BACK ANALYSIS OF RECLAMATION BY PUMP-DREDGED MARINE CLAY
—INFLUENCE OF GROUND WATER LOWERING—

MASAAKI KATAGIRI, MASAAKI TERASHI and AKIRA KANEKO

ABSTRACT

When pump-dredged clays are discharged into a pond, suspended soil particles settle loosely to create sediments, which subsequently consolidate due to their own weight over a long period of time. In planning the capacity of such a disposal pond, it is important to estimate the time dependent volume change of dredged clays during the reclamation process. As the land thus created is extremely soft, ground improvement work is necessary if there exists a further plan of utilising the land. Predicting the soil profile of reclaimed land is absolutely necessary for designing the ground improvement. In this paper the authors i) outline the 18-year reclamation history of the Kanda Disposal Pond, ii) introduce a program to analyse self-weight consolidation under fully submerged condition, iii) modify the program to represent the suction effect due to ground water lowering, and iv) verify the applicability of the modified program by comparing the calculated results with the measured data.

A simple analysis under fully submerged condition cannot explain the record of an 18-year reclamation, even if various combinations of consolidation parameters are used. The code modified to include the suction effect successfully simulates the actual behaviour when the appropriate parameters concerning the suction are chosen.

Key words: case history, effect of suction, reclamation, self-weight consolidation (IGC: H11/D5/D4)

INTRODUCTION

Dredging of the sea-bottom sediment in harbours has long been performed for maintaining the required depth of navigation channels and anchorage areas, and this will continue in the future. For the protection of the marine environment, dredged materials (mostly clays) have been and will continue to be discharged into a pond surrounded by containment dikes in the sea. Implementation of such a disposal pond is an important but costly project. If, however, there is further need to utilise the land, reclamation with this sort of waste material becomes reasonably economical. As the land created by use of dredged clays is very soft and will drastically change its volume over a long time-span (Fig. 1), ground improvement to accelerate its consolidation will become absolutely necessary. To design such a ground improvement approach and to estimate the appropriate volume of dredged soil and extra-fill materials, the prediction of the soil profile prior to the project is necessary. Hence a tool to analyse the sedimentation to self-weight consolidation of dredged clay would be extremely useful.

Previous studies that have dealt with the numerical analysis of sedimentation or self-weight consolidation of dredged materials are limited in number, and can be summarised as follows. Yamauchi et al. (1990) proposed a laboratory test procedure called the multi-sedimentation test and its interpretation by back-analysis of test data in order to determine consolidation parameters of clay sediment. In this analysis, the model of sedimentation of clay suspension and the numerical procedure were based on Imai's concept (1981) and Imai's method (1989), respectively. The initial condition for the calculation was also discussed in relation to the analysis of a laboratory test

\[ \text{Fig. 1. Flow of reclamation by dredged materials} \]

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Manuscript was received for review on August 21, 2000.

Written discussions on this paper should be submitted before May 1, 2002 to the Japanese Geotechnical Society, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101-0063, Japan. Upon request the closing date may be extended one month.
with a roughly 20 cm-thick clay sediment. Yamauchi et al. (1991) applied their method to field measured data, and concluded that their method was applicable to actual dredging work.

Kobayashi et al. (1990) developed a finite element method for analysing settling and consolidation of very soft clay. By the use of the linear log-f-log p relation and the tri-linear relationship between void ratio and coefficient of permeability, the laboratory test on self-weight consolidation of clay suspension from sedimentation to consolidation was successfully simulated.

Kokubo et al. (1995) also back-analysed the settlement behaviour of reclaimed land by grab-dredged clay using Imai's method (1989). They reported the numerical simulation agreed extremely well with the monitored data.

Henmi et al. (2000) and Sato et al. (2000a) simulated the monitoring results in the earlier phase of reclamation by modifying the consolidation parameters, and predicted the subsequent settlement behaviour of reclaimed lands and the soil profiles of reclaimed lands. In their analyses, the computer codes employed were also based on Imai's method (Imai, 1989; Imai, 1995).

The full scale reclamation projects reported above were carried out within three years, and were successfully simulated by the settlement and self-weight consolidation analyses under the fully submerged condition.

