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Evaluation of long-term settlement behavior of preload-improved soft clay using the isotache model

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ABSTRACT: In this study, long-term settlement of soft clay ground improved with preload was evaluated using the isotache model. Preloading in conjunction with vertical drains is often used to increase the undrained shear strength of the ground and reduce the residual settlement. The aim of this study was to develop a method for accurately evaluating residual settlement after construction. A method for evaluating secondary consolidation using the isotache model was newly proposed. To solve the consolidation equation, the finite difference method was adopted using the ADI method, which considers vertical and radial drainage. To verify the effectiveness of the proposed method, a case analysis was conducted. The results showed that: 1) the deeper the ground layer, the slower the reduction in strain rate. Consequently, thicker ground layers experience more visco-plastic strain. 2) When the preload is removed, unloading temporarily stops the occurrence of visco-plastic strain. However, as the effective stress increases during reloading prior to the start of service, settlement due to visco-plastic strain resumes. 3) The isotache model by Watabe and Leroueil (2012) tends to show convergence when calculating very long-term secondary consolidation. In contrast, use of the constant C_α/C_c concept by Mesri and Godlewski (1977) and Mesri and Choi (1985). The results of this study provide a practical approach to evaluating long-term settlement in preloaded soft clayey ground.

KEYWORDS: Isotache model, preload method, residual settlement.

1 INTRODUCTION

The preloading method is a ground improvement technique for increasing the strength of soft clay and reducing residual settlement. This method is often combined with vertical drains to accelerate consolidation, and is also adopted in many technical standards (e.g., OCDI, 2025). The issue with construction using this method is the evaluation of residual settlement after the start of service. To ensure the required design ground level, it is important to evaluate the residual settlement caused by secondary consolidation. Although various analytical methods have been proposed in previous studies, as Nash (2001) indicated, accurately predicting creep behavior after unloading remains challenging. In this study, the isotache model proposed by Watabe and Leroueil (2012) is adopted for the evaluation of secondary consolidation, and an analysis method for preloaded soft ground is proposed. The effectiveness of the proposed method is demonstrated through analysis examples.

2 SIMPLE EVALUATION OF UNLOADING AND RELOADING BASED ON THE ISOTACHE CONCEPT

Figure 1 illustrates a conceptual diagram of the isotache model that considers unloading and reloading. This figure was drawn with reference to Watabe and Leroueil (2012). The gray broken lines are compression curves corresponding to the visco-plastic strain rates, and the red broken line is compression curve with an infinitesimal visco-plastic strain rate. Figure 1 is used to consider the isotache concept for unloading and reloading. When the preload is removed at point A_1, the system transitions to point A_2. If the immediate expansion after unloading is attributed to elastic deformation, the unloading effect moves horizontally from A_1 to A_2. Subsequently, until an additional load such as pavement or service loads is applied, the strain rate gradually decreases, and the state shifts downward crossing the compression curves on the left. Since the consolidation stress remains unchanged without additional loading, the system progresses to point A_3. Upon reloading, the state moves to point A_4, and visco-plastic strain gradually accumulates over time following the commencement of service. Based on this concept, it is possible to quantitatively determine the secondary consolidation from the start to the completion of the preloading work. It should be noted that the evaluation method in Figure 1 is an application of the isotache concept established based on the loading process to unloading and reloading, and is not a strict application of the isotache concept for unloading proposed by Fan and Watabe (2025), which is a sort of kinematic isotache model in unloading stage. Therefore, unloading expansion cannot be calculated using the conventional isotache model. Furthermore, in this study, when the stress state after unloading shifts to the left of the compression curve with an infinitesimal strain rate, as shown in Figure 2, the visco-plastic strain is temporarily assumed to be zero, and only elastic strain is considered to occur.

