Comparative study of long-term consolidation for subsoils under Kansai Airport and Pisa Tower

Etude comparative de la consolidation à long terme pour les sous-sols d'aéroport de Kansai et de tour de Pise

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ABSTRACT: In both the Kansai International Airport and Leaning Tower of Pisa, long-term consolidation settlement is a very important geotechnical issue. In this study, a series of long-term consolidation tests were conducted for undisturbed samples retrieved from these two sites. The isotache concept observed in the long-term consolidation behavior was successfully modeled by a simple equation, and then the difference in long-term consolidation behavior between the Osaka Bay clay (significant delayed consolidation) and Pisa clay were compared and discussed. Using the isotache model, the long-term consolidation settlement can be quantitatively predicted in association with the strain rate dependency.

RÉSUMÉ: Pour l'aéroport international de Kansai et la tour penchée de Pise, le tassement de consolidation à long terme constitue une problématique géotechnique très importante. Dans cet article, on présente une série d'essais de consolidation à long terme réalisés pour des échantillons intacts prélevés sur ces deux sites. Le concept isotâche, observé dans la consolidation à long terme, a pu être modélisé par une équation simple. Les différences de consolidation à long terme observées entre l'argile de la baie d'Osaka (consolidation retardée significative) et l'argile de Pise ont été comparées et discutées. En utilisant le modèle isotâche, le tassement de consolidation à long terme peut être quantitativement évalué en association avec la dépendance en vitesse de déformation.

KEYWORDS: long-term consolidation, isotache, strain rate.

1 INTRODUCTION

In both the Kansai International Airport and Leaning Tower of Pisa, long-term consolidation settlement is a very important geotechnical issue. Observed settlements at the two sites are, however, difficult to be directly compared, because their scale and mechanism are different.

In this study, a series of long-term consolidation tests were conducted for undisturbed samples retrieved from these two sites. The test results were interpreted based on the most recent findings from the isotache concept, which considers strain rate dependency in preconsolidation pressure. Then, essential difference between the long-term consolidation behaviors at these two sites was clarified in association with the strain rate dependency.

2 PHYSICAL AND MECHANICAL PROPERTIES OF THE CLAYS

Osaka Bay clay (Kansai International Airport) and Pisa clay have common characteristics, such as soil consistency ($w_L \approx 80\%$, $I_p \approx 50$), grain-size distribution (clay fraction (< 2 μm) of 50%, fine particle fraction (< 75 μm) of 100%), void ratio ($e \approx 1.5$), overconsolidation ratio (OCR ≈ 1.4), etc, as shown in Figure 1. Dominant clay minerals from X-ray diffraction are different: smectite and kaolinite for Osaka Bay clay and illite for Pisa clay. Micro-fabrics observed by scanning electron microscope (SEM) are shown in Figure 2. Osaka Bay clay is consisted of flaky particles (typically smectite) forming aggregations with abundant microfossils (typically diatoms). Pisa clay is consisted of platy particles (typically illite) with a small number of microfossils.

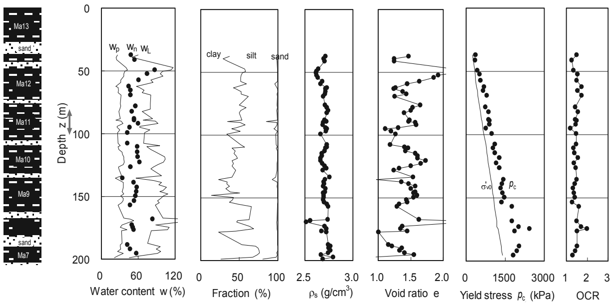


Figure 1a. Depth profiles of soil properties for the Osaka Bay clay.

