Case history and back-analysis of large-scale embankment construction on peat using vacuum consolidation

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Abstract. This presentation discusses engineering considerations for designing and constructing large-scale embankments on peat deposits in Hokkaido, northern Japan, using the vacuum consolidation method with Prefabricated Vertical Drains (PVDs). Field measurements revealed that the pore water pressure behavior of peat between drains differs markedly from that of clay. To investigate the mechanism underlying this difference, axisymmetric elasto-plastic finite element analyses were performed on a unit cell containing a PVD. The permeability and consolidation coefficient of the peat decrease significantly during compression, resulting in the delayed dissipation of excess pore water pressure. Under vacuum consolidation, negative pressure is rapidly applied around the drains, accelerating consolidation and further reducing permeability near the drains. This leads to slower dissipation of excess pore water pressure at midpoints between drains, a trend successfully reproduced in analyses that considered a variable coefficient of consolidation. Consequently, peat exhibits a larger discrepancy between settlement-based and effective stress-based degrees of consolidation than clay. This difference has significant implications for estimating strength gain during vacuum consolidation. Exploiting the effective stress-based degree of consolidation provides a rational and reliable approach for predicting strength gain for design in peat deposits subjected to vacuum consolidation.

1 Introduction

Extensive peat deposits are distributed throughout the Sapporo region in Hokkaido, where various geotechnical problems—such as excessive settlement and embankment instability—have frequently emerged during construction. The authors have accumulated numerous case studies involving the application of vacuum consolidation combined with vertical drains as countermeasures for such issues, thereby confirming the method's effectiveness. Notably, when vacuum consolidation is applied to peat during embankment construction, the dissipation of excess pore water pressure is often markedly slower than anticipated, despite continuous settlement.

To elucidate this behavior, detailed field monitoring was conducted using multiple pore pressure gauges installed between drains, together with axisymmetric finite element method (FEM) analyses. The results indicate that the significant reduction in permeability associated with increasing stress, as well as the low initial effective stress that amplifies the stress ratio under embankment loading, are key factors controlling the delayed dissipation of excess pore water pressure in peat.

This paper presents a vacuum-assisted embankment construction case, field measurements of pore water pressure, and corresponding FEM simulation results. Based on these data, the characteristic behavior of excess pore pressure in peat deposits and its governing mechanisms are discussed.

2 Overview of the method

The vacuum consolidation drain method applies negative pressure directly to each vertical drain through a collector pipe connected individually to the drains. Unlike conventional vacuum consolidation systems, this method does not require an airtight membrane, as the low-permeability ground itself serves as a vacuum-retaining layer. This eliminates the risk of vacuum leakage due to membrane damage and allows the method to be applied even under submerged conditions, such as in marine construction (Fig. 1).

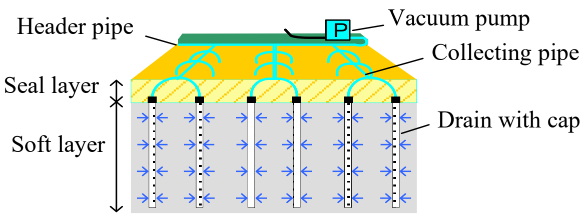

Fig. 1. Overview of the construction method.

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In peat deposits, the method can significantly reduce improvement costs—often to less than one-third of those required for deep mixing. This cost advantage arises because deep mixing in peat demands specialized cementitious binders, as organic components inhibit the strength development of ordinary stabilizers.

3 Outline of construction

The case examined herein involves the construction of an embankment for a flood-control retarding basin [1]. Extremely soft peat deposits are widely distributed within the site, and embankments exceeding 9 m in height were planned. Because the predicted post-construction settlement was extremely large without any ground improvement—approximately 4 m—vacuum consolidation drains were employed to accelerate consolidation and ensure embankment stability.

The improvement target consisted of soft layers approximately 35 m thick with a planned embankment height of 8.1 m (Figs. 2 and 3). The vacuum consolidation treatment was applied to the peat and organic clay layers to a depth of about 8 m above the intermediate sand layer. Although deeper clay layers contribute to overall settlement, they satisfy the required safety factors for slope stability; thus, conventional prefabricated vertical drains (PVDs) were installed instead of applying vacuum pressure. The combined improvement pattern incorporating both vacuum and non-vacuum PVD zones will be presented separately.

