\Delta\log t$	$\Delta\varepsilon^{H}/\Delta\log\varepsilon_{H}$	$\Delta\varepsilon^{C}/\Delta\log t$	$\Delta\varepsilon^{C}/\Delta\log\varepsilon_{C}$
10	0.01	0.01	0.01	0.005
20	0.01	0.01	0.01	0.01
40	0.015	0.015	0.01	0.03
80	0.015	0.025	0.01	0.02
160	0.02	0.025	0.015	0.02
320	0.025	0.03	0.015	0.015
640	0.035	0.035	0.015	0.02
1280	0.03	0.03	0.015	0.02

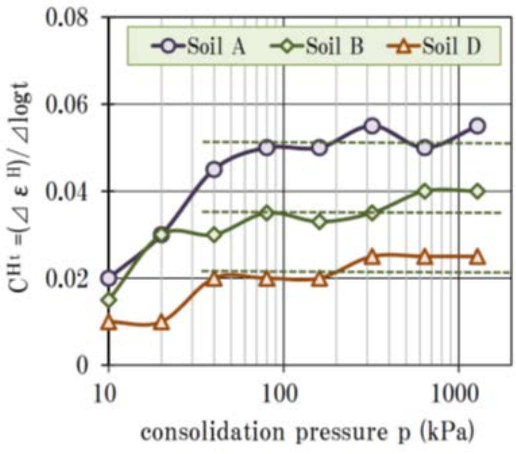


Fig. 8 Relationship between C^{Ht} and p

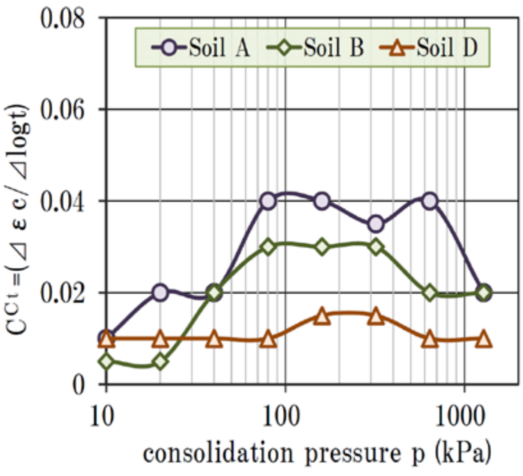


Fig. 9 Relationship between C^{Ct} and p

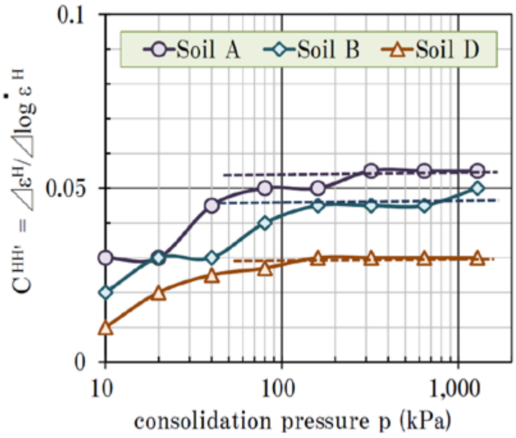


Fig. 10 Relationship between $C^{HH'}$ and p

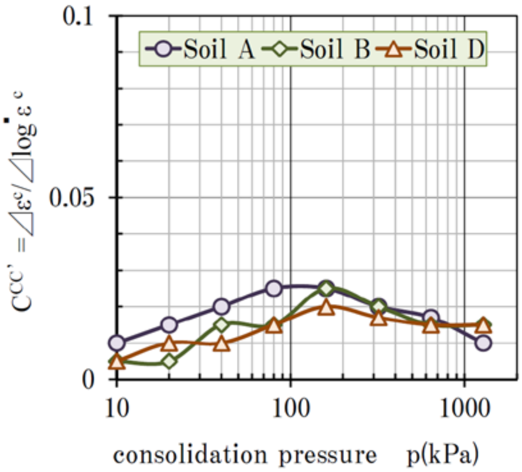


Fig. 11 Relationship between $C^{CC'}$ and p

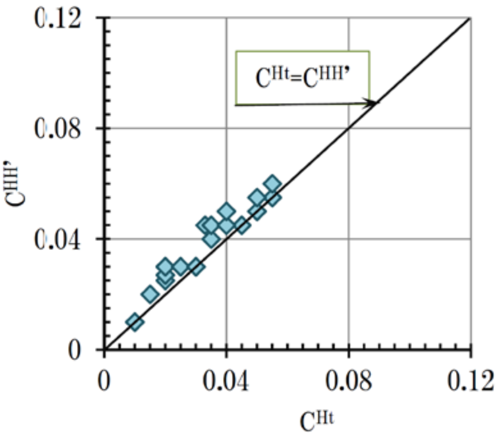


Fig. 12 Relationship between C^{Ht} and $C^{HH'}$

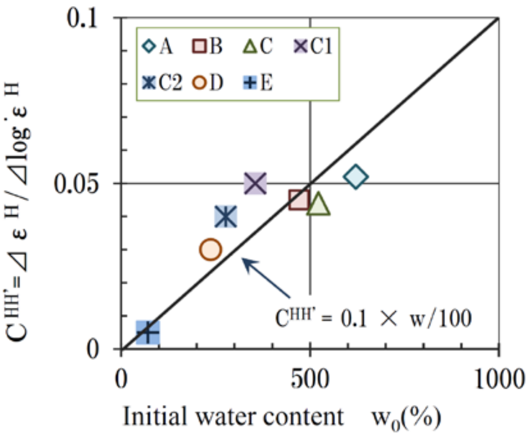


Fig. 13 Relationship between $C^{HH'}$ and w

$$C^{HH'} = 0.1 \times w / 100 \tag{7}$$

where w: initial water content (%)

That is, in order to predict the rate of long-term settlement at the site, it is possible to predict the water content of the soil.

