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Preloading effect on highly organic soft soil

Shoji Kamao[1*], and *Satoshi* Shigemura[1]

[1] Department of Civil Engineering, College of Science & Technology, Nihon University, Tokyo, Japan

Abstract. The preloading method is a technique used to reduce residual settlement in soft clay soils. It is particularly effective in highly organic soils and has been widely used in the design and construction of embankment works. However, when highly organic soft ground that had been improved using the preloading method was subjected to preloading and subsequent unloading in order to artificially induce an overconsolidated state, long-term secondary consolidation settlement occurred. This settlement damaged both above- and below-ground structures, becoming a significant construction issue. Laboratory experiments revealed that, unless the overconsolidation ratio — defined as the ratio of the consolidation pressure before to after preload removal — is set correctly, soil expansion during preload removal will subsequently result in resettlement. Consequently, when using the preloading method to improve highly organic soft ground, setting the overconsolidation ratio correctly is critical. This paper presents model experiments that simulate the preloading method implemented in the laboratory on several types of highly organic soils and silts sampled in Japan. The optimal overconsolidation ratio for reducing resettlement was determined for each soil type. Subsequently, a prediction method based on soil properties was employed and compared with field-measured data. The results showed a strong correlation between the predictions and the measured values.

1 Introduction

In recent years, there has been brisk urban development around large cities in Japan. Due to the limited amount of land available, many structures have been built on peat and/or highly organic, soft ground that used to be marshland.

Such soils are characterised by large voids, low strength and high compressibility. Consequently, settlement and deformation due to loading occurs not only in the short term during the construction period, but also in the long term, leading to an increasing number of reported cases of damage. Predicting settlement due to long-term secondary compression is not sufficiently researched. Theoretical explanations for secondary compression settlement are scarce, with most settlement prediction methods relying on experimental techniques. The prevailing approach to embankment construction on highly organic, soft ground involves implementing in-situ monitoring techniques. Consequently, accurate settlement prediction at the design stage proves challenging, yet precise settlement prediction is imperative for the successful execution of construction. Recent research in the field of consolidation settlement has increasingly emphasized the isotache law, which facilitates the evaluation of settlement, including secondary compression.

According to the isotache law, in the context of soil compression, the void ratio and effective stress of the soil skeleton exhibit a unique relationship specific to each compression rate. In this framework, consolidation pressure serves as an indicator of applied load, while various indicators have been used to assess settlement quantity and settlement rate.

2 Research evaluation method

2.1 The isotache law

Recently, the consolidation theory concerning the isotache law, initiated by Šuklje [1], has been the subject of extensive research by numerous scholars.

The isotache law, as proposed by Šuklje, is a time-dependent consolidation law that represents the soil's intrinsic consolidation behaviour when focusing on settlement rate or strain rate. Significant contributions to research on the isotache law include reports by Imai [2], Matsuo [3], den Haan et-al [4], and Watabe et-al [5].

Imai conducted staged loading tests using a segmented consolidation testing machine, thereby experimentally demonstrating the isotache law in cohesive soils and identifying the uniqueness of the relationship between the state index and natural strain rate ($\Gamma \sim \log \varepsilon$). In a similar vein, Matsuo performed laboratory tests on highly organic soils and explained the isotache law for normally consolidated highly organic soils. With a particular focus on the inverse S-shaped curve of the relationship between void ratio and load ($e \sim \log p$), which is characteristic of highly organic soils, it was reported that, when applying the isotache law to such soils, it is preferable to focus on the linearity of the relationship between volume ratio and load ($\log f \sim \log p$) rather than void ratio and load ($e \sim \log p$).

* Corresponding author: kamao.shoji@nihon-u.ac.jp

Furthermore, den Haan proposed the a-b-c model for predicting long-term settlement. This model utilises natural strain and focuses on the state plane constructed by natural strain, consolidation pressure, and rate of natural strain.

