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Applicability of elasto-viscoplastic one-dimensional consolidation model to long-term consolidation behavior of quasi-overconsolidated clays

Applicabilité d'un modèle élasto-viscoplastique de consolidation á une dimension sur le comportement de consolidation à long-terme des argiles quasi-surconsolidées

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ABSTRACT

An elasto-viscoplastic one-dimensional consolidation model was proposed for quasi-overconsolidated clays in stress level range from the current overburden pressure to over the consolidation yield stress, followed by confirming its applicability to the long-term consolidation behavior of Pleistocene clays of Osaka Bay through numerical simulations of a series of long-term consolidation tests. Then, a series of numerical simulations was carried out to investigate the effect of drainage path length on the consolidation behavior of quasi-overconsolidated clays in stress level less than the consolidation yield stress. As the results, it was concluded that the proposed model was one of available effective techniques for predicting the long-term consolidation behavior of the quasi-overconsolidated clays.

RÉSUMÉ

Un modèle élasto-viscoplastique de consolidation á une dimension a été envisagé pour les argiles quasi-surconsolidées dans un champ des contraintes de la pression courante des terres sus-jacentes à par-dessus la contrainte d'écoulement de consolidation, suivi par confirmant son applicabilité sur le comportement de consolidation à long-terme des argiles de Pléistocène à la Baie d'Osaka par simulations numériques d'une série des essais de consolidation à long-terme. Puis, une série des simulations numériques a été exécutée pour exàminer l'effet de longueur de drainage sur le comportment de consolidation des argiles quasi-surconsolidées dans un champ des contraintes moins de la contrainte d'écoulement de consolidation. En conséquence, il a été conclu que le modèle envisagé a été l'une des techniques efficaces pour prédisant le comportement de consolidation à long-terme des argiles quasi-surconsolidées.

1 INTRODUCTION

The consolidation yield stress of Pleistocene clays of Osaka Bay is greater than the current overburden pressures in-situ, although they have not been applied any greater pressure than the current overburden pressure, judging from the geological findings. These clays are called "quasi-overconsolidated clay" (Akai and Sano, 1981). It has been known that the consolidation characteristics of quasi-overconsolidated clays are quite distinguished from that of mechanically overconsolidated clays of loading/unloading history. That is, a remarkable secondary consolidation occurs even under a stress level less than the consolidation yield stress. Also, the significantly greater compression occurs just after the yielding. Furthermore, based on the field measurements, remarkable residual settlements of reclaimed lands and man-made islands in Osaka Bay have occurred, although the applied pressure due to reclamation is smaller than the consolidation yield stress (Matsui et al, 2001). Consequently, a new consolidation model which can express such unique consolidation characteristics of quasi-overconsolidated clays should be developed, in order to precisely predict the settlement behavior of large-scale offshore man-made islands, such as in Kansai International Airport and Kobe Airport projects.

In this paper, firstly, an elasto-viscoplastic one-dimensional consolidation model is proposed for predicting long-term consolidation behavior of quasi-overconsolidated clays (Oda, et al, 2003, 2004), followed by confirming its applicability to the long-term consolidation behavior of Pleistocene clays of Osaka Bay in stress level range from the current overburden pressure to over the consolidation yield stress. Then, the effect of drainage path length on the long-term consolidation behavior of quasi-overconsolidated clays in stress level less than the consolidation yield stress is investigated through a series of numerical simulations. Finally, the availability of the model proposed for predicting the consolidation behavior of the Pleistocene clay layers is discussed.