The peat layer exhibited extremely soft conditions and was moderately decomposed, with water content w_n = 250–420% and cone resistance q_t = 200–350 kN/m². The organic clay layer was also soft, with w_n = 50–290% and q_t = 200–300 kN/m². The deeper clay improved with conventional PVDs had w_n = 38–66% and q_t = 400–600 kN/m².

Pore water pressure was measured at three depths (Peat, Organic Clay (OC), and Clay) near the embankment shoulder. Sensors were installed at distances of 10, 30, and 50 cm diagonally from the drain, and an additional sensor was placed 30 cm orthogonally, allowing high-resolution monitoring of pore pressure distributions (Fig. 4).

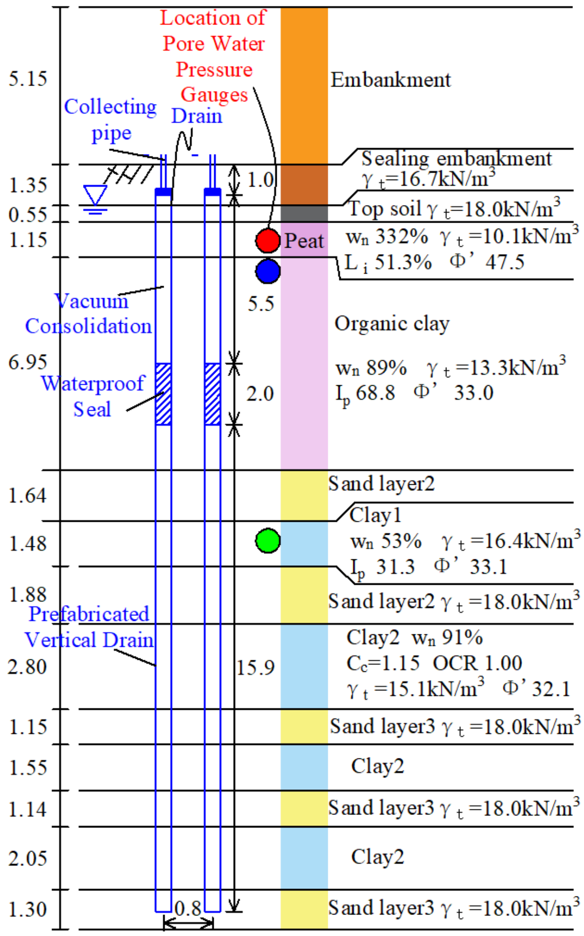

Fig. 3. Drain installation conditions.

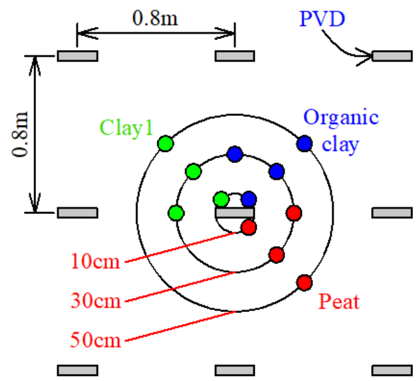

Fig. 4. Instrumentation layout plan.