2.2 Evaluation using natural strain

The highly organic soils addressed in this study exhibit prolonged, minute settlement over extended periods, necessitating accurate evaluation of their compressibility increment. Therefore, as demonstrated in Fig. 1, natural strain, which forms a linear relationship with applied load and enables appropriate assessment of residual settlement and natural strain rate, as an indicator of settlement velocity, is employed for analysis. Here, the natural strain is expressed by Eq. 1 using the linear strain.

$$\varepsilon^{H} = -\ln\left(1-\varepsilon^{C}\right) \qquad (1)$$

where ε^{H}: Natural strain and ε^{C}: Linear strain.

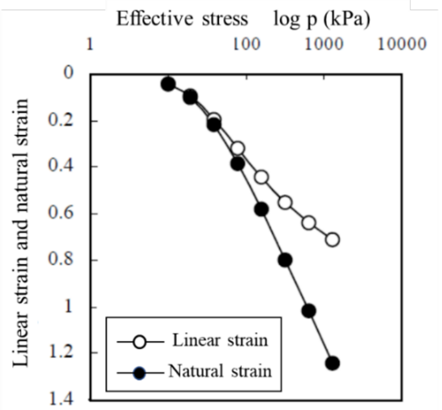

Fig. 1. Relationship between effective stress and strain.

2.3 *Overview of the a-b-c model*

Fig. 2 and 3 illustrate the a-b-c model [4] proposed by den Haan. Fig. 2 shows the relationship between natural strain and natural strain rate. The straight lines in the figure represent the natural strain-natural strain rate curves for each loading stage. The organisation of settlement behaviour through the utilisation of natural strain and natural strain rate reveals that the natural strain versus natural strain rate curves for each loading stage become straight lines with a slope equivalent to c during the secondary consolidation process within the normal consolidation region. Furthermore, the spacing between these lines is also given by b. As shown in Fig. 3, the plot from Fig. 2 has been reorganised according to the relationship between natural strain and applied load. The equidistant straight lines are shown in Fig. 3 indicate states where the natural strain rate during the secondary consolidation process in the normal consolidation region is equal. It is evident that the natural strain rate increases towards the top and decreases towards the bottom. The slope of the straight lines is given by b, and the spacing is given by c. It is therefore evident that the increment of natural strain is governed by the applied load and the natural strain rate; this relationship is expressed by Eq. 2.

Fig. 2 shows that the straight line in the overconsolidation region is defined by the parameter "a". This is the gradient when reloading is performed after preloading and unloading. As no tests involving reloading are conducted in this study, a detailed explanation is omitted here.

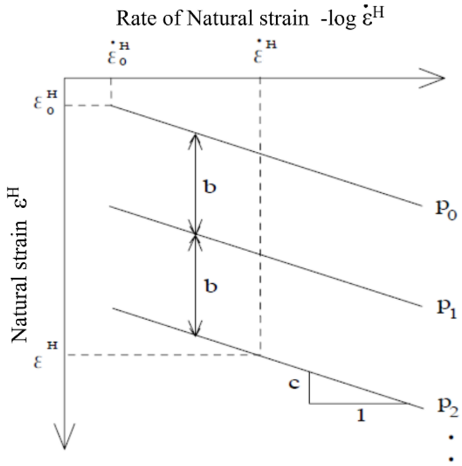

Fig. 2. Relationship between natural strain and rate of natural strain (a-b-c isotache model).

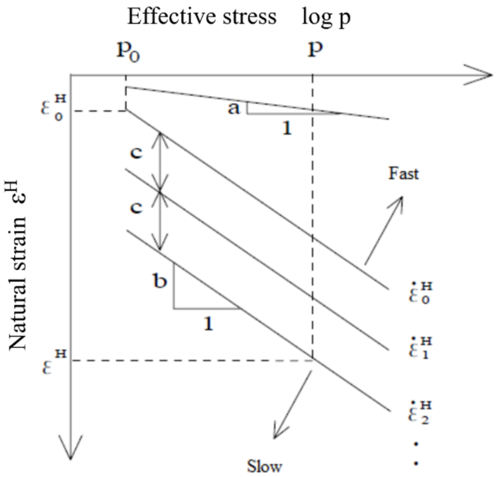

Fig. 3. Relationship between effective stress and natural strain (a-b-c isotache model).

