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PERFORMANCE AND PREDICTION OF DREDGED CLAY RECLAIMED LAND BY VACUUM CONSOLIDATION METHOD

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ABSTRACT: One of the methods for increasing the capacity of disposal pond for dredged marine clay is the volume reduction in already reclaimed dredged clay ground. In the vacuum consolidation method, the pore water in the reclaimed clay ground is squeezed by vacuum pumps, and ground surface settles. In this paper, the performance of reclaimed land with dredged clay by the vacuum consolidation method is introduced, and is compared with the prediction of consolidation behavior at the design. In addition, the back analysis of settlement behavior of such reclaimed ground is performed, and the design procedure of vacuum consolidation for reclaimed ground with dredged clays is proposed.

Keywords: Dredged Clay, Vacuum Consolidation, Monitoring, Analysis

1. INTRODUCTION

The dredging of sea bottom sediment has been continuously conducted along the Japanese coastal area. One of the major purposes of dredging is the widening and deepening of existing navigation channels and anchorage areas to accommodate larger ship traffics. Dredging process normally comprises three phases that starts with the underwater excavation, then transportation and ends with disposal. The most common disposal method for dredged clay is to discharge dredged clay into a disposal pond in the sea surrounded by containment dikes.

As the construction of a disposal pond in the sea requires huge cost in general, it is becoming difficult to construct a new one. Therefore, the long use of existing disposal ponds has become important and urgent technical issue.

While the dredged clay is discharged into the pond, the clay layer increases its thickness and gradually approaches to the capacity of disposal pond. In parallel to the above process, the dredged clay layer is subjected to time-dependent self-weight consolidation and reduces its volume. Therefore the water content and consolidation characteristics of dredged clay at the time of discharging are influential factors for the life of disposal pond.

One of an extension means of the life of disposal pond is the quick reduction of volume in already reclaimed dredged clay ground. The vacuum consolidation method is one of ground improvement methods with vertical drainage for very soft ground. In this method, the atmospheric pressure as the loading pressure is used, and the banking of fill materials is not necessary. The maximum pressure, however, may be 70 to 80 kPa at most due to the effectiveness of vacuuming pump.

At a part of the S3-area in Shin-Moji Oki disposal pond, a vacuum consolidation method was performed. In this paper, a construction example of the vacuum consolidation method for the reclaimed land with dredged clay is introduced. The results of monitoring and soil investigation after the vacuuming are described, the behavior of consolidation settlement during vacuum consolidation is expressed. In addition, the prediction and back analysis for the vacuum consolidation method are compared with the ground condition. The prediction procedure of vacuum consolidation method for reclaimed land with dredged clay is proposed.

2. OUTLINE OF SHIN MOJIOKI DISPOSAL POND

Figure 1 shows the Strait of Kanmon between the

Fig. 1 Site of Shin-Moji Oki disposal pond

Honshu and Kyushu Islands in Japan. Kanmon waterway located in this Strait is one of the busiest sea routes in Japan. To accommodate larger ship traffics, the dredging in this waterway has been conducted. For the protection of marine environment, dredged materials, mostly clays have to be discharged into the Kanda Oki and Shin-Moji Oki disposal ponds shown in Fig.1.

Figure 2 shows the plan view of Kanda Oki and Shin-Moji Oki disposal ponds. The Shin-Moji Oki disposal pond is separated into three areas, S1-, S2- and S3-areas. The S1- and S2-areas were reclaimed with dredged clays up to 2002, and are used as an airport at present[1]. The S3-area is working as disposal pond at present. The rest capacity of S3-area deceases gradually, and the mud surface will arrive at the designed level in the next years.

In the S3-area, the additional embankment that constructed with mechanical dewatered clay lumps is mounted near the revetment for an increase in the capacity of disposal pond. The mechanical properties of dewatered clay lumps and its aggregates were reported by Moriki et al.[2].