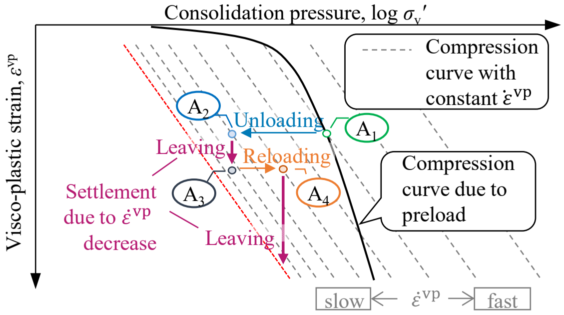


Figure 1. The isotache concept considering unloading and reloading

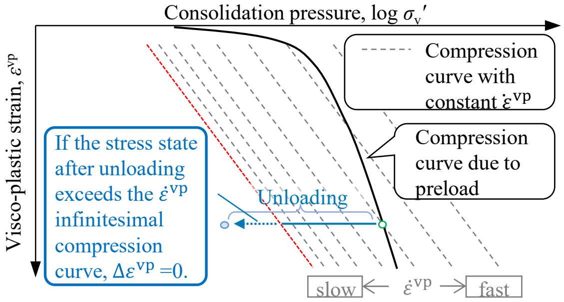


Figure 2. The stress state after unloading

To apply this to actual problems, it is necessary to solve the consolidation phenomenon and update the consolidation yield stress and plastic strain according to the isotache concept in accordance with the plastic strain rate that changes moment by moment. In this study, the following equation was adopted as the governing equation for the consolidation phenomenon.

$$\frac{\partial u}{\partial t} = c_{\mathrm{v}} \frac{\partial^2 u}{\partial z^2} + c_{\mathrm{h}} \left(\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} \right) \tag{1}$$

Where u is excess pore water pressure, t is time, z is vertical displacement, r is the radial distance from the drain center, c_{v} is vertical coefficient of consolidation, and c_{h} is horizontal coefficient of consolidation. This equation takes into account vertical drainage in a hollow cylindrical consolidation equation. In this study, the consolidation equation was solved using the Alternating Direction Implicit method (ADI method), which is a type of finite difference method. Equation (1) is solved under the given initial and boundary conditions to calculate the excess pore water pressure u. In the following, the time step n corresponding to the time interval Δt is indicated by a subscript. The effective stress rate $\dot{\sigma'}_{n+1}$ is calculated from the excess pore water pressure u_{n+1}, and the effective stress is updated accordingly.

$$\dot{\sigma'}_{n+1} = \frac{-(u_{n+1} - u_n)}{\Delta t} \tag{2}$$

$$\sigma'_{n+1} = \sigma'_n + \dot{\sigma'}_{n+1} \Delta t \tag{3}$$

Next, the visco-plastic strain $\varepsilon_n^{\mathrm{vp}}$ is updated. The isotache model proposed by Watabe and Leroueil (2012) is used as the relationship between the visco-plastic strain rate $\dot{\varepsilon}_{n+1}^{\mathrm{vp}}$ and the consolidation yield stress σ'^{p}.

$$\ln \frac{\sigma'^{\mathrm{p}}_{n+1} - \sigma'^{\mathrm{pL}}}{\sigma'^{\mathrm{pL}}} = c_1 + c_2 \ln \dot{\varepsilon}_{n+1}^{\mathrm{vp}} \tag{4}$$

Where c_1 and c_2 are isotache parameters, σ'^{pL} is the consolidation yield stress at an infinitesimal strain rate, and both are constants. The compression curves calculated by Equation (4) corresponds to the gray broken lines in Figure 1. The constant c_1 is equal to $\ln\{(\sigma'^{\mathrm{p}} - \sigma'^{\mathrm{pL}})/\sigma'^{\mathrm{pL}}\}$ at $\dot{\varepsilon}^{\mathrm{vp}} = 1$, which represents the relative position of the $\log \sigma'^{\mathrm{p}} - \log \dot{\varepsilon}^{\mathrm{vp}}$ curve. The constant c_2 represents the degree of strain rate dependence. The isotache parameters c_1 and c_2 can be obtained from long-term consolidation tests (Watabe & Kaneko, 2015) and multi-stage constant strain rate consolidation tests (Yoneda & Watabe, 2019). The lower limit σ'^{pL} is proposed to be $\sigma'^{\mathrm{pL}} = 0.7\sigma'^{\mathrm{p0}}$ in relation to the consolidation yield stress σ'^{p0} at the visco-plastic strain rate $\dot{\varepsilon}^{\mathrm{vp}} = 1.0 \times 10^{-7}$ s^{-1} of 24 hours after the incremental loading consolidation test (Watabe & Leroueil, 2012). Based on Equation (4), the visco-plastic strain $\varepsilon_{n+1}^{\mathrm{vp}}$ can be expressed in two forms.

