Bulk Compression of Dredged Soils by Vacuum Consolidation Method Using Horizontal Drains

Hiroshi Shinsha[1] and Takahiro Kumagai[2]
[1]*Research Institute of Technology, Penta-Ocean Construction Co., Ltd., Tochigi, Japan*
[2] *Research Institute of Technology, Penta-Ocean Construction Co., Ltd., Tochigi, Japan*
[1]*E-mail*: Hiroshi.Shinsha@mail.penta-ocean.co.jp
[2]*E-mail*: Takahiro.Kumagai@mail.penta-ocean.co.jp

ABSTRACT: Two landfill sites were constructed on shore to dispose of dredged soil, and dredged soil was reclaimed after the placement of horizontal drains. In this manner, bulk compression of the soil has been achieved by application of vacuum consolidation method. The horizontal drain was a plastic board drain (PBD) with a width of 100 mm, a thickness of 10 mm, and a length of 117 to 171 m. The PBDs were set at both the bottom and the intermediate height of the landfill sites with a horizontal spacing of 0.8 m, and were completely overlaid with the dredged soil. By alternately placing the drain material and disposing of dredged soil at two landfill sites and applying negative pressure continuously to the sedimentary soil, it was possible to deposit an amount of sedimentary soil that corresponds to about 1.1 times the disposable volume at the landfill sites. This paper outlines the implemented construction and presents various measurement results and a settlement analysis.

1. INTRODUCTION

In Japan, over 20 million m^3 of dredging is carried out each year in navigation channels and anchorage areas for construction and maintenance of ports. The dredged soil is mainly dumped at landfill sites near soil dredging areas. However, in recent times, the available space at landfill sites has become scarce, and it is difficult to construct new landfill sites owing to environmental protection concerns. As a result, Japan is currently experiencing a shortage of landfill sites to dispose of dredged soil.

As a means for disposing of more dredged soil at a landfill site with limited volume, bulk compression of previously dumped and depositing soil at the site by accelerating consolidation is effective.

The water content of dredged soil is normally 100–150% (ratio of it to liquid limit: 1.0 to 1.5); therefore, it is possible to reduce the volume of the bulky soil by consolidation using a very small load. However, the shear strength of such dredged soil is low, and surcharge fill cannot be placed as the consolidation load on the soil with low bearing capacity. For this reason, vacuum consolidation method by use of negative pressure (ex. Yoneya et al., 2003) has been proposed.

Furthermore, as a means to accelerate the consolidation of clay materials, plastic board drain (PBD) materials are placed. However, when a landfill site is only several meters high, it may be extremely inefficient to place a vertical drain because the length of a single vertical drain will be too short. Therefore, a horizontal drain may be more efficient and economical because it can be laid over long distances. Several construction design examples of such a horizontal drain have been reported (Shinsha et al. (1991)).

This paper describes a construction case in which bulk reduction of sedimentary soil is performed by a vacuum consolidation method utilizing horizontal drains. This paper also presents a comprehensive settlement analysis.

2. SUMMARY OF CONSTRUCTION

2.1 Summary

The construction site was located in the coastal region in Japan. In this case, the purpose for dredging was to maintain the depths of waterways, and the dredging depth was comparatively shallow at G.L. - 1.5 m. The construction sequence from dredging to transportation of soil and then to application of vacuum consolidation method is illustrated in Figure 1. A grab-type bucket dredger was used for the dredging, and the dredged soil was transported by a soil carrier to a location near the landfill site. The dredged soil was then transported to the onshore landfill site by pneumatic pressure feeding. During grab dredging, water is usually carried along with the soil, and water is also added during pneumatic pressure feeding in order to avoid wear and tear on the machinery. As a result, the water content of the dredged soil is often significantly increased. The average water content of the ground in a normal construction scenario is about 125%. When dredged soil is dumped into a landfill site, the average water content is about 200%.

Figure 2 shows a plan view of the landfill sites. The sites were constructed at two locations, and their dimensions are as follows.

- Landfill site A: Width: 250 m; Depth: 160 m; Height: 5.5 m
- Landfill site B: Width: 160 m; Depth: 150 m; Height: 5.0 m

A vacuum consolidation method employing PBDs was used as the method for consolidating the sedimentary soil. The PBD used in this case was 100 mm wide, 10 mm thick, and 117 to 171 m long. The PBDs were set at both the bottom and the intermediate height of the two landfill sites.

The intermediate PBD was set at a height of G.L. + 3.0 m for Landfill site A and G.L. + 2.5 m for Landfill site B. A total of 957 PBDs were laid out at a horizontal spacing of 0.8 m for a total length of 143,000 m. After the PBD was placed, dredged soil was pumped in and negative pressure was continuously applied to the sedimentary soil until the average consolidation reached 80% or greater.

2.2 Construction

2.2.1 Process

Figure 3 shows the process chart for this construction. The dredged soil is dumped as described below. The dredged soil is first pumped into Landfill site A, which has PBDs installed at the bottom. Next, the dredged soil pump inlet is closed off when the sedimentary soil reaches a height of G.L. + 3.0 m, and the dredged soil is then pumped into Landfill Site B. An intermediate PBD is placed at Landfill site A while the dredged soil is pumped into Landfill site B. The pump inlet is closed off when the sedimentary soil reaches a height of G.L. + 2.5 m at Landfill site B, and the dredged soil is then pumped into Landfill site A.