$$\varepsilon^{H} - \varepsilon_{0}^{H} = b \cdot \log\frac{p}{p_0} + c \cdot \log\frac{\dot{\varepsilon}_{0}^{H}}{\dot{\varepsilon}^{H}} \qquad (2)$$

where:

$\dot{\varepsilon}_{0}^{H}$: Reference natural strain rate

$\dot{\varepsilon}^{H}$: Arbitrary natural strain rate

p_0: Reference consolidation pressure

p : Arbitrary consolidation pressure

b : Slope of natural strain and consolidation pressure relation

c : Slope of natural strain and natural strain rate relation

2.4 Study positioning

The objective of this study is to predict long-term settlement of highly organic soft ground using the a-b-c isotache model. The efficacy of the isotache model has been substantiated through a series of laboratory tests conducted on normally consolidated highly organic soils and silts, encompassing a range of soil properties, loading conditions, and specimen dimensions. This research builds on the paper by den Haan and Kamao [6] which examined the effects of varying soil properties, loading conditions, and specimen dimensions on the isotache model's performance. Furthermore, the primary focus of this paper is the investigation of long-term settlement behaviour within the overconsolidated area, with the aim of verifying the findings through a comparative analysis of laboratory test results and field measurement data.

3 Experimental overview

3.1 Soil samples used

The soil samples selected for testing were highly organic soils A collected in the northern part of Japan (Hokkaido). Highly organic soils B and C were collected near Tokyo (Chiba), while silt F was collected in Tokyo. Mixture soils D and E were mixed with soils C and F to change the soil properties. The typical soil properties of the samples are shown in Table 1.

Test specimens were prepared by adding water to the collected samples until a slurry consistency was achieved, then mixing them uniformly using a mixer. Reconstituted specimens were then formed using a large-scale one-dimensional consolidation testing apparatus (φ=30 cm) under a pre-consolidation pressure of 20 kPa.

Table 1. The typical soil properties of the used soils.

Soil Profile	A	B	C	D	E	F
Soil particle density ρ_s(g/cm^3)	1.56	1.50	1.86	2.22	2.38	2.60
Water content w_L (%)	367	619	349	196	155	50
Plasticity index Ip	221	268	147	88	67	18
Loss of ignition Lig (%)	50.0	90.2	35.0	20.8	14.5	6.2
Water content w_0 (%)	277	574	358	189	148	52
e_0 (%)	8.01	10.26	8.33	3.37	3.82	1.32
Location	Hokkaido	Chiba	Chiba	-	-	Tokyo

w_0, e_0 : after preconsolidatiom pressure of 20kPa.
Soil D and E are mixture of Soil C and F

3.2 Experimental method

The present paper reports the findings of an investigation into the overconsolidation ratio (OCR) test, with the objective of understanding long-term settlement within the overconsolidated area following unloading of the preload.

In the context of highly organic soft ground, the ability to comprehend long-term settlement behaviour within the overconsolidated area constitutes a significant consideration. For instance, there have been reports of cases in which, following preloading methods, secondary compression settlement persisted over the long term after unloading the preload, resulting in issues or damage to superstructures. The OCR test was conducted to investigate the relationship between the overconsolidation ratio OCR (OCR = $p_0 + p_p / p_f$, where pf is the post-unloading load) and the post-unloading expansion and secondary compression settlement behaviour. The objective of the present study was to vary the OCR across four values (1.33, 1.60, 2.00, 2.67). The experimental method was conducted as described in Fig. 4 and Table 2. The test was performed using a fixed ring oedometer device with a diameter of 6 cm and a height of 2 cm.

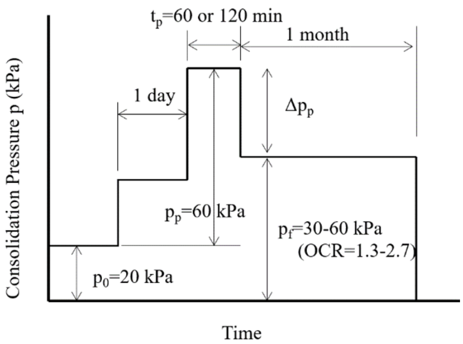

Fig. 4. Loading scheme of the OCR test.