Fig. 2 Plan view of disposal pond

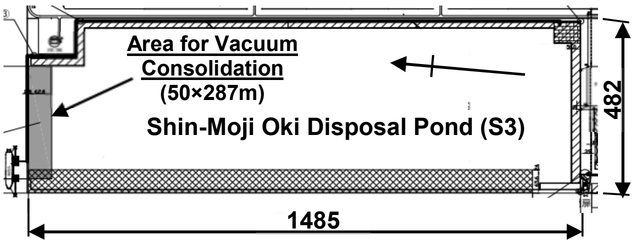


Fig. 3 Condition of S3-area and construction site

3. MONITORING PLAN FOR VACUUM CONSOLIDATION

Figure 4 shows the schematic cross section of vacuum consolidation area near the North revetment. The left hand side is the North revetment constructed with rubble mound and replaced sand. The original elevation of sea bottom was DL-6.7 m, and the alluvial clay having about 7 m of thickness overlaid the diluvial layer. The elevation of revetment was DL+8.0 m, and that of dredged clay layer was at DL+6.2 m.

In the design of vacuum consolidation, the upper and lower sealing layers were determined as 1 m of thickness according to the manual of vacuum consolidation drain method[3]. The void water squeezed from dredged clay layer by vacuuming was gathered into horizontal tubes, and was flowed through them up to the vacuum pump. For the control of vacuum pressure, the origin, edge and tip pressures shown in Fig. 4 were measured. The origin pressure was the output value of a vacuum pump. The edge and tip pressures were measured at the end of horizontal tube on the ground and at the tip of plastic board drain (PBD) as a vertical drain, respectively.

The pitches of vertical drains were set at 1.0 m and 1.7 m in the S-type and R-type areas, respectively. Here, the R-type area was designed as a buffer zone of vertical settlements between S-type and non-treatment areas. Each pitch was determined by Barron's equation at the design and the details of this design were described later.

The settlement plates were set at the grid with intervals of about 10 m. After about 30 days from the stop of vacuuming, the post soil investigations at the center of the S-type area and near the boundary of the R-type were performed at four lines and as shown in Fig. 4.

4. MONITORING RESULTS IN VACUUMING WORK

Figure 5 shows the settlement behavior of vacuum consolidation area measured by the settlement plates. The number of horizontal axis is the construction points from the edge of west revetment, and S-1

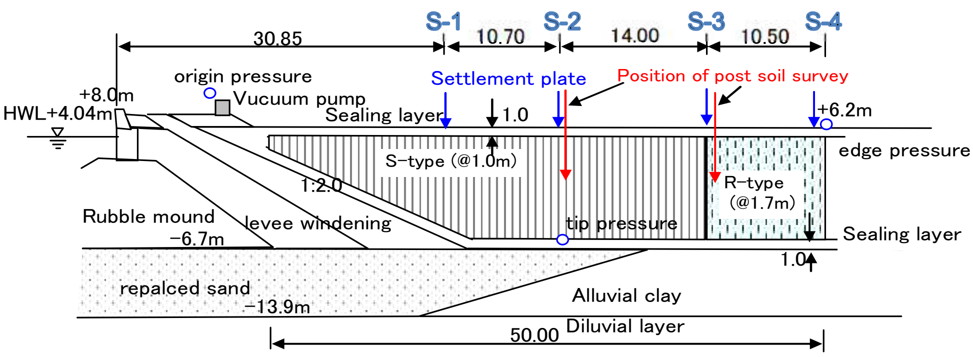


Fig. 4 Design of ground improvement and monitoring plan in vacuum consolidation

through S-4 are the positions of settlement plate in Fig. 4. In the initial condition before the installing of PBDs, the elevations were around 6.2 m shown in Fig.5 (a). Figure 5 (b) is the state at the end of June before the working of vacuum. The maximum consolidation settlement is about 1.2 m due to the disappearance of excess pore water pressure occurred after the installation of PBDs. Figure 5 (c) shows the ground elevations on 12/02/2013 and that was one month later after stopping the vacuuming. The total settlements after the installation of PBDs were 1 to 3 m. The maximum settlement of about 3 m generated around the cross point of No. 32 and S-2 (No. 32-2).