This procedure is then repeated. The procedure described above has the following two advantages: First, there is no need to halt the dredging works because the dredged soil can be continuously dumped. Second, negative pressure is immediately applied to the sedimentary soil (negative pressure is applied when the thickness reaches 0.5 m or more, and therefore, the sedimentary soil is continually subjected to consolidation pressure during the dredged soil depositing cycles).

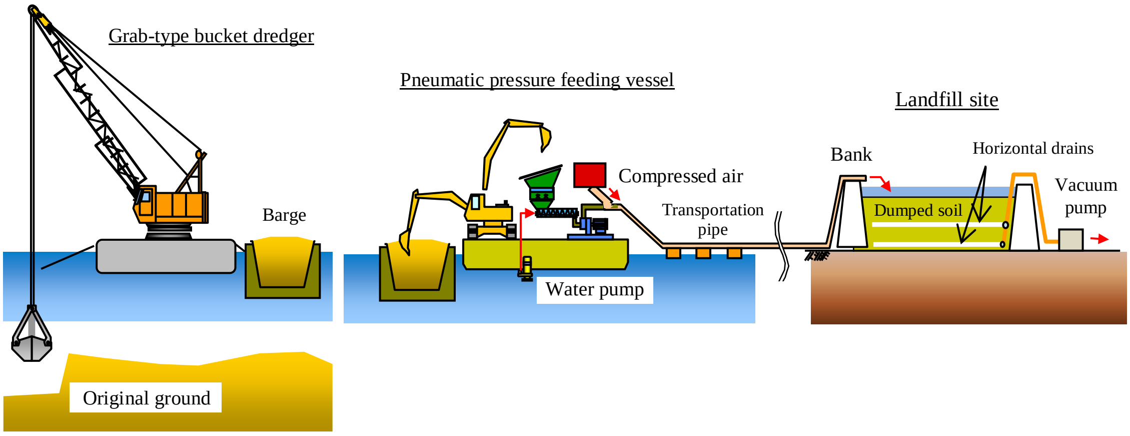


Figure 1 Construction sequence

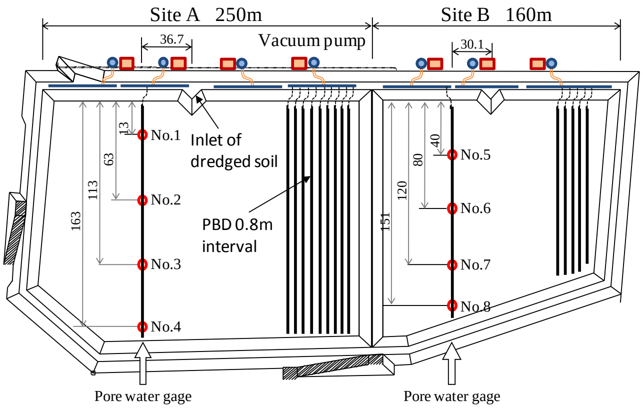


Figure 2 Plan view of landfill sites

2.2.2 Construction of the bottom PBD

First, a cap connecting to drain hose is attached to the PBD at the manufacturing plant. Next, a PBD unit is constructed using a rope to tie together 12 PBDs every 5 m (see Photo. 1), and the length is adjusted to meet the necessary length for the site.

The PBD unit was placed at the site in a rolled up fashion; it was then rolled out and a rope was used to fasten the PBD unit together into one integrated unit (see Photo. 2).

2.2.3 Dumping of the dredged soil

Photo.3 shows the aspect of dumping of soil into the landfill site. The dredged soil was transported into the landfill site by pneumatic pressure from the working vessel at a rate of about 10 m^3 every several 10 s. To prevent the horizontal spacing of the PBD from being disturbed when the dredged soil was dumped, for bottom PBDs, a large 1,000 kg sand bag was placed on the PBDs closest to the dredged soil pump outlet and a water level of about 1 m was maintained to reduce the impact of the soil as it was pumped in. For the intermediate PBD, the dredged soil was deposited only after a water level of 1 m or greater was reached.

2.2.4 Construction of the intermediate PBD

The intermediate PBD was constructed by first maintaining a water level of 1 m or more. A PBD placement barge dropped the PBDs on the sedimentary soil layer while advancing. The PBDs were pressed down to a depth of 0.3 m using a presser bar. This configuration is shown in Photo. 4.

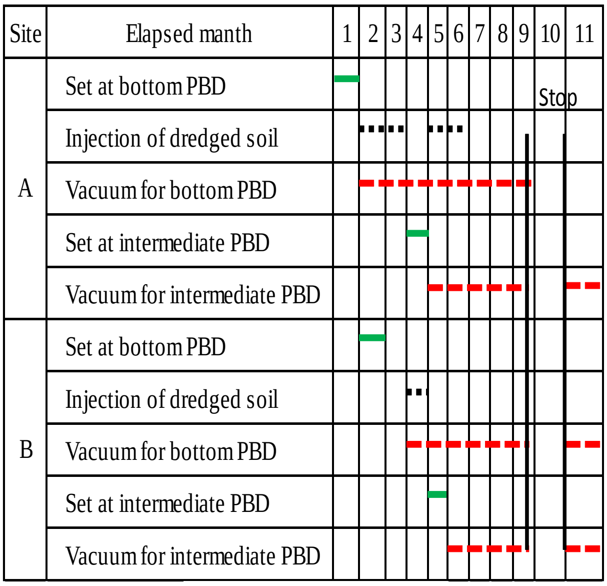


Figure 3 Process chart

2.2.5 Application of negative pressure

Negative pressure was applied by connecting the drain hose of the capped PBDs to a vacuum pump using a water collection line. The total number of vacuum pumps for the bottom PBDs and the intermediate PBDs was seven. The arrangement of the vacuum pumps is shown in Figure 2.