$$\varepsilon_{n+1}^{\mathrm{vp}} = \varepsilon_n^{\mathrm{vp}} + \exp\left(-\frac{c_1}{c_2}\right) \left(\frac{\sigma'^{\mathrm{p}}_{n+1} - \sigma'^{\mathrm{pL}}}{\sigma'^{\mathrm{pL}}} \right)^{(1/c_2)} \Delta t \tag{5}$$

$$\varepsilon_{n+1}^{\mathrm{vp}} = (\lambda_\varepsilon - \kappa_\varepsilon) \ln \left(\frac{\sigma'_{n+1}}{\sigma'^{\mathrm{p}}_{n+1}} \right) \tag{6}$$

Where λ_ε and κ_ε are the compression index and swelling index in the strain space. Equation (5) is an updated from Equation (4) using the visco-plastic strain rate, and Equation (6) is an equation derived from the geometric relationship in the $\ln \sigma' - \varepsilon^{\mathrm{vp}}$ plane. Equation (5) and Equation (6) can be combined to form a nonlinear equation for $\sigma'^{\mathrm{p}}_{n+1}$, and $\sigma'^{\mathrm{p}}_{n+1}$ can be determined using an iterative method. The total strain ε_{n+1} and the total strain rate $\dot{\varepsilon}_{n+1}$ are calculated using the following equations.

$$\varepsilon_{n+1} = \kappa_\varepsilon \ln \left(\frac{\sigma'_{n+1}}{\sigma'_0} \right) + \varepsilon_{n+1}^{\mathrm{vp}} \tag{7}$$

$$\dot{\varepsilon}_{n+1} = \frac{\varepsilon_{n+1} - \varepsilon_n}{\Delta t} \tag{8}$$

The above is the method for calculating stress and strain at time step $n+1$. Vertical displacement is calculated by multiplying the strain by the thickness. Figure 3 shows the analysis of flow chart.

