LONG-TERM CONSOLIDATION CHARACTERISTIC OF DILUVIAL CLAY IN OSAKA BAY

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ABSTRACT

On large-scale reclamation works, the consolidation settlement of diluvial clays which lie deep underground should be discussed. The diluvial clay in Osaka Bay is in a quasi-overconsolidated state by cementation bonding. The values of the compression index and the void ratio are very large in spite of the large overburden pressure. Therefore, its consolidation characteristic is considered to be different from that of the alluvial clay. In this paper, a series of long-term consolidation tests is carried out, and it is revealed that the value of coefficient of secondary compression (C_α) under a load in the quasi-overconsolidated region becomes to be that in the normally consolidated region as time elapses. Considering the effect of strain rate, this result shows that the yield stress is dependent on the strain rate. This also means that even if a clay behaves as an overconsolidated clay in the test, it might behave as a normally consolidated clay in the site. Therefore, it should be considered that the in-situ secondary compression settlement was underestimated if it was calculated by using C_α of the laboratory test. In addition, the settlements on two reclamation works in Osaka Bay are calculated by a proposed long-term settlement analyzing method using strain rate and time relationship, and the results are in good agreement with the observed settlement data at sites.

Key words: diluvial deposit, overconsolidation, secondary compression, settlement, time effect, void ratio (IGC: D5/E2)

INTRODUCTION

In recent years, large-scale reclamation works have been carried out for so-called water-front developments in Japan. The reclamation load has become heavier due to such large scale works. Therefore, it is necessary to estimate the settlements of clay layers at the deeper

depth under the large reclamation works.

Under an alluvial clay layer in Osaka Bay which is about 10-25 meters thick, diluvial clay layers lie alternately with sand and gravel layers. This diluvial clay is considered to be a quasi-overconsolidated clay (Akai, 1984) and has high mechanical strength because of secondary compression called "aging" and chemical

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bonding action called "cementation" between clay particles. Its consolidation yield stress is usually large and considered to sustain the loads of large reclamation works.

However, it has been reported in many cases that the observed settlements at sites of the diluvial clay layers in Osaka Bay appeared to be very large compared with the calculated settlements using the compression curves obtained from conventional consolidation tests. It has also been found that, although its primary consolidation is considered to finish in a few years, the settlement due to the secondary compression steadily increases with time and becomes about twice as much as that of the primary consolidation in five to ten years (e.g. Yoshikawa et al., 1988).

The aim of this study is to determine the consolidation characteristics of the diluvial clay in Osaka Bay and clarify the causes of the large long-term settlement of the diluvial clay layers under the large-scale reclamation works as mentioned above. In this paper, the sedimentary characteristics and the long-term consolidation characteristics of the diluvial clay in Osaka Bay are reported. A simple settlement calculation method is proposed and the long-term settlement of the diluvial clay is estimated by comparing the calculation results with field data.

THE EFFECT OF CEMENTATION ON DILUVIAL CLAY IN OSAKA BAY

Soil Profile in Osaka Bay

In order to evaluate the deformation and strength of clays, it is necessary to investigate the variations of physical and mechanical properties of the clays with depth.

Fig. 1 shows one of the soil profiles in Osaka Bay. There are 14 marine clay layers named from Ma0 to Ma13 in Osaka Bay (Ikebe et al., 1970), where Ac (Ma13) is an alluvial marine clay layer, and Ma12, Ma11 and Ma10 are diluvial marine clay layers which deposited 10,000 to 200,000 years ago. Both of the alluvial and diluvial clays in Osaka Bay are highly plastic clays, with the liquid limit ranging from 80 to 130% and the plastic limit rang-

Fig. 1. Soil profile of Osaka Bay ($1 \text{ kgf/cm}^2 = 98 \text{ kN/m}^2$)

ing from 30 to 45%. The change of water content in each layer shown in Fig. 1 corresponds to the change of consistency, and which has a shape like a bow. This is due to the change of the sea water level in geological time. During the glacial epoch, the sea water level had been low and coarse-grained clays with low plasticity or sands had deposited. Conversely, in the interglacial epoch, the sea water level had been high and fine-grained clays with high plasticity had deposited. As a result, the plasticity tends to change with depth by the repetition of the glacial and the interglacial epochs.