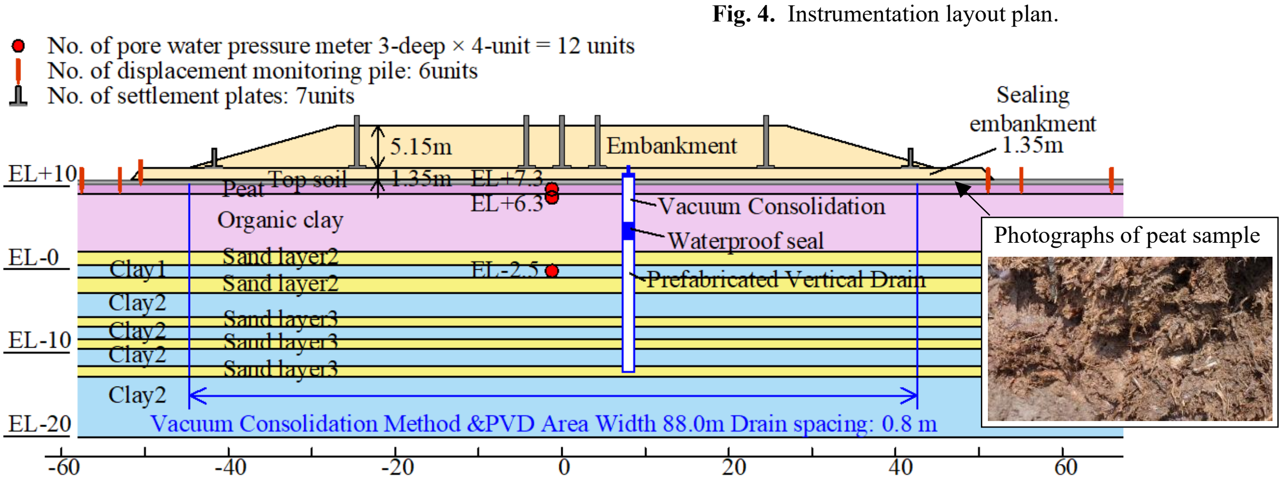

Fig. 2. Overview of the construction work and Photographs of peat sample.

4 Field monitoring results

Embankment construction proceeded over 69 days (17 September–24 November 2025), while vacuum loading continued for 105 days (12 September–25 December 2025) (Fig. 5). Although the design vacuum pressure was -60 kN/m², the actual pressure gradually decreased during construction, reaching approximately -70 kN/m² (Fig. 6). Initial pore pressure values were set to those recorded at the start of the fiscal year's construction.

The observed ground settlement during the current year was approximately 170 cm, excluding the 45 cm settlement attributable to the 1 m sealing embankment constructed in the previous year (Fig. 7). The embankment load at the monitoring location was estimated at 92 kN/m². Under this loading, excess pore pressure partially dissipated but also accumulated. The average excess pore pressure in the peat layer was about 28 kN/m², with a maximum of 31 kN/m² at the center between drains (Fig. 8).

The total applied load—combining vacuum pressure and embankment load—was approximately 152 kN/m². Of this, roughly 40% (61 kN/m²) dissipated during construction.

A distinct convex-upward pore pressure distribution developed between drains, characterized by very low values at the 10 cm point and steep increases with distance in the peat and organic clay layers (Fig. 9). Conversely, in the clay layer at 12.3 m depth, where vacuum pressure was not applied, the excess pore pressure remained small and its distribution relatively uniform.Measurements at diagonal and orthogonal distances of 30 cm showed consistent values across all layers, confirming that pore pressure around a drain is nearly axisymmetric (Fig. 9), as previously reported [2)].

5 Analysis conditions

An axisymmetric elastoplastic FEM model was developed to reproduce the pore pressure behavior observed in vacuum-assisted embankment loading (Fig. 10). A single drain served as the axis of symmetry, enabling simulation of drainage behavior and stress development in the surrounding ground.

Drains were modeled as drainage boundaries, and a vacuum pressure of −60 kPa was applied as an equivalent piezometric head referenced to the hydrostatic pressure at 6 m depth. To prevent propagation of vacuum pressure into the conventional PVD zone below, a 2 m impermeable joint was introduced at the boundary.

The initial ground condition reflected the 1.35 m sealing embankment constructed prior to the current fiscal year. The remaining 5.15 m of embankment height was applied incrementally according to actual construction stages. The unit weight of the embankment fill was set to 17.8 kN/m³ based on field measurements.

The initial groundwater profile was derived from installation records of the pore pressure gauges. Soil parameters were determined from CU triaxial tests and incremental loading consolidation tests performed on thin-walled samples collected near the site (Table 1),

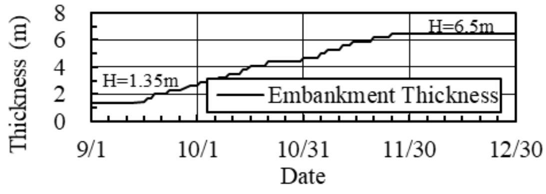

Fig. 5. Embankment construction process.