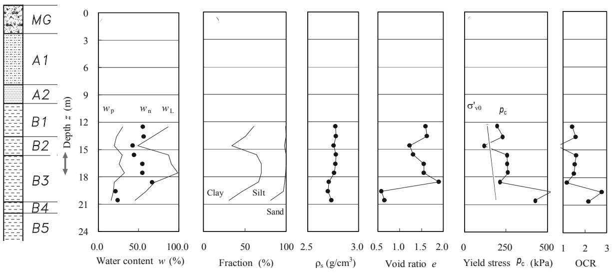
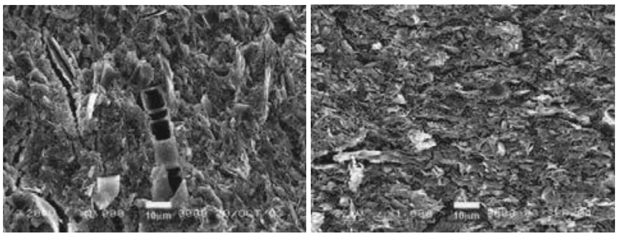


Figure 1b. Depth profiles of soil properties for the Pisa clay.



(a) The Osaka Bay clay. (b) The Pisa clay.

Figure 2. Microfabrics observed by SEM.

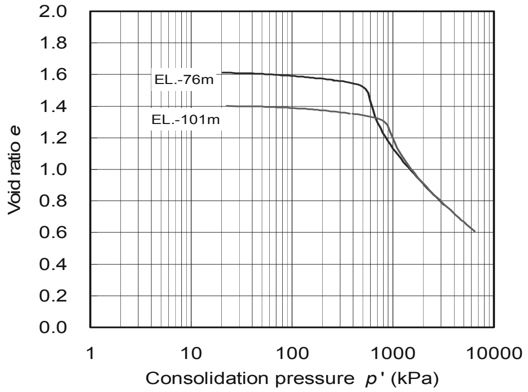


Figure 3a. Compression curves for the Osaka Bay clay.

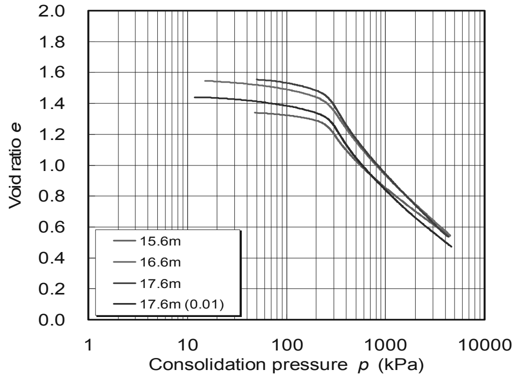


Figure 3b. Compression curves for the Pisa clays.

3 CONSOLIDATION TESTS

Compression curves (*e*–log *p* curves) for the two clays are shown in Figure 3. Undisturbed samples collected from G.L.–76 and –101m (Ma11) for Osaka Bay clay and from G.L.–15.6 and –17.6 m (B3) for Pisa clay were examined. Compression indices C_c at these two sites were commonly 0.7 with very similar compressibility. Preconsolidation pressures σ'_p for Osaka Bay clay and Pisa clay were 600–900 kN/m^2 and 250 kN/m^2, respectively. For these values, a common overconsolidation ratio (OCR = σ'_p/σ'_{v0}) of approximately 1.4 were calculated with the overburden effective stress σ'_{v0} of 750 kN/m^2 and 250 kN/m^2, respectively.

In the long-term consolidation test, a specimen with 60 mm in diameter and 20 mm in height was trimmed from an undisturbed sample, then it was set in the oedometer with double side drainage condition, then it was preliminary consolidated by 24-h incremental loading up to the overburden effective stress σ'_{v0}, and then a target pressure for the long-term consolidation test was loaded (the overburden effective stress σ'_{v0}, preconsolidation pressure σ'_p, and twice of preconsolidation pressure $2\sigma'_p$). Consolidation curves observed at the target pressures were drawn in Figure 4. In the case of σ'_{v0}, Osaka Bay clay shows significant delayed consolidation with convex curve, which means that the secondary consolidation index $C_{\alpha\varepsilon}$ gradually increases with time. Pisa clay, however, shows concave curve, which means that the secondary consolidation index $C_{\alpha\varepsilon}$ gradually decreases with time. In the case of $2\sigma'_p$, the both clays continuously shows the secondary consolidation with concave curve after the primary consolidation. In the case of σ'_p, observed behaviors for the two clays were between the above two cases, respectively.