Table 2. Experimental conditions.

p_0 kPa	p_p kPa	Δp kPa	p_f kPa	OCR -	t_p min
20	60	20	60	1.33	60
		30	50	1.60	120
		40	40	2.00	
		50	30	2.67	

4 Experimental results

4.1 Investigation concerning the OCR

The OCR experiments were conducted to assess the impact of variations in the loading force following unloading of the preload on the secondary compression settlement behaviour, under the assumption of a preloading method for highly organic soft ground.

Fig. 5 shows the relationship between the expansion behaviour of the specimen after preload removal and the subsequent long-term secondary compressive settlement behaviour for each overconsolidation ratio (OCR). These results were obtained from the OCR test of soil sample A. As shown in this figure, the specimen initially expands upon preload removal, then remains in an equilibrium state with neither expansion nor settlement, before exhibiting resettlement behaviour after a certain period of time. Furthermore, as OCR increases, the amount of expansion after load removal increases, while the amount of resettlement decreases. Similar results were obtained for other soil samples.

The experimental results were plotted for natural strain and its rate, as shown in Fig. 3. The value of parameter c remained almost constant for each soil sample, regardless of the overconsolidation ratio shown in Fig. 6. Fig. 7 therefore shows the relationship between parameter c and the plasticity index, indicating the properties of the soil. A proportional relationship was confirmed between the plasticity index and parameter c. The investigation focuses on parameter c when organising the resettlement behaviour after preload unloading at varying overconsolidation ratios in terms of natural strain and its rate.

Fig. 8 shows the OCR test results, in addition to the settlement behaviour obtained from standard consolidation tests at 40 kPa, 60 kPa, and 80 kPa. In this figure, the settlement behaviour at OCR=1.33 (i.e., a loading of 60 kPa) is shown along as approximately on the 69 kPa line. Similarly, the settlement behaviour at

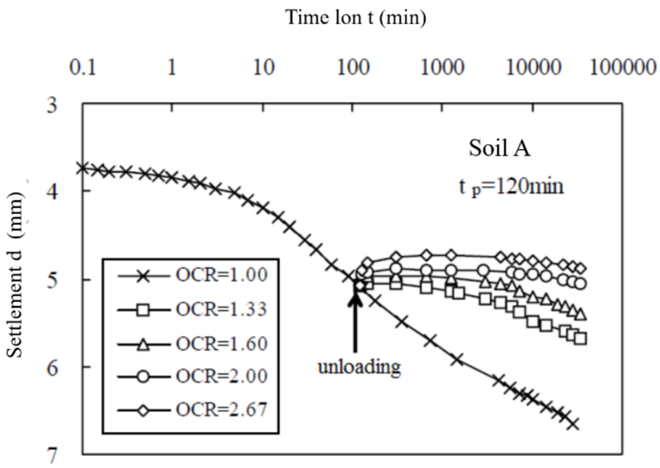

Fig. 5. The OCR test results (Time – settlement curves).

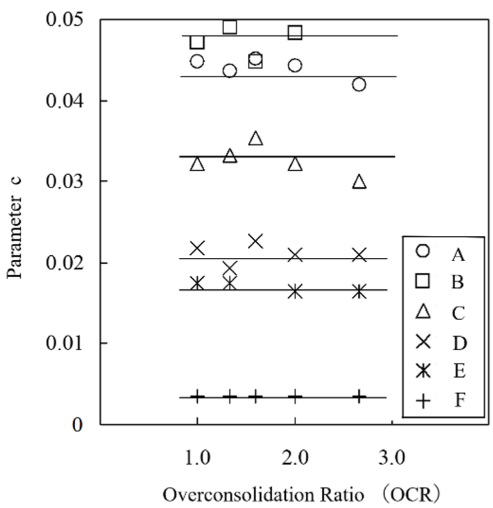

Fig. 6. The OCR test results (Relationship between parameter c and OCR).