It is generally considered that marine clay layers at the deeper depth become densified and their water content is expected to be low on the whole, because they have been consolidated under large overburden stresses for a long period of time. However, the water contents of the diluvial clay layers in Osaka Bay vary from 50% to 80% for the different marine clay layers and there is no trend of decreasing water contents with depth on the whole as is noticed when comparing Ac with Ma12, Ma11

Fig. 2. Compression curve of the diluvial clay in Osaka Bay ($1 \text{ kgf/cm}^2 = 98 \text{ kN/m}^2$)

and Ma10. The profile of void ratio shows the same trend as that of the water content. This is considered to be caused by cementation bonding (Kamon et al., 1989). As mechanical strength of clay increases in the development of the cementation bonding, the diluvial clay layers in Osaka Bay have probably kept the high water contents and prevented the decrease of voids.

Compression Characteristics of Diluvial Clay

A typical compression curve of the diluvial clay in Osaka Bay is shown in Fig. 2. The yield stress (p_c) is larger than the overburden stress (p_0). We define C_{c1} by the steepest gradient of the curve which is generally used as a compression index (C_c). We also define C_{c2} by a gradient of the tangent of the curve which intersects the point of the overburden stress. In the case of the alluvial clay in Osaka Bay, the values of C_{c1} are usually equal to those of C_{c2} .

Murayama et al. (1955) reported that there is a relationship between the liquid limit (w_L) and the compression index (C_c) for alluvial clays in Osaka Bay, as given by Eq. (1).

Fig. 3. Calculated and measured compression index relationships

$$C_c = 0.01(w_L - 12), \quad (\text{alluvial clays in Osaka Bay}) \quad (1)$$

Provided that the diluvial clay in Osaka Bay has the same relationship, we can calculate the C_c values ($C_{c(\text{cal})}$) from their liquid limits. The differences between the calculated $C_{c(\text{cal})}$ from Eq. (1) and the measured C_{c1} (diluvial clay), C_{c2} (diluvial clay) or C_c (alluvial clay) from the consolidation tests are shown in Fig. 3. A higher value of C_{c1} compared with the calculated $C_{c(\text{cal})}$ is considered to arise from cementation bonding developed in the diluvial clay. As soon as the consolidation pressure exceeds the yield stress of the diluvial clay, this cementation bonding starts to break down and thus the diluvial clay deforms more than the alluvial clay. When the consolidation stress becomes much higher, the value of deformation of the diluvial clay becomes comparable to that of the alluvial clay because all the cementation bondings in the diluvial clay have probably broken down.

The relationship between plasticity index (I_p) and C_{c1} is given in Fig. 4. The values of C_{c1} increase in proportion to the geological time because cementation bonding develops with time. This trend is more pronounced in highly plastic clays.

Fig. 4. Plasticity index vs. compression index relationships

High In-Situ Void Ratio of Diluvial Clay

In order to make clear the effect of cemen-

tation on the diluvial clay layers in Osaka Bay, we compare the in-situ void ratio data with the calculated void ratios using the compression index (C_c) and the coefficient of secondary compression (C_α) obtained from a series of consolidation tests. The calculation procedure is presented in Fig. 5. The calculated void ratio (e_{cal}) is estimated from the decrease in void ratio caused by the overburden stress and the secondary compression with time after the clay particles deposited.

