DESCRIPTION OF TIME-DEPENDENT BEHAVIOR OF QUASI-OVERCONSOLIDATED OSAKA PLEISTOCENE CLAYS USING ELASTO-VISCOPLASTIC FINITE ELEMENT ANALYSES

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ABSTRACT

The Pleistocene clays in Osaka Bay exhibit slight overconsolidation with OCR of 1.2 to 1.5 in average although they are geologically normally consolidated. Therefore, this seeming overconsolidation is thought not to arise from the mechanical reason but to be subjected to the effect of diagenesis, such as aging effect and/or development of cementation among clay particles. In the sense, the Pleistocene clay deposited in Osaka Bay is so-called “quasi-overconsolidated clays” without definite mechanical overconsolidation history. A new concept is introduced to evaluate the time-dependent behavior of the quasi-overconsolidated Pleistocene clays. In the present study, the stress, p_c derived from conventional step loading consolidation test is regarded as the one changing the phase of deformation due to fading the structural effect. Then, the behavior in the region less than p_c is assumed no longer elastic but elasto-viscoplastic. The compression curve in terms of e -log p is used but the viscoplastic deformation is assumed to occur even in the region less than p_c with the coefficient of deformation, C_s . By implementing this concept into elasto-viscoplastic finite element code, the experimental time-dependent compression behavior is found to be well described numerically. Furthermore, the proposed procedure is validated by analyzing the in-situ stress and deformation of one of the reclaimed islands in Osaka Port. The calculated performance can well describe the actual records of settlement for each Pleistocene clay layers monitored by the differential settlement gauges.

Key words: elasto-viscoplastic finite element analysis, long-term settlement, quasi-overconsolidated Pleistocene clay, reclaimed foundation, time-dependent behavior (IGC: D5/E2)

INTRODUCTION

In Osaka Bay, the development of the metropolises has been associated with the expansion of coastal areas as well as the construction of the offshore reclaimed islands. It is well known that those man-made reclaimed islands have suffered from serious long-term settlement mainly due to the delayed compression of the Pleistocene clays (Kiyama et al., 1991; Research Committee on Ground in Osaka Bay, 2002; Mimura et al., 2003). Figure 1 shows the oval shape of Osaka Bay (60, 30 km in size). This beautiful creation was shaped by couple of rising surrounding mountains and precipitation of the base ground in the center of the bay. The seabed deposits of Osaka Bay have been formed due to the soil supply from the rivers. Although it is common that the clay deposits formed under this environment should be normally consolidated, the Pleistocene clays in Osaka Bay exhibit slight overconsolidation with OCR of 1.2 to 1.5 in average. This apparent overconsolidation is thought not to arise from the mechanical reason but due to the fact that it was subjected to the effect of diagenesis, such as

Fig. 1. Plan view of Osaka Bay and the depth of the sea

aging effect and/or development of cementation among clay particles. In the sense, the Pleistocene clays deposited in Osaka Bay are so-called “quasi-overconsolidated clays” without definite mechanical overconsolidation

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history. Long-term and large deformation has been a serious issue because the loading increment, Δp , has become large for the overconsolidated Pleistocene clay, enough to undergo plastic yielding due to large-scale reclamation in a deep-sea area. Furthermore, it is difficult to predict the time-dependent long-term settlement of the Pleistocene clay deposits in Osaka Bay because the time-dependent behavior occurs even in regions less than p_c (Research Committee on Ground in Osaka Bay, 2002).

It has been recognized that time could be an important factor, since a decrease of void ratio under constant effective stress was observed (Buisman, 1936). The approaches developed by Koppejan (1948) and Bjerrum (1967) with rheological equations. Crawford (1965) and Leroueil et al. (1983) confirmed that the strain rate influenced the compression curves of clays. Mesri et al. (1995) and Mesri (2001) showed the procedure to evaluate the primary and secondary consolidation based on the EOP concept. To take the time-dependent behavior into account, rheological models have been developed (Taylor and Merchant, 1940; Gibson and Lo, 1961; Barden, 1965; Wu et al., 1966; Sekiguchi and Toriihara, 1976; Oka, 1981; Kabbaj et al., 1985). Those achievements have produced so-called generalized elasto-viscoplastic constitutive models for normally consolidated clays (Sekiguchi, 1977; Adachi and Oka, 1982).

In the conventional procedure, as it is commonly done, an elastic response is assumed in the region less than p_c whereas an elasto-viscoplastic behavior is assumed in the normally consolidated region. It was reported that the calculated settlement by the conventional procedure was underestimated for the Pleistocene clays the stress state of which remained less than p_c because the Pleistocene clays in Osaka Bay do not deform as elastic but as time dependent materials (Mimura et al., 2003).

In this paper, a new procedure in terms of elasto-viscoplastic framework is introduced to describe those curious behaviors of the Pleistocene clays in Osaka Bay. The authors have introduced the procedure assuming that the deformation in the quasi-overconsolidated region is no longer elastic but elasto-viscoplastic on the basis of the fact that the quasi-overconsolidated Osaka Pleistocene clays can be considered as normally consolidated aged ones. The compression curves derived from conventional consolidation tests are used as the reference, but the recompression index C_s in the quasi-overconsolidated region is thought to be the one caused by the elasto-viscoplastic deformation although it is assumed to be elastic in the conventional framework. A series of finite element analyses is conducted to assess the long-term consolidation tests reported by Mimura et al. (2003). The validity of the set up parameters for the elasto-viscoplastic finite element analyses is confirmed by comparing the calculated settlement with the experimental results. Descriptive accuracy of the remarkable time-dependency of the compression curves in terms of ε -log p relations is also discussed. Finally, the same framework is extended to an in-situ problem. Maishima Reclaimed Island in Osaka Port is selected to validate the calculated perform-

ance of the proposed method. The calculated results are validated by comparing it with the in-situ measured settlement for each Pleistocene clay layers, Ma12, Ma11 and Ma10 that were measured with the differential settlement gauges for a long time.