2 ONE-DIMENSIONAL CONSOLIDATION MODEL FOR QUASI-OVERCONSOLIDATED CLAYS

The compression behavior of quasi-overconsolidated clays in stress level range from the current overburden pressure to over the consolidation yield stress does not follow the conventional e-log p' relationship. The authors proposed a time-independent compression relationship, which can express the smooth change of time-independent compression behavior in the stress level range above-mentioned, through applying the subloading surface theory (Hashiguchi, 1989). Based on the proposed model, a plastic volumetric strain, v^p, is given as follows:

$$v^p = \int \frac{1+e}{1+e_0} dv^p \tag{1}$$

$$dv^p = \frac{\lambda - \kappa}{1+e}\left(\frac{dp'}{p'} - \frac{dR}{R}\right) \tag{2}$$

where λ and κ are the compression and swelling indices, e and e_0 the void ratio at current and reference states, respectively, p' the vertical effective stress at current state. R is defined as the following equation.

$$R = \frac{p'}{p'^*} \tag{3}$$

where p'* is the normal yield stress. Therefore, R corresponds to the reciprocal of over-consolidation ratio. Following Hashiguchi (1989), the evolution law of R can be expressed in terms of v^p as follows:

$$dR = -\nu \ln R \cdot v^p \tag{4}$$

where ν is a material constant.

On the other hand, the flow surface model (Sekiguchi, 1977), which has been widely used to express the time-dependent behavior of clays, is given as the following equation.

$$v^{vp} = \mu \ln\left\{ \frac{\dot{v}_0 t}{\mu} \exp\left(\frac{v^p}{\mu} \right) + 1 \right\} \tag{5}$$

where v^{vp} is the viscoplastic volumetric strain, $\dot{v}_0$ the reference viscous volumetric strain rate, μ the coefficient of secondary compression and t the elapsed time. By the way, v^p in Equation (5) is treated for scalar parameter in the derivation process. That is, both kinds of v^p given by the conventional e-log p' relationship and by an arbitrary compression relationship can be used in Equation (5). Therefore, v^p given by Equation (1) can be used as that in Equation (5). The time-independent compression behavior of quasi-overconsolidated clays can be expressed by Equation (1), so that the time-dependent compression behavior of quasi-overconsolidated clays under stress levels less than the consolidation yield stress can be expressed by substituting v^p in Equation (1) to Equation (5). Consequently, the proposed elasto-viscoplastic one-dimensional consolidation model is given by applying the non-conventional compression relationship to the flow surface theory.

3 APPLICABILITY FOR PLEISTOCENE CLAYS OF OSAKA BAY

In this paper, the proposed model is applied to a series of long-term consolidation tests for Ma10 clay, one of Pleistocene clays of Osaka Bay (Mimura et al. 2003). Table 1 shows physical properties of Ma10 clay. In Table 1, p_0 and p_y denote the current overburden pressure and the consolidation yield stress in a constant rate of strain loading test, respectively. This sample exhibits high plasticity judging from the liquid limit and plasticity index. Furthermore, it is suggested that this sample has high in-situ structure, because it has a greater void ratio in spite of comparatively greater p_0.

Figure 1 shows the applied pressure in a series of long-term consolidation tests for Ma10 clay. The solid curve in Figure 1 represents the relationship between applied pressure and vertical strain in a constant rate of strain loading test. In experimental cases from Case-10-1 to Case-10-3, a series of long-term consolidation tests were carried out in stress levels less than the consolidation yield stress. In Case-10-4, the test was carried out in a stress level of about consolidation yield stress, and in Case-10-5 and Case-10-6, in stress levels more than the consolidation yield stress.

In the numerical simulation, a one-dimensional elasto-viscoplastic consolidation finite element method is applied. Table 2 shows parameters used in the numerical analysis, in which k_0 represents the coefficient of permeability at the reference state and C_k the index of variation of permeability. The details of the numerical simulation can refer to the reference (Oda et al. 2003).