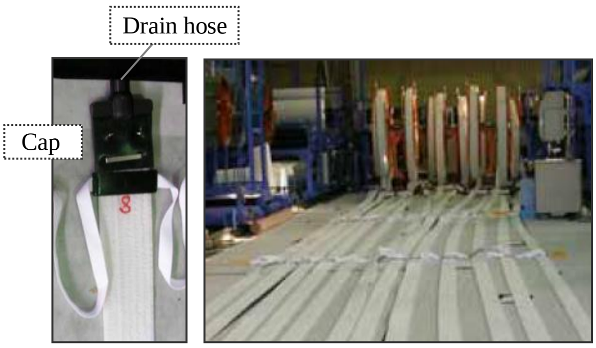


Photo. 1 PBD unit

Photo. 2 One integrated unit for bottom PBD

Photo. 3 Aspect of dumping of soil into the landfill site

Photo.4 Construction barge for intermediate PBD

2.3 Soil Properties

The soil properties of the dredged soil in the ground state are shown in Table 1. The natural water content was 115% to 135% (average 125%), the liquid index was 85% to 117% and the amount of sand was 12% to 54%.

The compression index Cc obtained by the incremental loading consolidation test was 0.63 to 0.76 (average of 0.72), and the coefficient of consolidation Cv under normal consolidation conditions was 30 to 100 (average of 80) cm^2/day.

3. MEASUREMENT RESULTS

3.1 Summary

During the deposition of dredged soil and negative pressure cycles, measurements were performed for the total amount of dredged soil, average height of the sedimentary soil, negative pressure within the PBDs, and water content of the sedimentary soil. The main results are listed below.

3.2 Changes in the total amount of dredged soil and sedimentary soil height

Figure 4 shows the change in time of the amount of dredged soil dumped into Landfill sites A and B (amount of soil transported by pneumatic pressure from dredging vessel, including water added artificially). This graph clearly shows that in this operation, dredged soil can be continuously dumped without halting the dredging and disposing work.

Table 1 Soil properties of dredged soil

Soil particle density ρ_s:		2.62 g/cm^3
Natural water content w_n:		115 – 135%
Texture	Sand:	12 – 54%
	Silt:	34 – 59%
	Clay:	12 – 33%
Consistency	Liquid limit w_L:	85 – 117%
	Plastic limit: w_P:	42 – 47%
	Plasticity index I_P:	43 – 70
Ignition loss L_i:		11 – 14%

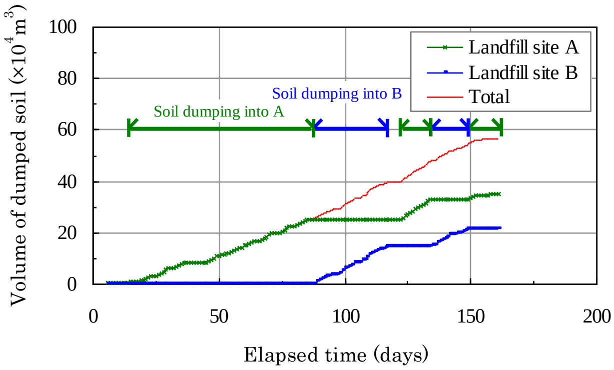


Figure 4 Change in time of amount of soil transported into the landfill sites

Figure 5 shows the change in time of the amount of dredged soil dumped into the landfill sites and the average heights of the sedimentary soil. The average height of the sedimentary soil was obtained by dividing the site into a 50 m square grid and taking the average of the height measured at the intersecting points of the grid. The height of the sedimentary soil increased during the dredged soil deposition cycles at both sites, and gradual settling was observed after the deposition has been completed.

3.3 Application of negative pressure to the sedimentary soil

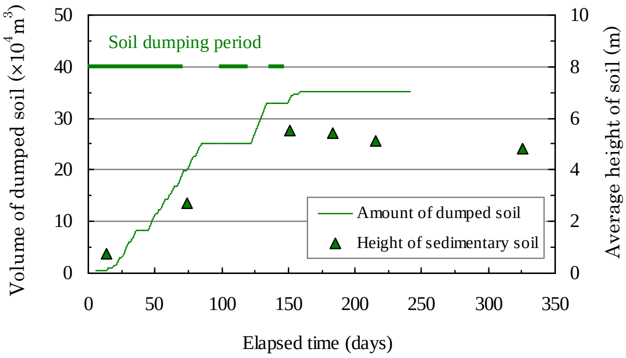
A pore water pressure gauge is installed to the bottom PBDs in order to measure the negative pressure applied to the sedimentary soil. The measurement locations are shown in Figure 2 as No. 1 through No. 8, and the measurement results obtained at location No. 2 at Landfill site A are shown in Figure 6.