5. COMPARISON BETWEEN PREDICTION AND FIELD MEASUREMENT DATA

In this chapter, the author shall compare the laboratory experiments and field measurement data. Following example is the previous field measurement data of highway embankment construction in Japan. This example (Japan Highway public corporation, [18]) is the measurement data of Tomei Highway at Aiko area. The thickness of highly organic soil deposit is about 5.3 m and water contents are 350～700 %. The construction details and soil profiles are shown in Fig. 13 and Table 5, respectively.

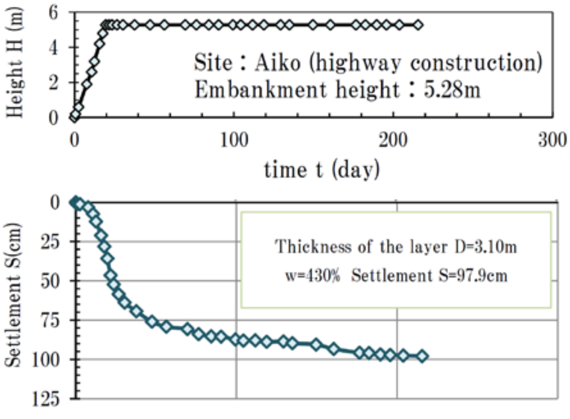


Fig. 14 Field measurement data

Table 5 Details of construction and soil profiles

Name of Site				Aiko
Embankment height		H	m	5.28
Enbankment loading		p	kPa	85
Duration		t	day	216
Total settlement		S	cm	97.9
Soil profile	Thickness of layer	D	cm	310
	Wet density	ρ_t	g/cm^3	1.08
	Water content	w_n	%	430
	Liquid limit	I_p	—	214
	Ignition loss	L_{ig}	%	38

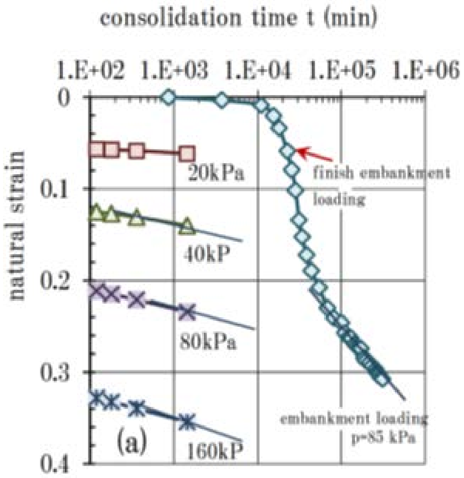


Fig. 15 Comparison between laboratory experiment and field measurement data (ε^H-log t)

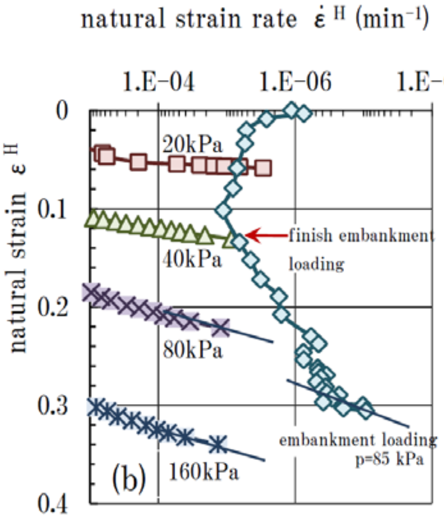


Fig. 16 Comparison between laboratory experiment and field measurement data (ε^H- $\dot{\varepsilon}^H$)

Fig. 15 shows a plot of the natural strain and elapsed time. Because the origin of time is set as the embankment start time, it can be seen that the long-term speed of the indoor experiment and field measurement data do not match in the figure.

That is, this signifies that the gradient of the straight line differs.

However, rather than a logarithmic scale of time, the natural strain rate is shown in Figures 2, 3 and 4; from these figures, it was shown that the rate of long-term settlement of laboratory experiments and field measurement data were mostly consistent.

It is recommended to use natural strain and its rate when making this type of prediction.

6. CONCLUSIONS

The summary of this study is as follows:

The rate of long-term settlement(**C^{Ht}**) is given as a substantially constant value during normally consolidated region of highly organic soil.

When the elapsed time is displayed using a logarithmic scale in EH-log t curves, the gradient of the straight line changes depending on the origin of the time.

The rate of long-term settlement (**$C^{HH'}$**) can be predicted also in the method using the natural strain rate instead of log t. The value of **$C^{HH'}$** can be predicted using the properties of soil (water content, etc.).

The value of **$C^{HH'}$** was found to be useful also in the comparison between laboratory test and field measurement data.

7. ACKNOWLEDGMENTS

Several helpful discussion and suggestion with Dr. E. Fukazawa of Central Giken co., LTD. are gratefully acknowledged.

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