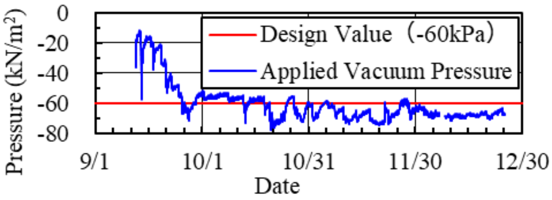

Fig. 6. Vacuum loading status.

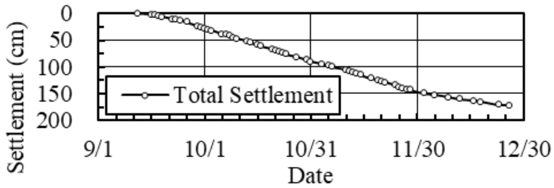

Fig. 7. Time variation of settlement.

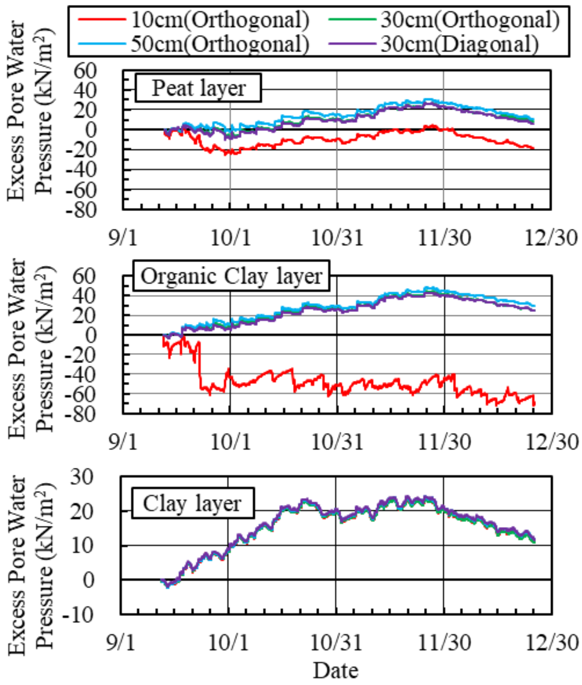

Fig. 8. Time variation of excess pore water pressure.

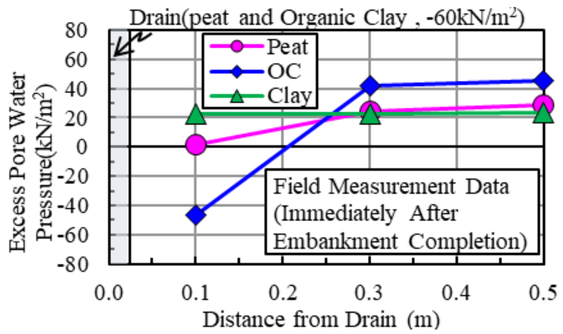

Fig. 9. Distribution of excess pore water pressure between drains.

ensuring realistic representation of compressibility and permeability.

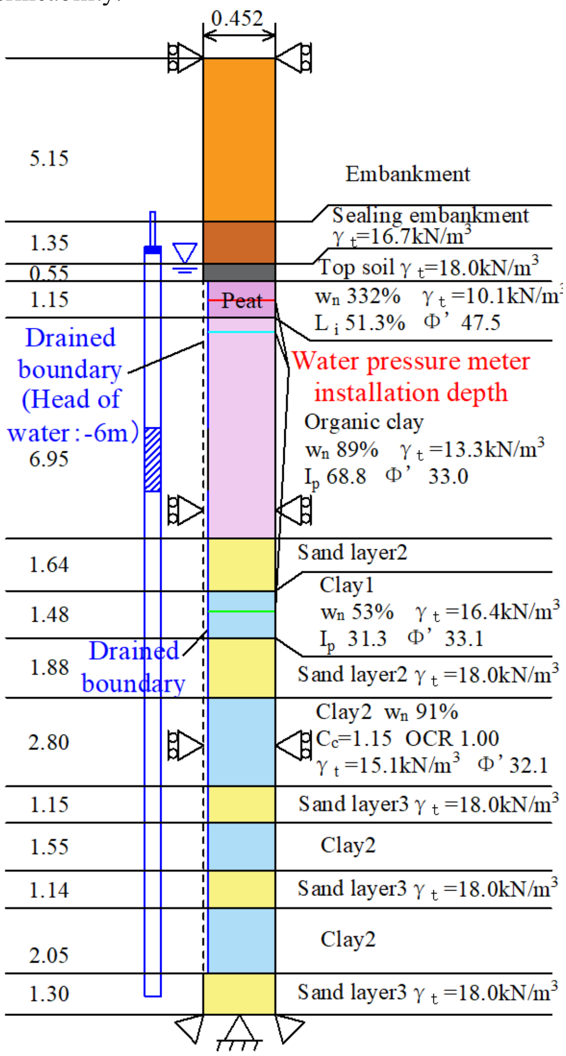

Fig. 10. Overview of the analysis model.