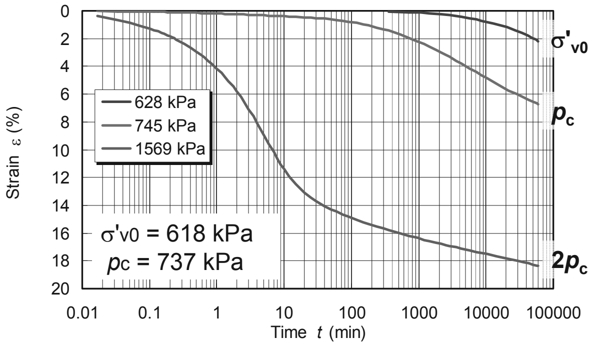


Figure 4a. Consolidation curves for the Osaka Bay clay.

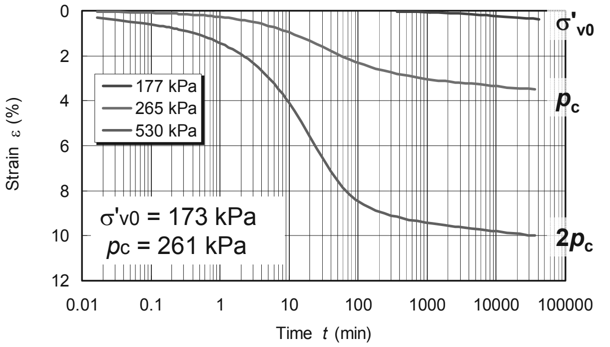


Figure 4b. Consolidation curves for the Pisa clay.

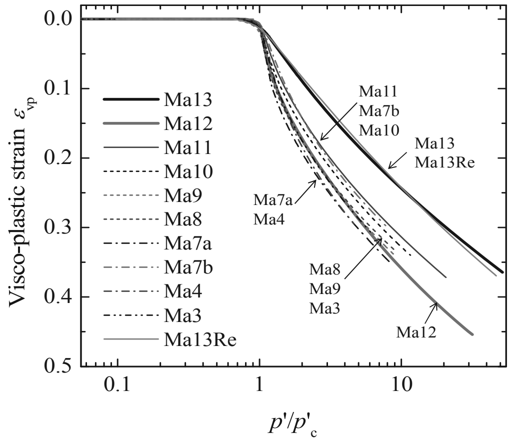


Figure 5a. Reference compression curves for the Osaka Bay clays.

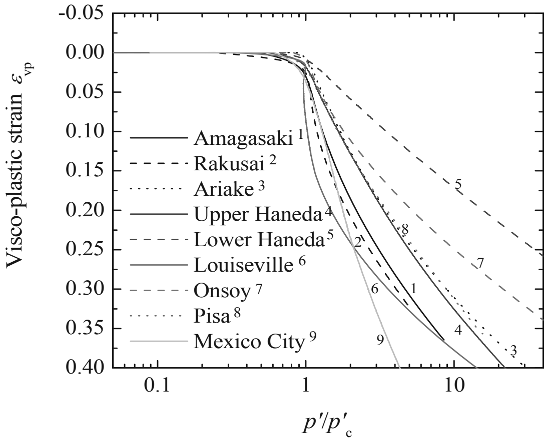


Figure 5b. Reference compression curves for the worldwide clays.

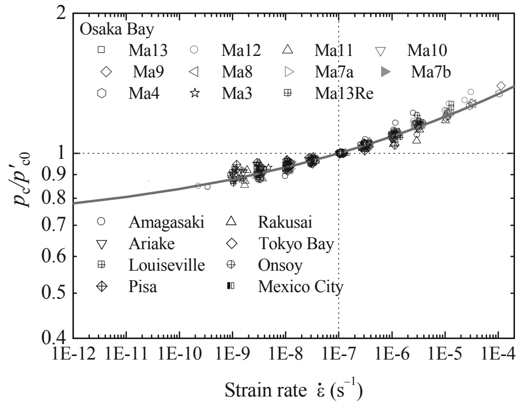


Figure 6a. Strain rate dependency for the worldwide clays.

