Stabilization of embankment on compact vacuum consolidation

Stabilisation de remblai sur la fusion compacte de vide

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ABSTRACT: This paper discusses the "vacuum consolidation method" in comparison with the conventional "surcharge method" for improvement of soft subsoil. The vacuum consolidation method provides speedy construction and overcomes the "critical height." Based on the field observations, specific factors in relation to vacuum efficiency (by forced-dehydration consolidation) for improving the integrity of filled lands and reliable evaluation are discussed.

RÉSUMÉ: Nous comparons dans cette étude la consolidation par le vide avec la méthode habituelle de surcharge pour l'amélioration de sols meubles à partir de résultats observés lors de remblayages expérimentals.En cas de remblai avec la consolidation par le vide, des travaux rapides (à court terme) dépassant la hauteur critique d'un talus se sont avérés possible.A partir d'observations faites sur place, nous étudions les facteurs concrèts et les calculs d'équilibre des effets de la pression(la consolidation compacte par le vide) en vue de l'amélioration de la stabilité des sols de fondation.

1 INTRODUCTION

One of the advantages of the vacuum consolidation method is that collapse of fill-up lands does not occur even when 60-80 kPa is applied at a time(Kjellman. 1952, Cognon. 1952, Holm. et al. 1996). With respect to the evaluation of deformation resistance of lands, there are reports on the "finite element analysis" using the "three-dimensional consolidation theory"(Qian et al. 1992) or analytical researches studying the safety factor by the "circular arc method" using a vacuum well model(Mitchell et al. 1984), but there are few field studies (Shang et al. 1998). In the text, cases where organic soil was filled to a height which for exceeded the "critical height" are discussed. In addition, factors that enabled the rapid reclamation over the critical height are disclosed. As this present method is capable of controlling of pore water and consolidation of land, this method is called the compact vacuum consolidation (CVC) method in the text with our eyes kept on its practical features.

2 OUTLINE OF SOIL

Figure 1 is a plan view showing the experiment lands. The experiment lands were located at the Ishikari lowland zone about 5 meters above sea level, where peat layers and viscous layers deposited 20 meters deep or more.

3 EXPERIMENT

Figure 2 shows the experiment plan and Table 1 shows the experimentoutline. Where the planned filling height is lower than 3 meters, "slow construction" was adopted, and where it is 3 meters or higher, the CVC method was utilized to carry out rapid reclamation. The CVC area (20,870 m^2) was divided into 13 blocks. The vertical drain installation length was 20 meters and the installation pitch was varied from 0.7 to 0.9 meters because of the difference in filling thickness and desired residual settlement rate.

4 EXPERIMENT RESULTS

4.1 *Surcharge Area*

4.1.1 *Reclamation*

Figure 3 (a) shows the change of filling height against time. Filling work started at a speed of 6cm/day on the 36th day after having laid sand mats. On the 88th day, about 3 meters of layers were filled up.

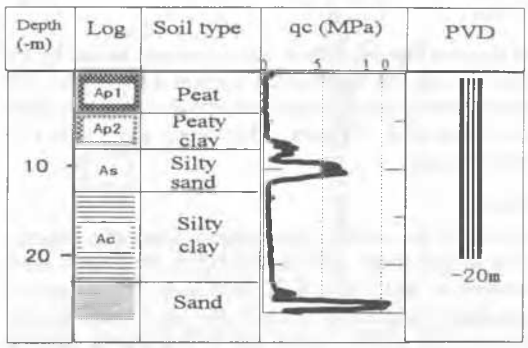

Figure 1. Experiment lands.

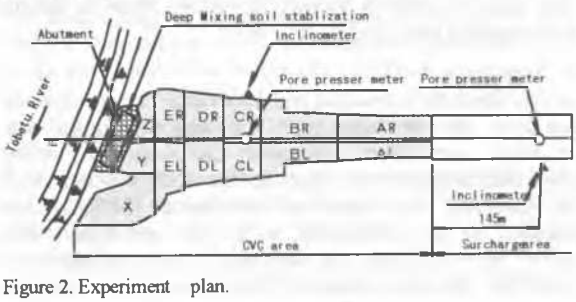

Figure 2. Experiment plan.

