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A Case Study of Peat Ground Improvement by Vacuum Consolidation in Hokkaido, Japan

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ABSTRACT This paper presents the field performance of vacuum consolidation method on peat ground and some technical learning from the field trial. Peat is well known to be a soft soil which has particular characteristics, including extremely high compressibility and greatly low undrained shear strength. In case of an embankment building over peat ground, sliding failure and large settlement often occur due to the particular characteristics. For actual construction sites on peat ground, therefore, some kinds of ground improvement methods are commonly used. One of the methods is the vacuum consolidation method which can load vacuum pressure with the soft ground by vacuum pumps and prefabricated vertical drains to accelerate the consolidation and increases the strength of soft ground. Peat ground distributed widely in Hokkaido, the northernmost land of Japan. A full-scale trial construction of vacuum consolidation was conducted in a highway project over peat deposit in Hokkaido of Japan to reveal its performance. Although the undrained shear strength of peat ground at the trial construction site was approximately 10 kN/m^2 and extremely low, a 10.7 m high embankment was successfully built in only 45 days. This experimental fact implies that the vacuum consolidation method has extremely high effects in improving the stability of peat ground. Based on a result of the trial construction, it also revealed that the increase of undrained shear strength of the peat ground using vacuum consolidation and the suitable spacing of prefabricated vertical drains for peat ground.

KEYWORDS Peat; Organic Clay; Ground Improvement; Vacuum Consolidation; Trial Construction

1 INTRODUCTION

Peat is well known to be a very soft soil which has particular characteristics, including greatly low undrained shear strength (S_u) and extremely high compressibility (Huat et al., 2014; Mesri & Ajlouni, 2007; Noto, 1991). In case of an embankment building (e.g., road, railway and river dike) over peat ground, the particular characteristics cause some problems in geotechnical engineering, including large settlement and sliding failure (den Haan, 1993; Kurihara et al., 1993).

Therefore, some ground improvement methods are commonly used for construction sites over peat ground. The vacuum consolidation (Kjellman, 1952) is a ground improvement method of loading vacuum pressure with the soft ground by both vacuum pumps and prefabricated vertical drains (PVDs), in order to accelerate the consolidation and increases the S_u of soft ground. The vacuum consolidation has been applied often to clay ground (e.g., Bergado et al., 1998; Chai et al., 2006; Chai et al., 2008; Chu et al., 2000; Griffin & O'Kelly, 2014; Indraratna et al., 2004; Indraratna et al., 2011; Lopez-Acosta et al., 2019; Saowapakpiboon et al., 2010). At the present time, however, an use of the vacuum consolidation against peat ground has been limited (Cognon et al., 1994; Hayashi et al., 2021; Hayashi & Hashimoto, 2022; Karunawardena, 2007; Osorio et al., 2010).

Peat ground can be found widely in Hokkaido and Tohoku regions of Japan. There is an area of approximately 2,000 km^2 of peat ground in Hokkaido (Figure 1). In this study, a full-scale trial construction was conducted in a highway project over peat ground in Hokkaido. Based on a result of the trial construction, this paper presents the field performance of vacuum consolidation method on peat ground and some technical learning from the field trial.