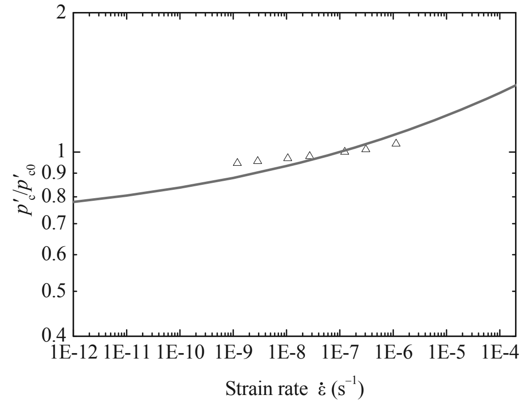


Figure 6b. Strain rate dependency for the Pisa clay.

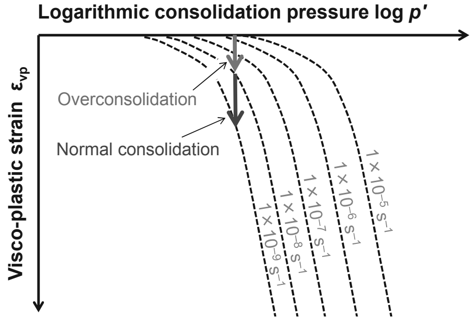
4 MODELLING WITH ISOTACHE CONCEPT

In this study, isotache concept (Šuklje, 1957) is modeled by simple equations proposed by Leroueil et al. (1985), but applied them only to visco-plastic strain $\varepsilon_{\mathrm{vp}}$. Watabe et al. (2008) modeled strain rate dependency of preconsolidation pressure σ'_p as Equation (1):

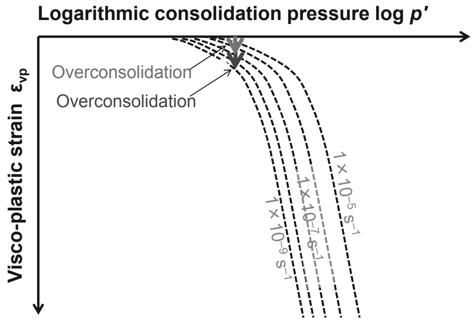
$$\ln\frac{\sigma'_\mathrm{p}-\sigma'_\mathrm{pL}}{\sigma'_\mathrm{pL}} = c_1 + c_2 \ln\dot{\varepsilon}_\mathrm{vp} \qquad (1)$$

Here, σ'_pL, c_1 and c_2 are constants. Equation (1) expresses that the preconsolidation pressure σ'_p converges to a lower limit of σ'_pL.

Watabe et al. (2008) investigated the strain rate dependency of preconsolidation pressure for Osaka Bay clays at various depths from Holocene clay (Ma13) to Pleistocene clay (Ma12 to Ma3) up to 300 m depth, and Watabe et al. (2012) examined the applicability of Equation (1) to worldwide clays with various characteristics. Reference compression curves, in which the consolidation pressure σ'_v is normalized by the preconsolidation pressure σ'_p, obtained from the constant rate of strain consolidation tests are drawn in Figure 5. The clays examined show various compressibility. For each clay, long-term consolidation test was conducted in normal consolidation range, then the relationship between preconsolidation pressure σ'_p and strain rate $\dot{\varepsilon}_\mathrm{vp}$ was obtained (Figure 6a). Here, preconsolidation pressure σ'_p is normalized by a reference value σ'_p0 that corresponds to a strain rate of 1.0×10^{-7} s^{-1} (equivalent to 24-h incremental loading oedometer test). Strain rate dependency can be approximated by a unique model curve with parameters $\sigma'_\mathrm{pL}/\sigma'_\mathrm{p0} = 0.7$ and $c_1 = 0.935$ for Osaka Bay clays at all of the depths (Watabe et al., 2008). Note here that, when the approximate curve passes a certain point, the parameter c_2 automatically determined by the other two parameters σ'_pL and c_1.