The reclamation reported in this paper, however, was carried out over eighteen years. After the surface of reclaimed soils has been elevated above the sea level, subsequent reclaimed layers are repeatedly exposed to the air. The consolidation process may be influenced by seepage and drying, among other factors. In this paper, an outline of long-term reclamation, the results of back-analysis under fully submerged condition, and simple modelling of seepage force and suction due to lowering of ground water table will be described.

OUTLINE OF KANDA DISPOSAL POND

Kanda Disposal Pond is 850 m by 1,700 m and is located near the Strait of Kanmon between the Honshu and Kyushu Islands in Japan (Fig. 2). The pond was reclaimed mainly by marine deposits pump-dredged from nearby navigation channels and harbours for 18 years between July 1979 and March 1997. The total amount of dredged soil measured at their borrow areas was about 29 million cubic meters.

The seabed was at an average DL of −7.0 m, and the thickness of the alluvial clay layer in the pond was approximately 5 m before reclamation. Toward the end of reclamation, the ground surface level reached a DL of approximately +11.5 m, and the original seabed settled to DL −7.8 m due to the weight of the reclamation materials.

Open circles in Fig. 3 show the soil profile of the Kanda Disposal Pond (referred to as the K0-area in the following) in September 1995, 16 years after the beginning of reclamation (Sato et al., 2000a). Figure 3(a) indicates that the water content of the top 2 m layer is around 150%, that of the layer between DL +7 m and DL −2 m ranges from 30 to 110%, and that of the layer beneath DL −2 m exceeds 70%. It is interesting to see the variation of the preconsolidation pressure, p0, with the elevation in Fig. 3(b). The broken line in the figure is the effective overburden stress, σ’. The magnitude of p0 in the top 2 m layer is nearly the same as that of σ’. In contrast to this, p0 and σ’ are different in the deeper layers. The layer between DL +6 m and DL −3 m exhibits the overconsolidated condition while the layer beneath DL −3 m is still underconsolidation. As the reclamation of the K0-area was slow, taking about 16 years, the annual lift of the ground surface was relatively minor. Also in each year there was a halt in reclamation work of approximately six months. The high preconsolidation pressures in the middle layer are thought to have been caused by desiccation during these repeated intermissions.

Adjacent to the K0-area, a new reclamation project was started (K1-area) where the rate of reclamation was much faster than that of the K0-area. The solid triangles in Fig. 3(a) show the water contents of the K1-area in November 1998, two years after the beginning of the reclamation at this site. The water content of the top 5 m ranges from 100 to 250%. The water content decreases with depth, and that in the lower part of the reclaimed
layer ranges from 30 to 100%.

Although similar sea bottom sediments from nearby navigation channels were discharged into both the K0- and K1-areas, a marked difference was found in the soil profile of the completed grounds. This is thought to have been caused by the different reclamation processes. In order to predict the subsequent settlement behaviour with high accuracy, it is important to develop a model which can explain this difference.

**BASIC SEDIMENTATION CONSOLIDATION ANALYSIS**

The process from settlement and sedimentation to self-weight consolidation of soil particles is explained in Fig. 4 (Imai, 1981). Settlement means the condition in which single particles or their flocs fall down in the water, sedimentation means the phenomenon that sinking particles or flocs settle at the top of others to create a loose sediment, and self-weight consolidation is the process where the sediment consolidates due to its own weight.

When the soil particles in a dilute clay-seawater mixture settle in the water the particles first become cohered and form flocs, which then fall in the form of zone settling as shown in Fig. 4. Subsequently, the particles that have settled become a part of sediments \( (t=t_1) \). From the viewpoint of the development of effective stress there must exist a boundary that moves upward with time. This boundary is known here as the 'depositional surface', as proposed by Yamauchi et al. (1991). With the progress of sedimentation, the top surface of the settling zone always sinks, while the depositional surface rises. After the depositional surface reaches the top surface of sediment, all the sediment is in self-weight consolidation \( (t=t_2) \).