ELASTO-VISCOPLASTIC FINITE ELEMENT ANALYSIS

Constitutive Model and Formulation

The elasto-viscoplastic constitutive model used in this paper was proposed by Sekiguchi (1977). Sekiguchi et al. (1982) modified the model to a plane-strain version. The viscoplastic flow rule for the model is generally expressed as follows:

$$\dot{\varepsilon}_{ij}^p = A \frac{\partial F}{\partial \sigma_{ij}} \quad (1)$$

in which F is the viscoplastic potential and A is the proportional constant. Viscoplastic potential F is defined as follows:

$$F = \alpha \cdot \ln \left[1 + \frac{\dot{v}_0 \cdot t}{\alpha} \exp \left(\frac{f}{\alpha} \right) \right] = v^p \quad (2)$$

in which α is a secondary compression index, $\dot{v}_0$ is the reference volumetric strain rate, f is the function in terms of the effective stress and v^p is the viscoplastic volumetric strain. The concrete form of the model is shown in the reference (Mimura and Sekiguchi, 1986). The resulting constitutive relations are implemented into the finite element analysis procedure through the following incremental form:

$$\{\Delta \sigma'\} = [C^{ep}] \{\Delta \varepsilon\} - \{\Delta \sigma^R\} \quad (3)$$

Where $\{\Delta \sigma'\}$ and $\{\Delta \varepsilon\}$ are the associated sets of the effective stress increments and the strain increments respectively, and $[C^{ep}]$ stands for the elasto-viscoplastic coefficient matrix. The term $\{\sigma^R\}$ represents a set of 'relaxation stress', which increases with time when the strain is held constant. The pore water flow is assumed to obey isotropic Darcy's law. In relation to this, it is further assumed that the coefficient of permeability, k , depends on the void ratio, e , in the following form:

$$k = k_0 \cdot \exp \left(\frac{e - e_0}{\lambda_k} \right) \quad (4)$$

in which k_0 is the initial value of k at $e = e_0$ and λ_k is a material constant governing the rate of change in permeability subjected to a change in the void ratio. Note that each quadrilateral element consists of four constant strain triangles and the nodal displacement increments and the element pore water pressure is taken as the primary unknowns of the problem. The finite element equations governing those unknowns are established on the basis of Biot's formulation (Christian, 1968; Akai and Tamura, 1976) and are solved numerically by using the semi-band method of Gaussian elimination.

Fig. 2(a). Conventional compression model

Fig. 2(b). Proposed compression model

Compression Modeling for Quasi-overconsolidated Pleistocene Clays

In the present study, a new assumption for compression is introduced to the conventional procedure. Based on the in-situ measured data, the long-term settlement has been found to take place in the reclaimed islands of Osaka Port even in the Pleistocene clay layers that do not undergo the plastic yielding (Mimura et al., 2001). As it is also stated, the seabed deposits of Osaka Bay have been formed due to the soil supply from the rivers on the sinking base. Therefore, those sediments such as the Pleistocene clays should be normally consolidated although they exhibit the apparent overconsolidation with OCR of 1.2 to 1.5. The authors consider those quasi-overconsolidated Pleistocene clays as “normally consolidated aged clays” with seeming overconsolidation due to diagenesis effect. In the sense, the following assumption is introduced:

The Pleistocene clays in Osaka Bay is “normally consolidated aged clays” that exhibit the elasto-viscoplastic behavior even in the region $p_0 + \Delta p \leq p_c$, while an elastic behavior is assumed to occur in this region by the conventional constitutive models. Figure 2 shows the conventional and the proposed compression models schematically. Here, the Pleistocene clays are assumed to exhibit the time-dependent behavior not only in the normally consolidated region but also in the overconsolidated region. The stress, p_c in the proposed model does not denote the conventional yield stress but is

Fig. 3(a). e - $\log p$ curve and the loading points for the long-term consolidation simulation for Ma12 Fig. 3(b). e - $\log p$ curve and the loading points for the long-term consolidation simulation for Ma10

regarded as the one changing the phase of clay deformation on the reference consolidation curve for monotonic compression due to fading the structural effect. The elastic deformation in the quasi-overconsolidated region is assumed to occur on the basis of the assumption as will be seen later in Eq. (8). But once those clays undergo additional loading, the corresponding stress should be p_c and unloading-reloading region clays exhibit elastic behavior as is conventionally assumed. In short, only the virgin loading for the Pleistocene clays can provide elasto-viscoplastic behavior and once clays experience additional load increment Δp , they exhibit the conventional OC behavior in the range of p_0 to $p_0 + \Delta p$.

Simulation of Long-term Consolidation Tests on Quasi-overconsolidated Pleistocene Clays

In order to confirm the validity of the framework, a series of laboratory long-term consolidation tests on undisturbed Pleistocene clay samples is numerically simulated by the elasto-viscoplastic finite element method with the proposed procedure. The long-term consolidation tests were performed to evaluate the characteristics of time-dependent behavior of the Pleistocene clays obtained from Osaka Bay (Matsui et al., 2001; Mimura et al., 2002; Mimura et al., 2003). As for the soil properties

Fig. 4. Finite element mesh and boundary conditions

for Ma12 and Ma10, refer to Mimura et al. (2003). Figure 3 shows typical consolidation curves derived with laboratory consolidation tests for Ma12 and Ma10 together with the loading stress points, p_1 to p_6 for the long-term consolidation tests. As is known in those figures that a series of long-term consolidation tests is conducted by loading the prescribed vertical stress, p_1 to p_6 . For comparison, the prescribed stresses are set on both sides of p_c . The elasto-viscoplastic finite element analyses are carried out for each long-term consolidation tests, the applied stresses of which are denoted by p_1 to p_6 in Figs. 3(a) and 3(b). The finite element mesh and boundary conditions adopted are shown in Fig. 4. For all cases, the simulations are started from the in-situ effective overburden stress, p_0 . The soil parameters required for the input to the finite element code are determined rationally based on the prescribed procedure (Mimura et al., 1990). The determination of principal soil parameters for analysis with proposed procedure is explained as follows:

- (a) Compression index λ in the normally consolidated region

The definition of compression index λ in the NC region is

$$\lambda = 0.434C_c \quad (5)$$

Here, C_c is a compression index in terms of the common logarithms of consolidation pressure, which can be derived by conventional oedometer test. In general, the value of C_c is not constant, but non-linear against consolidation pressure particularly for clays with developed structure. As shown in Fig. 3, C_c becomes the largest just after plastic yielding and gradually decreases (C_{cl}) with the increase in consolidation pressure. For the cases that the applied stress point is larger than p_c , except p_6 for Ma12, the value of C_c is used as compression index in the NC region. In the case of p_6 for Ma12, as the applied stress is almost twice as large as p_c , the secant compression index C'_c is used to avoid overestimation for a vertical strain as shown in Fig. 3(a).

- (b) Recompression index κ

The definition of recompression index κ

$$\kappa = 0.434C_s \quad (6)$$

Here, C_s is a recompression index in terms of the common logarithms of consolidation pressure, which can be also derived by conventional step loading consolidation test. Based on the fact that most values of the ratio C_s/C_c (κ/λ) are in the range of 0.02 to 0.2 (Terzaghi et al., 1996), it is assumed that C_s is one-tenth of C_c as a representative in the present study.

- (c) Compression index λ_{QOC} and recompression index κ_{QOC} in the quasi-overconsolidation region

In the present analysis, the above-mentioned new procedure is adopted, namely, the compression curve in the quasi-overconsolidated region with inclination of κ is assumed to have elasto-viscoplastic component as same as in the NC region. As e - $\log p$ relations are adopted as reference consolidation curves for clays, the recompression index, κ is assumed to be the compression index in the quasi-overconsolidated region ($p_0 \leq p \leq p_c$). Therefore, the compression index in the quasi-overconsolidated region, λ_{QOC} is introduced in the present study as follows:

$$\lambda_{QOC} = \kappa \quad (7)$$

Calladaine (1971) showed that the ratio κ/λ is directly related to a coefficient of friction $\mu (= \tan \phi')$ that is constant irrespective of a consolidation state. Here, ϕ' denotes an angle of shear resistance. Karube (1975) also confirmed that the relation of the ratio $A (= 1 - \kappa/\lambda)$ and slope of critical state line M is constant for some clays. As M is constant irrespective of the stress state, the ratio κ/λ is constant for the specific clay. Based on those findings, κ_{QOC} is defined in the following relation as is already discussed in the previous section (b):

$$\kappa_{QOC} = \frac{\kappa}{\lambda} \lambda_{QOC} \quad (8)$$

- (d) Secondary compression index α

Secondary compression index α_{NC} governing the time-dependant behavior is determined in the NC region using the relationship between $C_{\alpha c}$ and C_c for Osaka Pleistocene clays (Ishii et al., 1984), that is,

$$C_{\alpha c} = 0.05C_c \quad (9)$$

Here, $C_{\alpha c}$ denotes the secondary compression index in terms of void ratio. The value of α_{NC} then can be determined as follows:

$$\alpha_{NC} = 0.434 \frac{C_{\alpha c}}{1 + e_0} \quad (10)$$

Mesri and Godlewski (1977) showed that the value of α was small at effective stresses less than consolidation yield stress, increased as the consolidation yield stress was approached. Murayama and Shibata (1966) explained that $C_{\alpha c}$ for the Pleistocene clays increased linearly with consolidation pressure in the quasi-overconsolidated region, but which became to be constant in the NC region. In the present analysis, it is assumed that α_{QOC} at p_0 is one-tenth of the prescribed value in the NC region on

the basis of the fact that the adopted ratio of C_s and C_c is 0.1 in this particular case and the adopted relationship between C_c and α (Eq. (9)). Figure 5 shows the assumed modeling for the secondary compression index together with the co-ordinates of the modeling curve based on the above-mentioned experimental findings in terms of relative yield stress index defined by $(p - p_0)/(p_c - p_0)$. It is set up that α increases gradually with the relative yield stress index in the quasi-overconsolidated region thereafter remains constant irrespective of the stress level in the NC region. In this particular simulation, it is because of the fact that the variation of α with increase in the effective stress can be ignored during the consolidation process, the specified α is defined for each applied current consolidation stress. The pull and open circles represent the adopted α for Ma12 and Ma10 in the quasi-overconsolidated region. Tanaka (personal communication, 2003) also pointed out the similar characteristics between α and the relative yield stress index in the quasi-overconsolidated region.

(e) Reference volumetric strain rate $\dot{v}_0$

The rate of consolidation is another significant factor to control the process of deformation. The ratio of secondary compression index α to the reference volumetric

strain rate $\dot{v}_0(\alpha/\dot{v}_0)$ means characteristic time related to the completion of the primary consolidation. The characteristic time t_c in the constitutive model is closely related to a coefficient of consolidation c_v . The value of t_c is determined both for the quasi-overconsolidated region and the NC region as a dissipation time of excess pore water pressure, which is calculated using c_v in the NC region obtained from conventional oedometer test. It is because of the fact that c_v in the quasi-overconsolidated region is approaching that of the NC region, although c_v in the OC ($p < p_0$) region is sufficiently large compared to that in the NC region (Research Committee on Ground in Osaka Bay, 2002). Based on these findings, the same values for t_c are introduced for both in quasi-overconsolidated and NC region in the present study. Based on the parameters, α and t_c , the reference volumetric strain rate, $\dot{v}_0$ becomes a constant maximum value in the NC region. In the quasi-overconsolidated region, $\dot{v}_0$ decrease with decrease in the relative yield stress index, and at $p = p_0$ the value becomes one-tenth of that in the NC region as schematically shown in Fig. 6.