Figure 2 shows the variation of the vertical strains with elapsed time in the analysis, comparing with the experimental data in a series of long-term consolidation tests of Ma10 clay. In Case-10-1 to Case-10-3, only about 2% of vertical strain occurs, even in the elapsed time of about 1000 minutes (about 1 day). However, a remarkable vertical strain occurs in each test after the elapsed time of about 1000 minutes. The greater the applied pressure is, the earlier the remarkable vertical strain occurs. It is considered that the remarkable increase of vertical strain is caused by secondary consolidation after the elapsed time of about 1000 minutes, because the excess pore water pressure dissipates completely at that time. That is, the significant secondary consolidation occurs even in applied pressure levels less than the consolidation yield stress. In Case-10-4, the slope of the curve between vertical strain and logarithmic elapsed time slightly increase after the elapsed time of about 100 minutes. In Case-10-5 and Case-10-6, the slope of each curve becomes gradually steeper until about 100 minutes, then decreasing, and becoming constant after the elapsed time of about 1000 minutes. The numerical simulation reproduces the variation of the vertical strain with the elapsed time very well in a series of experiments, except that the vertical strain in the numerical simulation is slightly smaller than the experimental one in Case-10-5 and Case-10-6.

Figure 3 shows the experimental and analytical relationships between vertical strain and logarithmic strain rate in a series of long-term consolidation tests. In Case-10-1 to Case-10-3, the vertical strains are very small until strain rate of about 1.0×10^{-6} (1/sec), but a remarkable vertical strain occurs in smaller strain rates than that. The greater the applied pressure, the greater the strain rate at which a remarkable vertical strain occurs. After

Table 1. Physical properties of Ma10 clay

Sampling depth	120m~135m
Liquid limit: w_L (%)	111
Plastic Limit: w_p (%)	52
Plasticity index: I_p	59
Density of soil particle: ρ_s (g/cm^3)	2.606
Natural water content: w_0 (%)	72
Void ratio in-situ: e_0	1.91
Overburden pressure: p_0 (kN/m^2)	1020
Consolidation yield stress: p_y (kN/m^2)	1530

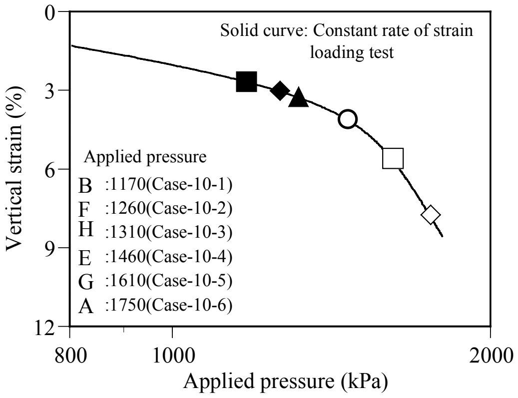

Figure 1. Applied pressure in a series of long-term consolidation tests for Ma10 clay

Table 2. Parameters used in numerical analysis

	Ma10 clay
λ	0.801
κ	0.106
μ	0.008
$\dot{v}_0$ (1/min)	5.6×10^{-8}
ν	0.024
R_0	0.435
k_0 (cm/min)	6.94×10^{-7}
C_k	0.25

that, each curve is almost straight with an approximately equal slope. In Case-10-4, the slope of the curve between vertical strain and logarithmic strain rate slightly increases at the strain rate of about 1.0×10^{-6} (1/sec), and after that, the curve becomes almost straight with an approximately equal slope to that in Case-10-1 to Case-10-3. In Case-10-5 and Case-10-6, the remarkable vertical strains occur, even in higher strain rates than 1.0×10^{-5} (1/sec). Each curve of vertical strain and logarithmic strain rate is almost straight in case of smaller strain rates than 1.0×10^{-6} (1/sec), in which the slope of each curve is approximately equal with that in Case-10-1 to Case-10-4. The numerical simulation reproduces the relationship between vertical strain and logarithmic strain rate in each test reasonably well.

Figure 4 shows the experimental and analytical compression curves in a series of long-term consolidation tests of Ma10 clay. The slope of compression curve becomes gradually steeper until the elapsed time of 1000 minutes, and then the slope hardly changes, parallel shifting the compression curve downward after the elapsed time of 1000 minutes. The numerical simulation reproduces such characteristics reasonably well. Consequently, the proposed elasto-viscoplastic one-dimensional consolidation model is applicable to the long-term consolidation behavior of quasi-overconsolidated clays.

