Anisotropy in permeability of peats in context of vacuum consolidation by vertical drains

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1 Introduction

Construction on soft ground usually requires settlement prediction and control. Accelerating the settlement by primary consolidation assisted by vertical drains is a cost-effective option in reducing the post-construction settlement, which distresses the superstructure and affects its serviceability. Peats are amongst the softest and most problematic of soft soils encountered frequently in cold regions, often exhibiting compression index an order of magnitude greater than typical alluvial clays. As applying vacuum consolidation with Prefabricated Vertical Drains (PVDs) to peat ground has become more common [1], some characteristics peculiar to peats need to be understood more thoroughly, given their relevance to settlement prediction. For example, very rapid reduction of the coefficient of permeability (k), and hence of the coefficient of consolidation (c_v), upon consolidation leads to formation of low c_v region around each drain, and severely limits the reach of drain effect. As a result, PVDs need to be installed at shorter intervals in peat ground than in clay ground in practice [2]. Another less established feature is permeability anisotropy, despite many years of investigation [3, 4]. The experiences from numerical back analysis tend to suggest that the horizontal permeability, k_h, is somewhat greater than the vertical permeability k_v [2]. Quantifying this anisotropy in laboratory is not straightforward, however, due to the technical difficulties set out below. Another factor complicating the problem is the large Representative Element Volume (REV) of peat. Berry and Vickers noted that a sample size of 250mm was still not fully sufficient to secure test representativeness [5]. It follows that more than a few repeated tests are required to obtain reliable measurement of permeability anisotropy, if a typical laboratory specimen size is adopted.

This study presents laboratory investigation of permeability characteristics of two peats sampled from Hokkaido, Japan. Particular attention is paid to the anisotropy and density-dependence of the permeability under isotopic stress states, which represents the ground stress conditions under PVD-assisted vacuum consolidation better than K_0 conditions [1]. The technical consideration and innovation involved in the test method design are described.

2 Tested peat samples

Two peat samples were tested in this study. They were sampled from Bansui district, Namporo, and from Kitamua district, Iwamizawa, in Hokkaido, Japan. Their typical properties are shown in Table 1. The peats in Hokkaido typically exhibit a natural water content (w_n) range of 200-1100%. Bansui peat and Kitamura peat represent mid-range and lower-range w_n, respectively. Figure 1 shows vertical cross-sections of both peats visualised by X-ray CT under unconfined states. Horizontally oriented fabrics are recognised in both peats, with macropores (shown as black blobs) left around twig remnants. The samples were retrieved from the bottom of a 1m-deep pit, below the ground water level. The method described in [6] was adopted; an acrylic tube with an outer diameter of 80mm, an inner diameter of 76mm and a height of 120mm (140mm in some cases) with a sharply tapered edge was driven by hammer. The surrounding ground was then excavated by hand and the tube was retrieved. The tubes were driven either vertically (towards the pit base) or horizontally (towards the pit wall) to take differently oriented samples. Fibrous peats are difficult to trim into a regular cylindrical shape in laboratory. Cutting the fibre with the sharp sampler edge while exploiting the natural ground's confinement turned out to be the best way to retrieve cylindrical specimen with less disturbed lateral surface. The sample was used for laboratory testing without further trimming the lateral surface. Multiple identical tests were repeated for specimens with both vertical and horizontal cutting orientations. The test cases are named V1, V2, … and H1, H2, …, respectively.

Table 1. Typical (average) properties of tested peat samples.