(a) In a case of high strain rate dependency.



(b) In a case of low strain rate dependency.

Figure 7. Illustration of long-term consolidation settlement in over-consolidation domain.

The parameters determined for the Osaka Bay clays are applicable to the worldwide clays examined in the previous study (Watabe et al., 2012). Consequently, the isotache concept can be commonly modeled by the unique approximation curve for the worldwide clays. The unique approximation curve is very useful; however, data for some clays, particularly for Pisa clay, is apart from it. The relationship between preconsolidation pressure σ'_p and strain rate $\dot{\varepsilon}_\mathrm{vp}$ for Pisa clay is compared to the unique approximation curve in Figure 6b. Preconsolidation pressure for Pisa clay does not decrease so much with decrease of strain rate, indicating that the strain rate dependency of Pisa clay is smaller than that of the other clays.

5 DISCUSSION

The key factor to model the isotache concept is the strain rate dependency of preconsolidation pressure. From the previous studies, it was found out that the strain rate dependency can be expressed by the unique approximation curve. Pisa clay, however, shows particularly smaller strain rate dependency than the other clays. This different dependency strongly influences the long-term consolidation behavior in over-consolidated domain. In practice, consolidation settlement is predicted based on the compression curve corresponding to a stain rate of 1.0×10^{-7} s^{-1}. Because the Osaka Bay clay has high strain rate dependency, overconsolidation with a higher strain rate at the beginning can be eventually changed to normal consolidation with a smaller strain rate. Figure 7a illustrate the mechanism for the significant delayed long-term consolidation when the Osaka Bay clay was loaded in slightly overconsolidation. On the other hand, because the Pisa clay has low strain rate dependency, overconsolidation with a higher strain rate at the beginning can be eventually maintained in overconsolidation with a smaller strain rate. Figure 7b illustrate the mechanism for that the Pisa clay remained in overconsolidation when it was loaded in slightly overconsolidation.

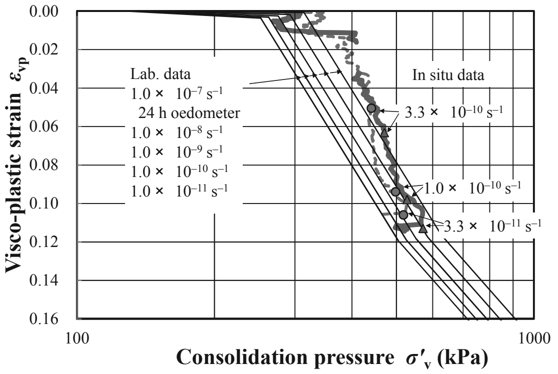


Figure 8. Measured field compression curves in Kansai International Airport Phase 1 (Ma12).

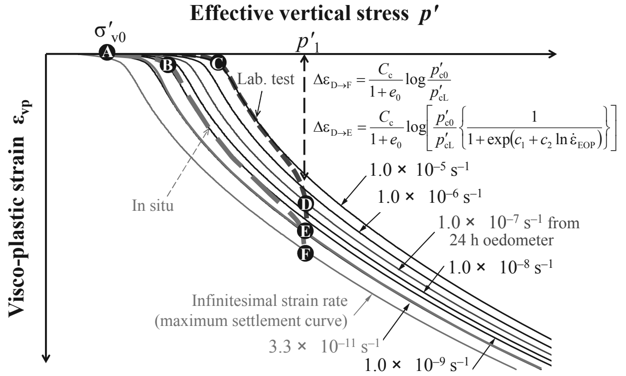


Figure 9. Isotache compression curves in the laboratory and prediction of long-term consolidation settlement.