Table 1. Parameters for FEM.

Parameter	Value (Peat)	Value (OC)	Value (Clay)
C_c : Compression index	3.877	1.433	0.478
C_s : Swelling index	0.388	0.143	0.048
e_0 : Initial void ratio	6.592	3.000	1.330
k_{v0} (m/s) : Coefficient of permeability	1.96×10^{-8}	1.99×10^{-9}	9.57×10^{-9}
C_k : Coefficient of permeability index	1.344	1.033	0.437
ν : Poisson's ratio	0.208	0.313	0.312
M : Critical state parameter	1.955	1.331	1.335
p_c (kN/m^2) : Consolidation yield stress	28.9	42.5	88.4
OCR : Over-consolidation ratio	1.071	1.100	1.276
K_{0NC} : coefficient of earth pressure at rest of normally	0.263	0.455	0.454

6 FEM analysis results

6.1 Reproducibility of settlement and pore pressure behavior

Because the FEM and the Barron method both utilized identical laboratory consolidation data, the resulting settlement curves agreed closely and reproduced the field observations (Fig. 11a,b,c). The FEM analysis also reproduced the observed pore pressure trends, capturing both the generation and partial dissipation during embankment loading.

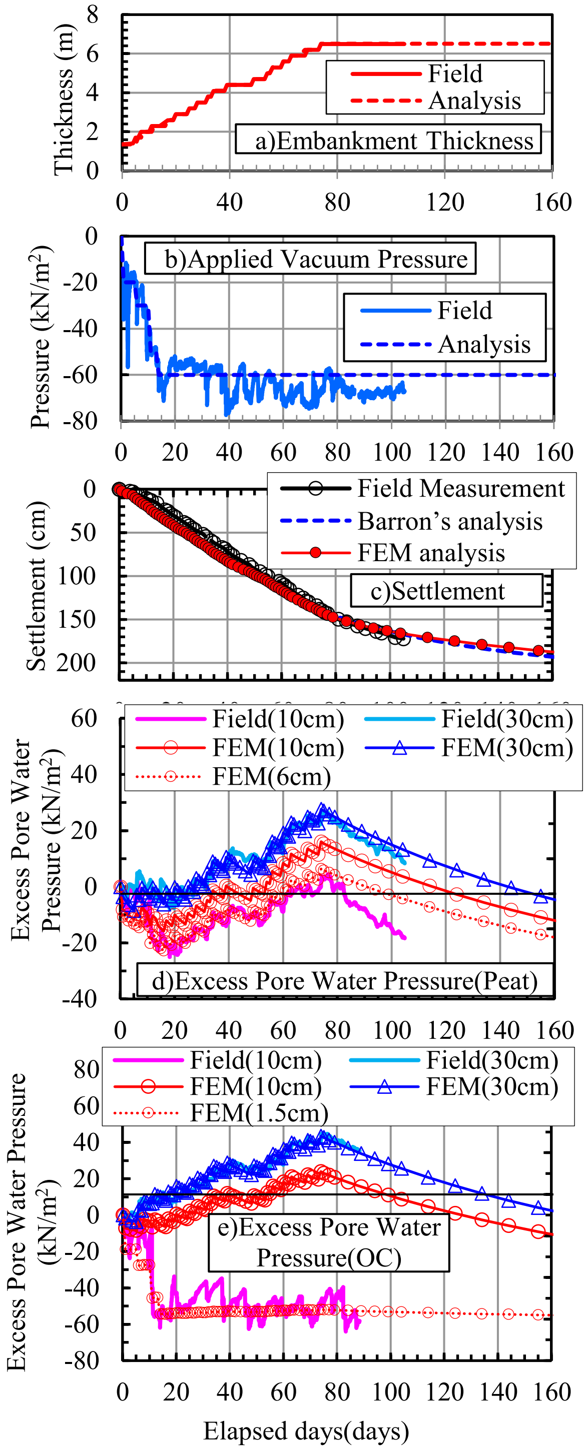

Fig. 11. Analysis results.