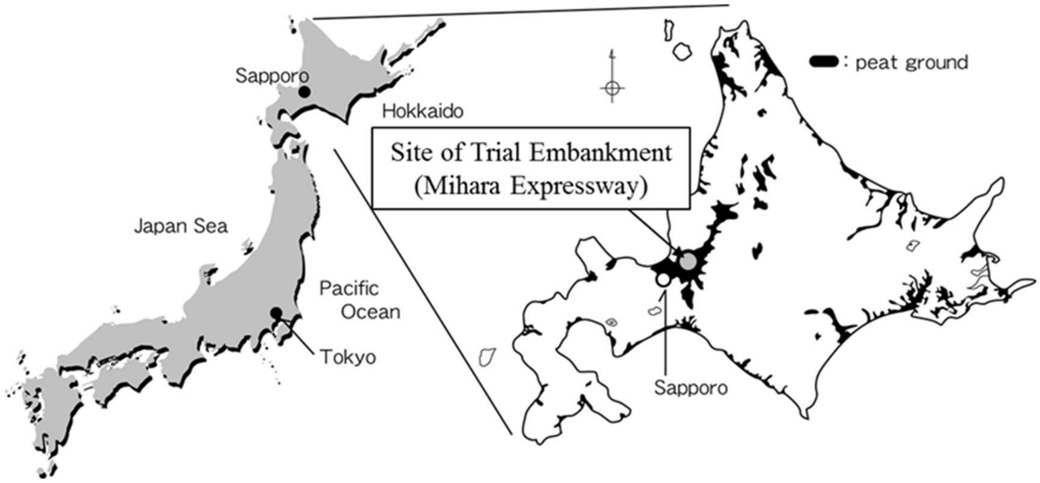

Figure 1. Position of the site of the trial construction (area of peat ground after Noto, 1991)

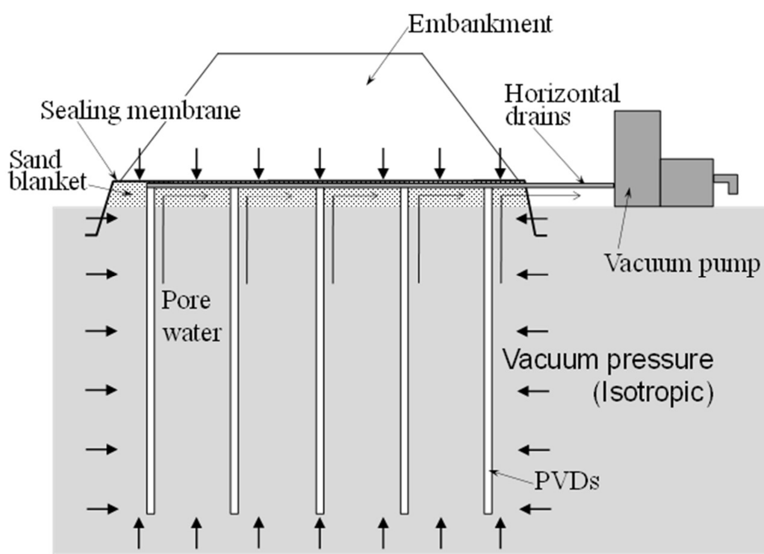

Figure 2. Schematic diagram of the vacuum consolidation method used in the trial construction

2 METHOD

The trial construction was performed at a site on the Mihara Expressway near Sapporo, the regional capital of Hokkaido (Figure 1). As the ground at the site was very soft including peat, a vacuum consolidation setup as shown in Figure 2 was used to reduce post-construction settlement and avoid sliding failure.

A sectional plan of the trial construction is shown in Figure 3. The ground consisted of fibrous peat, organic clay, fine sand and clay, in order from top to bottom. The w_n of the peat and the organic clay was from 230% to 730% and from 50% to 300%, respectively. The L_i of the peat ranged from 23% to 79% (Figure 4).