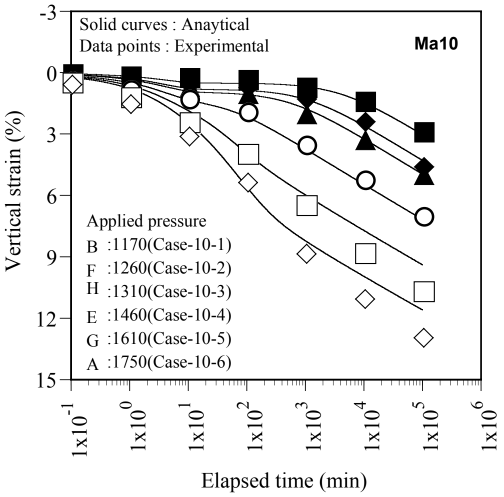

Figure 2. Variation of the vertical strain with elapsed time in the analysis, comparing with the experimental data in a series of long-term consolidation tests of Ma10 clay

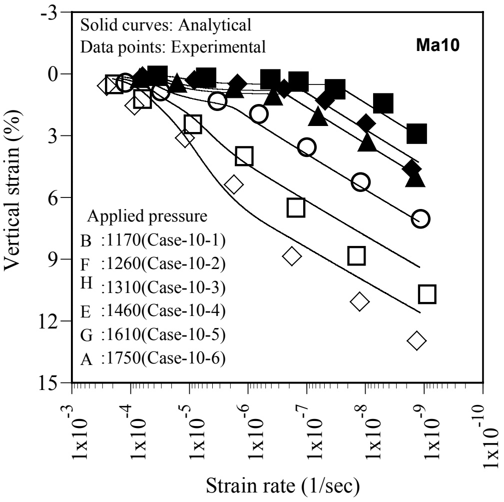

Figure 3. Experimental and analytical relationships between vertical strain and logarithmic strain rate in a series of long-term consolidation tests of Ma10 clay

4 EFFECT OF DRAINAGE PATH LENGTH ON LONG-TERM CONSOLIDATION BEHAVIOR

The residual settlements of Pleistocene clay layers have occurred in Osaka Bay, although the applied pressure in-situ is smaller than the consolidation yield stress by conventional consolidation tests. A parametric study, in which the drainage path length, $\overline{H}$, is chosen as a variable parameter, is carried out to discuss the applicability of the proposed model to above-mentioned consolidation settlement behavior. In the parametric study, $\overline{H}$ is varied from 0.01cm to 10.0m. The applied pressure of 1310kPa is less than the consolidation yield stress (see Figure 1). The analytical parameters in the numerical simulation are similar as in Table 2.

Figure 5 shows the variation of vertical strain and normalized average excess pore pressure with the elapsed time. In the case of $\overline{H}$ less than 0.1m, the vertical strain becomes temporarily stable at about 1.5%, and the required time to become about 1.5% is longer as $\overline{H}$ increases. The remarkable vertical strain occurs again after the elapsed time of about 10^4 minutes, regardless of $\overline{H}$. Comparing the vertical strain with the excess pore pressure, it is seen that the increasing of vertical strain stops, as the excess pore pressure dissipates completely in each case. Therefore, the vertical strain of about 1.5%, which occurred before the elapsed time of about 10^4 minutes, is caused by the primary consolidation. In contrast, the remarkably increasing vertical strain after the elapsed time of about 10^4 minutes occurs due to the secondary consolidation.

In the case of $\overline{H}$ longer than 0.5m, the vertical strain in each case monotonically increases. In the case of $\overline{H}$ of 0.5m, the excess pore pressure still remains a little at the elapsed time of about 10^4 minutes, and in the case of $\overline{H}$ of 1.0m, about 40% of excess pore pressure still remains. In these cases, the time-dependent mechanical characteristics can not be ignored before finishing the primary consolidation, so that the vertical strains can increase continuously. In the case of $\overline{H}$ longer than 5.0m, the excess pore pressures hardly dissipate at the elapsed time of about 10^4 minutes, at which the remarkable secondary consolidation occurs in case of $\overline{H}$ less than 0.1m. Therefore, the primary consolidation behavior in these cases is affected significantly by time-dependent mechanical characteristics. As the proposed model is based on the isotach law, the relationships between vertical strain and elapsed time are coincident with each other after the excess pore pressure dissipates completely.