Although the FEM-predicted pore pressure at 10 cm from the drain deviated somewhat from the measurement, simulation results at 1.5 cm (organic clay) and 6 cm (peat) from the drain closely matched observations(Fig.11d,e). This discrepancy likely reflects minor drain inclination or bending during installation or settlement, reducing the true distance between sensors and drains. Taking these factors into account, it can be considered that the simulation successfully reproduces the characteristic excess pore water pressure distributions of the peat and organic clay between drains immediately after embankment completion (Fig. 12).

Peat and organic clay exhibit substantial variability in consolidation and permeability parameters, particularly at low stress levels (Fig. 13). Consequently, initial permeability significantly influenced analytical outcomes: variation of one order of magnitude produced large differences in both settlement and pore pressure behavior (Fig. 14). Therefore, this result indicates that it is essential in practical design to conduct scenario analyses that take into account the variation rate of permeability as well as the range of initial permeability values obtained from consolidation tests and in-situ permeability tests.

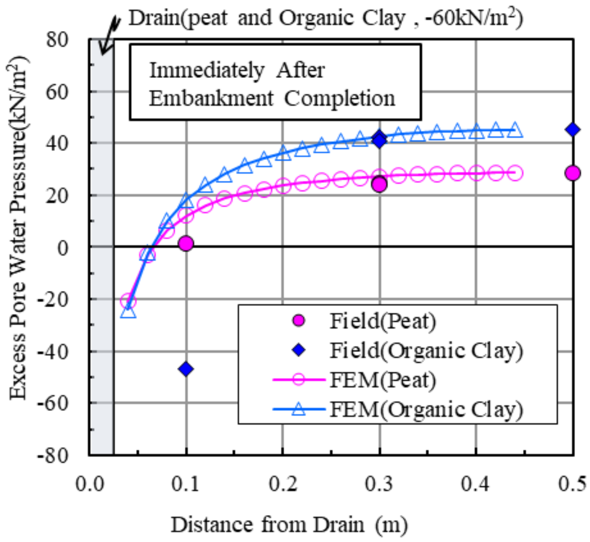

Fig. 12. Excess pore water pressure distribution between drains immediately after embankment completion.

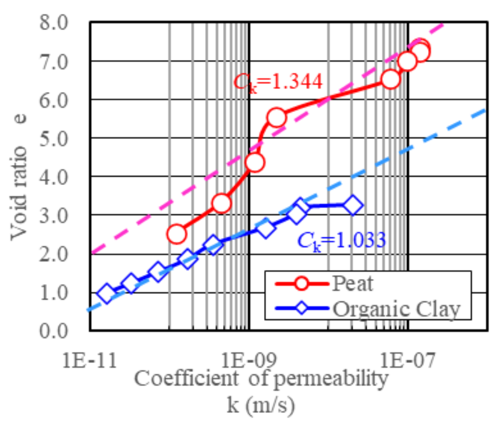

Fig. 13. Permeability obtained from oedometer tests.

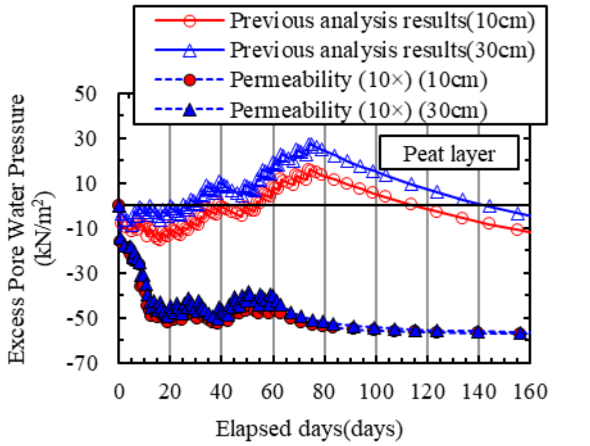

Fig. 14. Parametric study with varying permeability coefficients.