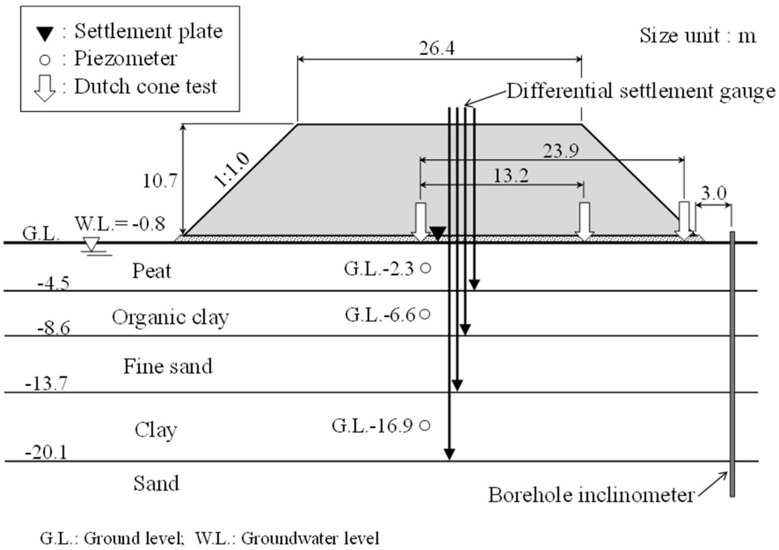

Figure 3. Sectional plan of the trial construction

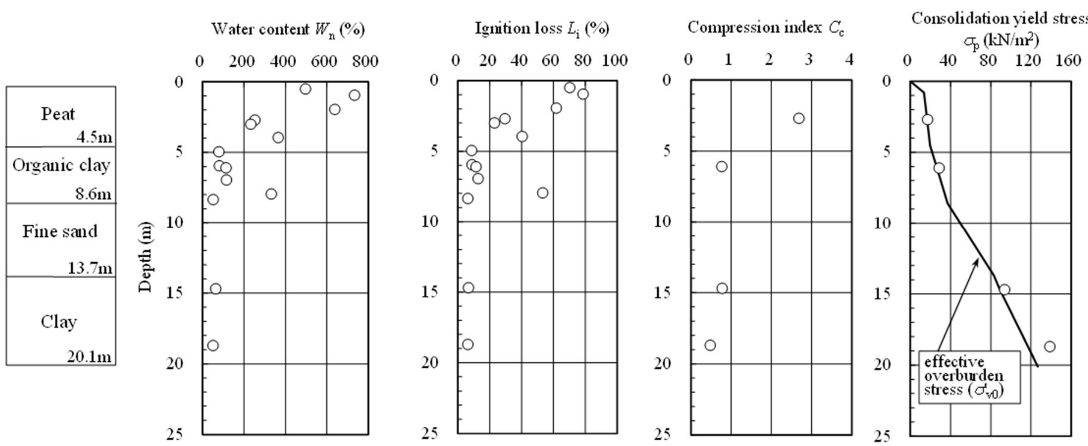

Figure 4. Geo-profile of the site

In the trial construction, one vacuum pump was used for the improvement area of approximately 2000 m^2. The PVD materials used had width of 100 mm and thickness of 4 mm (Hayashi et al, 2011). The arrangement of the PVDs was a square grid pattern with a spacing of 0.8 m. The vacuum pressure (p_v) monitored at the vacuum pump was 80 kN/m^2, and the p_v of 60–65 kN/m^2 was measured directly under the sealing membrane. It is important for successful vacuum consolidation to generate and continue such a high p_v. If the sealing membrane is laid directly on the peat ground surface, there is a risk that undecomposed dead wood contained within the peat stick into the sealing membrane and create holes, decreasing its performance to maintain a high p_v. Therefore, a sand blanket of 0.8 m thick was first constructed over the ground, and then the sealing membrane was laid on the sand blanket (Figure 2 and Figure 3). In addition, the sand blanket has a function of lateral drainage.

Before the beginning embankment construction, the p_v was applied for 15 days. Next, a 10.7 m high embankment was built over 45 days while the p_v was continuously applied. Then, the vacuum loading was kept for 145 days after the embankment was completed. While this period, the behavior of the ground was measured in detail using the equipment shown in Figure 3.

3. RESULTS OF FIELD MONITORING

The time history in the measured settlement values (total ground settlement and different soil layers) and the pore water pressure (Δu) is shown in Figure 5. Here, Δu is obtained by subtracting the hydrostatic pressure (u_0) from the piezometer measurement. Figure 5 also indicates the time history of embankment construction. Although the ground was very soft and the mean construction speed was 0.24 m/day (10.7m /45 days), which was very fast for peat ground (Figure 5(a)), no sliding failure of the ground occurred. The observational fact indicates the remarkable effect of the vacuum consolidation method in improving for the stability on peat ground.

The negative Δu values were measured during the period when only p_v was applied before embankment construction (elapse of up to 15 days) for all soil layers. During embankment construction, the Δu values changed to positive value (excess Δu), reached a peak at the end of the embankment building. Then the Δu values gradually decreased. The Δu (excess value) for peat and organic clay became hydrostatic pressure (Δu is zero) at the elapsed time of 80 days. This shows that the Δu generated by the embankment loading fully dissipated. After that, the p_v continued to be loaded, and the Δu returned to a negative value. After vacuum pump operation was ended, the Δu values finally reached a hydrostatic pressure (Δu is zero). This indicates that the ground changed to over-consolidation due to the p_v being unloaded by stopping the vacuum pump.