To perform a numerical analysis simulating the accumulation of sediment, the model shown by the step-like line in Fig. 5 (Yamauchi et al., 1990) is used. A new uniform sediment with predetermined thickness is instantaneously piled on the top surface of the sediment already formed, and is considered as a consolidation layer just after piling. In the analysis of reclamation by the above model of successive piling of sediments, all the events of settlement, sedimentation and self-weight consolidation are assumed to take place under the water (under fully submerged condition).

**Consolidation Theory Used**

The general one-dimensional consolidation equation can be expressed as follows:

A) Mass conservation:

\[
\frac{\partial v}{\partial z} = -\frac{\partial e}{\partial t} .
\]  

(B) Darcy’s law and balance of momentum neglecting acceleration:

\[
v = \frac{k}{\gamma_w} \left( \frac{1}{1+e} \times \frac{\partial a'}{\partial z} + \gamma' \right).
\]
(C) Constitutive equation of soil skeleton:

\[ f(\sigma', e, \varepsilon) = 0. \]  

(3)

Where, \( e, \varepsilon \): void ratio and rate of void ratio, \( \sigma' \): effective stress, \( k \): coefficient of permeability, \( v \): exit water velocity relative to soil skeleton, \( \gamma' \): submerged unit weight of soil, \( \gamma_w \): unit weight of water, and \( z \): reduced co-ordinate.

To simplify the constitutive equation, Eq. (4), which does not take viscosity into account, has been used in this paper.

\[ f(\sigma', e) = 0. \]  

(4)

The \( k \) is determined according to \( e \) as follows:

\[ k = k(e). \]  

(5)

A numerical calculation that satisfies Eqs. (1), (2), (4) and (5) can be carried out by the coupling method “CONAN” (Imai, 1989; Imai, 1995).

The most general one-dimensional consolidation theory considering no creep effect was proposed by Mikasa (1963) and Gibson et al. (1967). Both the theories are expressed by complicated partial differential equations of the second order obtained from combining Eqs. (1), (2) and (4). The theory used in this paper is completely equivalent to the above two theories.

**Boundary Condition of Self-Weight Consolidation**

To analyse the consolidation of new fresh sediment piled on the top of existing sediment, the determination of the boundary condition of the fresh sediment becomes important. In this paper, the boundary condition at the top of the fresh sedimentation is fixed at 9.8 Pa as proposed by Yamauchi et al. (1990).

**Applicability of Present Analysis to the Reclamation Process**

Before carrying out back analyses of complicated real problems from the K0-area, it is important to confirm the applicability of the program by well defined simple sedimentation consolidation phenomena. Figure 6 shows the simulation results of the multi-sedimentation test (MST) performed by Yamauchi et al. (1990). In the MST, slurry with a water content of 1,000% was poured into the cleared water above the sediment in a cylinder at the rate of once per day, which was a simulation of the sedimentation process shown in Fig. 5. Drainage at the bottom of the sediment was not permitted but drainage at the top was. The consolidation parameters used in this analysis and the boundary condition at the top of the fresh sedimentation were the same relations and 9.8 Pa, respectively as in Yamauchi et al. (1990). The present numerical simulation by solid curve in the figure showed a fairly good agreement with the measured data.

Figure 7 shows the centrifuge self-weight consolidation test results together with the simulation by the present program (Nishimura et al., 2000). The parameter of compressibility was determined from the distribution of water content of the sediment at the end of primary consolidation. The parameter of consolidation rate was chosen by trial and error to fit the measured data. With suitable consolidation parameters selected, the solution fits not only with settlement but with excess pore pressure distribution in the clay sediment.

Henni et al. (2000) and Sato et al. (2000a) also used the present program to simulate huge sea reclamation projects. They modified the consolidation parameters so as to fit the monitoring results in the earlier phase of reclamation, and successfully predicted the subsequent consolidation settlement behaviour and the soil profile of reclaimed ground at the end of reclamation.

It is confirmed that the method of analysis and the consolidation parameters for the numerical analysis are adequate, provided most of the reclamation proceeds under fully submerged condition.