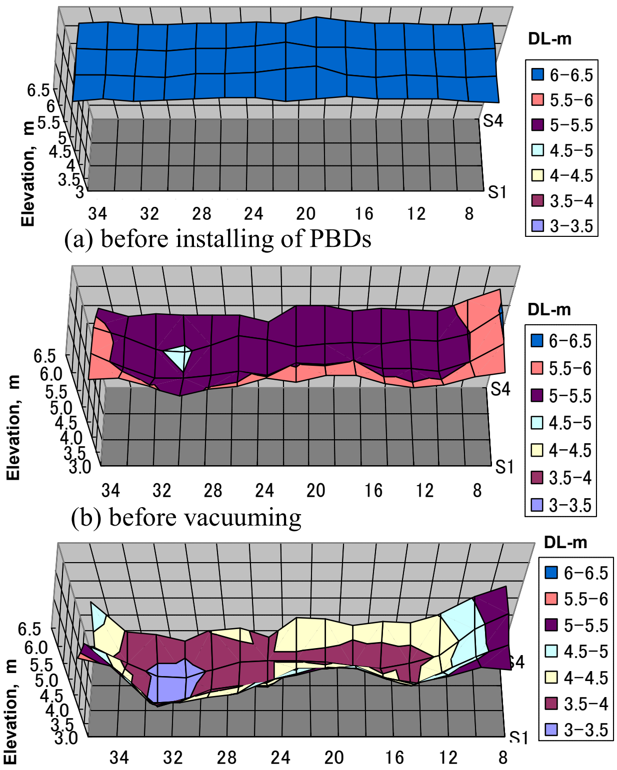


Fig. 5 Settlement behavior in ground improvement

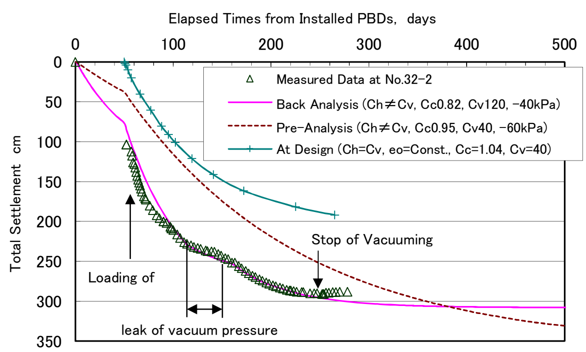


Fig. 6 Monitoring result and pre- and back- analyses

Figure 6 shows the time – settlement relation at the cross point of No.32 and S-2 (No.32-2). The origin of horizontal axis is the installation of PBDs. In this figure, the prediction at the design are expressed.

The consolidation settlement at the point of No.32-2 before the vacuuming generated about 1 m after the installation of PBDs. The initial rate of consolidation settlement was high, and then decreased gradually. On the middle of this behavior during the vacuuming, a decrease in the rate of consolidation settlement occurred. This is the leak of vacuum pressure. After the change of vacuum pump after 150 days from the start, the consolidation settlement increased. After about 200 days from the installation of PBDs, the consolidation settlement converged to form 300 cm of total settlement. Using the approximation of hyperbolic curve, the time with consolidation degree 90 % was equivalent to 230 days from the install of PBDs.

5. RESULTS OF SOIL INVESTIGATION AFTER VACUUMING

The soil investigation was performed one month later after the stop of vacuuming. The sites of soil investigation were eight points set at the intersections between S-2 and S-3, and No.16, 24, 28 and 32.

Figures 7(a) and 7(b) show the distribution of consolidation yield stress at the S-2 and S-3 lines, respectively. The anticipated vertical effective stress distributions at 60 kPa of working vacuum pressure and 80 % of working pressure are also drawn. The