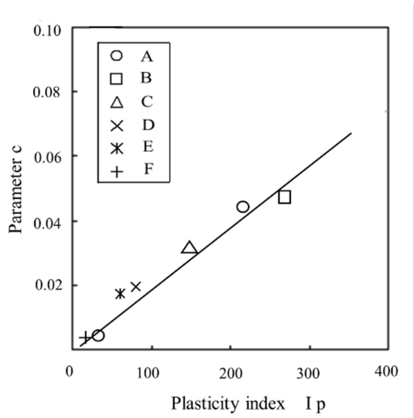

Fig. 7. Relationship between Parameter c and overconsolidation ratio.

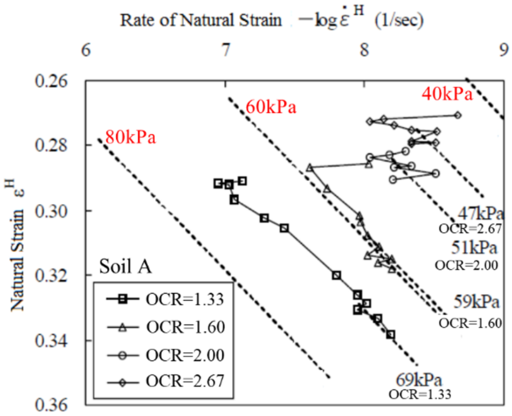

Fig. 8. The OCR Test results (Relationship between Natural strain and its rate).

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OCR=1.60, 2.00, and 2.67 is represented not at the original positions of 50 kPa, 40 kPa, and 30 kPa, but at 59 kPa, 51 kPa, and 47 kPa, respectively. This phenomenon is thought to occur because changes in the soil particle skeleton result from the removal of the preload.

This phenomenon is defined as the disturbance factor (F_D), as shown in Fig. 9. The disturbance factor F_D is used to evaluate the settlement behaviour after expansion due to unloading. The disturbance factor F_D was computed for each soil specimen, and its correlation with the plasticity index Ip was summarised by the overconsolidation ratio (OCR), as demonstrated in Fig. 10. As shown in fig. 10, despite some observed variation, the resettlement behaviour of highly organic soils following unloading of the preload demonstrated a nearly constant disturbance rate across all OCRs, irrespective of soil type. While the disturbance to the structure caused by unloading the preload is more significant in highly organic soils, this phenomenon can be consistently assessed by categorising it according to OCR. Conversely, the disturbance rate for silt sample F (Ip=18) remained consistent irrespective of OCR. This is presumed to be a consequence of the minimal preload in silt, resulting in reduced structural disturbance.

As shown in Fig. 8, the investigation focuses on parameter c, derived from the experimental resettlement behaviour of each sample soil with respect to its overconsolidation ratio (OCR). (Refer to Fig. 2 for parameter c.) This figure supports the hypothesis that, when using natural strain and its rate, the parameter c in the overconsolidation region remains constant relative to that in the normally consolidated region (OCR=1.0).

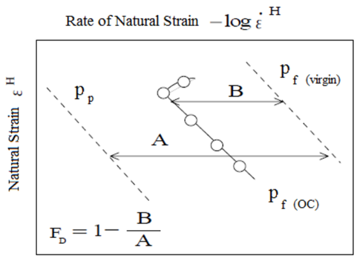

Fig. 9. Definition of disturbance factor (F_D).

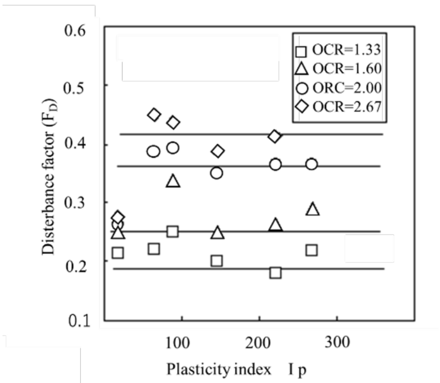

Fig. 10. Relationship between disturbance factor and plasticity index.