**BACK ANALYSIS OF K0-AREA**

**Material Properties and Condition of Existing Seabed**

The physical properties of several materials sampled from the K0-area are summarised in Fig. 8 and Table 1. These materials are classified between sand and fine-
Fig. 7. Simulation of centrifuge self-weight consolidation of clay (after Nishimura et al., 2000): (a) change of height of sediment, (b) change of excess pore pressure

Fig. 8. Grain size distribution of samples from K0-area

Table 1. Physical properties of dredged materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of soil particles</td>
<td>g/cm³</td>
</tr>
<tr>
<td>Liquid limit</td>
<td>%</td>
</tr>
<tr>
<td>Plasticity index</td>
<td>NP-80</td>
</tr>
<tr>
<td>Natural water content</td>
<td>%</td>
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</tbody>
</table>

The consolidation parameters to be used in the back analyses should be within the wide range of variations shown in Fig. 9. Figure 10 shows selected consolidation parameters. Solid line #1 in Fig. 10(a) and solid line #A in Fig. 10(b) correspond to the average relation of samples from three navigation channels. For the compressibility, the inclination of the log $f$-log $p$ relation is changed by a fixing point at $p=100$ kPa on the average relation, as #2 and #3 in Fig. 10(a). The parameter concerning the rate of consolidation is changed by shifting the log $c_v$-log $p$ relation in parallel to the average one, as #B and #C in Fig. 10(b). As the coefficient of permeability $k$ is necessary for the present analyses, the value is converted by the equation:

$$k = c_v \cdot m_v \cdot \gamma_w.$$

The conditions of the existing seabed are as follows. The alluvial clay layer before the reclamation is 5 m thick and is in a normally consolidated state. The consolidation parameters are determined by the test results of undisturbed samples from the seabed, and are $C_v = 1.05$ and $c_v = 50$ cm²/day.

**Back Analyses under Fully Submerged Condition**

Back analysis of the K0-area was carried out by the program assuming that all the events took place under fully submerged condition. Figure 11 shows the change of elevation of reclaimed land with the progress of reclamation. The measured data shown by open circles in the
figure represent the average value of elevations out of about 200 measurements by means of sonic prospecting. Three plots shown by solid circles are the elevation measured by levelling at a given location for the soil investigation. The numerical simulations are carried out using all the combination of consolidation parameters. Hereafter case-2B, for example, denotes the analysis done using relation #2 and relation #B in Fig. 10 for the f-p and c_v-p relations respectively. By the combination of consolidation parameters, the predicted elevation is different. The best-fit solution for the measured time-elevation relation is case-3C.

Figures 12, 13 and 14 show the calculated water content and effective stress distributions on September 1995 and the consolidation parameters of each figure correspond to Figs. 11(a), (b) and (c), respectively. These figures also show the measured data explained in Fig. 3. All the calculated water content distributions indicate monotonous decrease with depth. The measured data, on the other hand, show the minimum value of about 50% at the elevation of around DL +5 m, and the water contents at the bottom and surface of reclaimed layer are around 100% and 180%, respectively.

All the calculated effective stress distributions increase with increasing depth although the magnitude of effective stress depends on the consolidation parameters. The calculated distributions do not simulate the distribution of preconsolidation stress obtained from the undisturbed samples.

As far as the elevation change with time is concerned, it was possible to find the best-fit calculation by modifying consolidation parameters (Fig. 11). However the same calculation under the fully submerged condition could not explain even the trend of water content and effective stress distribution with depth (Figs. 12-14).

**Difference between Measured and Calculated Results**

In the sedimentation-consolidation process of real reclamation by clay suspension, there are two different phases.

One is the accumulation below the sea level, in which soil particles settle at the bottom and the sediment consolidates due to its own weight. All the events take place under water; this has been called the fully submerged con-
the ground water level, and desiccation.

As described earlier, the analyses under the submerged condition could simulate not only the change of elevation of the reclaimed land but the water content distributions in the reclaimed layer as well, if the reclamation was completed in the short-term and if the appropriate parameters were selected. In contrast to this, in the slow reclamation at the K0-area, the current analyses could not explain simultaneously the settlement and water content distribution. The most probable reason for this difference may be that additional factors above the sea level did influence the consolidation process substantially in the long-term construction, but not in the short-term construction. To predict the slow reclamation process accurately, an analysis taking these additional effects into account has to be developed.