From comparison between the Osaka Bay clay and Pisa clay, one of the main reasons of those different long-term consolidation tendencies seems to be the existence of microfossils, which are found abundantly in Osaka Bay clay, but barely in Pisa clay. However, it is not true. Because the unique approximation curve was determined for worldwide clays with various characteristics with or without microfossils, it cannot be said that the main reason is the existence of microfossils. From X-ray diffraction, clay minerals in most of the clays examined in the previous studies were smectite and kaolinite. As mentioned above, the Osaka Bay clay also mainly consists of smectite and kaolinite, but only the Pisa clay among the clays examined mainly consists of illite. Therefore, it indicates that illite results in a small strain dependency; i.e., one of the main reasons of different strain dependency is the clay minerals.

For the Pisa clay, because strain rate dependency is not significant, long-term consolidation settlement can be approximately predicted based on the compression curve corresponding to a strain rate of 1×10^{-7} s^{-1}. In fact, settlement of the Leaning Tower of Pisa has been successfully predicted without regard to strain rate effect (Burland et al., 2003), even after about 800 years since its construction. In contrast, because strain rate dependency of the Osaka Bay clay is significant, long-term consolidation settlement predicted based on the compression curve corresponding to a strain rate of 1×10^{-7} s^{-1} results in underestimation. In situ compression curves observed by sublayered measurements of settlement and pore-water pressure at the first phase of the Kansai International Airport are drawn in Figure 8 together with isotache curves deduced from 24-h incremental loading oedometer test. The in situ measured data crosses the isotache compression curves diagonally from higher to lower strain rates, indicating that the behavior is consistent with the isotache modeling.

Because the strain rate dependency of the Osaka Bay clay is similar to the other worldwide clays, it can be said that the strain rate dependency has to be considered in prediction of long-term consolidation settlement for most of the clays. Prediction method of field settlement from the overburden effective stress σ'_{v0} to a certain consolidation pressure p_1 is illustrated in Figure 9. The compression curve observed in the laboratory long-term consolidation test follows the path A→C→D→E. At the end of primary consolidation, strain rate is in an order of 1.0×10^{-5} s^{-1}, then it passes the point D at 1.0×10^{-7} s^{-1}, and then it reaches the point E at a much smaller strain rate. When long-term consolidation test is conducted, strain rate easily decreases to 1.0×10^{-9} s^{-1} in 2–4 weeks, but it hardly decreases to 1.0×10^{-10} s^{-1} because it requires several months. In situ strain rate for the Osaka Bay clay is in an order of 1.0×10^{-11} s^{-1}, which is much smaller than the laboratory strain rate of 1.0×10^{-9} s^{-1}, and the compression curve follows a path A→B→E→F. According to a conventional method, the field settlement is predicted as point D based on the result of 24-h incremental loading oedometer test; however, the real filed settlement could be point E. In practice, in situ consolidation settlement can be predicted corresponding to the strain rate, which is predicted in association with the thickness of the clay layer. In addition, ultimate consolidation settlement possibly reaches point F. Using the initial void ratio e_0 and compression index C_c, the additional consolidation strains from D to E ($\Delta\varepsilon_{D\to E}$) and from D to F ($\Delta\varepsilon_{D\to F}$) can be calculated from geometric relationship (equations are shown in Figure 9). These in situ additional strains in association with the strain rate dependency are significant, particularly in a case of thick clay layer.

6 SUMMARY

In the present study, the isotache concept observed in the long-term consolidation behavior was successfully modeled by Equation (1), in which preconsolidation pressure decreases with decrease of strain rate and converges to a lower limit at an infinitesimal strain rate, then the difference in long-term consolidation behavior between the Osaka Bay clay and Pisa clay were compared and discussed using this model. In the long-term consolidation in an overconsolidation domain, significant delayed settlement was observed in the Osaka Bay clay, but not in the Pisa clay. The significant delayed settlement seems strange; however, it can be said that this strange behavior is inherently natural because it is caused by the common strain rate dependency for the worldwide clays. Therefore, the little delayed settlement observed in the Pisa clay is rather strange. Using the isotache model, the long-term consolidation settlement can be quantitatively predicted in association with the strain rate dependency.

6 REFERENCES

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