According to these charts, it is confirmed that the base pressure p_0 of the vacuum pump was an average of -85 kN/m^2, where a high vacuum pressure was continually applied. The water level gradually increased with the deposition of the dredged soil, and when the dredged soil was completely deposited, an overflowing state was reached with the water at G.L. + 5.5 m.

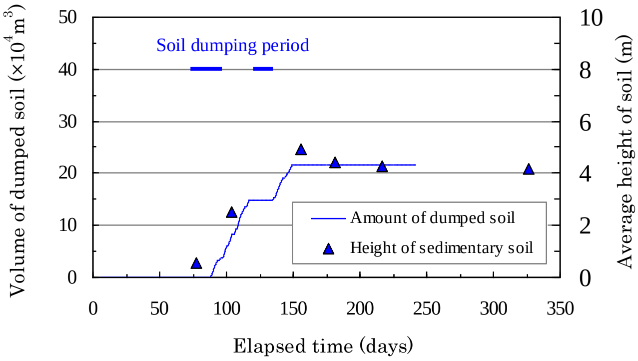
Meanwhile, according to the results of the negative pressure in the PBDs, the negative pressure was maintained in the range of -15 to -20 kN/m^2 with no relationship to the water level. The negative pressure was almost equal to the vacuum-pump pressure p_0 minus the pressure corresponding to the difference of elevation heads between the PBDs and the crown of bank (p_1). The substantial negative pressure for contributing to consolidation of the sedimentary soil $\hat{p}$ is expressed in Eq. (1) below, where the hydrostatic pressure p_2 at the bottom of the landfill site is also taken into account.

According to Figure 6, the substantial negative pressure applied to the sedimentary soil at location No. 2 increased as the water level increased with each dredged soil deposition cycle and leveled off to a constant of approximately −75 kN/m^2 after the water level reached at G.L. + 5.5 m.

$$\hat{p} = -p_0 + p_1 - p_2 \quad (1)$$



(1) Landfill site A



(2) Landfill site B

Figure 5 Change in time of average height of sedimentary soil

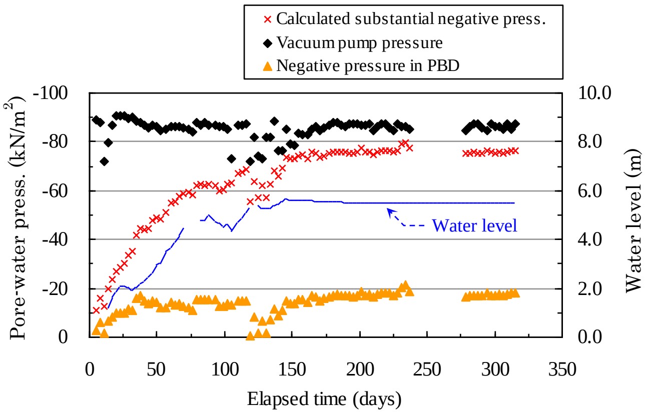


Figure 6 Negative pressure to sedimentary soil

Figure 7 shows the substantial negative pressures applied to the sedimentary soil at four locations, which are different in the distances from the location of the vacuum pump. In the results for Landfill site A, the negative pressure was essentially the same for location No. 1, which was located at 13.4 m, and location No. 4, which was located at 163.0 m. This indicates that no pressure loss was incurred owing to differences in distance from the vacuum pump. However, after more than 150 days, the applied negative pressures at different locations at Landfill site A were different. Normally, the applied negative pressure would be greater in the vicinity of the vacuum pump, and it would decrease with distance from the pump owing to the well-resistance effect. However, this sequence was not observed around the location of No.3. The reason for this is thought to be that the PBDs shifted in the vertical direction owing to the dump of soil from the levee crown, and thus, the reference values of pressure had changed.

Normally, a PBD with a width of 100 mm and a thickness of 3 mm is often used to improve clay-type soil, and the water permeation rate of such a PBD is 40 to 50 cm^3/s (according to a triaxial test at a confined pressure of 4.9 to 343 kN/m^2); therefore, the length of placement may be limited to about 30 to 40 m. In contrast, because the drain length for this construction is 171 m at maximum, a thicker PBD with a width of 100 mm and a thickness of 10 mm is used. The water permeation rate of this thicker PBD is 250 cm^3/s (according to a triaxial test at 4.9 kN/m^2), and therefore, the water permeation rate is five to six times more than that of a normal PBD. Compared with the PBDs in this construction case and general cases, the thicker PBD in this case is about 4.3 to 5.7 times as long, and the water permeation rate is still five to six times as high. In this construction, there are no tendencies for the negative pressure to decrease owing to increased PBD length resulting from negative pressure applied to the sedimentary soil.

Therefore, the thicker PBD appears to have sufficient drainage functionality.

3.4 Change in water content distribution over time

Figure 8 shows the change in water content distribution over time at location No. 2. The water content tends to decrease overall as the height of the sedimentary soil increased. On days 215 and 312, the water content was low at G.L. + 2.0 to + 3.0 m, where the bottom and intermediate PBDs are assumed to be located.