Block No.	Area of improvement (m^2)	Interval of vertical drain (cm)	Filling height (m)
AR	2, 178	90	5. 2
AL	1, 580	90	5. 2
BR	2, 213	80, 90	8. 9
BL	1, 756	80, 90	8. 9
CR	1, 533	70	10. 4
CL	1, 340	70	10. 4
DR	1, 690	70	10. 2
DL	1, 520	70	10. 2
ER	1, 469	70	12. 0
EL	1, 554	70	12. 0
X	2, 522	70, 80	10. 8
Y	827	70	12. 0
Z	688	70	12. 0

Table 1. Experiment outline.

The work stopped this time because signs of land sliding were observed.

4.1.2 *Subsidence*

Figure 3 (b) shows subsidence against time. The subsidence was scarcely caused by sand mats. After 3 meters reclamation, the observed subsidence was about 0.5 meter, which rapidly increased thereafter. After that , the subsidence curve becomes nearly straight. It appears that sliding shows when the fill-up is 3 meters over.

4.1.3 *Water pressure*

Figure 4 shows changes in pore water pressure. The water pressures of Ap1 layer, Ap2 layer, and Ac layer increased for a few days after completion of 3-meter-filling on the 88th day, and subsequent dissipation was small. The rate of increase in water pressure was the greatest in Ap2 layer and was about 38 kPa. The decrease in water pressure As layer was assumed to be clue to the of block A which is the decompression start time earlier.

4.1.4 *Horizontal displacement*

Figure 5 shows changes in horizontal displacement against time. The horizontal displacement in the surcharge area occurred towards the outside of the improved area and increased as the fill-up went on. The maximum horizontal displacement occurred in the vicinity of Ap2 layer, GL-5m deep, and about 120mm towards the outside of the improved area. The increase rate of horizontal displacement became larger after the fourth layer filling(about 1.8 meters thick including the sand mat).

4.2 *CVC Area*

Figures 6(a)-(c) and Figure7-8 show the experiment results by the CVC method. Filling was continuously carried out from the 42nd day on after the vacuum pump began its operation until 9.90m thick layer was provided after 108 days. The filling speed was 16.5 cm/day on the average.

4.2.1 *Vacuum*

Figure 6(b) shows the vacuum immediately below the vacuum pump and an airtight sheet. The vacuum below the airtight sheet changed between 60 and 70kPa at the beginning. The increase in vacuum immediately after filling could be attributed to the increase of air-tightness on the ground surface and the subsequent decrease of vacuum pressure could be attributed to the increase of water pressure. After the pumping stopped, the vacuum below the airtight sheet decreased by about 30 kPa in 10 days.

4.2.2 *Subsidence*

Figure 6(c) shows the subsidence and dehydration rate compression of each layer, and dehydration rates. The subsidence immediately before filling was 142cm. Thereafter, the subsidence rapidly increased and reached 405 cm when the vacuuming stopped, which greatly exceeded the theoretical subsidence (341cm). The compression for the combination of the peat and organic clay accounted for 51% of the total subsidence. The dehydration rate was recorded 180 t/day for about 10 days immediately after the vacuum pumping began. However, it gradually decreased and converged to 25t/day. The dehydration rate was close to inverse proportion to the subsidence.

4.2.3 *Water pressure*

Figure 7 shows changes in water pressure in each layer against time. The water pressure of Ap1 (GL-2.5m), Ap2 (-6.0m), and Ac (GL-15.0, -21.0m) decreased immediately after the vacuuming started, which increased immediately after filling. It again decreased when filling stopped. After the vacuuming stopped, the rate of dissipation in water pressure decreased. On the other hand, the increase of water pressure during filling on the As (GL-10.5m) was insignificant, indicating a nearly constant value after filling stopped. The behavior of water pressure associated with the vacuuming and filling operation appears to be related to the vacuum efficiency and water permeability of the soil.

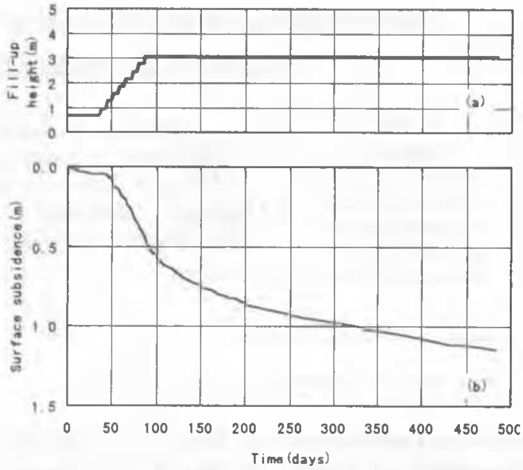

Figure 3. Change in thickness and subsidence.