Values of the principal soil parameters adopted for the simulation of the long-term consolidation test are summarized in Table 1.

Fig. 5. Assumed model for secondary compression index

Fig. 6. Relationship between the reference volume strain rate and the relative yield stress

Table 1. Input parameters for the simulation of the long-term consolidation test

Load (kPa)	Quasi-OC region				NC region				M	ν'	p_0 (kPa)	p_c (kPa)	e_0	k_0 (cm/s)	λ_k
	λ_{QOC}	κ_{QOC}	α_{QOC}	$\dot{v}_{0QOC}$ (sec ⁻¹)	λ	κ	α_{NC}	$\dot{v}_{0NC}$ (sec ⁻¹)							
$p_1:510$	0.084	0.008	3.02×10^{-3}	3.70×10^{-7}					1.3	0.36	431	627	2.13	1.00×10^{-7}	0.842
$p_2:588$	0.084	0.008	8.13×10^{-3}	9.96×10^{-7}					1.3	0.36	431	627	2.13	1.00×10^{-7}	0.842
$p_3:666$	0.084	0.008	1.34×10^{-3}	1.65×10^{-7}	0.842	0.084	1.34×10^{-2}	1.65×10^{-6}	1.3	0.36	431	627	2.13	1.00×10^{-7}	0.842
$p_4:745$	0.084	0.008	1.34×10^{-3}	1.65×10^{-7}	0.842	0.084	1.34×10^{-2}	1.65×10^{-6}	1.3	0.36	431	627	2.13	1.00×10^{-7}	0.842
$p_5:823$	0.084	0.008	1.34×10^{-3}	1.65×10^{-7}	0.842	0.084	1.34×10^{-2}	1.65×10^{-6}	1.3	0.36	431	627	2.13	1.00×10^{-7}	0.842
$p_6:1254$	0.084	0.008	1.04×10^{-3}	1.27×10^{-7}	0.649	0.065	1.04×10^{-2}	1.27×10^{-6}	1.3	0.36	431	627	2.13	1.00×10^{-7}	0.649
$p_1:1170$	0.073	0.007	2.86×10^{-3}	3.41×10^{-7}					1.3	0.36	1020	1377	1.91	2.90×10^{-8}	0.733
$p_2:1260$	0.073	0.007	4.92×10^{-3}	5.86×10^{-7}					1.3	0.36	1020	1377	1.91	2.90×10^{-8}	0.733
$p_3:1310$	0.073	0.007	7.03×10^{-3}	8.37×10^{-7}					1.3	0.36	1020	1377	1.91	2.90×10^{-8}	0.733
$p_4:1460$	0.073	0.007	1.26×10^{-3}	1.50×10^{-7}	0.733	0.073	1.26×10^{-2}	1.50×10^{-6}	1.3	0.36	1020	1377	1.91	2.90×10^{-8}	0.733
$p_5:1610$	0.073	0.007	1.26×10^{-3}	1.50×10^{-7}	0.733	0.073	1.26×10^{-2}	1.50×10^{-6}	1.3	0.36	1020	1377	1.91	2.90×10^{-8}	0.733
$p_6:1750$	0.073	0.007	1.26×10^{-3}	1.50×10^{-7}	0.733	0.073	1.26×10^{-2}	1.50×10^{-6}	1.3	0.36	1020	1377	1.91	2.90×10^{-8}	0.733

Fig. 7(a). Calculated e -log p relation for each applied stress (Ma12)

Fig. 8(a). Experimental and calculated strain-time relations (Ma12)

Fig. 7(b). Calculated e -log p relation for each applied stress (Ma10)

Fig. 8(b). Experimental and calculated strain-time relations (Ma10)

Figures 7(a) and 7(b) show the calculated e -log p relations of each applied stress for Ma12 and Ma10 together with the set up compression curves. The set up compression curve is regarded as a reference one with a finite strain rate. The adopted reference compression curve in terms of e -log p in the present analysis is derived from the conventional step loading consolidation tests as shown by the solid lines. The parameters for the model are determined based on this reference state. Then the set up p_c is also considered as the stress separating the different phases of clay deformation on the reference consolidation curve. For the case of p_6 in Fig. 7(a) that the applied stress is much larger than p_c , the calculated compression curve exhibits a remarkable time-dependent behavior associated with stress overshoot just beyond plastic yielding compared to the set up e -log p relation due to strain rate effect. For this calculation, as the applied stress is large enough, the secant compression index C_c' denoted by hatched line in Fig. 7(a) is used for simplicity. The secondary compression then takes place without increase in an effective stress after a remarkable decrease in void ratio due to increase in effective stress. This behavior is typical for normally consolidated clay.

On the contrary, the calculated results that the applied stress is slightly larger than p_c such as p_3 to p_5 for Ma12 and p_4 to p_6 for Ma10 also exhibit similar behavior, but the contribution of the primary consolidation to the total deformation is not so large and the decrease in void ratio is mainly due to secondary compression. It is because the generation of the excess pore water pressure is not sufficient due to relatively small load increment. The calculated performance with the proposed procedure clearly exhibits the time-dependent behavior taking place not only in the post yield region but also in the region that the stress states remain within the quasi-overconsolidated region.

The calculated performance of compression strains with time at various stress level for Ma12 and Ma10 is shown in Figs. 8(a) and 8(b) together with the laboratory experimental results. The calculated compression strains are average ones derived as $\Delta h/h_0$. Here, h_0 is the initial height of the specimen prior to loading, and Δh is the total vertical displacement. For the cases that the stress states become normally consolidated due to load increment, the secondary compressions occur after a significant strain mobilization at the early stage of consoli-

Fig. 9(a). Calculated ε -log p curves of equi-strain rate for Ma12 Fig. 10(a). Calculated ε -log p curves of equi-strain rate for Ma10 Fig. 9(b). Experimental ε -log p curves of equi-strain rate for Ma12 Fig. 10(b). Experimental ε -log p curves of equi-strain rate for Ma10

dation. On the contrary, it can be seen that the compression strains are developed with time after a quiet period in the early stage for the cases that the total overburden stresses remain within the quasi-overconsolidated region. The calculated results coincide well with the laboratory long-term consolidation test results.