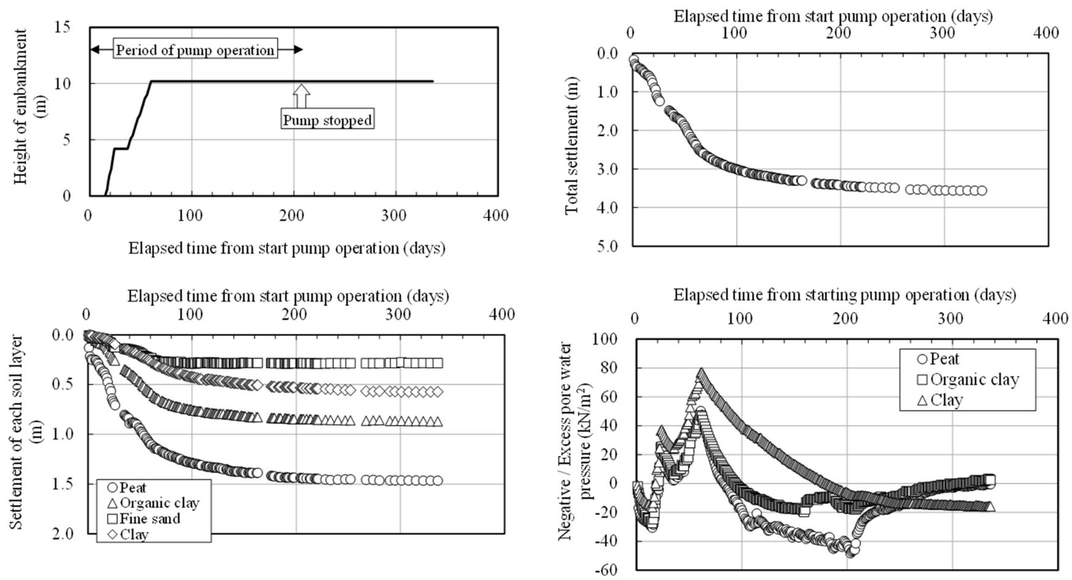

Figure 5. Time history of the ground behavior and the embankment construction

Figure 6 shows the lateral displacement of the ground. The lateral displacement was measured below the toe of the embankment slope (Figure 3) at three different times: 15days after the vacuum pump operation (before the start of embankment construction), at the end of the embankment building, and at the end of vacuum pump operation. Soft ground that has been loaded with an embankment generally causes outward lateral displacement due to shearing. It is known that peat ground is particularly sensitive to such shearing. In this trial construction, however, inward displacement occurred when only p_v was applied before embankment construction. This deformation mode indicates that isotropic p_v acting on the ground caused isotropic consolidation deformation instead of shear deformation. Peat and organic clay have a lower initial effective overburden pressure than that of clay, and are therefore strongly affected by isotropic p_v. For this reason, peat and organic clay show relatively significant consolidation deformation as mentioned above. In other words, vacuum consolidation, which can apply an isotropic load to the ground, has the effect of reducing shear deformation, especially in peat and organic clay. Further, no deformation such as progressing shearing was observed even after the vacuum pump was stopped.

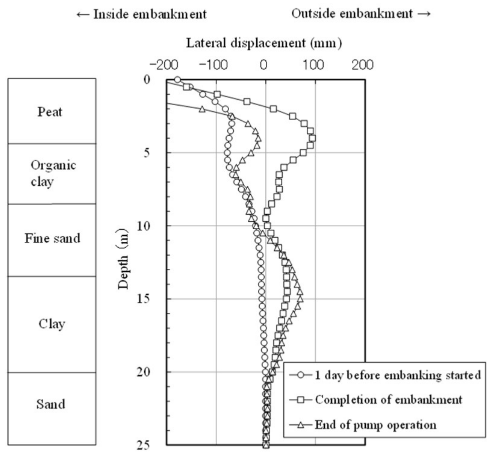

Figure 6. Lateral displacement of the ground below the toe of the slope

4. LEARNING FROM TRIAL CONSTRUCTION ON PEAT

4.1 Increase in S_u of Improved Ground by Vacuum Consolidation

This sub-section discusses the increase in S_u of peat ground by vacuum consolidation. As peat and organic clay are very heterogeneously deposited, the S_u was calculated using Eq. (1) from the mean value of cone penetration resistance (q_c) in this study. Where, σ_v is the total overburden stress and N_k is the cone factor. The q_c value was obtained from the mechanical cone penetrometer test (JIS A 1220: Japanese Geotechnical Society, 2015).