Figure 6 shows the relationship between vertical strain and average of vertical effective stress. As shown in Figure 5, the secondary consolidation does not occur before finishing the primary consolidation in the cases of $\overline{H}$ less than 0.1m, so that the compression curves between vertical effective stresses of 1020kPa and 1310kPa are almost straight lines. The direction of

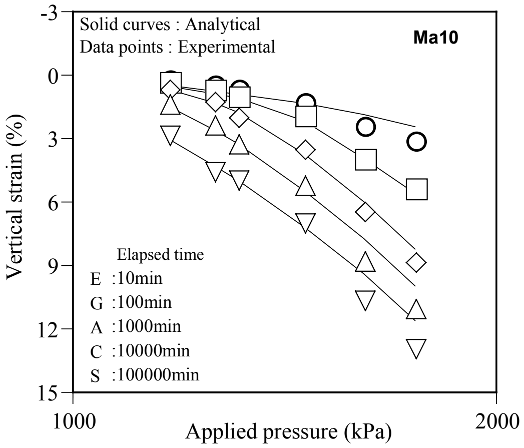

Figure 4. Experimental and analytical compression curves in a series of long-term consolidation tests of Ma10 clay

compression curves sharply turn downward at the vertical effective stress of 1310kPa. The vertical strains significantly increase due to the secondary consolidation without any change of vertical effective stress.

On the other hand, the compression curves in the cases of $\overline{H}$ greater than 0.5 m, are affected by time-dependent mechanical characteristics. The longer the $\overline{H}$, the higher the remaining excess pore pressure, as shown in Figure 5. Therefore, the longer the $\overline{H}$ is, the earlier the compression curves is separated from that in the cases of $\overline{H}$ less than 0.1m, in which the secondary consolidation occurs. Especially, the compression curve in the case of $\overline{H}$ of 10.0m is separated at around the beginning. After the compression curve being separated, the slope of compression curve becomes steeper. The excess pore pressure dissipates completely in the vertical effective stress of 1310kPa, so that the remarkable vertical strain occurs only due to the secondary consolidation.

By the way, $\overline{H}$ of 0.01m corresponds to that of specimen in conventional consolidation tests such as oedometer, while $\overline{H}$ of 10.0m is almost equivalent to field size of Pleistocene clay layers in Osaka Bay. It is suggested that the remarkable residual settlement of Pleistocene clay layers in-situ may be caused by the time-dependent mechanical characteristics, even if the vertical strain hardly occurs in the conventional consolidation tests. Also, the proposed elasto-viscoplastic one-dimensional consolidation model can reproduce not only quantitatively the consolidation behaviors in a series of long-term consolidation tests of Pleistocene clays of Osaka Bay, but also qualitatively consolidation behavior of field size Pleistocene clay layers. Therefore, the proposed model might be one of the available effective techniques for predicting the consolidation behavior of quasi-overconsolidated clays, such as Pleistocene clays in Osaka Bay.

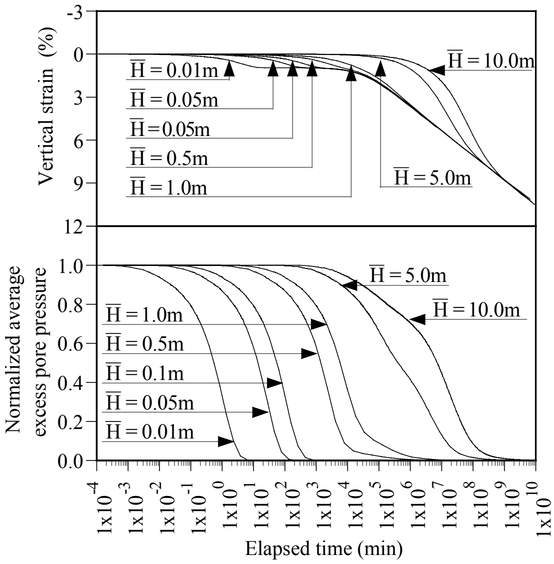

Figure 5. Variation of vertical strain and normalized average excess pore presure with elapsed time