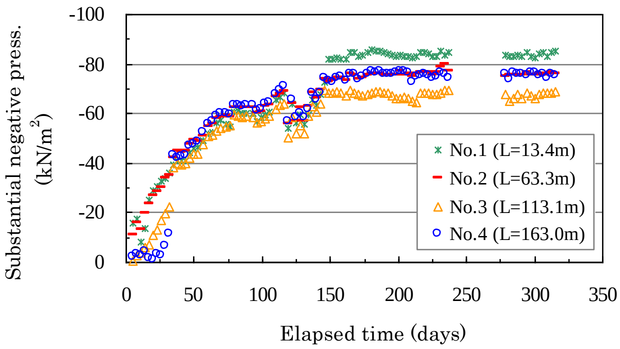


Figure 7 Negative pressure to sedimentary soil at four locations

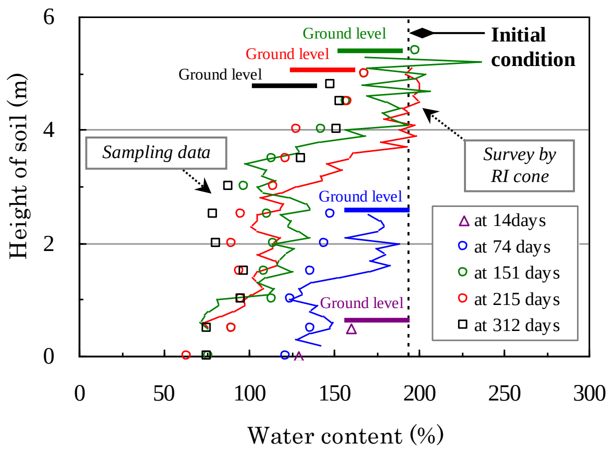


Figure 8 Changes in water content ratio distribution over time

Figure 9 shows the vertical profile of the water content as measured when negative pressure was stopped after 320 days. This figure outlines the results measured at locations No. 1 to No. 4 at Landfill site A. According to the results, the water content in the bottom and intermediate PBDs (supposed depth thereof) was low at 60 – 100% (liquid limit of 85 to 117%). The overall water content distribution had an arc shape between the bottom and intermediate PBDs and had more of a linear shape between the intermediate PBD and the ground surface. The water content near the ground surface was about 140%, which is lower than the 200% average water content observed at the time of deposition. This is owing to the settling and consolidation of the soil particles under their own weight.

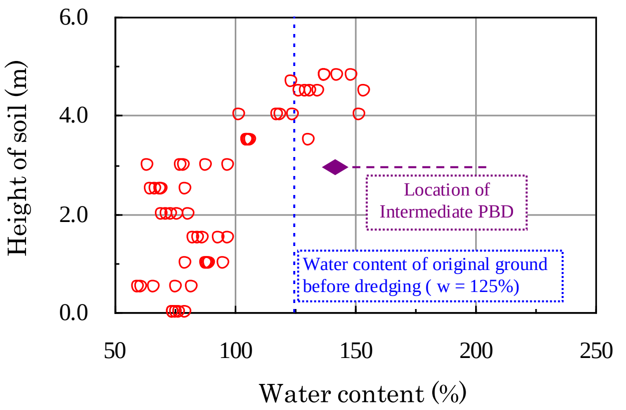


Figure 9 Depth distribution of water content after 320 days

3.5 Soil Bulking Factor

The soil bulking factor η can be found using the water content distribution shown in Figure 9. The definition of η is the volume ratio of the sedimentary soil at the landfill site to the soil when in the original ground state. The volumes are calculated by use of the distribution of void ratio in the landfill sites and void ratio of original ground, which is constant of 125%.

η is calculated on the assumption that the actual soil particle volume in each case is exactly the same. In particular, the actual soil particle volume V_s of the sedimentary soil is obtained by Eq.(2) and is converted to the volume V_d of the soil in the ground state using Eq.(3). η is finally calculated using Eq.(4).

$$V_s = \sum \left(\frac{H_i}{1+e_i} \right) \tag{2}$$

$$V_d = V_s (1+e_d) \tag{3}$$

$$\eta = \frac{\sum H_i}{V_d} \tag{4}$$

where H_i and e_i are the thickness and void ratio of sedimentary soil at each ground level respectively, and e_d is the void ratio of the dredged soil in the original ground state.

As a result, the values of η are obtained as 0.88 at Landfill site A and 0.93 at Landfill site B respectively. According to the water content distribution in Figure 9, the portion of depositing soil with average water content over 125%, which is equivalent to the original ground state, was located only within about 1.5 m depth from the surface. The water content of the soil in the deeper area was significantly below 125%, and therefore, the rate of change of the soil volume was assumed to be less than 1.0.

Accordingly, it was possible to dispose of some amount of dredged soil in the original ground state equivalent to 1.1 times the volume of the landfill site.

4. SETTLEMENT ANALYSIS

4.1 Summary

The change in the height of the sedimentary soil at Landfill site A is reproduced by consolidation analysis. The proposed method of analysis is shown in Figure 10. The analysis is conducted in two steps. In the first step, the effect of vertical and horizontal spacing of drains on consolidation rate was analyzed using two-dimensional plane-strain analysis based on infinitesimal deformation theory. Next, one-dimensional consolidation analysis using finite deformation theory was conducted considering vertical spacing of drains and the imposition of negative pressure. an elastic body. An ordinary program for the analysis of ground deformation was used in this study.