**Effect of Seepage Force**

When the surface of reclaimed land rises above the sea level, a downward seepage flow may be induced in the sediment. Then, the vertical effective stress acting on soil particles increases and the void ratio decreases accordingly. Yamauchi et al. (1991) developed a program of self-weight consolidation coupled with seepage, and applied it to the back analysis of the reclamation at the Fukushima Daini Nuclear Power Station.

In this paper, the following simple method to express the seepage force is introduced in order just to investigate the order of influence by the seepage force. As shown in Fig. 15, 1) one-dimensional vertical seepage from the ground surface to the bottom drainage layer under the constant difference of water head, and 2) the constant seepage force throughout the depth of reclaimed layer were assumed. When the authors look at the real problem, once the discharge of clay suspension is terminated, the difference of water head decreases with time and the seepage travels a long distance from the middle of the reclaimed land towards the surrounding sea wall if there is no drainage layer at the bottom of the reclaimed layer. Therefore, the assumed seepage force in Fig. 15 is thought to be much greater than the reality. For the numerical simulation, the seepage force (body force) can be represented by increasing the density of soil particles. An imaginary density of soil particles is obtained from the following equation:

\[
\gamma' H + j H = \gamma' H + i \gamma_{\omega} H = \rho^* - \rho_c \frac{\Delta h}{H} g H
\]

\[
\rho^* = \rho_c + (1 + e) \rho_{soil} \frac{\Delta h}{H}.
\]

(7)

Where, \(j\) : seepage force, \(i\) : hydraulic gradient, \(g\) : gravity, \(\rho_{soil}\) : density of pore water, \(\rho_c\) : density of soil particles, \(\rho^*\) : imaginary density of soil particles, \(\Delta h\) : difference of water head, and \(H\) : thickness of reclaimed layer.

In this paper, \(H\) and \(e\) are fixed at 21 m and 2.930, respectively. The assumed void ratio is an average void ratio of the reclaimed layer in case-2B. To exemplify the effect of seepage on the self-weight consolidation, the re-
Fig. 12. Distributions of water content and effective stress in $\log f/\log \rho$ relation: (a) water content distribution, (b) effective stress distribution

Fig. 13. Distributions of water content and effective stress in $\log f/\log \rho$ relation: (a) water content distribution, (b) effective stress distribution

Fig. 14. Distributions of water content and effective stress in $\log f/\log \rho$ relation: (a) water content distribution, (b) effective stress distribution
Illustration between the difference of water head and the imaginary density are shown in Table 2. The combination of consolidation parameters used in this calculation is case 2B.

Figure 16(a) shows the calculated and measured relationships between time and elevation of reclaimed land. The elevation of the reclaimed land becomes lower as the difference of water head gets larger. In the case where the difference of water head is 12 m, which is an extreme exaggeration, the calculated change in elevation approximately agrees with the measured data.

Figures 16(b) and (c) indicate the water content and effective stress distributions, respectively. All the calculated results show that the water content monotonously decreases with depth, and that the effective stress monotonously increases with depth. The distributions of measured water content and effective stress are quite different from those calculations taking the seepage force into account. It is concluded that the calculation with only the seepage effect cannot simulate the reclamation record of the K0-area.

**Effect of Ground Water Lowering**

Watari et al. (1983) measured the water content change with time of the top layer of reclaimed land, and showed the decrease rate of water content in the top 2 m layer. They pointed out that the decrease of water content in the top layer was induced by suction and/or desiccation triggered by the lowering ground water table. However, they did not recommend reflecting the effect of suction on the consolidation settlement of the reclaimed layer.