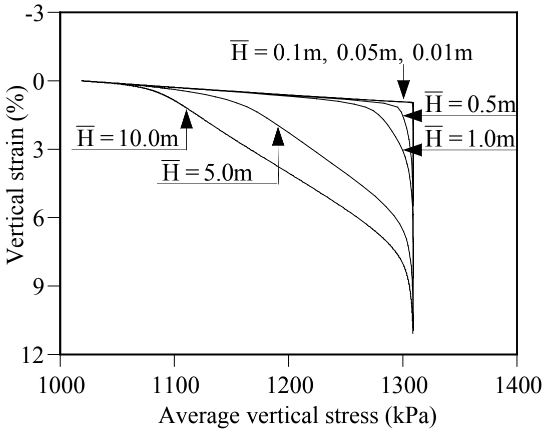

Figure 6. Relationship between vertical stain and average vertical stress

5 CONCLUSIONS

In this paper, an elasto-vicsoplasitc one-dimensional consolidation model for predicting the long-term consolidation behavior of quasi-overconsolidated clays was proposed, followed by confirming its applicability to consolidation behavior of Pleistocene clays of Osaka Bay. Main conclusions are summarized as follows:

1. The proposed elasto-viscoplastic one-dimensional consolidation model can reproduce consolidation behaviors in a series of long-term consolidation tests of Pleistocene clay in Osaka Bay.
2. In the case where the drainage path length is shorter, the remarkable secondary consolidation occurs after finishing the primary consolidation. While, in the case where the drainage path length is comparatively longer, the primary consolidation behavior is affected by the time-dependent mechanical characteristics before dissipating the excess pore pressure completely. Especially, in the case where drainage path length is equivalent to field size, the influence of time-dependent mechanical characteristics on consolidation behavior can not ignored from the beginning of primary consolidation.
3. The longer the drainage path length, the steeper the slope of compression curve. It is suggested, therefore, that the remarkable residual settlement occurs due to the time-dependent mechanical behavior, even if the applied pressure is smaller than the consolidation yield stress.
4. The proposed elasto-viscoplastic one-dimensional consolidation model might be one of the available effective techniques for predicting the long-term consolidation behavior of quasi-overconsolidated clays.

REFERENCES

Akai, K. and Sano, I. 1981. Long-term consolidation of Osaka upper diluvial clay, *Tsuchi-To-Kiso*, 29(3), 43-47 (in Japanese)

Mimura, M., Oda, K., Ohshima, A., Takeda, K., Yamamoto, K., Nagaya, J. and Fujiwara, T. 2002. Time-dependent stress-strain properties and long-term consolidation behavior of Pleistocene marine clay deposit in the Osaka Bay, *Proc. of Symposium on Recent Researches and Practices of Clay Ground*, 151-158. (in Japanese)

Matsui, T., Oda, K., Mimura, M., Takeda, K., Yamamoto, K. Fujiwara, T. and Suwa, S. 2001. Settlement behavior of Pleistocene marine clay deposits due to reclamation in Osaka Bay, *Proc. of 3rdIinternational Conference on Soft Soil Engineering,* 429-434.

Oda, K., Matsui, T., Cho, Y. S., Kamitake, H., Yamamoto, K. and Fujiwara, T. 2003. One-dimensional consolidation model based on both subloading surface theory and flow surface theory and its applicability to consolidation behavior of Pleistocene clays in Osaka Bay, *Proc. of 48th Geotechnical Symposium*, 417-424. (in Japanese)

Oda, K. and Matsui, T. 2004. One-dimensional consolidation model for quasi-overconsolidated clay and its application for Pleistocene clays of Osaka Bay, *Proc. of the International Symposium on Engineering Practice and Performance of Soft Deposits*, *IS-OSAKA 2004,* 117-120.