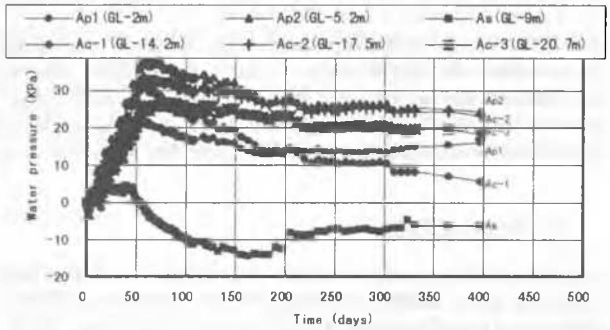

Figure 4. Changes of water pressure.

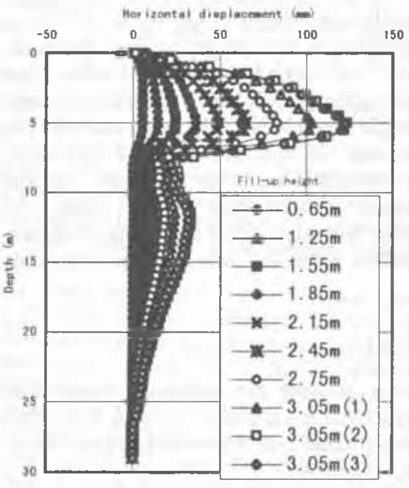

Figure 5. Horizontal displacements in the neighborhood of surcharge area.

4.2.4 *Horizontal displacement*

Figure 8 shows the observation results provided by the in-situ inclinometer installed at the position 1 meter away from the embankment edge. Immediately after the vacuuming started, observable deformation appeared in Ap1 and Ap2 towards the improved area. Ap1 deformation before filling was 570mm. The deformation of Ap1 after filling progressed towards the improved area. Ap2, As, and the top of Ac gradually deformed towards the outside of the improved area. The deformation of the soil towards the outside when the fill-up operation stopped was 120 mm maximum at the top of the silts.

4.2.5 *Soil Test*

In order to verify the improvement provided by the CVC method, undisturbed samples of Ap1 ,Ap2 , and Ac were collected from the base soil section before execution of the filling work as well as from

Soil Layer	Sampling condition	Filling height: H=6.0m							Filling height: H=10m			
		Moisture content (%)	Porosity (e)	qu kN/m²	Pc kN/m²	Qc MN/m²	LLT* results Km ** kN/m³	LLT* results Em*** kN/m²	Moisture content (%)	qu kN/m²	Pc kN/m²	Qc MN/m²
Ap1	Before CVC	600	11.58	21.4	17.7	0.37	44	245	600	21.4	17.7	0.22
	After filling	300	5.17	73.4	64.9	1.26	524	2950	250	108.8	107.2	1.65
Ap2	Before CVC	150	3.52	19.6	26.0	0.24	24	130	150	19.6	26.0	0.28
	After filling	85	2.13	46.5	76.3	0.82	153	893	70	79.5	93.4	0.99
As	Before CVC	-	-	-	-	2.20	-	-	-	-	-	3.01
	After filling	-	-	-	-	4.06	-	-	-	-	-	5.77
Ac	Before CVC	53	1.42	49.8	91.9	0.63	144	801	53	49.8	91.9	0.54
	After filling	50	1.25	74.4	154	0.96	103	569	43	117.6	244.0	1.01

*Lateral load tester in borehole. **coefficient of subgrade reaction. ***modulus of elasticity