Toh et al. (1991) carried out a centrifuge model test on the self-weight consolidation of clay with surface water table lowering, and proposed a numerical model to express the behaviour of the ground in the process. Fahey and Fujiyasu (1994) tried the modelling of a ground undergoing evaporative drying for the design of tailings dams in arid areas, and showed the importance of evaporation in the consolidation behaviour. Seneviratne et al. (1995) and Seneviratne et al. (1996) performed parametric studies on the effect of evaporation and base drainage condition on self-weight consolidation in the reclamation process, using knowledge gained from Toh et al. (1991) and Fahey and Fujiyasu (1994). They pointed out that the effect of evaporation appeared to be minimal for lower rates of evaporation but significant for higher rates, and that the effect of base drainage was significant except for high evaporation rates. They commented that these might depend on the deposition rate and the material parameters. However, a determination method for parameters concerning evaporation was not proposed.

In sea reclamation by dredged marine clay, the soil particles are piled up in the fully submerged condition until the surface of the reclaimed land reaches the sea level. Subsequent reclaimed layers more or less undergo the effect of lowering ground water table. The effect is schematically shown in the Fig. 17. The magnitude of suction and extent of layers influenced by lowering of the ground water table may depend on many factors such as the thickness of the soil layer in one lift (rate of reclamation), the duration of ground water lowering (the time of intermission between the successive pouring of clay suspension), the rate of ground water lowering, the final depth

### Table 2. Condition of seepage force analyses

<table>
<thead>
<tr>
<th>Difference of water head $\Delta h$ (m)</th>
<th>Imaginary density of soil particles $\rho_s$ (g/cm³)</th>
</tr>
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<tbody>
<tr>
<td>12</td>
<td>4.90</td>
</tr>
<tr>
<td>5</td>
<td>3.60</td>
</tr>
<tr>
<td>2</td>
<td>3.03</td>
</tr>
<tr>
<td>0</td>
<td>2.66</td>
</tr>
</tbody>
</table>

Assumption: $H=21$ m
of reclamation, with thinner lift and frequent exposure to ground water lowering.

When the ground water table lowers below the ground surface after reclamation, the soil layer between the ground surface and ground water table will be subject to a negative pore pressure caused by suction, and the uppermost layer may be further influenced by evaporation, as shown in Fig. 17. In such a case, the effective stress in the ground influenced by the lowering of the ground water table and by evaporation will be complicated because of the many effects mentioned earlier. In addition, its distribution will change with time. In the present model, this complicated transient process is ignored. In order to simplify the model, additional effective stress with the same value, \( \sigma_{\text{des}} \), is applied to the top layer with a given depth, \( z_{\text{des}} \), shown as a thick solid line in Fig. 17(b). That is, the magnitude of additional effective stress and the depth influenced by the stress are parameters for the back-analysis.

In the case of the K0-area, the reclamation work continued for 18 years and 3 years after the beginning of the reclamation, the ground surface reached the sea level. Subsequent reclamation continued for 15 years. In each year the reclamation work continued for six months under the fully submerged condition and the ground water was lowered for another six months during the intermission. The lift per year was only around 100 cm. Thus the reclaimed layers influenced by ground water lowering occupy a substantial portion of all the reclaimed layers. Therefore, it can be assumed that a reclaimed layer consolidated by the additional effective stress is piled once a year on top of the existing sediment. The subsequent self-weight consolidation analysis will be performed the same as the procedure of the analysis stated before i.e., under the fully submerged condition.

The magnitudes of suction are assumed as 9.8, 29.4, 49.1 and 68.7 kPa. Here, the range of suction is assumed as the total thickness of each new annual incremental sediment (new lift) from 4 years after the start of reclamation.

The constitutive relationship of the clay layer subjected to suction is assumed as shown in Fig. 18. This relationship governs the consolidation behaviour of the layer during its subsequent reclamation. In the stress range exceeding \( \sigma_{\text{des}} \), the same constitutive relation for the dredged soil applies. In the stress range below \( \sigma_{\text{des}} \), the slope of the log-log \( p \) relation is zero to simplify the calculation as shown in Fig. 18(a). This means the clay layer subjected to \( \sigma_{\text{des}} \) does not consolidate unless the acting stress exceeds its value. In the relationship between \( c' \) and \( p' \), the \( c' \)-value in the stress range less than \( \sigma_{\text{des}} \) is a constant as shown in Fig. 18(b). In the \( k-p \) relation used in the actual calculation, the \( k \)-value in the range less than \( \sigma_{\text{des}} \) is a constant.