Figures 9 and 10 show the comparison between the calculated results and the experimental results in terms of ε -log p relations for Ma12 and Ma10, respectively. It can be seen that the delayed compression takes place in all results with the elapse of time, as well as the ε -log p curves are placed lower with the decrease in the strain rate. It is also quite interesting that the sharp bending point denoted by consolidation yield stress becomes more dull and lower with the decrease in the strain rate. In particular, it is noteworthy that the delayed compression is shown not only for the NC region but also for the quasi-overconsolidated region for all cases. From those comparisons shown in Figs. 9 and 10, it is confirmed that the present procedure can well describe the experimental time-dependant behavior of the Pleistocene clays in Osaka Bay.

NUMERICAL ASSESSMENT OF LONG-TERM SETTLEMENT OF THE RECLAIMED MARINE FOUNDATION AT MAISHIMA IN OSAKA PORT

Monitored Long-term Settlement of Maishima Reclaimed Island

In Osaka Port, Maishima Reclaimed Island had started to be constructed in 1965 by dumping the dredged disposals and after 7 years, sand drains were driven to the Holocene deposits following the set of sand mat. Then the dredged soils were used as filling materials and reclamation work was started in 1981. Finally the final embankment was completed in 1990. The construction sequence is shown in Fig. 11 together with corresponding events and the monitored data (Research Committee on Ground in Osaka Bay, 2002). During the 1st and 2nd filling with dredged materials, the total settlement of the Pleistocene deposits was monitored by double tube settlement gauges at the center of the island. Again during the final sand mat setting prior to embankment, a set of differential settlement gauges was installed to measure the compression of each Pleistocene clay layers, such as Ma12 and Ma11U, Ma11L, Ma10 and the below

Fig. 11. Construction sequence and the monitored settlement at Maishima Reclaimed Island

Fig. 12. Subsurface model for Maishima Reclaimed Island

Ma9. As shown in Fig. 11, as it is a pity that the continuous measurement could not be done in this site, we can get only the total settlement of the Pleistocene deposits during the 1st and 2nd filling and the differential settlements together with those summation during embankment construction. It should be noted that a large amount of settlement continues for the Pleistocene deposits, particularly, even below Ma9, non-negligible long-term settlement takes place with the elapsed time.

Finite Element Analysis Assessing the In-situ Performance of the Reclaimed Foundation

One-dimensional finite element analysis is adopted in the present study to assess the long-term settlement of Maishima Reclaimed Island. The adopted subsurface condition is shown in Fig. 12. As the target point for calculation is located at the center of the island, about 1000 m from the revetment, the effect of lateral deformation on the settlement can be ruled out. As it is also

Fig. 13. Adopted relation the secondary compression index and the relative yield stress index for settlement analysis of Maishima Reclaimed Island

clearly seen in Fig. 12 that the sand layers in Osaka Port are thick and their continuity is guaranteed (Research Committee on Geotechnical Information of Osaka Bay Seabed Deposits, 1995). Then, the effect of the permeability resistance is unnecessary to be taken into account. From those results, one-dimensional finite element analysis is adopted. Based on the boring database for the Maishima reclaimed area (Research Committee on Ground in Osaka Bay, 2002), the soil parameters for the finite element analysis are also determined by using the procedure by Mimura et al. (1990). The used data are obtained mainly from the original seabed before construction except Ma9, the information of which can be derived from the only one boring developed after reclamation. The input parameters adopted are summarized in Table 2. In the present analysis, the proposed compression model shown Fig. 2(b) is also adopted to evaluate the time-dependent behavior of Osaka Pleistocene clays occurring even in the quasi-over-

Table 2. Principle soil parameters for the elasto-viscoplastic finite element analysis