Figure 11 shows the domain of analysis. In the analysis, the vertical drain spacing d_v was fixed at 2.5 m, and the ratio d_H/d_v between the vertical drain spacing and the horizontal drain spacing d_H was set at 0.0 (when the entire horizontal drain is laid out over the designated depth), 0.08, 0.20, 0.40, and 0.80. The load was adjusted so that the volumetric strain ε_V could be 20% and 40%. Regarding a drainage condition, 0.1 m wide drainage boundaries were set at the positions of PBDs.

Figure 12 shows the analyzed results. In the analysis, non-dimensionalized influence factor α is introduced. The factor is defined by t_{80} / t_{80}(at d_H/d_v=0), which means the ratio of time required to attain average consolidation degree of 80% to that in the condition at d_H/d_v = 0.0 of entire horizontal drains laid. According to the diagram, as d_H/d_v increases, the value of factor α tends to increase. There is no discrepancy in α even when the strain varies to 20% and 40%.

Note that the analysis was performed on the basis of infinitesimal deformation theory, and the analysis may vary if the finite deformation theory is applied.

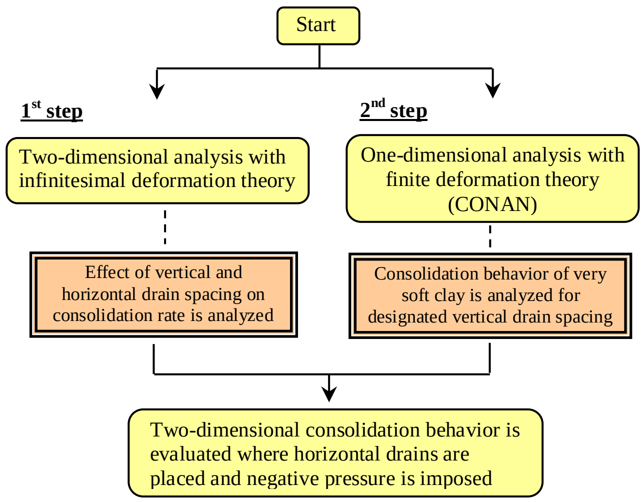


Figure 10 Analysis method proposed in this study

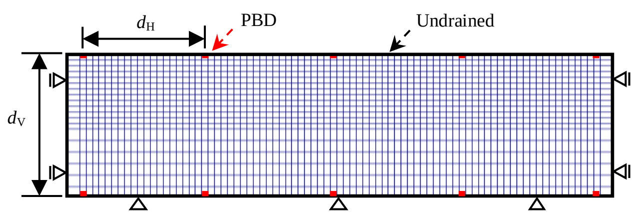


Figure 11 Domain of FEM analysis

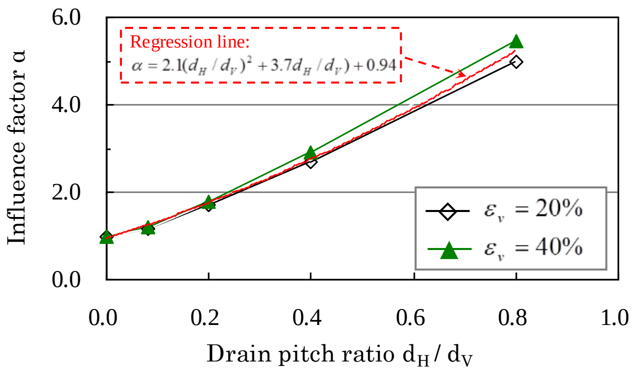


Figure 12 Analyzed results regarding the effect of drain spacing

The method composed with two step analyses is proposed in this study because the target soil for analysis is very soft and effective stress within the soil is extremely low at the initial state, and no other analysis method appears to be established to describe two-dimensional consolidation behavior of very soft clay where horizontal drains are placed and negative pressure is imposed.

In the proposed analysis, the conditions of actual dredged soils are modeled, and the progress of soil deposition in the site and the imposition of vacuum pressure are reproduced. Finally, the change of height and water content in dumped soil are compared with the monitored data.

4.2 Two-dimensional consolidation analysis (effect of vertical and horizontal drain spacing)

Two-dimensional consolidation analysis based on infinitesimal deformation theory was performed to determine the effect of differences in vertical and horizontal drain spacing on the consolidation rate. In this analysis, the goal was to investigate the effects stated above as a more generalized attribute. Therefore, the analysis model was simplified and the ground was considered to be

4.3 One-dimensional settlement analysis with finite deformation theory

When the thickness, compressibility, and coefficient of permeability significantly vary during consolidation, the effects of such variations must be considered in the consolidation analysis. The consolidation theory proposed by Terzaghi is based on the infinitesimal deformation theory and is not really applicable to the consolidation behavior of dredged soil that is greatly deformed. Imai et al. (1992) proposed a coupling analysis method "CONAN" in which the three governing equations of the laws of conservation of mass and momentum together with the constitutive law are incorporated. In this study, a consolidation analysis of that accompanies large deformations was performed using "CONAN".