Since the alluvial clay in Osaka Bay shows hardly any cementation bonding, we can apply Eq. (2) to calculate the void ratio at the time of its deposition.

$$e_0(0.3 \text{ kgf/cm}^2) = e - C_c \log(0.3/p_0) \quad (2)$$

The initial void ratio (e_0) is estimated at a pressure of 0.3 kgf/cm^2 (29.4 kN/m^2) by using the overburden stress (p_0) ranging from 0.03 (2.94) to 1.1 kgf/cm^2 (107.8 kN/m^2), the void ratio (e), and the compression index (C_c) of the alluvial clay data. The liquid limit is plotted against the void ratio at 0.3 kgf/cm^2

Fig. 5. Procedure of estimating the in-situ void ratio ($1 \text{ kgf/cm}^2 = 98 \text{ kN/m}^2$)

Fig. 6. Liquid limit vs. void ratio at 0.3 kgf/cm² (29.4 kN/m²)

(29.4 kN/m²) in Fig. 6, and this relationship can be approximated written in a form of:

$$e_0(0.3 \text{ kgf/cm}^2) = 0.0181w_L + 0.6468 \quad (3)$$

By using Eq. (3), the calculated void ratio (e_{cal}) of the diluvial clay in Osaka Bay can be obtained from the liquid limit (w_L), the compression index (C_{c2}) and the coefficient of secondary compression (C_α) of each diluvial clay as given by Eq. (4).

$$e_{cal} = e_0(0.3 \text{ kgf/cm}^2) - C_{c2} \log(p_0/0.3) - C_\alpha \log(t_2/t_1) \quad (4)$$

where t_1 and t_2 are the geological times of alluvial and diluvial clay. The values of C_{c2} are used for calculation instead of C_{c1} , because C_{c2} is the compression index for the case that there is no effect of cementation. The value of C_α in the normally consolidated region are used in Eq. (4).

Both of the distributions of the calculated void ratio (e_{cal}) and the in-situ void ratio (e_1 and e_2) with depth are shown in Fig. 7. The in-situ void ratio, e_1 , is the measured value at the time when the overburden stress was released after sampling, while e_2 is the value of void ratio at the overburden stress (p_0) on the $e-p$ (or $\log p$) compression curves obtained from consolidation tests.

As shown in Fig. 7, the values of in-situ

Fig. 7. Depth distributions of the calculated void ratio (e_{cal}) and the in-situ void ratio (e_1 and e_2)

void ratio are much larger than the calculated void ratios (e_{cal}). This means that the diluvial clays in Osaka Bay have large void ratios and have not been densified as much as we expect in natural sedimentation environment due to the formation of cementation.

LONG TERM CONSOLIDATION TESTS ON DILUVIAL CLAY

Although the diluvial clay in Osaka Bay has

Table 1. Physical properties of the test sample

Sample	Osaka Bay diluvial marine clay (Ma12)
Liquid limit	96.0%
Plastic limit	40.4%
Plasticity index	55.6
Specific gravity	2.675
Water content	59.5%
Sand fraction	2%
Silt fraction	65%
Clay Fraction	33%

high mechanical strength due to the cementation bonding, there are many cases reported that the diluvial clay layers deform more than they are expected especially when the applied load is smaller than the yield stress of the clay. In such cases, the in-situ settlement increases even after primary consolidation is completed. This means that the rate of secondary compression designated by C_α is very large and the settlement thus continues

for such a long period, say ten to twenty years. Therefore, the value of C_α becomes an important factor to estimate the settlement.

In this study, long-term consolidation tests under loads near the yield stress as well as under the overburden stress are performed for up to 90 days, and the variation of the coefficient of secondary compression with time is examined.

Samples and Testing Procedure

Test samples were obtained from a block of diluvial clay taken out below 50 meters from the sea water level in Osaka Bay. This clay belongs to Ma12 shown in Fig. 1. Its physical properties are given in Table 1. The overburden stress after the completion of the reclamation work is about 4.0 kgf/cm^2 (392 kN/m^2) calculated from the wet unit weight of the soil above the block.