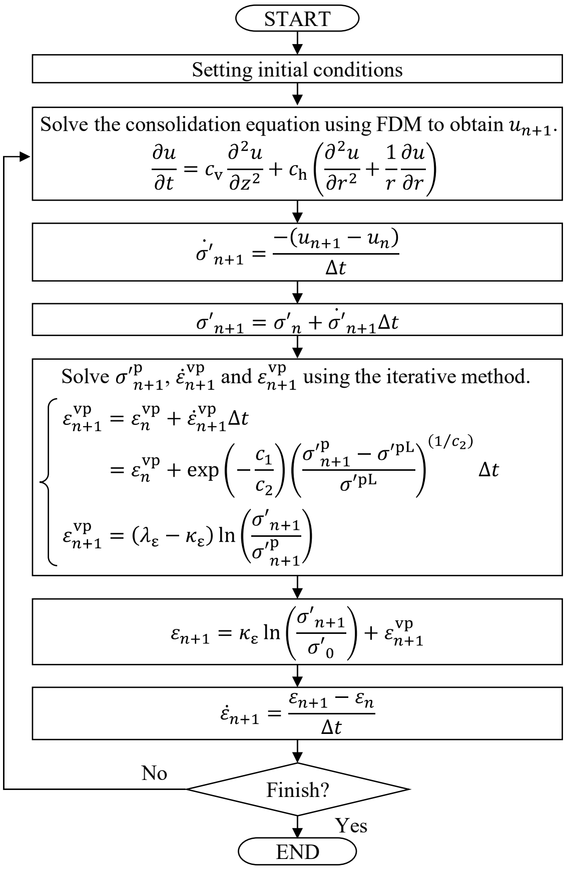


Figure 3. Flow chart of the analysis

3 ANALYSIS EXAMPLE OF PRELOAD METHOD

3.1 *Analysis conditions*

Long-term consolidation analysis was performed on the ground model shown in Figure 4 using the proposed method. The ground was cohesive soil with the material properties shown in Table 1, and the initial state was assumed to be in normal consolidation due to self-weight. The isotache parameters for the clay were set to typical values (Watabe & Leroueil, 2012). A prefabricated vertical drain (PVD) method was used for the clay soil, and PVD were installed in a square pattern arrangement at 1.0 m intervals. The analysis cases are shown in Table 2. To examine the effect of layer thickness, three cases were considered with clay layer thicknesses of 5, 10 and 20 m, and both cases with and without application of the isotache model were calculated. In cases where the isotache model was not applied, the amount of settlement was calculated using the general C_{c} method. The depth distribution of the initial stress and initial void ratio are shown in Figure 5. Assuming that a container terminal would be constructed on this initial state of clay deposit, the load history shown in Figure 6 was applied to the clay soil. First, a preload of 50 kPa was applied until the degree of consolidation $U = 90\%$ (approximately 177 days) was reached. The preload was removed, leaving 10 kPa, and the soil was left for 100 days until 277 days. Subsequently, paving was carried out with a load of 10 kPa. Service started 100 days after paving. The service load was set at 30 kPa. All of these loads were applied and removed instantaneously. Since the proposed method is solved using the finite difference method, the clayey soil must be divided into grids. In this study, the number of grids was set to 100 in both the vertical and radial directions. The analysis was performed from the start of the analysis when the preload was applied until 10 000 days.

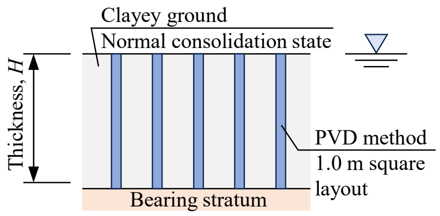


Figure 4. Model of the original ground in the analysis

Table 1. Material parameters

Parameter	Value	Unit
Unit weight, γ'	5.0	kN/m^3
Compression index, C_c	1.2	-
Swelling index, C_s	0.12	-
Coefficient of vertical consolidation, c_v	0	m^2/s
Coefficient of horizontal consolidation, c_h	5.8×10^{-8}	m^2/s
Isotache parameter, $\sigma'^{pL}/\sigma'^{p0}$	0.7	-
Isotache parameter, c_1	0.935	-
Isotache parameter, c_2	0.111	kN/m^3

Table 2. Analysis cases

Case	Case1	Case2	Case3	Case4	Case5	Case6
Thickness, H	5 m	10 m	20 m	5 m	10 m	20 m
Isotache model	Application			Not application		