One-dimensional consolidation analysis is conducted by considering vertical spacing of drains and negative pressure in the vacuum consolidation method.

Two-dimensional consolidation behaviour where horizontal drains are placed is evaluated by correcting the result of one-dimensional analysis by use of the influence factor α, which accounts for the effect of two-dimensional horizontal spacing of drains on consolidation rate as described in the previous section.

4.3.1 Soil parameter and drainage conditions

Samples were extracted for soil tests during soil dumping into the landfill sites, and incremental loading consolidation tests and constant strain rate consolidation tests were performed.

The initial water content ratio of the samples was high at 200%; therefore, the consolidation tests were performed after consolidating these soft soil samples with preliminary pressure of 5kN/m^2.

The physical properties were as follows: sand content 12.3%, silt content 64.4%, clay content 23.3%, and liquid index 114.5%. The samples consist of finer grains in comparison with the soil properties shown in Table 1.

According to the consolidation tests of these samples, the compression index was C_c = 0.87, the consolidation index C_v was 20 to 80 cm^2/day (average of 45cm^2/day). In addition, the relationship between specific volume f (=1+e) and consolidation pressure p and that between void ratio e and coefficient of permeability k were substantially the same for both the incremental loading consolidation test and the constant-stress-rate consolidation test as shown in Figure 13. As input parameters for the analysis, log f and log p share a linear relationship because initial effective stress is low, and the coefficient of permeability also has a linear relationship of e and log k. Table 2 shows the input parameters and drainage conditions for analysis.

The amount of dumped soil as a condition of analysis is taken from the data on cumulative amount of transported soil recorded on the working vessel, and the overall height of the deposited soil H_0 in the condition of w_0 = 200% was calculated by dividing the total volume of dumped soil by the area of the landfill site. Thus, H_0 at Landfill site A was 8.87 m.

Table 2 Input parameters for one-dimensional analysis

Soil particle density:	ρ_s =2.62 g/cm^3
Initial water content	w_0 = 200 %
Compressibility:	log f = -0.115 log p + 0.665 (p: kN/m^2)
Permeability:	e = 1.313 log k + 7.143 (k: m/s)
Drainage condition:	Ground surface: drainage (no excess pore-water pressure)
	Intermediate PBD: Negative pressure of -60kN/m^2
	Bottom PBD: Negative pressure of -60kN/m^2

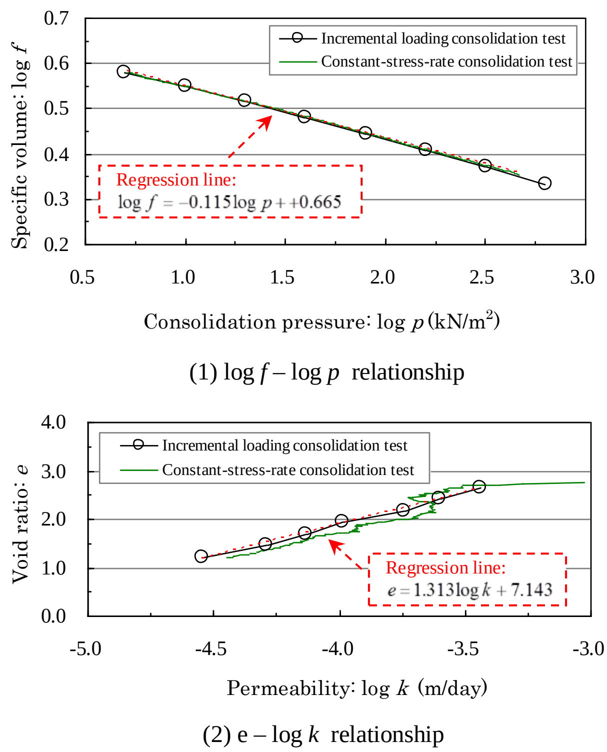


Figure 13 Results of consolidation tests

Regarding drainage conditions in the analysis, negative pressure was imposed at the locations of the intermediate and bottom PBDs, and ordinary drainage condition was given at the upper surface of the sedimentary soil.

4.3.2 Comparison of the analyzed and measured results at Landfill site A

Figure 14 shows the change of height of soil over time in comparison of measured and analyzed results. In this figure, the black line indicates the height of the deposited soil at Landfill site A (w_0 = 200%), the circle and triangle symbols indicate the negative pressure acting on bottom and intermediate PBDs respectively. The blue square symbols indicate the measured height of the sedimentary soil (see Figure 5). According to the analyzed results, in Case 1, which directly employed the coefficient of permeability k obtained in the consolidation tests, the height of the sedimentary soil was greater than that obtained in the measurements. In the case that coefficient of permeability is adjusted at four times the consolidation test result, the analyzed results agree with the measured results, as in Case 2. The reason for this is assumed to be that the average consolidation coefficient C_v of the entire landfill site is considerably larger than the consolidation coefficient C_v of the sample subjected to the consolidation test.