MTYP	Quasi-OC region				NC region				M	ν'	p_0 (kPa)	p_c (kPa)	e_0	k_0 (m/day)	λ_k	
	λ_{QOC}	κ_{QOC}	α_{QOC}	$\dot{\nu}_{0QOC}$ (day ⁻¹)	λ	κ	α_{NC}	$\dot{\nu}_{0NC}$ (day ⁻¹)								
23	0.077	0.008	1.15×10^{-3}	2.49×10^{-7}	0.768	0.077	1.15×10^{-2}	2.49×10^{-6}	1.3	0.36	285	385	2.34	8.64×10^{-5}	0.768	Ma12
22	0.109	0.011	1.64×10^{-3}	3.55×10^{-7}	1.089	0.109	1.64×10^{-2}	3.55×10^{-6}	1.3	0.36	305	412	2.32	8.64×10^{-5}	1.089	Ma12
21	0.084	0.008	1.60×10^{-3}	3.46×10^{-7}	0.842	0.084	1.60×10^{-2}	3.46×10^{-6}	1.3	0.36	325	439	1.63	8.64×10^{-5}	0.842	Ma12
20	0.02	0.002	4.81×10^{-4}	1.04×10^{-7}	0.204	0.020	4.81×10^{-3}	1.04×10^{-6}	1.3	0.36	346	467	1.12	8.64×10^{-5}	0.204	Ma12
19	—	—	—	—	—	—	—	—	—	0.33	429	558	0.93	2.16×10^{-2}	—	Sand
18	0.031	0.003	6.82×10^{-4}	1.03×10^{-6}	0.308	0.031	6.82×10^{-3}	1.03×10^{-5}	1.3	0.36	513	667	1.26	6.05×10^{-5}	0.308	Ma11U
17	0.024	0.002	5.96×10^{-4}	8.97×10^{-7}	0.243	0.024	5.96×10^{-3}	8.97×10^{-6}	1.3	0.36	537	698	1.04	6.05×10^{-5}	0.243	Ma11U
16	—	—	—	—	—	—	—	—	—	0.33	582	728	0.93	2.16×10^{-2}	—	Sand
15	0.077	0.008	1.40×10^{-3}	1.34×10^{-6}	0.774	0.077	1.40×10^{-2}	1.34×10^{-5}	1.3	0.36	625	750	1.76	5.18×10^{-5}	0.774	Ma11L
14	0.049	0.005	9.77×10^{-4}	9.36×10^{-7}	0.490	0.049	9.77×10^{-3}	9.36×10^{-6}	1.3	0.36	649	779	1.51	5.18×10^{-5}	0.490	Ma11L
13	0.024	0.002	6.36×10^{-4}	6.09×10^{-7}	0.243	0.024	6.36×10^{-3}	6.09×10^{-6}	1.3	0.36	676	811	0.91	5.18×10^{-5}	0.243	Ma11L
12	—	—	—	—	—	—	—	—	—	0.33	865	1038	0.93	2.16×10^{-2}	—	Sand
11	0.063	0.006	1.33×10^{-3}	2.15×10^{-7}	0.629	0.063	1.33×10^{-2}	2.15×10^{-6}	1.3	0.36	1051	1261	1.45	2.59×10^{-5}	0.629	Ma10
10	0.081	0.008	1.47×10^{-3}	2.37×10^{-7}	0.812	0.081	1.47×10^{-2}	2.37×10^{-6}	1.3	0.36	1075	1290	1.87	2.59×10^{-5}	0.812	Ma10
9	0.092	0.009	1.43×10^{-3}	2.30×10^{-7}	0.916	0.092	1.43×10^{-2}	2.30×10^{-6}	1.3	0.36	1102	1322	2.21	2.59×10^{-5}	0.916	Ma10
8	0.056	0.006	1.25×10^{-3}	2.01×10^{-7}	0.560	0.056	1.25×10^{-2}	2.01×10^{-6}	1.3	0.36	1126	1351	1.24	2.59×10^{-5}	0.560	Ma10
7	—	—	—	—	—	—	—	—	—	0.33	1226	1471	0.93	2.16×10^{-2}	—	Sand
6	0.044	0.004	1.12×10^{-3}	6.01×10^{-8}	0.438	0.044	1.12×10^{-2}	6.01×10^{-7}	1.3	0.36	1330	1596	0.95	3.46×10^{-5}	0.438	Ma9
5	0.072	0.007	1.51×10^{-3}	8.08×10^{-8}	0.716	0.072	1.51×10^{-2}	8.08×10^{-7}	1.3	0.36	1352	1622	1.37	3.46×10^{-5}	0.716	Ma9
4	0.072	0.007	1.51×10^{-3}	8.08×10^{-8}	0.716	0.072	1.51×10^{-2}	8.08×10^{-7}	1.3	0.36	1389	1667	1.37	3.46×10^{-5}	0.716	Ma9
3	0.064	0.006	1.22×10^{-3}	6.54×10^{-8}	0.638	0.064	1.22×10^{-2}	6.54×10^{-7}	1.3	0.36	1420	1704	1.61	3.46×10^{-5}	0.638	Ma9
2	0.064	0.006	1.22×10^{-3}	6.54×10^{-8}	0.638	0.064	1.22×10^{-2}	6.54×10^{-7}	1.3	0.36	1446	1735	1.61	3.46×10^{-5}	0.638	Ma9
1	0.095	0.010	2.21×10^{-3}	1.18×10^{-8}	0.950	0.095	2.21×10^{-2}	1.18×10^{-7}	1.3	0.36	1464	1757	1.15	3.46×10^{-5}	0.950	Ma9

consolidated region. It should be noted that e -log p relation for the corresponding Pleistocene clays is unchanged at all except the virgin compression contains irreversible time-dependent behavior. Figure 13 shows the adopted relation α and the relative yield stress index for the settlement analysis of Maishima reclaimed area. As shown in the figure, it is assumed that the change in α_{QOC} is divided in the three linear regions with the different rate of increase. It is because of the fact that the non-linear modeling of the change in α_{QOC} with the stress level can lead to the mathematical complexity and instability for the constitutive equation. The values of $\dot{\nu}_0$ then in the quasi-overconsolidated region increase as same as the proportion of the increase in α .

Results and Discussion

The calculated e -log p relations for the Pleistocene clay layers during reclamation at Maishima are shown in Fig. 14 together with the set up compression curves. In all figures, the set up compression curves are illustrated by the solid lines, the results by the conventional and the present elasto-viscoplastic analysis are plotted by the pull circles and open triangles respectively. It is clearly seen from Fig. 14(a) that the stress strain relations for the representative elements of Ma12 are very similar between the conventional and proposed procedure. In contrast, the proposed procedure provides the outstanding time dependent compression which can be seen for Ma11U and Ma11L as shown in Figs. 14(b) and (c). It is natural that the stress paths by the conventional approach trace the setup e -log p curve in the quasi-overconsolidated region because of the assumption of elastic compression. Once the stress surpasses p_c , the typical viscoplastic

behavior is obtained. The difference in time-dependent compression between Ma12 and Ma11U, Ma11L is attributed to the difference in the reference volumetric strain rate, $\dot{\nu}_0$. As shown in Fig. 12, the thickness of Ma12 is much larger than that of Ma11U and Ma11L. As the values of $\dot{\nu}_0$ are determined from c_v and the thickness of the corresponding clay layers, values of $\dot{\nu}_0$ for Ma12 becomes smaller compared to those for Ma11U and Ma11L. Consequently, the time-dependent compression in terms of secondary compression for Ma11U and Ma11L is naturally developed earlier than that for Ma12. Ma10 in Fig. 14(d) is a representative of those layers that the final stress becomes close to p_c and Ma9 in Fig. 14(e) is a representative of those layers that the final stress remains less than p_c respectively. In all cases, the calculated compression curves in terms of e -log p relations move slightly lower than the set up e -log p curves whereas those by the conventional analysis move on the set up e -log p curves. It is natural that the time-dependent behavior such as that shown in Fig. 14 takes place because the present procedure assumes that the time-dependent behavior occurs even in the quasi-overconsolidated region. Due to the assumption introduced in the present study, the advance in compression of the Pleistocene clays in the region less than p_c is found to be well described.