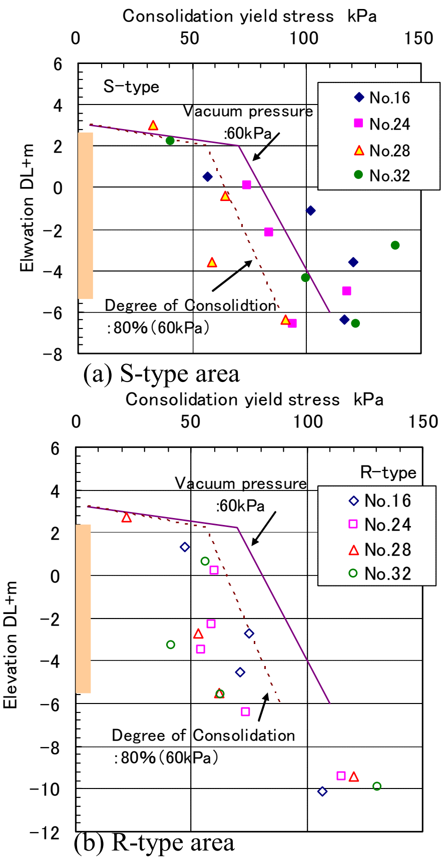
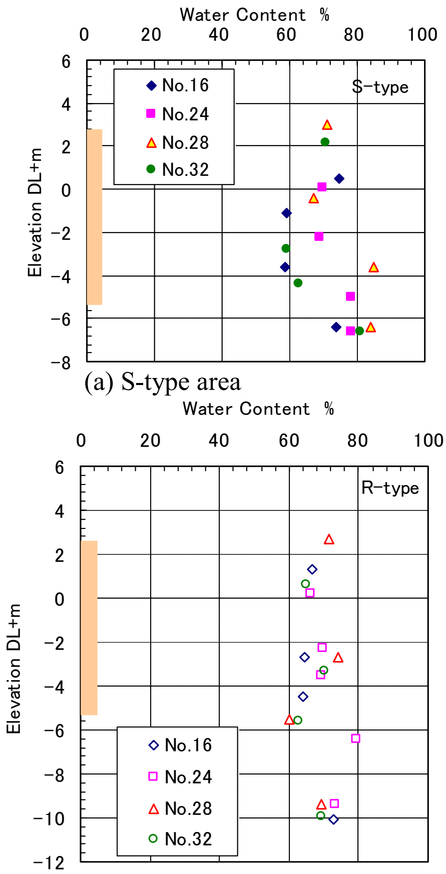


Fig. 7 Distribution of consolidation yield stress

consolidation yield stresses of S-2 line with the installing pitch of 1.0 m exceeded over 80 % of 60 kPa of vacuum pressure. The S-3 line located at the boundary between S- and R-types did not reach 80 % of effective stress. The degree of consolidation was recognized to be dependent on the pitch of installed PBDs.



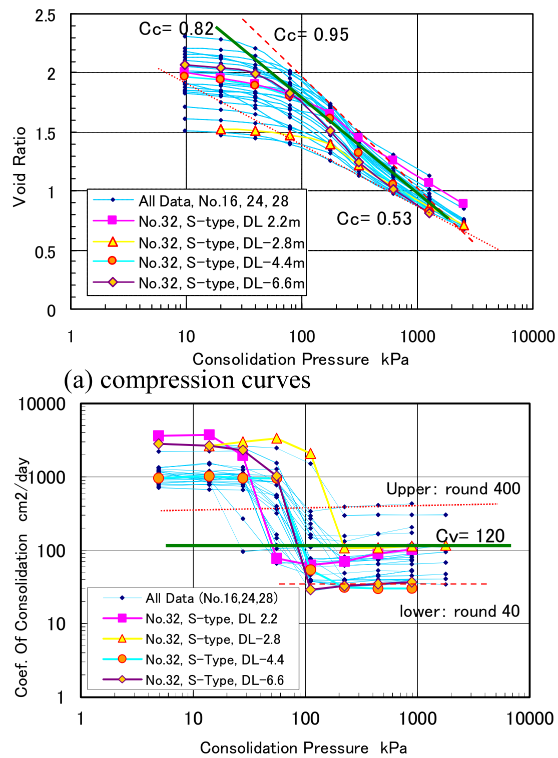
(a) S-type area

(b) R-type area

Fig. 8 Vertical distribution of water content

Figure 8 shows the water content distribution at each area. The water contents at the S-2 line ranged from 60 to 80 %, and those at the S-3 line were also distributed from 60 to 80 %. Both the distributions were almost the same. The reason was thought that the change of water content in the high degree of consolidation is small.