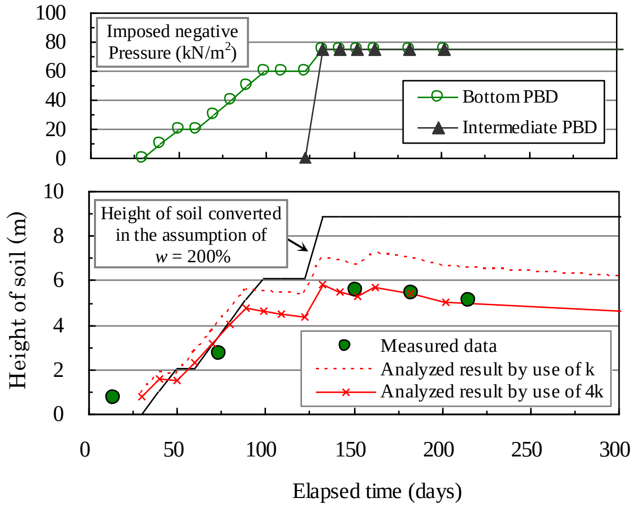


Figure 14 Change of height of soil over time

Figure 15 shows a comparison of the water content distribution of the measured and analyzed results in Case 2. According to the results after 151 days, the overall water content decreased as the depth increased, whereas in the analysis, the water content was low at the depth of the intermediate PBD, and the overall trend was different from the measured results.

The reason for this is assumed to be that effects of the horizontal drain were not modelled accurately in the proposed two-step analysis. Another reason for the discrepancy is thought to be that the water content results vary depending on whether the water content is measured near or apart from the PBDs. On the other hand, the water content distribution of the actual measurements and the analysis tended to be very similar after 294 days.

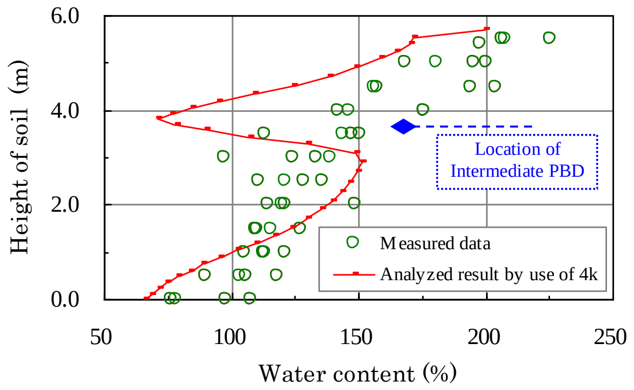
Incidentally, the average consolidation degree U was calculated after 151 days and 294 days passed. U_{151} at 151 days was 69.0 %, and U_{294} at 294 days was 95.0 %.

5. CONCLUSIONS

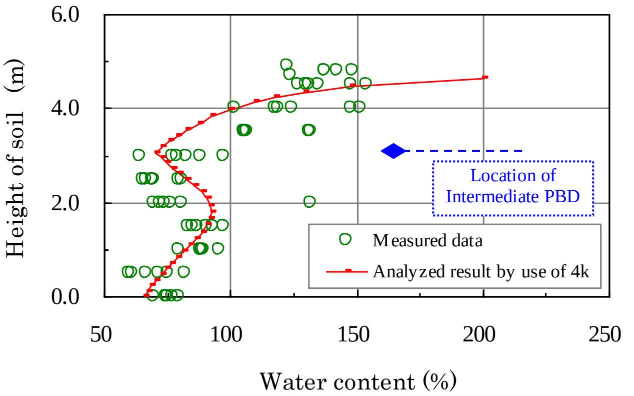
To dispose of as much dredged soil as possible at a landfill site with limited volume, the soil was dumped along with bulk compression work by employing a vacuum consolidation method at landfill sites. Two levels of PBDs were horizontally placed at the bottom and intermediate layers with a horizontal spacing of 0.8 m. The main conclusions are as follows:

1) The negative pressure applied to the deposited dredged soil increases with water level at the landfill site and can be expressed by using Eq. (1). In this case, a negative pressure ranging from −75 to −80 kN/m^2 can ultimately be applied to the sedimentary soil.
2) A PBD with a width of 100 mm, a thickness of 10 mm and a maximum length of 171 m can be used as the horizontal drain material. It is confirmed that negative pressure transmits to the ends of the PBDs without dissipation.
3) The average ratio of volume of dredged soil in original ground state to that of sedimentary soil after application of vacuum consolidation method was 0.88 to 0.93. The amount of dredged soil with 1.1 times the volume of the landfill site was dumped at the landfill site.
4) The consolidation analysis was achieved using two-dimensional analysis based on the infinitesimal deformation theory to determine the effect of horizontal drain spacing on the overall consolidation, and then performing one-dimensional analysis by considering this effect. Regarding the change in sedimentary soil height over time, the measurement results closely corresponded to the analysis with coefficient of permeability adjusted at four times the consolidation test result.

In the construction example employed in this paper, two landfill sites were constructed on shore, and dredged soil disposal and placement of horizontal drains were performed alternately, whereby dredged soil can be dumped without stopping the work convoy. This is extremely beneficial to construction work.



(1) After 151 days passed



(2) After 294 days passed

Figure 15 Distribution of water content

Finally, when soil improvement by consolidation using horizontal drains is conduced, there remain soft layers in the surface area in which the consolidation improvement effect is not apparent. Therefore, solidification treatment by cement addition was conducted at the surface area of 1 m deep intending for future land use in this construction area.

6. REFERENCES

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