The height of specimen is 2 cm and the diameter is 6 cm. Consolidation tests are performed under a double-sided drainage condition. The inside of consolidation ring is coated with molybdenum, and silicon oil is applied to reduce the side friction between the

Table 2. Consolidation test conditions ($1 \text{ kgf/cm}^2 = 98 \text{ kN/m}^2$)

Consolidation test	Consolidation time	Loading procedure (kgf/cm^2)
90 Days consolidation test	1 Day	4.0 0.4→0.8 4.2 small loading increment →1.6→3.2→4.6→ $\Delta p=0.2, 0.4, 0.8$ 5.2 (60 minutes) 6.4 (90 days)
7 Days consolidation test	7 Days	0.4→0.8→1.6→3.2→6.4→12.8→25.6
Standard consolidation test	1 Day	0.4→0.8→1.6→3.2→6.4 →12.8→25.6→51.2
Repeated consolidation test	1 Day	0.4→0.8→1.6→3.2→0.4→0.8→1.6 →3.2→6.4→12.8→25.6→51.2
Small loading increment consolidation test 1	1 Day	0.4→0.8→1.6→3.2 → $\Delta p=0.4$ (up to 6.4)→12.8→25.6→51.2 (60 minutes)
Small loading increment consolidation test 2	1 Day	0.4→0.8→1.6 → $\Delta p=0.8$ (up to 12.8)→25.6→51.2 (60 minutes)

Fig. 8. Compression curve at the end of primary consolidation ($1 \text{ kgf/cm}^2 = 98 \text{ kN/m}^2$)

ring and the specimen. A nylon mesh is used for filter because it has low compressibility.

Table 2 presents the conditions of the tests conducted. As the diluvial clay of Osaka Bay exists at deeper depth, stress release is one of the problems during consolidation tests. When we attempted to consolidate a specimen of diluvial clay under a small load such as 0.1 kgf/cm^2 (9.8 kN/m^2), the specimen tended to swell by absorbing water against the applied load and this tendency became significant with time. It was therefore necessary to perform a rapid consolidation pretreatment under the loads of 0.1 (9.8) and 0.2 kgf/cm^2 (19.6 kN/m^2) for 60 minutes. By this pretreatment, the influence of absorption became minimized. Thus, the consolidation tests started from the load of 0.4 kgf/cm^2 (39.2 kN/m^2).

The e - $\log p$ compression curve at the end of primary (EOP-line) is given in Fig. 8, together with the results of the consolidation test with small loading increments ($\Delta p = 0.4$ (39.2), 0.8 kgf/cm^2 (78.4 kN/m^2)) so as to make the compression curve clear and to determine the yield stress accurately. The yield stress

Fig. 9. Consolidation settlement curve of 90 days consolidation tests ($1 \text{ kgf/cm}^2 = 98 \text{ kN/m}^2$)

of this diluvial clay is about 5.5 kgf/cm^2 (539 kN/m^2) and the value of compression curve C_{e1} is larger than that of C_{e2} due to the cementation bonding. The primary consolidation ends in 10 minutes approximately. In this paper, we define “the normally consolidated region” as the region beyond the yield stress (p_c), “the quasi-overconsolidated region” as the region between the overburden stress (p_0) and the yield stress (p_c), and “the overconsolidated region” as the region under the overburden stress (p_0).

The consolidation tests with 90 days pre-consolidation are performed under loads near the yield stress (4.0 (392), 4.2 (411.6), 4.6 (450.8), 5.2 (509.6), 6.4 kgf/cm^2 (627.2 kN/m^2)) after the specimens were consolidated on a load increment ratio of $\Delta p/p = 1$ for 1 day up to 3.2 kgf/cm^2 (313.6 kN/m^2).

Test Results

The e - $\log t$ curve under sustained consolidation loads for 90 days period is shown in Fig. 9. Even a load is smaller than the yield stress such as 4.0 (392) to 4.6 kgf/cm^2 (450.8 kN/m^2) in this case, the secondary compression behavior tends to be similar to that of the normally consolidated region (6.4 kgf/cm^2 (627.2 kN/m^2)) with time.