Figure 9 shows the results of consolidation tests on the samples acted the vacuum pressure. The compression curves shown in Fig.9 (a) were represented from the over-consolidated to normal consolidated conditions, and the consolidation yield stresses were from 40 to 140 kPa mentioned earlier. The compression indexes, C_c ranged from 0.53 to 0.95. The coefficients of consolidation in the normal consolidation condition were distributed from 40 to 400 cm^2/day.



(a) compression curves

(b) coefficient of consolidation

Fig. 9 Consolidation characteristics

6. BACK ANALYSIS FOR VACUUM CONSOLIDATION METHOD

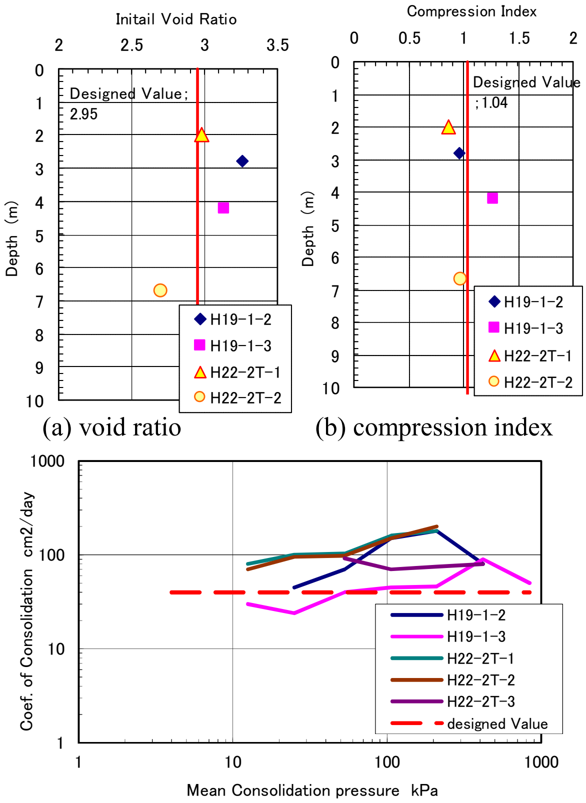
Using the results of monitoring and soil investigation, several back analyses were performed. The back analysis were used the C_c-method for consolidation settlement and Barron's Equation for progress of consolidation. To express the consolidation behavior of lower seal layer, the practical method for partial vertical drains proposed by Hitachi et al. [4)] was adapted.

6.1 Evaluation of prediction at design

At the design of vertical drains, the elevation of reclaimed land was increasing as the dredged clays were poured into the disposal pond. Then, the ground model as uniform condition shown in Fig.10 (a) was assumed. The compression index was also set at 1.04 as shown in Fig.10 (b), and the coefficient of consolidation was 40 cm^2/day as the lowest limit of test results shown in Fig.10 (c).

The design of installation pitches of vertical drains was determined by the results of Barron's equation and consolidation constants shown in Fig.10 The effective diameter of drain, d_e was set at 1.128 by diameter of drain. And equivalent diameter of drain, d_w was 8 cm. The coefficient of horizontal consolidation was assumed as the same of vertical value. The used consolidation value and several assumptions are shown in Fig. 11.

The working term of vacuum pump was set at 180 days in this design. And the designed consolidation degrees at the S-type area and R-type were 90 % and 50 % of consolidation degrees, respectively. From the designed conditions and consolidation degrees, the pitches of vertical drains at the S-type and R-type were set at 100 and 170 cm, respectively, as shown in Fig. 11.



(a) void ratio (b) compression index

(c) coefficient of consolidation

Fig. 10 Results of early soil investigations

The prediction at the design was shown as "+" in Fig. 6. To compare to measured data, the prediction was plotted from 50 days from installing of PBDs. This time was when the vacuuming started. The settlement was measured from the installation of PBDs, and was approximately generated 100 cm just before the vacuuming and 200 cm during the vacuuming process. The prediction at design was not represented for the behavior after the installation of PBDs before vacuuming, and was expressed the behavior only after the vacuuming. The settlement after the installation of PBDs was the disappearance of excess pore water pressure accumulated during the reclamation of dredged clay. The model at the design did not consider this excess pore water pressure, and could not express the measured settlement.