Figure 19 shows the change of elevation of reclaimed land with the progress of reclamation. Figures 19(a) and (b) correspond to the combinations of consolidation parameters of case-2A and case-1B, respectively. The surface of reclaimed soil appeared above the sea level after
three years. New sediment piled up on the ground water lowering. Therefore, the increase rate of the elevation after 36 months is smaller for cases with a larger $\sigma_{\text{des}}$. In case-2A, the curves with 50 or 70 kPa of suction are almost consistent with the measured data. In case-1B, the relations with 50 kPa or 70 kPa of suction are also thought to be appropriate.

Figure 20 (case-2A) and Fig. 21 (case-1B) show the calculated distributions of water content and effective stress in September 1995, 190 months after the start of reclamation.

The water content distribution obtained from the numerical analyses in all the cases except for case-1B with $\sigma_{\text{des}} = 70$ kPa, shifts generally to the left side (decrease in water content) as the magnitude of suction increases (Figs. 20(a) and 21(a)). This tendency is consistent with the lowered elevation shown in Fig. 19.

The pattern of water content distribution differs with the combination of consolidation parameters and the magnitude of $\sigma_{\text{des}}$. In case-2A (Fig. 20(a)), for cases with $\sigma_{\text{des}} \geq 30$ kPa, in deeper reclaimed soil which has not experienced the ground water lowering, water content distribution is convex rightward and has the maximum water content in the distribution. These distributions are similar to those of measured water contents except for the newly sedimented top 2 m layer which had not undergone desiccation at the time of ground investigation.

In case-1B (Fig. 21(a)), on the other hand, all the water content distributions except for the one with $\sigma_{\text{des}} = 70$ kPa decrease monotonously with depth, and are not similar to the measured distribution.

The pattern of effective stress distributions in each case is consistent with the corresponding water content distribution. In case-2A with $\sigma_{\text{des}} \geq 30$ kPa (Fig. 20(b)), the effective stress distribution is concave rightwards and has the minimum value in the deeper layer which has not experienced ground water lowering. The distribution of effective stress in $\sigma_{\text{des}} = 70$ kPa almost agrees with that of the preconsolidation pressure except for the top 2 m layer.

In the case-1B (Fig. 21(b)), on the other hand, all the effective stress distributions except for the one with $\sigma_{\text{des}} = 70$ kPa increase monotonously with depth, and are not similar to the measured distribution. In the case with 70 kPa, the minimum value of effective stress exists in the deeper layer.

In Figs. 20 and 21, two different patterns of effective stress distribution were observed. One is a monotonous increase with depth. The other is a straight portion in the upper layer and a convex portion in the deeper layer. The deeper layers were sediment at around DL $- 5$ m which has not experienced ground water lowering. The reason for the difference in these patterns may be explained as follows.

When the authors look at the deeper layer which settled and consolidated under the fully submerged condition, all the soils initially sedimented with an effective stress of 9.8 Pa (by definition). After the fourth year, the layers of new sediment with assumed $\sigma_{\text{des}}$ successively piled up until the end of reclamation. In the K0-area, the submerged weight per unit area of the reclaimed soil from the fourth year to the end of reclamation totalled 66 kPa. Therefore the effective stress at the top surface of the deeper layer $\sigma_{\text{des, top}}$ gradually increased from 9.8 Pa toward 66 kPa with the progress of consolidation. Therefore, if the assumed $\sigma_{\text{des}} = 70$ kPa, the discontinuity of effective stress at the boundary of the upper and deeper layers remains even at 100% consolidation. If the $\sigma_{\text{des}}$ was smaller than 66 kPa, $\sigma_{\text{des, top}}$ might be smaller than $\sigma_{\text{des}}$ at a given time depending on the degree of consolidation.
of the deeper layer, and there remains a discontinuity of effective stress at the boundary. Furthermore, soils subjected to the suction effect had smaller permeability as the suction grew larger (Fig. 18(c)). The consolidation for the deeper layer would usually be retarded. These are the reasons for the appearance of different patterns in effective stress distribution. The same reason applies to the different pattern in the water content distribution.