The rate of decreasing void ratio vs. time relationship is shown in Fig. 10. If the value of C_α is constant, its gradient should be -1 in

Fig. 10. Rate of decreasing void ratio vs. time relationship ($1 \text{ kgf/cm}^2 = 98 \text{ kN/m}^2$)

a bi-log scale given in Eq. (5).

$$\log \dot{e} = -\log t + \log(0.434C_\alpha) \quad (5)$$

Under a load in the normally consolidated region such as $6.4(627.2)$ and 25.6 kgf/cm^2 (2508.8 kN/m^2), its gradient is approximately -1 in a bi-log scale after the end of primary consolidation and the value of C_α is independent of applied loads and time. The value of C_α is calculated to be 0.03 to 0.035 from Eq. (5) and their average value is 0.0315 . We call this line as a normally consolidated line.

Under a load between p_0 and p_c such as 4.0 (392) and 4.6 kgf/cm^2 (450.8 kN/m^2), the rate of decreasing void ratio is small at the time of the end of primary consolidation compared to that of a load in the normally consolidated region, and thus, the value of C_α is small. However, the rate of decreasing void ratio approaches to that of the normally consolidated line as time elapsed. This means that the value of C_α in the quasi-overconsolidated region becomes close to that in the normally consolidated region after consolidating 10^4 to 10^5 minutes even the load is smaller than the yield stress of clay. Under a load below overburden stress such as 1.6 kgf/cm^2 (156.8 kN/m^2) the value of C_α is smaller than that in the nor-

mally consolidated region even after 90 days of consolidation.

Therefore, under a load in the quasi-overconsolidated region, the characteristic of the secondary compression changes considerably as time elapses. The value of C_α increases approximately tenfold after 90 days of consolidation. Since, at sites, the primary consolidation takes longer than a laboratory specimen does, the value of C_α at sites might be larger than that measured from the conventional consolidation test.

Discussion

Bjerrum (1972) explained the secondary compression behavior on an e - $\log p$ plane as shown in Fig. 11. The $t=t_p$ -line is a compression line at the end of primary consolidation. The isochronal compression lines, which are given by the dotted lines in the figure, can be equal to the equivalent strain rate lines. If the value of C_α is independent of both stress level and time, these lines will be parallel to each other. In addition, lines vary by one order of magnitude when the vertical width between the lines is equal to the value of C_α .

Under a constant load of overburden stress.

Fig. 11. Secondary compression behavior on the e - $\log p$ plane

(p_0), a clay consolidates down to point A at $t=t_c$ by secondary compression and the clay becomes a quasi-overconsolidated clay by the effect of aging. When a load increment Δp is applied, the rate of decreasing void ratio at the start of secondary compression ($t=t_p$) will be $\dot{e}_B$ instead of $\dot{e}_p$ because of the effect of aging. $\dot{e}_B$ will be larger than $\dot{e}_p$, but be smaller than $\dot{e}_p$. Thus, the value of load increment is essential to the starting rate of secondary compression such as $\dot{e}_B$. If an applied load is larger than the yield stress (p_c) such as point D, the rate of decreasing void ratio at the start of secondary compression will be $\dot{e}_p$.

It is also obvious that the secondary compression behavior can be predicted if the data of rate of decreasing void ratio at any time is known from laboratory tests.