$$S_u = \frac{(q_c - \sigma_v)}{N_k} \quad (1)$$

The N_k was determined by Eq. (2) proposed by Hayashi & Yamanashi (2018).

$$N_k = 0.12\, L_i\,(\%) + 14.1 \quad (2)$$

To investigate the increase in the S_u of the ground by vacuum consolidation, the q_c values were measured at two time points: before the starting the trial construction (q_{c0}), and 15 days after the vacuum pump operation immediately before the embankment building (q_{c1}). The initial cone resistance (q_{c0}) along depth is shown in Figure 7. It was found that the q_{c0} values of peat, organic clay and clay were from 169 to 544 kN/m^2, from 232 to 933 kN/m^2 and from 485 to 936 kN/m^2, respectively. Table 1 shows the mean q_{c0}, N_k, initial S_u (S_{u0}) calculated using the mean q_{c0}, and normalized S_{u0} by the effective overburden stress (S_{u0}/σ'_{v0}) of each soil.

Meanwhile, the S_u after improvement by vacuum consolidation (S_{u1} calculated from q_{c1}) was obtained at three positions: the center of the improved ground, below the top and the toe of the embankment slope (Figure 3). Figure 8 shows the S_{u1}/σ'_{v1} for each type of soil in the transverse direction. For all types of soil, almost the same S_{u1}/σ'_{v1} value was obtained at all three positions. For comparison with Figure 8, the lateral S_u/σ'_v distribution in the case of simple embankment loading without vacuum consolidation (Hayashi et al., 2002) is shown in Figure 9. The S_u/σ'_v values of peat and organic clay obtained at the top of the embankment slope were 28% and 20% lower than those values at the center of the ground, respectively. That is, the S_u of the ground improved by vacuum consolidation increased almost uniformly in the transverse direction compared to the increase in the S_u of the ground by embankment loading without vacuum consolidation. This uniform increase in S_u in the transverse direction is considered to be the reason for the successful construction of the 10.7m high embankment despite the ground in the trial site was extremely soft.

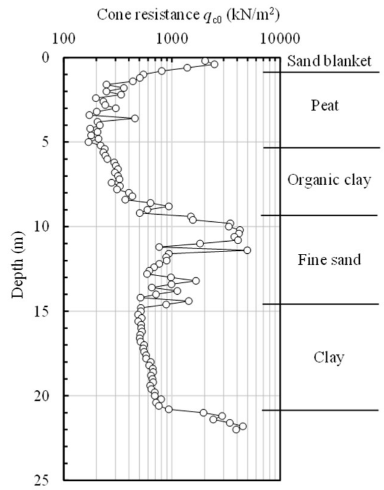

Figure 7. Initial cone resistance (q_{c0}) along depth

Table 1. Initial q_{c0} and S_u at the site

Soil type	q_{c0_mean} (kN/m^2)	N_k	S_{u0} (kN/m^2)	σ'_{v0_mean} (kN/m^2)	S_{u0}/σ'_{v0}
Peat	262	20.2	10.9	23.0	0.476
Organic clay	308	16.1	13.6	35.6	0.381
Clay	616	14.9	22.9	112.0	0.204

