Performance of vacuum consolidation for reducing a long-term settlement

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ABSTRACT

The problems of embankment construction over peat ground with high water content mostly relates to stability, and long-term settlement. Vacuum consolidation method is commonly used to assist the embankment construction over the soft ground for the purpose of accelerating a consolidation process as well as increasing an overall stability of soft ground for a rapidly embankment construction. Theoretically, the vacuum pressure is considered to be a surcharge load applying to the ground. This load will be removed immediately after the termination of vacuum operation. Basically, the settlement after construction can be minimized by waiting the primary consolidation process to complete at the higher degree prior the removal of surcharge resulting in the increase of over consolidation ratio. Nevertheless, the effect of vacuum consolidation as a surcharge load related to a long-term settlement characteristic has not been clearly investigated. This paper presented the measurement of the long-term settlement after the embankment constructions over peat ground assisted by vacuum consolidation. The effect of vacuum operation period was observed based on the field monitoring data. Moreover, the effect of surcharge by embankment and vacuum consolidation method was also studied and compared. It was found that the increasing vacuum pumping period and increasing the amount of surcharge by vacuum consolidation gave a very good performance to reduce the long-term settlement after the construction.

Keywords: vacuum consolidation, air-water separation system, soft ground, long-term settlement, soil improvement

1 INTRODUCTION

The problems of the embankment construction over soft ground such as peat containing high natural water content are mostly related to the supported ground stability during the construction, the large residual settlement soon after the completion of construction, and the long-term settlement problem. The use of vacuum consolidation method as a countermeasure has been increasing recently in Japan due to two advantages. Firstly, the depressurized atmospheric pressure inside the soft ground induces the temporary confining pressure to resist the outward movement after subjected to the vertical load. The effective stress increases while the total stress still remains the same. As the results, the embankment construction speed is allowed to increase comparing to the other methods such as vertical drain with surcharge preloading. Secondly, the temporary confining pressure is considered as a load to consolidate soft soil. This load will be immediately removed after the termination of vacuum pump but it does not consume the cost and time for removal like an embankment surcharge.

Basically, the long-term settlement can be reduced by increasing the over consolidation ratio. In practice, the amount of surcharge load as well as degree of consolidation play the vital role for the reduction of the long-term settlement. In Case of vacuum consolidation, the control of vacuum pressure inside the improved area as well as vacuum operation period are the key of success to minimize the long-term settlement problem.

This paper presents the field observed embankment construction assisted by vacuum consolidation regarding to the long-term settlement effect.

2 EFFECT OF VACUUM OPERATION PERIOD

The observed embankment was constructed in Hokkaido, Japan where the peat soil is dominated. Fig. 1 shows the simplified ground condition of the construction site. The soft ground consists of peat, organic clay, sand, and clay where the natural water content of peat and organic clay were 400~800% and 50~400%, respectively.

In practice, it is almost impossible to construct high embankment over this kind ground condition in a short period without the countermeasure. In Hokkaido, the most area is covered by a snow around 6~7 months. As
the result, the construction time for earthwork is very limited. Thus, vacuum consolidation method was utilized to enhance the ground stability under vacuum pressure for increasing the embankment construction rate. Vertical drains were installed deep to the clay layer in square grid pattern at 0.8 m interval for all test embankments.

Table. 1 shows the conditions of test embankments. The attention was paid for peat and presented in this paper. The thickness of embankments was similar while the rate of embankment construction was varied with high speed. The termination of vacuum operation period effect is the main objective in this study. Case 1 is soon after the completion of embankment when ensuring the stability concern. Case 2 is after the pore water pressure returned to the hydrostatic condition. Case 3 is after the pore water pressure returned to the induced value by vacuum pressure prior the start of embankment construction.

The settlement of peat layer was observed over the time period after the termination of vacuum operation in order to investigate the behavior of the long-term settlement as shown in Table. 2. It can be clearly seen that the longer period of vacuum operation, the less of the long-term settlement. The excessive settlement was clearly observed in Case 1. It should be noticed that the degree of consolidation was about 91% in Case 1 at the time of termination of vacuum operation and the residual settlement became closely to the value calculated by the predicted final settlement subtracted by the field settlement at the termination of vacuum operation. On the contrary, the degree of consolidation of Case 2 and Case 3 were higher at 96% and 98%, respectively. Small and very small residual settlement was observed in Case 2 and Case 3.

Fig. 2 shows the observed strain with time of peat layer since the start of construction. It can be seen that the strain characteristic after the construction 200 days showing the linear relationship which can be considered as the effect portion of the secondary consolidation. The secondary compression index was predicted at 6%, 3.2% and 2%, for Case 1, 2, and 3, respectively.