If a load is applied in the normally consolidated region, $t=t_q$ is an arbitrary time when the rate of decreasing void ratio is $\dot{e}_q$. However, if a load is applied in the quasi-overconsolidated region, $\dot{e}_q$ can be measured at actual time of t_a which is shorter than t_q due to the effect of aging. $\dot{e}_{Ba}$ is the measured rate of decreasing void ratio, which is equal to $\dot{e}_q$, and e_{Ba} is the measured void ratio at this time $t=t_a$. It can be said that the rate of decreasing void ratio after $t=t_a$ of a quasi-overconsolidated region loading is the same as that after $t=t_q$ of a normally consolidated region loading. Therefore, it is possible to calculate the change in void ratio and its rate of the quasi-overconsolidated region loading by shifting the time from t_a to t_q . Assuming that C_a is constant regardless of various loads applied in the normally consolidated region ($C_a=0.0315$), the time lag $\Delta t=t_q-t_a$ can be calculated as Eq. (6) by using the laboratory test result of e_{Ba} at $t=t_a$.

$$\Delta t=t_q-t_a=0.434 C_a/\dot{e}_q-t_a \quad (6)$$

By shifting Δt , the change of void ratio and its rate after $t=t_a$ can be predicted from Eqs. (7) and (8) which are based on the behavior of a normally consolidated region loading.

$$\dot{e}=0.434 C_a/(t+\Delta t) \quad (7)$$

$$e=-C_a \log \{(t+\Delta t)/t_a\} + e' \quad (8)$$

where e' is a postulated void ratio for this

calculation and it is given as follows;

$$e'=e_{Ba}+C_a \log \{(t_a+\Delta t)/t_a\} \quad (9)$$

If a clay is quasi-overconsolidated only by the effect of aging, the secondary compression behavior can be estimated from the rate of decreasing void ratio at the end of primary consolidation ($t=t_p$) obtained from the laboratory tests. Figs. 12 and 13 are test results of the rate of decreasing void ratio vs. time relationship and the void ratio vs. time relationship for a quasi-overconsolidated region loading of 4.6 kgf/cm^2 (450.8 kN/m^2). The yield stress is about 5.5 kgf/cm^2 (539 kN/m^2) and the overburden stress about 4.0 kgf/cm^2 (392 kN/m^2). The end of primary consolidation under this load is approximately 10 minutes. The behavior after 10 minutes can be calculated by Eqs. (6), (7) and (8), where $\dot{e}_q=3.5 \times 10^{-4}$ (1/min) is obtained from the laboratory test result at the time of 10 minutes and letting t_a be 10 minutes.

The difference between the calculated and measured values in the tests shows that there are some other factors affecting the settlement behavior other than aging. One of the factors is degradation of cementation bonding which may cause slow deformation. The effect of other factors can be discussed from various $t=t_a$ time. In Figs. 12 and 13, the settlement

Fig. 12. Rate of decreasing void ratio vs. time relationship on 4.6 kgf/cm^2 (450.8 kN/m^2)

Fig. 13. Void ratio vs. time relationship on 4.6 kgf/cm² (450.8 kN/m²)

Fig. 14. Void ratio vs. time relationship on 4.0 kgf/cm² (392 kN/m²)

behavior after 90 and 1440 minutes are calculated from Eqs. (6), (7) and (8) by using the laboratory test data of $\dot{\epsilon}_q$ at 90 and 1440 minutes and letting t_a time be 90 and 1440 minutes. If the laboratory test results are the same as the calculations, it can be said that there is no factor affecting the slow deformation of clay such as the degradation of cementation.

In Figs. 12 and 13, the calculated values agree with the laboratory results after the time between 90 and 1440 minutes. This means that cementation between clay particles breaks down between 90 and 1440 minutes of consolidation. The void ratio vs. time relationship on 4.0 kgf/cm² (392 kN/m²) is shown in Fig. 14. Under this condition, the effect of cementation still exists even after 1440 minutes.

Leroueil et al. (1985) proposed a unique stress-strain-strain rate relationship and showed a strain rate effect on the yield stress. The

Fig. 15. Stress-strain-strain rate relationship (1 kgf/cm² = 98 kN/m²)

similar stress-strain-strain rate relationship is obtained from our long-term consolidation tests as shown in Fig. 15. The strain is calculated from the specimen height at 0.4 kgf/cm² (39.2 kN/m²) of each test. The stress-strain-strain rate relationships from the test results as shown in solid lines and the relationships at lower strain rates of 10⁻⁸ and 10⁻⁹ (1/min) have been predicted as shown in broken lines. The arrow in Fig. 15 indicates the in-situ strain rate such as 10⁻⁹ (1/min). Since no excess pore water pressure is measured under these strain rates, the stress-strain-strain rate relationship illustrated by these lines can be used to examine the secondary compression behavior of the diluvial clay in Osaka Bay.