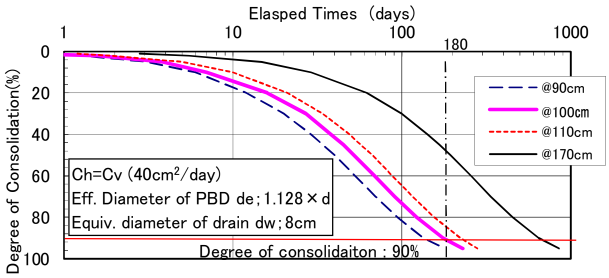


Fig. 11 Consolidation curves with different installation pitches and designed condition

6.2 Determination of ground model at installation of PBDs

To predict the stress condition of reclaimed ground, the reclamation analysis named 'CONAN' was used. The CONAN was developed based on a generalized one-dimensional consolidation theory[5]. The detailed procedure of this numerical method was described by Katagiri et al.[6].

The ground model including with consolidation parameters should be determined by numerical simulation of the reclamation stage. From the back analysis of preceding reclamation with dredged clay, the consolidation parameters are identified. Using these parameters the soil profile of the reclaimed ground at the installation of PBDs can be predicted by the CONAN.

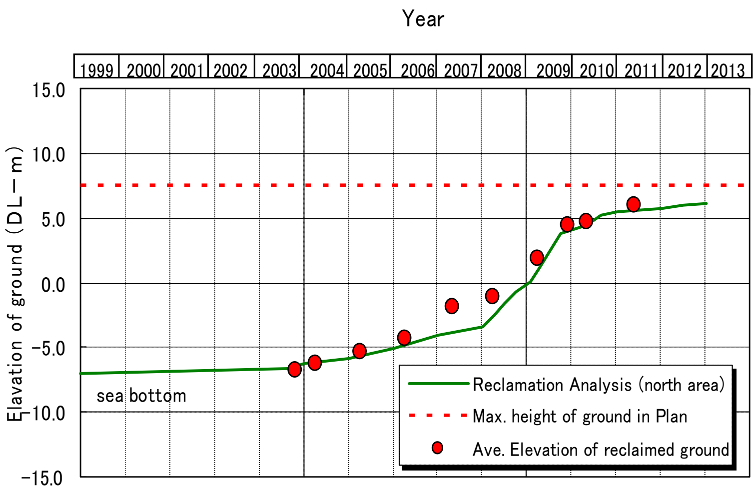
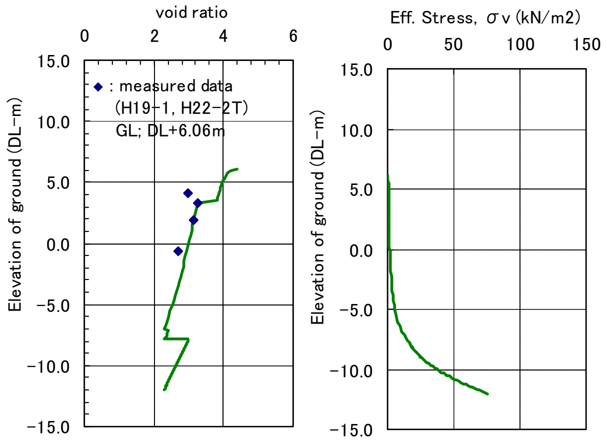


Fig. 12 Measured data and reclamation analysis result in the north area

Figure 12 shows the measured elevation of the north area of disposal pond monitored from 2003 to 2011. The result of reclamation analysis with the best-fit combination of consolidation parameters identified at the excavation area[7)] is simulated in the same figure. In this area, there was the Alluvial Clay layer within 5 m in thickness. The result of reclamation analysis was recognized to reproduce the measured data.



(a) viod ratio (b) effective stress

Fig. 13 Results of reclamation analysis

Figure 13 shows the distributions of void ratio and effective stress of the reclaimed ground in north area at the installation of PBDs obtained by the reclamation analysis. In Fig.13 (a), the measured values shown in Fig. 10 (a) were also plotted at elevation converted with (DL+6.06 m) of ground surface. The result of reclamation analysis presents the measured data and to be believable as ground condition of reclaimed land with dredged clay. Figure 13 (b) shows the distribution of effective stress in reclaimed land. The pore water pressure is the difference between total stress and effective stress.