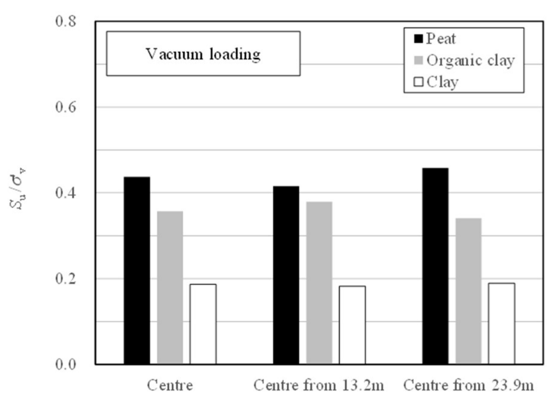

Figure 8. Normalized S_u in case of vacuum loading

Next, the reason why the lateral S_u increase of the ground improved by vacuum consolidation was relatively significant is considered. Compared to a simple preloaded embankment without vacuum consolidation (Figure 10), consolidation deformation dominates over shear deformation in the ground improved by vacuum consolidation due to an increase in isotropic effective stress (Figure 11). This ground behavior was also confirmed in the trial construction in this study (Figure 6). As a result, when vacuum consolidation is applied to the ground, the S_u increases uniformly throughout the improved ground. Even when embankment loading starts, shear deformation is suppressed compared to embankment preload without vacuum, and consolidation deformation becomes relatively dominant. Therefore, the range and degree of S_u increase in the improved ground by vacuum consolidation is considered to be larger than that in the case of embankment preloading without vacuum. In particular, peat is more susceptible to this effect of isotropic consolidation than clay at greater depths. This is because peat deposited at shallow depths, where σ'_{v0} is very small, shows a larger change from the initial anisotropic state for the same isotropic stress increment due to p_v.

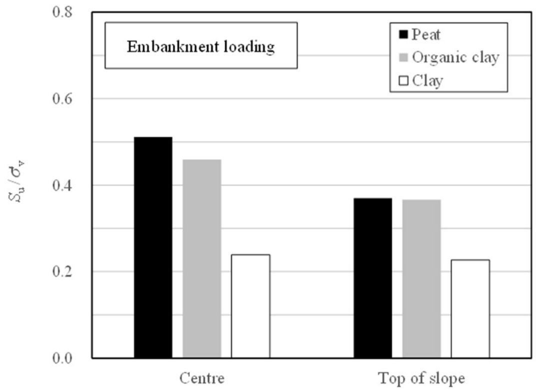

Figure 9. Normalized S_u in case of embankment loading without vacuum

4.2 Suitable Spacing of PVDs for Peat Ground

In applying vacuum consolidation to practice, the spacing of PVDs is one of the important keys from the viewpoint of the balance between improvement effect and cost. This sub-section describes the suitable spacing of PVDs for peat ground. Hayashi et al. (2003) conducted a trial embankment using only PVDs without vacuum consolidation on peat ground in Hokkaido, to verify the applicability of PVDs to peat ground. In the trial embankment, three cases by changing the PVDs spacing (0.7 m, 0.9 m and 1.1 m) were conducted. In addition, a case of non-countermeasure (trial embankment without PVDs) was also set to more clarify the effect of PVDs. To easily compare the amounts and rates of settlement each case, the embankment size (4.2 m in height) and construction speed were the same for all four cases. The results of this trial embankment (Hayashi et al., 2003) can be summarized below: Regarding the degree of consolidation (*U*) at the time of embankment completion, the *U* in the non-countermeasure case was 64%, while the *U* was 80%, 76% and 69% in cases with PVDs spacing of 0.7 m, 0.9 m and 1.1 m, respectively. Next, in the non-countermeasure case, the number of days required for the *U* to reach 90% was 450 days after the embankment was completed. On the other hand, in the cases with PVDs spacing of of 0.7 m, 0.9 m and 1.1 m, the *U* reached 90% on the 65th, 100th and 325th days after completion of embankment, respectively. The above results indicate that the spacing of PVDs for peat ground should be 0.9 m or less, to obtain a clear improvement effect of consolidation acceleration as compared to non-countermeasures. Based on this result, the spacing of PVDs was set to 0.8 m in the trial construction of vacuum consolidation carried out in this study as well. As mentioned in the Section 3, vacuum consolidation with this spacing of PVDs showed good applicability to peat ground.

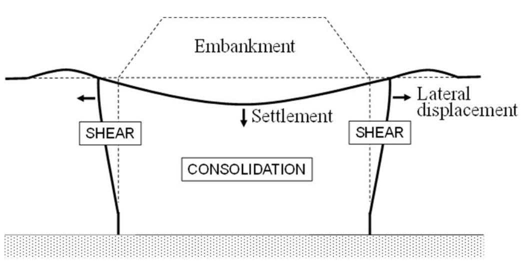

Figure 10. Deformation mode of ground in case of embankment preloading without vacuum