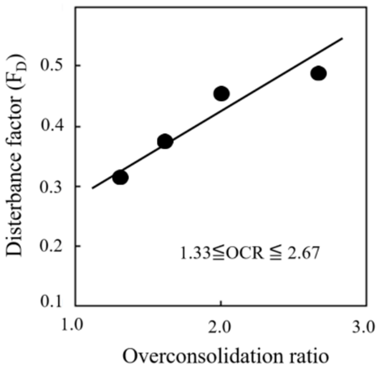

Fig. 11. Relationship between disturbance factor and overconsolidation ratio.

4.2 Comparison with field measurement results

In this section, a comparative analysis is undertaken between field-measurement data from embankments constructed using preloading techniques on highly organic, soft ground and the corresponding laboratory test results.

The case study is represented by the test embankment results from Site S [7]. The highly organic soil layer in Site S has been deposited as topsoil, exhibiting a thickness of 5.0 m shown in Fig. 12. This layer possesses a natural moisture content w_n = 838%, an average loss on ignition Li = 84%, and a plasticity index Ip = 344. As shown in Fig. 12, the time-settlement curve was obtained from the ground surface settlement data. The embankment scale is 15 hectares, and slow-filling construction is underway in an untreated state, without improvement.

Firstly, an embankment measuring 1.5m in height was left undisturbed for 50 days. This was followed by a 4.0m embankment, which was left for 600 days. Subsequently, a 6.5m high embankment (p_p = 110kPa) was left for 450 days to confirm a consolidation ratio of 90%. After this, unloading was performed to achieve a 4.1 m high embankment (p_f = 70kPa). The overconsolidation ratio (OCR) of the ground obtained through the aforementioned construction method was 1.57. In addition, consolidation tests in accordance with JIS A 1217 were conducted on test specimens sampled from the highly organic soil layer in Site S.

Figure 13 shows the relationship between natural strain and natural strain rate, obtained from standard consolidation tests and field measurement data for Site S, while Figure 14 provides an enlarged view, focusing on the field measurement data. Furthermore, the trend line for the 80 kPa load stage from standard consolidation tests is shown in the top-right corner of Figure 14. As shown in the figure, the final load on the embankment is 70 kPa (the load before removal was 110 kPa, with an OCR of 1.57), and re-settlement behavior is observed at around 85 kPa. The slope of the line in the graph of the field measurement results (parameter c) is approximately 0.065.

Figure 15 shows the field-measurement data plotted alongside the laboratory test results for both normal consolidation and overconsolidation states of values of parameter c. There is a good correlation between the parameter c values in the laboratory test results and the field measurement data.

As shown in Figure 10, there is a clear correlation between disturbance factor F_D, determined from laboratory test data, and the plasticity index. Figure 16 plots the degree of disturbance factor (F_D) from field measurement data at an OCR value of 1.57. A value close to that measured in the laboratory tests at an OCR value of 1.6 was obtained. In other words, there are similarities between the two.

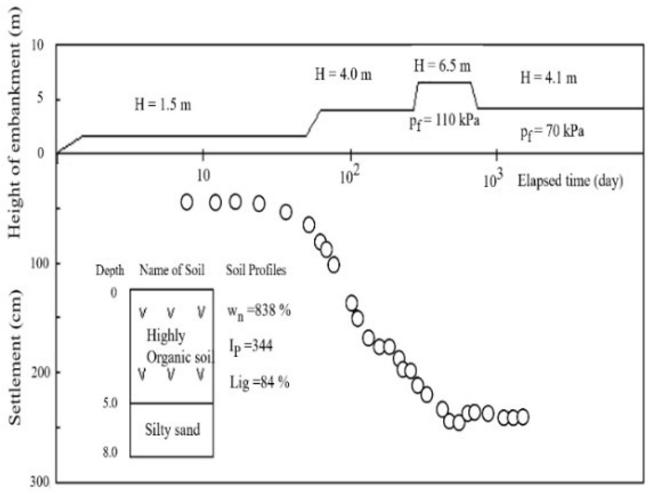

Fig. 12. Overview of field measurement data.