According to the observed results, it can be concluded that the longer period of vacuum operation advantages to reduce the long-term settlement. Thus, the key factors are related with the amount of surcharge load as well as degree of consolidation, which are presented in the next section.
3 EFFECT OF SURCHAGE PRELOADING

In this section, the effect of surcharge to the long-term settlement of embankment construction is presented. The ground condition at the construction site consists of 4 m thick peat layer with the natural water content about 600%, total unit weight 10–11 kN/m³ following by the soft clay layer with the natural water content 80–100%.

The conditions of constructions in order to minimizing the long-term settlement are shown in Table 3 based on surcharge pre-loading concept. Prefabricated vertical drain was utilized in Case 4 and 5 while no embankment surcharge load in Case 4 and 1 m in Case 5. Case 6 was utilized by vacuum consolidation to increase the stability of soft ground resulting in the allowable of applying the embankment to 2.4 m.

Table 3. Construction conditions

| Case | Method | Design height (m) | Total embankment thickness (m) | Surcharge thickness (m) | Observed field settlement (cm) | Estimated final settlement (cm) | Embankment construction time (month) | Degree of consolidation (%) |
|------|--------|-------------------|-------------------------------|------------------------|-------------------------------|---------------------------------|-----------------------------------|-----------------------------|
| 4    | PVD    | 8.1               | 10.6                          | 0.0                    | 210.0                         | 219.8                           | 7                                 | 96                          |
| 5    | PVD    | 8.7               | 13.1                          | 1.0                    | 295.0                         | 303.3                           | 6                                 | 97                          |
| 6    | VCM    | 8.2               | 13.0                          | 2.4                    | 237.5                         | 246.9                           | 3                                 | 96                          |

Fig. 3 shows the stage of embankment construction, vacuum pressure, and settlement of Case 6

4 SECONDARY CONSOLIDATION AND OVER CONSOLIDATION RATIO

According to the data in section 2, and 3, the secondary compression index can be calculated by Eq. (1) and over consolidation ratio (OCR) can be calculated by Eq. (2) and (3). Table 4 shows the calculation values.

\[ e_a = D \cdot S \frac{\log(t_2/t_1)}{D} \quad (1) \]
where
\( \varepsilon_0 \) : secondary compression index
\( \Delta S \) : settlement during \( t_1 \) to \( t_2 \)
\( D \) : initial compressible layer thickness
\( t_1 \) : time at the end of primary consolidation
\( t_2 \) : current time

Without vacuum
\[
OCR = \frac{P_0 + (P + P_1) \cdot U}{P_0 + P} 
\]  \hspace{1cm} (2)

With vacuum
\[
OCR = \frac{P_0 + (P + P_1 + P_v) \cdot U}{P_0 + P} \]  \hspace{1cm} (3)

where
\( P_0 \) : initial effective stress
\( \Delta P \) : design embankment load
\( \Delta P_1 \) : embankment surcharge load
\( \Delta P_v \) : vacuum pressure induced in the ground
\( U \) : Degree of consolidation at the time of surcharge removal

Table 4. Calculation of OCR & R

| Case | 1   | 2   | 3   | 4   | 5   | 6   |
|------|-----|-----|-----|-----|-----|-----|
| Design height (m) | 10.3 | 10.7 | 10.8 | 8.1 | 8.7 | 8.2 |
| Embankment thickness (m) | 10.3 | 10.7 | 10.8 | 10.6 | 13.1 | 13.0 |
| Settlement (cm) | 231 | 153 | 175 | 210 | 295 | 237 |
| Initial effective stress (kPa) | 0.5 | 0.5 | 0.4 | 15.3 | 13.8 | 12.0 |
| Construction stress (kPa) | 191 | 193 | 196 | 180 | 219 | 223 |
| Removal stress (kPa) | 7.6 | 27.6 | 46.1 |
| Final stress of embankment (kPa) | 191 | 193 | 196 | 173 | 192 | 177 |
| Vacuum pressure in soil, \( P_v \) (kPa) | 19 | 46.6 | 32.6 | 0.0 | 0.0 | 25.0 |
| Degree of consolidation | 91% | 96% | 98% | 96% | 97% | 96% |
| OCR | 1.00 | 1.19 | 1.14 | 1.00 | 1.10 | 1.33 |
| R | 1.00 | 0.48 | 0.30 | 1.00 | 0.58 | 0.21 |

Fig. 5. Reduction ratio of \( C_\alpha \) versus OCR, Fukazawa 1994

Fukazawa et al. (1994) proposed the relationship between the reduction ratio of secondary consolidation coefficient (R) VS over consolidation ratio (OCR) based on the field observation data as shown the boundary line in Fig. 5. The increase of OCR from 1 results in the rapidly decreasing of R until the maximum curvature at OCR = 1.3. At this point, the reduction ratio of secondary consolidation coefficient decrease to 0.2.