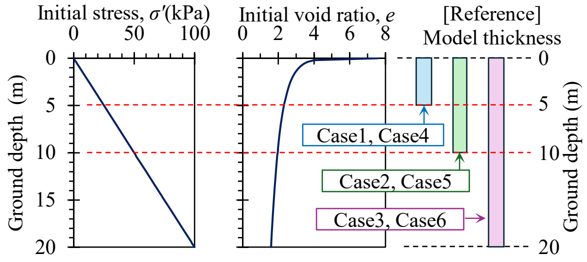


Figure 5. Depth distribution of initial stress and initial void ratio

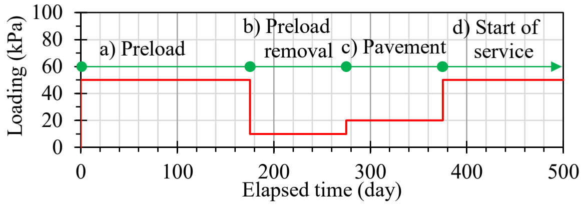


Figure 6. Construction history in the analysis

3.2 *The results of the analysis*

The results of the analysis are shown in Figure 7, which shows the time history of the settlement. The three figures show the load history in the upper graph, the total settlement in the middle graph, and the settlement due to visco-plastic strain in the lower graph. In Cases 1 to 3, where the isotache model was applied, settlement commenced immediately following preload application and continued after the onset of service. On the other hand, in Cases 4 to 6, where the isotache model was not applied, subsidence continued after the start of service, but converged after 1 000 days. The settlement that occurred after the start of service in Cases 4 to 6 was caused by the dissipation of excess pore water pressure and was not due to visco-plastic strain. Additionally, at 510 days, a bend-like point appears in the settlement time history curve, indicating that the settlement rate differs before and after this point. This is due to the clay entering an overconsolidated state after the removal of preload, which then reached a normal consolidation state at 510 days under the loading of pavement and service loads, resulting in a change in the settlement rate. When the amount of settlement was calculated based on the middle figure in Figure 7, using the isotache model, the settlement at the end of the analysis (10 000 days) was 0.15 m for the 5 m layer thickness model, 0.32 m for the 10 m layer thickness model, and 0.71 m for the 20 m layer thickness model. This shows that although the amount of settlement due to the application of the isotache model is not proportional to the layer thickness, the thicker the layer, the greater the amount of settlement. This is also evident from the time history of settlement due to visco-plastic strain shown in the lower graph of Figure 7. Since the isotache model cannot separate viscous strain and plastic strain, this figure shows the time history of settlement due to visco-plastic strain. After preload removal, settlement due to visco-plastic strain temporarily drops to zero, but settlement resumes after service begins. To investigate the cause of this settlement curve, the visco-plastic strain rate was examined. Figure 8 shows the time history of the visco-plastic strain rate output at the lowest grid cell of the soil model. Immediately after preload removal, the visco-plastic strain rate decreased sharply, but it recovered over time after the start of service. Based on this, the reason why no settlement due to visco-plastic strain occurred immediately after unloading is considered based on Figure 9. Figure 9 shows the effective stress and visco-plastic strain relationship for Case 3, an analysis example with a layer thickness of 20 m, at two points (a) at a depth of 5 m and (b) at a depth of 19.8 m, from the start to the end of the analysis. When the preload is removed, the state in Figure 9 moves to the left.

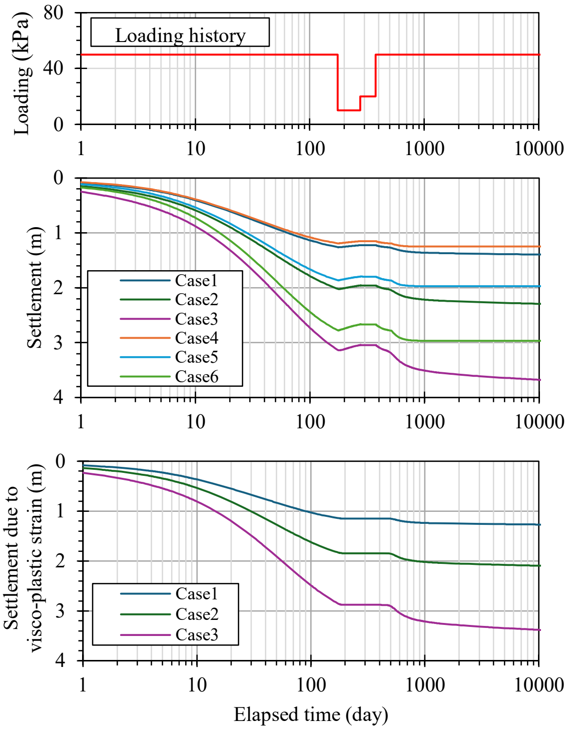


Figure 7. Time history of settlement

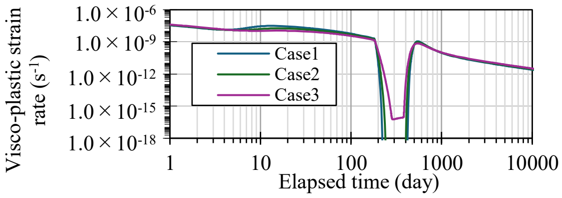
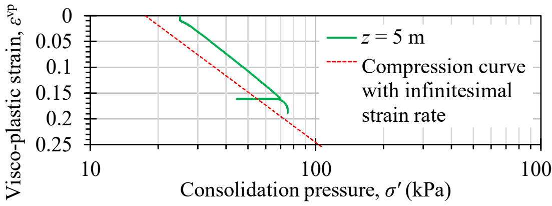
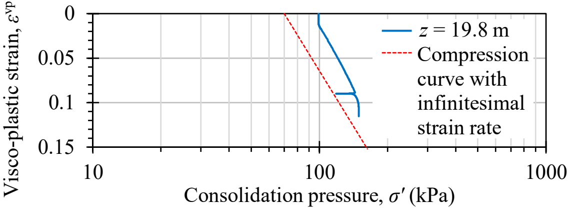