The calculated performance is compared with the measured settlement for each layer in Fig. 15. Here, the solid lines denote the results of the present study while the dash lines are those by the conventional analysis. For Ma12 and Ma11U, the calculated result by the present study and measured results show a good match. The result by the conventional analysis is slightly underesti-

Fig. 14(a). Calculated e -log p relations for the Pleistocene clay elements (Ma12)

Fig. 14(d). Calculated e -log p relations for the Pleistocene clay elements (Ma10)

Fig. 14(b). Calculated e -log p relations for the Pleistocene clay elements (Ma11U)

Fig. 14(e). Calculated e -log p relations for the Pleistocene clay elements (Ma9)

Fig. 14(c). Calculated e -log p relations for the Pleistocene clay elements (Ma11L)

ated because the summation of settlement for Ma12 and Ma11U is compared. As it is seen from Figs. 14(a) and 14(b), the upper Pleistocene clay layers such as Ma12 and Ma11U undergo the plastic yielding due to reclamation work. It is natural that the calculated performance by both the conventional and the proposed procedures are almost same for Ma12 that becomes normally consolidated in a short time. However, when the stress state of the Pleistocene clay layer such as Ma11U remains within the quasi-overconsolidated region for a long time, the calculated result by the conventional analysis can be underestimated even when final stress condition is larger than p_c . For Ma11L that the stress state also remains for a long time within the quasi-overconsolidated region, Ma10 and Ma9 the stress levels of which are close to p_c and less than p_c . It can be seen that the calculated performance with the proposed procedure shows much better coincidence with the measured settlement for Ma11L and Ma10, whereas the conventional approach shows a remarkable underestimation. As for the settlement of Ma9, the calculated performance with the proposed

Fig. 15. Comparison of advance in settlement for each Pleistocene clay layer

Fig. 16. Comparison of advance in total settlement for Pleistocene clay deposits

procedure shows larger settlement when compared to that of the conventional elasto-viscoplastic analysis because of the introduction of the time-dependent behavior in the quasi-overconsolidated region. Since, it is impossible to separate the contribution of Ma9 itself from the measured data, the comparison of the calculated performance for Ma9 to the measured data is not appropriate. However, the measured amount of settlement taking place below Ma9 is more than 20 cm in this limited monitoring period. Although it is not so clear that which layers in the lower Pleistocene clay deposits are affected by the reclamation load, it is very serious that such deeply sedimented Pleistocene clays can possibly contribute to the advance in settlement.

Figure 16 shows the advance in the total settlement of the Pleistocene deposits. Attention should again be paid

to the fact that the measured data contains the contribution by the layers below Ma9. But, the calculated performance with the proposed procedure can describe the settlement of the Pleistocene deposits much better than that with the conventional analysis.

CONCLUSIONS

A new procedure is introduced to describe the time-dependent compression of the Pleistocene clays in Osaka Bay. On the basis of the geological fact that the Pleistocene clays in Osaka Bay are considered as “normally consolidated”. The assumption that an elasto-viscoplastic behavior takes place even in the region less than p_c as well as in the normally consolidated region is adopted and implemented into the elasto-viscoplastic finite element code. The experimental results for long-term one-dimensional consolidation tests are calculated with the proposed approach and it is found that the remarkable time dependent compression in the region less than p_c is well predicted by the calculated performance. The Pleistocene clays in Osaka Bay exhibit remarkable time-dependent compression curves in terms of ϵ - $\log p$ relations with respect to the strain rate. The calculated performance can also well describe those compression curves both for Ma12 and Ma10. The framework adopted in the calculation for the laboratory experiments are also extended to the analysis of the in-situ long-term settlement at Maishima Reclaimed Island. For the upper Pleistocene clay layer such as Ma12, the calculated ϵ - $\log p$ relations with the proposed procedure exhibit almost the same with the conventional approach because Ma12 behaves as almost normally consolidated due to applied load. On the other hand, for the case that the stress condition of clays remains less than p_c , the present analysis shows the remarkable delayed compression with elapsed time even in the region less than p_c while the conventional analysis describes the typical elastic deformation with no gain in time-dependent strain at all in this region. The calculated performance can well describe the in-situ measured settlement for each clay layer such as Ma12, 11 and 10 irrespective of the final stress conditions with the proposed method although the conventional analysis definitely underestimates them. From these results, it is confirmed that the proposed procedure assuming that the elasto-viscoplastic behavior takes place in the region less than p_c as well as normally consolidated region is valid and functions well to assess the in-situ time-dependent long-term settlement occurred in the reclaimed area in Osaka Bay.