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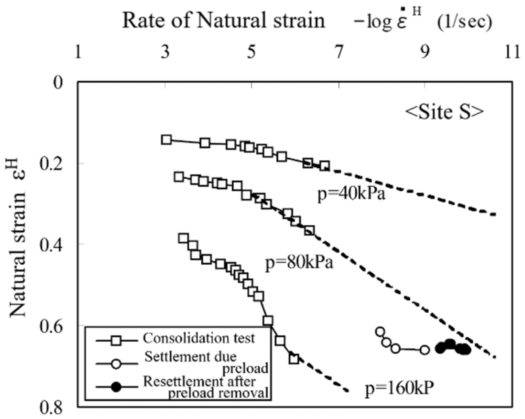

Fig. 13. Relationship between natural strain and its rate.

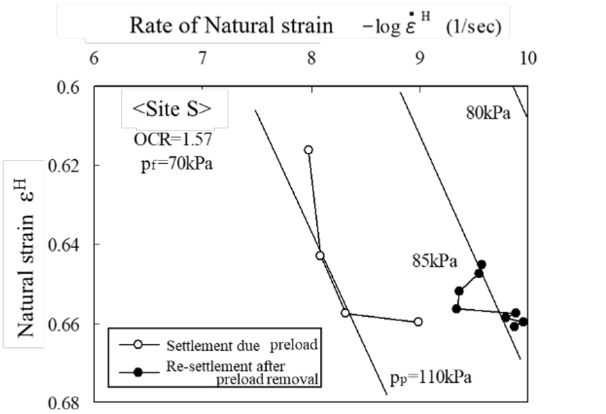

Fig. 14. Relationship between natural strain and its rate (Enlarged view of Fig. 12).

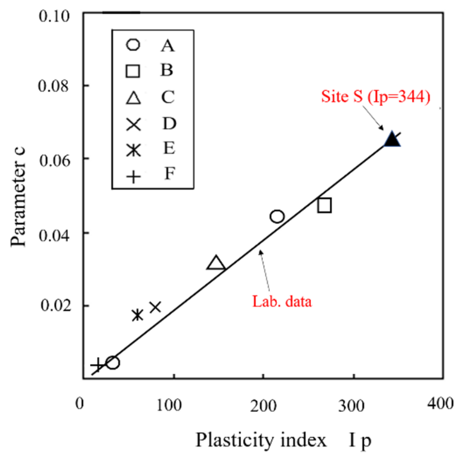

Fig. 15. Relationship between parameter c and Ip.

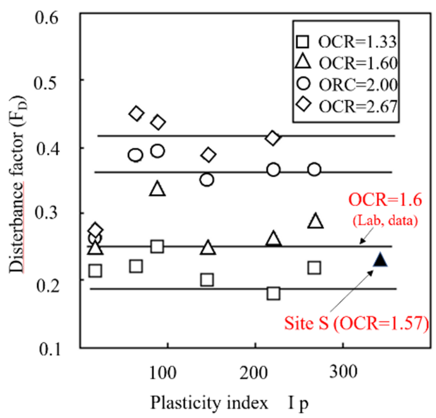

Fig. 16. Relationship between F_D and Ip.

5 Conclusions

In summary, the following findings were obtained. Firstly, with regard to long-term settlement behaviour in overconsolidated region, it was established that the relationship between natural strain and natural strain rate exhibited linear variation, in a manner analogous to that observed in normal consolidation tests. Furthermore, it was found that the value of parameter c, indicating the slope magnitude, was nearly identical to that observed in the normal consolidation zone.

In the context of geotechnical engineering, the investigation focused on the analysis of long-term settlement curves within the overconsolidation region. A comparative analysis was conducted between the post-unloading load and the load applied during standard consolidation. This analysis revealed that the settlement curves were not identical, indicating variations in the overconsolidation ratio (OCR). To address this observation, the disturbance ratio was introduced as an indicator, facilitating a unified evaluation of the degree of overconsolidation for each OCR, irrespective of soil type. This approach enabled a comprehensive assessment, contributing to a better understanding of the soil's behaviour under different conditions.

A comparison of results from laboratory tests and field measurements revealed a good correlation between the two sets. Furthermore, the parameter c values in the overconsolidation and normal consolidation regions were found to be almost identical, consistent with laboratory test results. This comparison identified the potential to predict resettlement behaviour using the disturbance-ratio F_D.

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