The calculated OCR and R of Case 1-6 were plotted into Fig. 5. It can be seen that the results falls in the boundary proposed by Fukazawa et al. (1994) except in Case 3, which is slightly lower than the lower bound probably due to the calculated OCR value in Eq. (3), which is more conservative in this study because the maximum induced vacuum pressures in the soil measured in Table 4 were used in calculations. In fact, the vacuum pressure in soil is quite lower than the applied vacuum pressure measured under the airtight sheet. Also, the observed vacuum pressure under the airtight sheet was gradually decreasing with time as shown in Fig. 3. Therefore, the substitution of \( \Delta P_v \) in Eq.3 is difficult to decide which is the correct value. Nevertheless, the recent technology in Japan can solve the loss of vacuum pressure problem in Fig. 3. Therefore, the performance of the vacuum consolidation to reduce ratio of \( C_\alpha \) would be better and easier to achieve than in this study. The system will be introduced in the next section.

5 LOSS OF VACCUM PRESSURE

According to the previous result, it confirms that vacuum pressure can be effectively used as a surcharge load to reduce the long-term settlement. Therefore, it is necessary to ensure that the vacuum pressure during vacuum operation is maintained at the design value.
The field monitoring of vacuum consolidation of Case 6 is shown in Fig. 6. It can be seen that the vacuum pressure measured at pump had been maintained slightly below 80 kPa at the start of vacuum pump and then increased up around 80 kPa after the completion of embankment construction. However, the vacuum pressure measured under the airtight sheet was gradually decreasing with time as shown in Fig. 6(c). This phenomenon was commonly found in Japan where the vacuum consolidation was utilized.

Therefore, the problem was recognized as the limitation of vacuum consolidation method. It may not be significant when the consolidation settlement is small (less than 1 m). However, the peat ground shows a large settlement after subject to the preloading pressure. As the result, the problem becomes more serious and required a solution.

To solve the mentioned problem, Imai (2005) proposed Air-water separation concept. The cause of problem is due to the elevation head loss as shown in Fig. 6(d). Vacuum Consolidation Technology Association developed the air-water separation concept to applicable in practice named as Compact Vacuum Consolidation Method (CVC). The system schematic is shown in Fig. 7.

Kosaka et al. (2012) reported the observation result of high embankment constructed over soft ground by using vacuum consolidation equipped with air-water separation system. The field monitoring data of vacuum operation is shown in Fig. 8. It can be seen that the vacuum pressure measured under the airtight sheet could be maintained over 80 kPa even after the consolidation settlement had been taken place over 10 m by the embankment 24 m thick.

The latest technology allows us to apply the maintainable high vacuum pressure to the soft ground, and eliminates the problem of vacuum pressure loss during the consolidation settlement. Consequently,
engineers who engage the construction over a soft ground now have a powerful tool to dealing with the instability of ground during the embankment construction as well as the excessive of long-term settlement during the service time of embankment.

6 CONCLUSIONS

Vacuum consolidation method is commonly used as the countermeasure for the embankment construction over soft ground due to the improvement of ground stability during the construction to shortening the construction time by increasing the rate of embankment construction. Vacuum pressured applied to the ground also acts as the temporary surcharge load to consolidate the soil and will be unloaded immediately after termination of vacuum operation. This paper presents the study of vacuum operation period and vacuum surcharge effecting to the long-term settlement behavior of ground.

Firstly, it was found that the termination of vacuum operation when the excess pore water pressure returns to the minimum value induced by vacuum pressure shows the better performance to reduce the long-term settlement comparing to the termination of vacuum operation soon after the excess pore water pressure return to the hydrostatic pressure. Moreover, the termination of vacuum operation soon after the completion embankment shows the poor performance to reduce the long-term settlement.

Secondly, it was found that the combination of vacuum and embankment surcharge shows the best performance to reduce the long-term settlement comparing to the case of no surcharge, and embankment surcharge. The use of vacuum consolidation allows to constructing the additional embankment surcharge without instability problem for the better performance.

Thus, it can be concluded that the vacuum consolidation method gives a good performance for reducing the coefficient of secondary consolidation.

Finally, to solve the loss of vacuum pressure during the consolidation settlement, the air-water separation system is useful to provide a high and maintainable vacuum pressure to the soft ground during vacuum operation. As the results, the long-term settlement reduction would be more effectively.

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