The pre-analysis in Fig. 6 is the prediction of the ground model obtained from Fig. 13. This analysis used the horizontal coefficient of consolidation depended on space of PBDs ($C_h = (0.77*d - 0.24)*C_v$, d; space of PBD)[7)]. The consolidation parameters obtained from the soil investigation shown in Fig. 10 ($C_c = 0.95$, $C_v = 40$ cm^2/day) were used. The vacuum pressure of 60 kPa was supplied. Whole settlement behavior after installing of PBDs to stop vacuuming was similar to measured data, but the magnitudes of settlement and consolidation rate were different.

6.3 Installation of vertical drains by PDF method

Photo 1 shows the ground surface just installed the vertical drains by Plastic board Drain by Floating System (PDF-System). In the vacuum consolidation method, it is important to seal the drain system. The drainage tubes in this project were fixed at the edge of plastic board drains. In Photo 1, the drainage tubes were taken. The edges of plastic board drains were taken in the front of same photo. This part was the construction area by ordinary vertical drain method.

Photo 1. Ground surface condition installed vertical drains by PDF-system

6.4 Identified parameters of consolidation and their evaluation

In the back-analysis, the parameters of consolidation and vacuum pressure were changed to fit the measured data. As a result, the C_c was identified as 0.82 and C_v was 120 cm^2/day. To identify the consolidation parameters, this fitting of time-settlement behavior was not enough and more evidence was needed. Figure 14 shows the analyzed water content distributions of reclaimed layer at U = 90 %. In this figure, the initial condition before installing of PBDs and the water contents obtained from the soil investigation conducted after the stop of vacuuming were also plotted. The analyzed results except of the upper part, which is about 1 m as sealing layer were piled on the surveyed results at No.32. From these two evidences such as time-settlement behavior and water content distribution, the consolidation parameters used in the analysis could be identified.

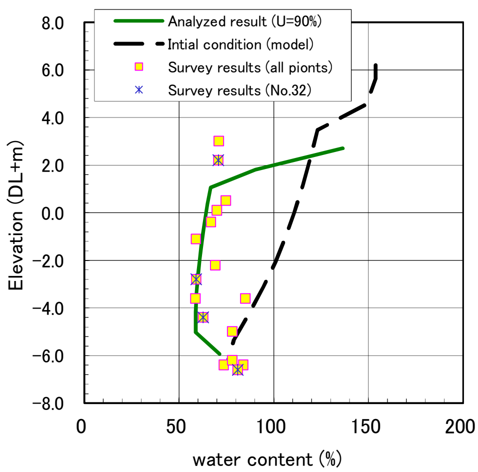


Fig. 14 Results of soil investigation and analysis

These identified consolidation parameters were plotted in Fig. 9. Both the compression index and coefficient of consolidation were located in the middle of scattering data. It was concluded that the identified parameters were suitable for this ground condition.

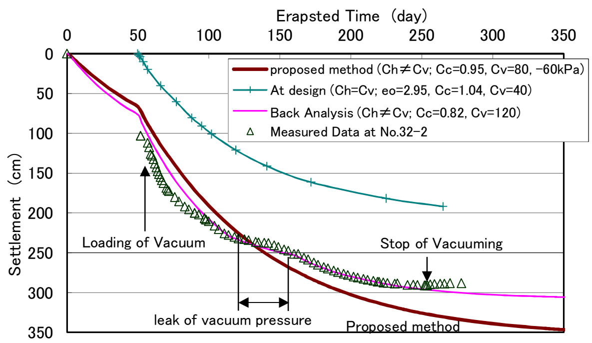


Fig. 14 Evaluation of proposed method

6.5 Identified parameters of consolidation and their evaluation

From above consideration and knowledge, a prediction procedure of vacuum consolidation method for a reclaiming land is proposed.