When a strain rate is fast in laboratory tests such as 10⁻⁴ (1/min), the yield stress is higher than the overburden stress due to the effect of cementation. However, in a slow strain rate at sites (10⁻⁹ (1/min)), the yield stress for that particular strain rate becomes close to the overburden stress as shown in Fig. 15. Therefore, we may underestimate the secondary compression settlement at sites by using conventional laboratory test results. Under a load in the quasi-overconsolidation region, it is more appropriate to use the value of C_α of the normally consolidated region for predicting the secondary compression behavior.

Fig. 16. Several methods of the long-term settlement calculation based on the consolidation test data

Fig. 17. Secondary compression behavior model

SETTLEMENT CALCULATION

Secondary Compression Model

As the diluvial clay in Osaka Bay is a quasi-overconsolidated clay which is affected considerably by cementation bonding, it is difficult to estimate the settlement by using the Bjerrum's concept discussed above.

Several simple methods of long-term settlement calculation based on the consolidation test data are shown in Fig. 16. Case (1) is calculated by using the law of H squared for primary consolidation and the value of C_α of 1 day for secondary compression. Case (2) is calculated by using the law of H squared for both primary consolidation and the secondary compression. However, both of these

calculations neglect the strain rate effect on secondary compression behavior which has been discussed previously.

Case (3) is calculated by using the law of H squared for primary consolidation and, for secondary compression, is based on the assumption that the time dependency of the strain rate in the laboratory test is the same as that at sites. However, it is impossible to conduct a laboratory test in the same time scale as happens at sites.

By considering the result of Fig. 10, a simple secondary compression behavior model is proposed as shown in Fig. 17. In this model, the value of C_α is constant under loads in the normally consolidated region as is given by (a) in Fig. 17. Under a load in the quasi-overconsolidated region, the strain rate becomes similar to the strain rate of the normally consolidated line as time elapses. From the assumption that the strain rate at any time will not be larger than the strain rate of the normally consolidated line, a model of the secondary compression behavior under loads in the quasi-overconsolidated loading will be bilinear as is given by (b) in Fig. 17.

From this model, the strain rate at the time when the primary consolidation finishes at sites can be estimated and the deformation behavior from the start of the secondary compression can be calculated using this strain rate and time relationship. This model is appropriate because the strain rate and time relationship is identical both in laboratory tests and in the site.

In this calculation, it is assumed that creep begins to occur near to the end of primary consolidation or the complete dissipation of the excess pore pressure, irrespective of thickness of clay layers.

Calculated and In-situ Settlement on Reclamation Works in Osaka Bay

(A) Osaka Nanko Area

The reclamation work at the Osaka Nanko area has been conducted to make an artificial island with the area of 940 ha. The water depth is 6-12 meters. The reclamation work was put over an alluvial clay layer of which

Fig. 18. Calculated and the in-situ settlements of the Ma12 layer on the reclamation work at Osaka Nanko Area

thickness is about 20 meters. The clay layer was consolidated rapidly with the aid of sand drains. The overconsolidation ratio ($OCR = p_c/p_0$) of Ma12 clay layer is about 1.1 after the completion of the reclamation work.

The secondary compression model at each layer is assumed from conventional and long-term consolidation tests on Ma12 to Ma9 samples. The in-situ monitoring started after a certain period of time since the reclamation work had started. Although the settlement calculation was conducted from the beginning of the reclamation work, the difference between field data and calculated values is discussed from the beginning of monitoring.