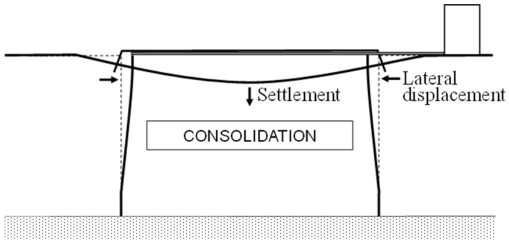

Figure 11. Deformation mode of improved ground by vacuum consolidation

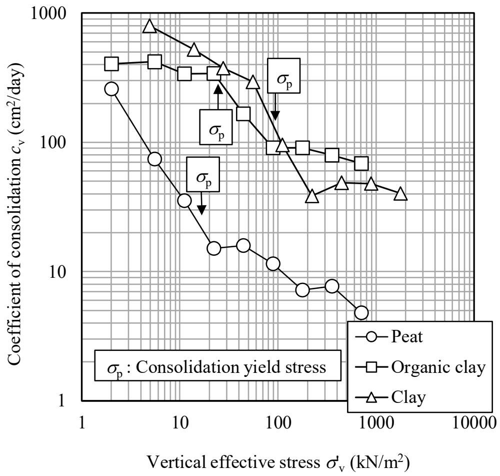

Figure 12. Comparison of the coefficient of consolidation of peat, organic clay and clay

It is interesting that the effective spacing of PVDs (0.9 m or less) for peat ground was narrower than 1.0 m to 1.5 m (Kamon and Miura, 2009) generally used for clay ground in Japan. This point is discussed below. Figure 12 shows a comparison of the coefficient of consolidation (c_v) of peat, organic clay and clay obtained from the oedometer test at the site of the trial construction of vacuum consolidation in this study. The c_v at the first loading step in the oedometer test does not differ significantly between peat and clay. Considering only this fact, it is erroneously judged that the spacing of PVDs on peat ground is not significantly different from that clay. However, it should be noted that the c_v of peat shows remarkable stress dependence. That is, the c_v of peat decreases remarkably with increasing consolidation stress, and in the range of high consolidation stress, the c_v of peat may be smaller than that of clay. It is interpreted that the experimental results of Hayashi et al. (2003) as mentioned above take this stress dependence of c_v into account. Furthermore, Yamazoe et al. (2020) explained the necessity of narrowing the PVDs spacing of peat ground compared to that of clay ground by numerical analysis. As PVDs are expected to reduce post-construction settlement and increase the S_u of the soft ground by accelerating consolidation when the embankment is completed, it should be noted that it is necessary to determine the spacing of PVDs by the c_v of peat when the consolidation has progressed.

5. CONCLUSION

Based on a result of a full-scale trial construction using vacuum consolidation which was conducted in a highway project on peat ground in Hokkaido, Japan. This paper presents the field performance of vacuum consolidation method on peat ground and some technical learning from the field trial. The results can be summarized below.

(1) Although the undrained shear strength (S_u) of peat ground at this trial construction site was approximately 10 kN/m^2 and extremely low, an embankment of 10.7 m high was successfully built in only 45 days. This experimental fact implies that the vacuum consolidation method is extremely effective in improving the stability of peat ground.

(2) In this trial construction, inward lateral displacement occurred when only p_v was applied. This deformation mode indicates that isotropic p_v acting on the ground caused isotropic consolidation deformation.

(3) The S_u of the ground improved by vacuum consolidation increased almost equally in the transverse direction compared to the S_u increase of the ground by embankment loading without vacuum consolidation. As a result, the mean S_u increase in the transverse direction was relatively significant. It is considered that the S_u characteristics of improved ground by vacuum consolidation described above caused that the high embankment with a height of 10.7 m was successfully constructed even though the ground in this trial site was very soft.

(4) The spacing of PVDs for peat ground should be 0.9 m or less, to obtain a clear improvement effect of consolidation acceleration. The spacing of PVDs was set to 0.8 m in this trial construction of vacuum consolidation carried out in this study, and vacuum consolidation with this spacing of PVDs showed good applicability to peat ground.

(5) As PVDs are expected to reduce post-construction settlement and increase the S_u of the soft ground by accelerating consolidation when the embankment is completed, it should be noted that it is necessary to determine the spacing of PVDs by the coefficient of consolidation of peat when the consolidation has progressed.

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