A ordinary procedure[3)] of prediction of vacuum consolidation method for a soft clay ground is i) determining the model ground using the results of soil investigation and ii) predicting the time-settlement behavior by Barron's equation and C_c-method. In a reclaiming clay ground, the elevation and ground condition are changed with time. The elevation and ground condition at the installation of vertical drains are different from those at the soil investigation. It is therefore necessary to predict the elevation and ground condition at the installation.

As mentioned earlier, the ground model can be determined by numerical simulation during the reclamation process. So, the consolidation parameters can be identified by back analysis, and the elevation and ground condition can be obtained by pre-analysis using CONAN[6)] program.

The design flow of vacuum consolidation method for a reclaiming clay ground are shown in Fig. 15. The prediction procedure proposed are as follows; i) identifying the consolidation parameters by back analysis during reclamation process using the reclamation history, monitoring data and so on, ii) predicting the elevation and ground condition of reclaimed clay ground at the installation of vertical drains by CONAN, iii) determining a ground model from the results of ii), and iv) predicting a settlement behavior of ground installed vertical drains under vacuuming. During the reclamation process, CONAN[6)] developed from a generalized one-dimensional consolidation theory[5)] can be used, Modified Yoshikuni's equation[8)] and C_c-method may be used during the vacuum consolidation process. Here, the modified Yoshikuni's equation can be considered the well resistance of deep drains.

The prediction by the proposed method is shown as a bold curve in Fig. 14. The gap between measured data (marked as "Δ") and prediction by the proposed method at 250 days from the installation of drains was 30 cm, and 10 % of predicted settlement. It is concluded that the proposed method is useful at the design of vertical drains for reclaiming lands.

7. CONCLUSION

In this paper, an actual construction example of vacuum consolidation method for the reclaimed ground with dredged clay is introduced. In this construction, the settlement behavior after the installation of vertical drains was measured, and soil investigation after the stop of vacuuming was performed. The pre-analysis and back analysis were also conducted. From these results and considerations, a prediction procedure of vacuum consolidation method for reclaiming clay ground is proposed.

The followings are obtained from this paper;

1) The ground model determined by limited ground information at initial design could not express the monitoring data. In particular, the settlement behavior after the installation of vertical drains was different.
2) The ground condition reclaimed with dredged clay such as this case was in partially consolidated condition, excess pore water

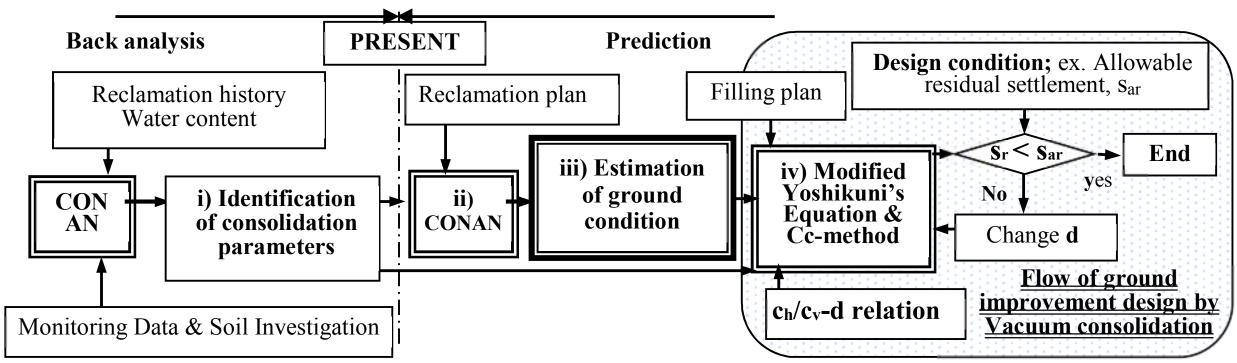


Fig. 15 Proposed design flow of vacuum consolidation for reclaimed ground with dredged clays

pressure was accumulated in the ground.
3) The settlement of reclaimed ground with dredged clay generated by disappearance of excess pore water pressure.
4) The ground model determined from the result of reclamation analysis could be represented the results of monitoring and soil investigation.
5) From these considerations, a prediction procedure of vacuum consolidation method for reclaiming clay ground was proposed.

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