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REFERENCES

- Adachi, T. and Oka, F. (1982): Constitutive equations for normally consolidated clay based on elastoviscoplasticity, *Soils and Foundations*, **22** (4), 57–70.
- Akai, K. and Tamura, T. (1976): An application of nonlinear stress-strain relations to multi-dimensional consolidation problems, *Annals DPRI*, Kyoto University, **21** (B-2), 19–35 (in Japanese).
- Barden, L. (1965): Consolidation of clay with non-linear viscosity, *Geotechnique*, **15**, 345–362.
- Bjerrum, L. (1967): Engineering geology of Norwegian normally-consolidated marine clays as related to settlements of buildings (7th Rankine Lecture), *Geotechnique*, **17** (2), 83–119.
- Buisman, A. S. (1936): Results of long duration settlement tests, *Proc. 1st ICSMFE*, Cambridge, **1**, 103–107.
- Calladaine, C. R. (1971): A microstructural view of the mechanical properties of saturated clay, *Geotechnique*, **15** (4), 345–415.
- Christian, J. T. (1968): Undrained stress distribution by numerical method, *Journal of the Geotechnical Engineering Division*, ASCE, **94** (SM6), 1333–1345.
- Crawford, C. B. (1965): The resistance of soil structure to consolidation, *Canadian Geotechnical Journal*, **2**, 90–97.
- Gibson, R. E. and Lo, K. Y. (1961): A theory consolidation for soils exhibiting secondary compression, *Report 41*, Norwegian Geotechnical Institute, Oslo, Norway.
- Ishii, I., Ogawa, F. and Zen, K. (1984): Engineering properties of marine clays in Osaka Bay (Part 2) physical properties, consolidation characteristics and permeability, *Technical Note of the Port and Harbour Research Institute Ministry of Transport*, Japan, **498**, 47–86 (in Japanese).
- Kabbaj, M., Oka, F., Leroueil, S. and Tavenas, F. (1985): Consolidation of natural clays and laboratory testing, *ASTM, Symposium on Consolidation Behaviour of Soils*, Fort Lauderdale, Special Technical Publication, American Society for Testing and Materials, 378–403.
- Karube, D. (1975): Procedure and problems of non-standard triaxial test, *Proc. 20th JSSMFE Symposium*, 45–60 (in Japanese).
- Kiyama, M. (1991): Settlement of the reclaimed land at the coastal area, *Proc. Int. Conf. on Geotech. Engrg. for Coastal Development—Theory and Practice on Soft Ground—*, **1**, 207–212.
- Koppejan, A. W. (1948): A formula combining the Terzaghi load compression relationship and the buisman secular time effect, *Proc. 2nd ICSMFE*, Rotterdam, **3**, 32–37.
- Leroueil, S., Samson, L. and Bozozuk, M. (1983): Laboratory and field determination of preconsolidation pressure at gloucester, *Canadian Geotechnical Journal*, **20**, 477–490.
- Matsui, T., Oda, K., Mimura, M., Takeda, K., Yamamoto, K., Fujiwara, T. and Suwa, S. (2001): Settlement behavior of Pleistocene clay deposits due to reclamation in Osaka Bay, *Proc. 3rd Int. Conf. Soft Soil Engineering*, 429–434.
- Mesri (2001): Primary compression and secondary compression, soil behavior and soft ground construction, *Geotechnical Special Publication*, ASCE, **119**, 122–166.
- Mesri, G. and Godlewski, P. M. (1977): Time and stress compressibility interrelationship, *Journal of the Geotechnical Engineering Division*, ASCE, **103** (GT5), 417–430.
- Mesri, G., Shahien, M. and Feng, T. W. (1995): Compressibility parameters during primary consolidation, *Proc. Int. Symp. Compression and Consolidation of Clayey Soils*, **2**, 1021–1037.
- Mimura, M. and Sekiguchi, H. (1986): Bearing capacity and plastic flow of a rate-sensitive clay under strip loading, *Bulletin of DPRI*, Kyoto University, **36** (2), 99–111.
- Mimura, M., Shibata, T., Nozu, M. and Kitazawa, M. (1990): Deformation analysis of a reclaimed marine foundation subjected to land construction, *Soils and Foundations*, **30** (4), 119–133.
- 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 behaviors of Pleistocene marine clay deposit in Osaka Bay, *Proc. Symp. Latest Research and Practice on Clay Foundations*, 151–158 (in Japanese).
- Mimura, M., Ohshima, A., Takeda, K., Yoshikawa, M., Suwa, S. and Nagaya, J. (2001): Settlement behavior of Pleistocene deposits due to reclamation in Osaka Port, *Proc. National Conf.*, JGS, 1007–1008 (in Japanese).
- Mimura, M., Takeda, K., Yamamoto, K., Fujiwara, T. and Jang, W. Y. (2003): Long-term settlement of the reclaimed quasi-over-consolidated Pleistocene clay deposits in Osaka Bay, *Soils and Foundations*, **43** (6), 141–153.
- Murayama, S. and Shibata, T. (1966): Flow and stress relaxation of clays, *I.U.T.A.M., Symposium on Rheology and Soil Mechanics*, Springer-Verlag, Grenoble, 99–129.
- Oka, F. (1981): Prediction of time-dependent behaviour of clay, *Proc. 10th ICSMFE*, Stockholm, **1**, 215–218.
- Research Committee on Geotechnical Information of Osaka Bay Seabed Deposits (1995): *Seabed Deposits*, JGS Kansai Branch, 590 (in Japanese).
- Research Committee on Ground in Osaka Bay (2002): *Ground and Construction of Bay Area*, Association of Research on Geotechnical Information in Osaka Bay, 660 (in Japanese).
- Sekiguchi, H. (1977): Rheological characteristics of clays. *Proc. 9th ICSMFE*, **1**, 289–292.
- Sekiguchi, H. and Toriihara, M. (1976): Theory of one-dimensional consolidation of clays with consideration of their rheological properties, *Soils and Foundations*, **16** (1), 27–44.
- Sekiguchi, H., Nishida, Y. and Kanai, F. (1982): A plane-strain viscoplastic constitutive model for clay. *Proc. 37th National Conf.*, JSCE, 181–182 (in Japanese).
- Tanaka, H. (2003): Personal Communication.
- Taylor, D. W. and Merchant, W. (1940): A theory of clay consolidation accounting for secondary compression, *Journal of Mathematics and Physics*, **19**, 167–185.
- Terzaghi, K., Peck, R. B. and Mesri, G. (1996): *Soil Mechanics in Engineering Practice*, 3rd ed., John Wiley and Sons, Inc. NY.
- Wu, T. H., Resendiz, D. and Neukirchner, R. J. (1966): Analysis of consolidation by rate process theory, *Journal of the Soil Mechanics and Foundations Division*, ASCE, **92** (SM6), 229–248.