6.2 Relationship between settlement-based consolidation, effective stress consolidation, and strength gain

At the end of embankment loading, the settlement-based degree of consolidation was 59% (Barron) and 68% (FEM), whereas the degree of consolidation based on measured effective stress increase was only about 42%. Using FEM-derived effective stress increments at the end of embankment loading and after full pore pressure dissipation under steady vacuum pressure yielded an effective stress–based consolidation degree of about 44%, consistent with measured values.

The discrepancy between settlement-based and effective stress–based consolidation is well known and expressed by Equation (1)[3]. Because the settlement curves were accurately reproduced by both FEM and the Barron method, the predicted effective stress consolidation degree also agreed with field results (Table 2). In peat, where initial effective stress is small and stress increment is large, the difference between these two indices becomes pronounced.

$$U_p = \frac{(p_2/p_1)^{U_\varepsilon} - 1}{(p_2/p_1) - 1} \qquad (1)$$

U_p : Stress–based consolidation degree
U_ε : Settlement–based consolidation degree
p_1 : Initial stress in the ground
p_2 : Stress in the ground after loading

The strength gain immediately after embankment construction is important for evaluating slope stability. If the strength gain is estimated solely from the settlement-based degree of consolidation and the shear strength ratio $m=s_u/\sigma'_v$ (s_u : undrained shear strength, σ'_v : effective vertical stress), it may be significantly overestimated. Meanwhile, the m values back-calculated from the measured strength gains and the effective-stress-based degree of consolidation were closer to the commonly known values of m =0.35-0.5 for peats (Table 3). This demonstrates that effective stress–based consolidation is essential for accurate strength evaluation in peat.

Table 2. Degree of consolidation based on the analysis results.

Analysis method	Item		Peat	OC
Field measurement data	Degree of consolidation based on pore water pressure U_u (%)	Average	42	32
		Central area of the drain	40	29
Barron's equation	Total settlement S_t (cm)		42	78
	Settlement during embankment construction S_e (cm)		25	44
	Degree of consolidation based on settlement $U_{s\text{-Barron}}$ (%)		59	56
	Degree of consolidation based on effective stress $U_{p\text{-Equation1}}$ (%)		37	35
FEM	Total settlement S_t (cm)		45	85
	Settlement during embankment construction S_e (cm)		31	45
	Degree of consolidation based on settlement $U_{s\text{-FEM}}$ (%)		68	53
	Degree of consolidation based on effective stress $U_{p\text{-Equation1}}$ (%)		47	33
	Degree of consolidation based on the increase in vertical effective stress $U_{p\text{-FEM}}$ (%)	Average	44	35
		Central area of the drain	40	30

7 Conclusions

This study investigated settlement and pore pressure behavior in peat deposits improved using vacuum-assisted embankment loading, based on detailed field measurements and FEM analysis. The main findings are summarized as follows:
Reproduction of settlement behavior: Both the Barron method and FEM reproduced settlement curves well using identical soil parameters, demonstrating the applicability of the FEM model.

- Characteristic pore pressure behavior: Peat and organic clay exhibited slow pore pressure dissipation and a distinct convex-upward pressure distribution between drains, which the FEM model successfully reproduced.

・Influence of permeability reduction and initial stress: Stress-induced permeability reduction and small initial effective stress—leading to a large stress ratio—were found to be the principal factors governing delayed excess pore pressure dissipation.

Table 3. Predicted strength increase ratio.

Method for determining the degree of consolidation		Degree of consolidation U (%)	Shear strength ratio m
Field mesured data	Average degree of dissipation of excess pore water pressure	42	0.39
Barron's equation	Settlement	59	0.28
	Equation (1)	37	0.45
FEM	Vertical strain	68	0.24
	Equation (1)	47	0.35
	Average vertical effective stress	44	0.37

・Discrepancy between the degrees of consolidation (U): Settlement-based U is significantly greater than effective stress–based U, particularly in peat. Effective stress–based estimates of U also produced strength gains consistent with measured values.

・ Implications for design and construction management: Given the heterogeneity and parameter variability of peat, especially at low stress levels, scenario analyses incorporating multiple permeability values are essential for accurate design and construction monitoring.

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