Table 2. Comparison of soil properties at before and after of CVC

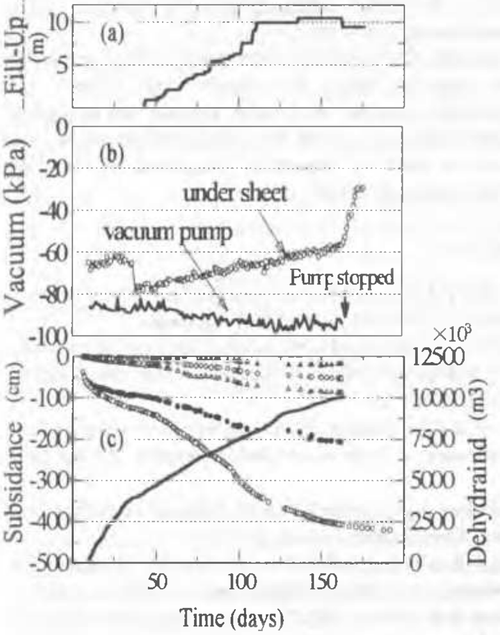

Figure 6. Experiment results of CVC method

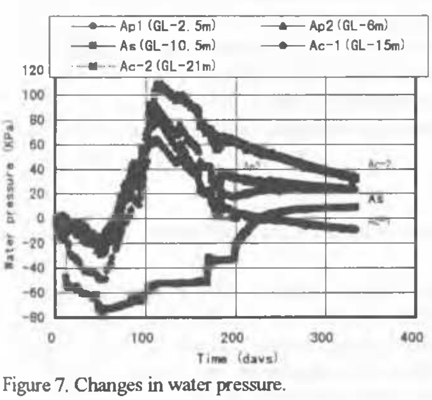

Figure 7. Changes in water pressure.

the points 6 meters height and 10 meters height after the CVC method was applied, and the laboratory soil tests were carried out., Simultaneously, the Dutch type double tube cone penetration test and borehole lateral loading test were carried out. Table 2 shows the test results as the mean values of a plurality of samples.

5 DISCUSSION

5.1 *Residual subsidence*

Figure 9 shows long-term subsidence trends in the surcharge area and the area where the CVC method was applied. The surface subsidence of the section filled 10 meters deep by the CVC method continued even after the vacuuming stopped. However, the rate of

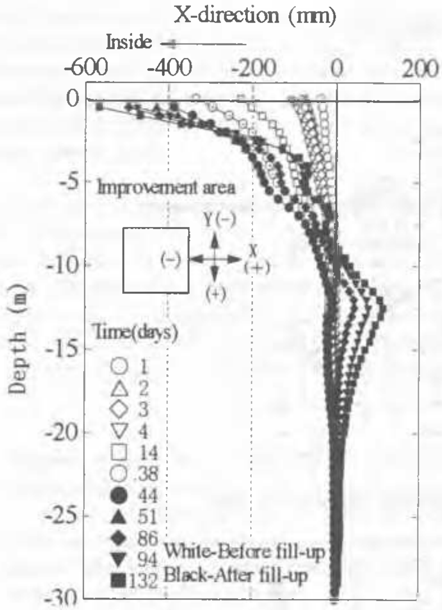

Figure 8. Horizontal displacements in the neighborhood of CVC area.

subsidence after 300 days was nearly equal to that for the area filled 3.0 meters deep by the surcharge method. The use of the CVC method indicates that the residual subsidence speed can be reduced to the level equal to that for the surcharged area.

5.2 *Displacement Vector*

Figure 10 shows the surface displacement vector at the beginning stage of the CVC method areas X, Y, and Z (5-meter intervals for initial 10 days). This figure shows a tandency that soil deforms towards the center of the improved soil. The consolidation and deformation are three-dimensionally provided towards the improved soil.

5.3 *Stability*

The undrained shear strength Cu of the organic soil by the laboratory test of the subsurface section was 10 kN/m², and the initial critical filling height Hc was 3 meters. When the strength increase is found with the degree of consolidation assumed to be 70% by the hyperbolic model in 42 days after the CVC method was implemented, Cu was about 25 kN/m², and the critical filling height Hc was 7.4 meters. It was decided difficult to stably fill up 9.9 meters in 42 days with the conventional surcharge embankment method. In the untreated area, 52 days were actually required to fill up 2.4 meters high. Figure 11 shows the rate of water pressure increase and rate of loading between the CVC method and the surcharge method. As the white symbols (CVC method) indicate, the rate of water pressure increase was kept nearly constant, even