The calculated and the in-situ settlements of Ma12 are shown in Fig. 18. Two lines of the calculated settlements are presented. The solid line is calculated by using the secondary compression model proposed herein (case (3)). The broken line was calculated using the value of C_α obtained from the 1 day conventional consolidation test under the same load as the overburden stress (Case (1)). By comparing the two results, case (3) is found to predict the in-situ settlement behavior better than case (1), as shown in Fig. 16.

The calculated and the in-situ settlements of the diluvial clay layers below Ma12 layer are shown in Fig. 19. The settlements of Ma11, Ma10 and Ma9 are calculated. The settlement of clay layers under Ma8 is ignored because

Fig. 19. Calculated and the in-situ settlements of clay layers below the Ma12 layer on the reclamation work at Osaka Nanko Area

Fig. 20. Calculated and the in-situ settlements of diluvial clay layers on the reclamation work at Nishinomiya East Area

the OCR of each layer is as large as 1.5 and the settlements of these clay layers are considered to be very small. This result of Fig. 19 shows that case (3) estimates the amount of settlement better than case (1). However, the settlement behavior is not the same as we expected, which needs further investigation.

(B) Nishinomiya East Area

The reclamation work of Nishinomiya East Area of 69ha is located in the north side of Osaka Bay, which is approximately 15 km away from the Osaka Nanko Area. The soil profile in this area is mostly the same as that of Osaka Nanko Area. Although the load bearing layer is the sand layer above Ma12, the

successive settlement of the diluvial clay layers becomes a problem in this reclamation work.

The calculated and the in-situ settlements of the diluvial clay layers under Ma12 are shown in Fig. 20. The OCR at Ma12 is about 1.3. The settlement of Ma12 to Ma9 is calculated. The calculation starts from the beginning of the reclamation work and that is the time of monitoring started. Comparing the data, case (3) seems to predict the in-situ behavior of secondary compression better than case (1).

In most cases, the value of C_α at sites is larger than that in the laboratory test under the same load. Therefore, we suggest to use the value of C_α obtained from the normally consolidated region loading for predicting settlements when OCR is 1.1 to 1.3, that is, the overburden stress is smaller than the yield stress of the clay. Additional investigation concerning to primary consolidation characteristic in the quasi-overconsolidation region is necessary for further study. We also expect that the primary consolidation characteristic changes with time similar to the secondary compression behavior discussed above.

CONCLUSIONS

The long-term consolidation characteristic of the diluvial clay in Osaka Bay is discussed based on the soil profiles and the results of a series of long-term consolidation tests. In addition, a simple settlement calculation method is proposed for predicting the settlement of secondary compression under a load near the yield stress. The main conclusions are summarized as follows.

- (1) The diluvial clay in Osaka Bay is a quasi-overconsolidated clay due to cementation bonding, and thus, it exhibits a large value of in-situ void ratio.
- (2) The compression index near the yield stress of the diluvial clay in Osaka Bay is very large because the cementation bonding tends to break down. This tendency is more pronounced in a highly plastic clay.
- (3) The deformation of diluvial clay will be comparable to that of alluvial clay under

a large consolidation stress and is considered as if there is no effect of cementation.

- (4) Under a load in the quasi-overconsolidation region, the value of C_α increases in proportion to time, and it approaches closely to the value of C_α in the normally consolidation region.

(5) Although the diluvial clay in Osaka Bay is a quasi-overconsolidated clay, it is difficult to predict the settlement by using the Bjerrum's concept because of the existence of cementation.

(6) The diluvial clay in Osaka Bay shows the same strain rate effect suggested by Leroueil et al. (1985). Therefore, the difference of strain rate between at a site and in the laboratory test should be considered in predicting the settlement.

(7) By using the strain rate and time relationship obtained from long-term consolidation tests, the secondary compression behavior at a site can be predicted.

(8) Even an overburden stress is smaller than the yield stress of the clay, the value of C_α in the normally consolidation region should be used to calculate the long-term settlement for the most cases of reclamation works in Osaka Bay.

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