In September 1995 when the soil investigation was performed, the reclaimed layer was still under consolidation. As the consolidation parameters are different between cases 2A and 1B, the calculated degree of consolidation and the magnitude of $\sigma_{\text{des \, log}}$ at this boundary differs in the above two cases.

Considering the agreement between measured data and calculations on the change of elevation with time (Fig. 19(a)), water content and effective stress distributions (Fig. 20), case-2A with $\sigma_{\text{des \, log}} = 70$ kPa gives the best simulation, although the calculated water content in the deeper layer is still smaller than the measured data. Authors consider that the current analysis taking suction into account is a practically useful tool for predicting long-term reclamation such as that in the K0-area.

**CONCLUSIONS**

The numerical code for settlement-consolidation analysis under the fully submerged condition can simulate the reclamation in a short term of within three years by modifying the consolidation parameters through observation (e.g., Henmi et al., 2000; Sato et al., 2000a), because the substantial consolidation has taken place under the
submerged condition in such a reclamation.

When, however, the same code is used for the back analysis of the 18-year reclamation case record at Kanda Disposal Pond, any combinations of consolidation parameters can not simultaneously explain the settlement behaviour and soil profile. This means that the assumption of back analysis differs from the actual condition. The most probable reason is thought to be the influence of downward seepage in the reclaimed soil layer and the influence of repetitive ground water lowering during the intermission of reclamation. Ground water lowering induces the development of negative pore pressure and desiccation due to evaporation.

For the simulation of long-term reclamation, two simple methods have been developed to explain the influence of seepage force and the influence of suction. By back analysis taking seepage into account, it has been found that the influence of seepage is small and insufficient to explain the case record.

With the appropriate selection of consolidation parameters, the magnitude of suction, and range of influence, the calculation gives rise to a good agreement in terms of settlement and soil profile (water content and effective stress distribution). It is concluded that the influence of ground water lowering should be taken into account for the simulation of the long-term reclamation process above the sea water level.

The back-analysis of reclamation by dredged marine clay was useful to obtain an initial condition for the design for further use of the Kanda reclaimed land.

From the scientific point of view, it may be interesting to develop an analytical tool in the future which can simultaneously simulate the complicated settlement, sedimentation, self-weight consolidation, seepage, negative pore pressure build-up due to ground water lowering and desiccation due to evaporation.
From the practical point of view, however, the authors recognize the importance of collecting similar well documented case records to find out i) the condition where fully submerged conditions are acceptable and ii) a determination method for the parameters of the proposed simple model.

ACKNOWLEDGMENT

The authors would like to thank Prof. G. Imai of Yokohama National University for technical advice on settlement-consolidation analysis. The authors also thank to the Fourth Port Construction Bureau of the Japanese Ministry of Transport for permitting the authors to publish the case records.

NOTATIONS

- \( c_{loc} \): \( c_v \)-value at \( \sigma_{loc} \)
- DL: datum line
- \( e_{loc} \): void ratio at \( \sigma_{loc} \)
- \( e' \): void ratio at \( p^* \)
- \( e_c \): rate of void ratio
- \( f_s' \): specific volume (= 1 + \( e \))
- \( j \): unit seepage force
- \( H \): thickness of reclaimed layer
- \( k_{loc} \): coefficient of permeability at \( \sigma_{loc} \)
- MSL: mean sea level
- \( p \): consolidation pressure
- \( p_c \): preconsolidation pressure
- \( p^* \): (imaginary) critical pressure between liquid and solid
- \( t_1, t_2 \): a given time
- \( \Delta t \): increment of time
- \( v \): exit water velocity related to soil skeleton
- \( z \): reduced coordinate
- \( z_{loc} \): range affected by suction
- \( \Delta h \): difference of water head
- \( \rho_s^* \): imaginary density of soil particles
- \( \sigma_{loc} \): magnitude of suction assumed
- \( \sigma_{loc, eff} \): effective stress at the top surface of the deeper layer

REFERENCES