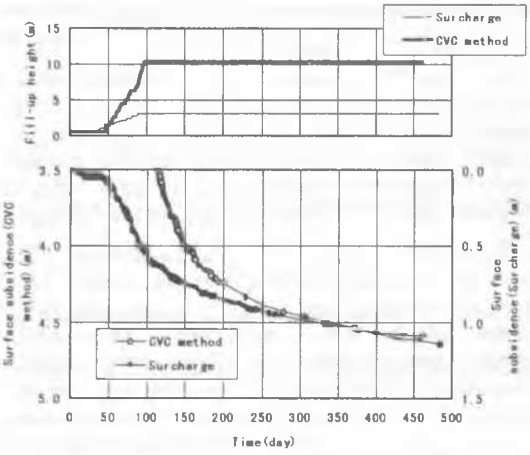

Figure 9. Long-term subsidence.

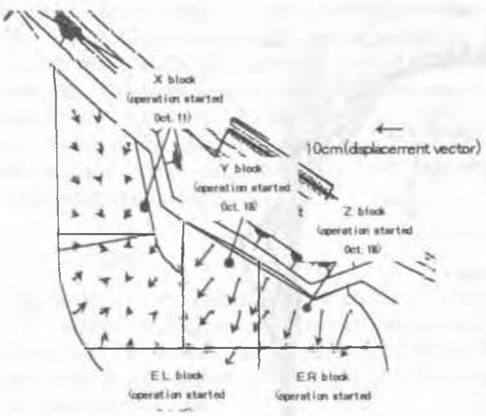

Figure 10. Surface displacement vector at CVC area.

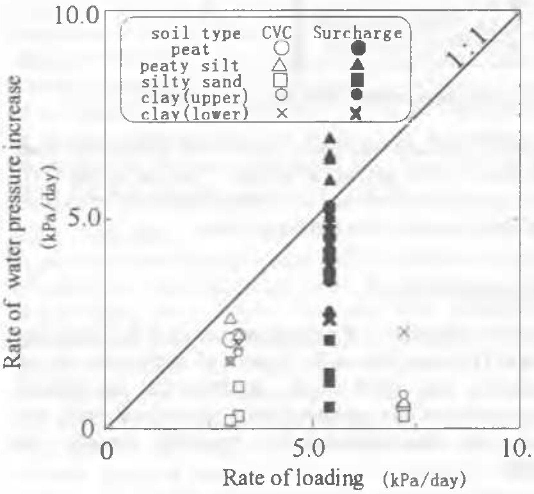

Figure 11. Relationship between rate of water pressure increase and rate of Loading.

when the rate of loading increased. As black symbols (surcharge method) indicate, both were nearly equal and had a 1:1 relation except for the silty sand layer. These facts are some of the factors that enabled the rapid filling up.

6 SUMMARY

The experiment has shown that vacuum by the compact vacuum consolidation method has greatly attributes to the stability of reclaimed lands on soft subsoil. The differences between the surcharge method and the present method are: (a) in the vacuumed region, the moment towards the center of the region is created; (b) excess water pressure generated by filling load is absorbed by the vacuum; (c) the difference between the external water level and the lowered water level of the improved soil (the external water is counterweight pressure) contributes to the stabilization of the reclaimed land; and (d) hard subsoil is formed on the surface soil section. These have been able to be judged by many field observation datas.

The calculation formula according to the total stress method is given below.

$$Fs = \frac{\sum Mr\,\phi + \sum Mrc_0 + \sum Mr\,\alpha}{\sum M_0} \qquad (1)$$

where, $Mr\,\phi$ is shearing resistance proportional to the internal frictional angle; Mrc is shearing resistance by initial cohesion Co, Mo is movement power, α is shearing strength increasing term under vacuum assuming, m'x(dP+u+dPcv)xU%+Scv; m' is compressive strength increase rate; dP is fillding load; u is difference in water pressure; dPcv is vertical confining force by vacuum; Scv is horizontal confining force by vacuum; U is degree of consolidation (70% over)

In the future, our efforts will be concentrated on the relationship between the confining force by vacuum and filling load, compressive strength increase ratio, water pressure, and strength of plasticized unsaturated soil, as well as on the development of a soil tester that can be used for theoretical elucidation of the CVC method and for design calculation.

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