Figure 8. Time history of visco-plastic strain rate



(a) Depth z = 5 m



(b) Depth z = 19.8 m

Figure 9. Effective stress - visco-plastic strain relationship in Case 3

Depending on the magnitude of preload removal and the internal stress state, (a) passes over the compression curve with an infinitesimal strain rate, while (b) stops just before it. Since the state shifted to the vicinity of this compression curve, it is considered that no further visco-plastic strain occurred, as shown in the lower graph of Figure 7. Subsequently, the state changes due to reloading. In this analysis example, since the load level at the start of service is equivalent to the preload, the state has transitioned to the right side of the figure, reaching the effective stress just before preload removal. Due to long-term loading after the commencement of service, visco-plastic (creep) settlement occurs, represented by movement toward the lower part of the figure. In this case, the analysis was terminated at 10 000 days, but since visco-plastic strain occurs until the state reaches a compression curve with an infinitesimal plastic strain rate, it is considered that more creep settlement will occur if left for a longer period of time.

Finally, Figure 10 shows an example of comparing the analysis of the isotache model with other models. Case 4′ to Case 6′ in the figure are the results of adding the secondary consolidation calculated using the concept of a constant ratio of the coefficient of secondary consolidation C_α to the compression index C_c by Mesri and Godlewski (1977) and Mesri and Choi (1985) to the analysis results of Case 4 to Case 6 without applying the isotache model. Because the isotache model accounts for creep during primary consolidation, the amount of settlement during the preload period is greater than that in Case 4′ to Case 6′. However, after the removal of the preload, the settlement calculated by the constant C_α/C_c concept gradually increases, and by the end of the analysis, the total settlement for both approaches becomes almost identical. The isotache model by Watabe and Leroueil (2012) is based on the theory that the amount of creep convergence with a decrease in strain rate, and is characterized by the fact that it provides realistic analysis results showing that creep settlement converges when ultra-long-term effects are considered. On the other hand, the evaluation method based on the constant C_α/C_c concept may overestimate secondary consolidation as the analysis period is extended.

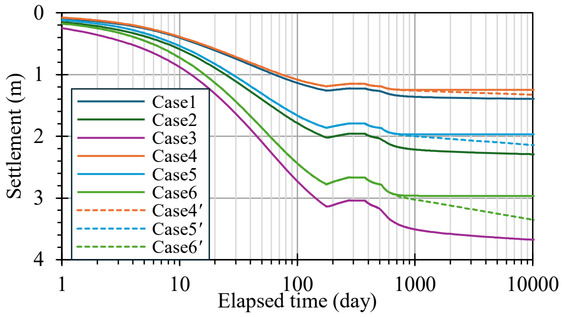


Figure 10. Comparison of secondary consolidation

4 CONCLUSION

A simple method for applying the isotache model by Watabe and Leroueil (2012) to ground improvement by preloading was proposed, and its applicability was confirmed by analyzing a model ground with construction history, simulating the stress levels associated with the construction and service of a container terminal. The following insights were obtained from the analysis examples. 1) Since the reduction in strain rate is slower in deeper soil layers, the thicker the soil layer, the greater the settlement caused by visco-plastic strain. 2) When preload is removed, a state in which visco-plastic strain does not occur temporarily due to unloading persists; however, as the effective stress increases during reloading before the start of operation, settlement due to visco-plastic strain continues. 3) When calculating ultra-long-term secondary consolidation using the isotache model by Watabe and Leroueil (2012), the results tend to converge, but when calculated using the constant C_α/C_c concept by Mesri and Godlewski (1977) and Mesri and Choi (1985), there is a risk of overestimating the amount of secondary consolidation. The validity of the settlement amounts calculated using this model should be further verified in future studies.

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