Peat	Natural water content (%)	Ignition loss (%)	von Post scale	Solid-part density (Mg/m^3)
Bansui	688	60.2	H5	1.74
Kitamura	329	41.9	H7	2.08

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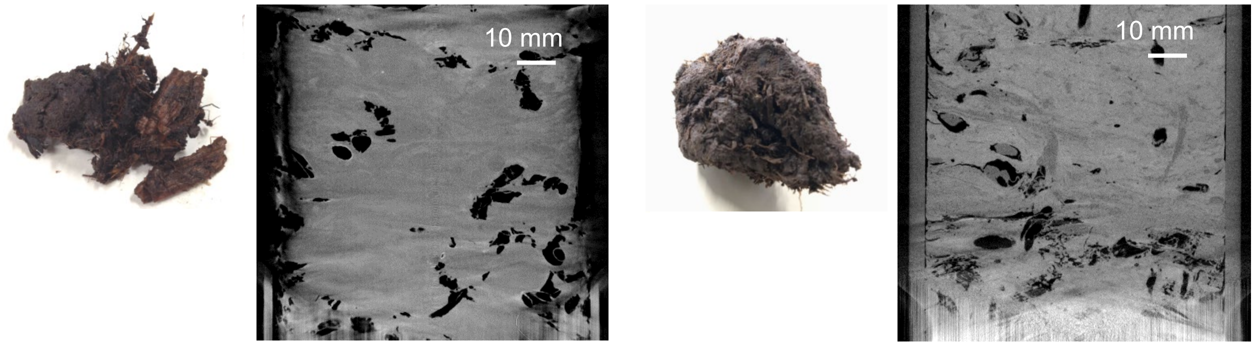


(a) (b)

Figure 1. Texture of tested peat samples: (a) Bansui peat and (b) Kitamura peat.

3 Testing method

Laboratory testing of peats usually follows methods and routines for clayey soils. This means that the permeability is quantified from the coefficient of consolidation c_v and the coefficient of volume compressibility m_v as established by incremental loading oedometer tests. However, an oedometer allows only K0 states with vertical seepage. Testing a horizontally cut specimen in an oedometer does not lead to measurement of the coefficient of horizontal permeability k_h under conditions representative of PVD-assisted vacuum consolidation. An alternative method is to install a vertical drain (porous core) in an the oedometer and test a vertically cut specimen [7]. By blocking the bottom and top drainage and allowing only drainage to the vertical drain, the seepage direction is horizontal while the deformation is K0. Another invention is to adopt triaxial apparatus, which allows application of isotropic pressure relevant to vacuum consolidation. Tsutsui and Tanaka [8] surrounded the lateral surface with a sheet of filter paper, such that the radial (horizontal) drainage occurred under isotropic stress states. However, they found that the filter paper needs to have about 1000 times higher permeability than the tested soil itself to assume a free-drainage condition at the specimen perimeter, and that this was difficult to satisfy in all test stages.

After considering all the known options, the authors chose to adopt triaxial apparatus, in view of the merit of isotropic pressure application. To separate the measurement of coefficient of permeability k from that of c_v and m_v, the principle of constant-head testing was adopted. This is because the conventional back-analysis of consolidation curves (i.e. deformation – time t relationships either in $\sqrt{t}$ or $\log t$ format) based on Terzaghi's consolidation theory is not always objectively applicable to peats, which have stress-sensitive c_v. Another advantage of the triaxial setup is use of flexible lateral boundary in form of rubber membrane. In oedometer testing, the specimen-ring gap forms a pathway for seepage in the initial stages of loading due to imperfect specimen installation. A thin rubber membrane (0.2mm thickness in this study) penetrates into macro voids under modest confining pressure and prevents the artefactual seepage along the lateral boundary.

The adopted setup is shown in Figure 2. The specimen size was 76mm in diameter, as obtained in the field. The height was typically 100mm, but some were as short as 50mm, to remove large inclusions. Silicone grease was applied to the lateral surface to prevent the seepage along the boundary. The sample was isotropically consolidated at 5, 10, 20 and 50 kPa. After the end of primary consolidation, the pressure difference was given between the top and bottom ends, such that the ratio of the effective stress at the top to that at the bottom remain above 0.65. The flux from the bottom end was measured by an electronic balance while the evaporation from the receiving pot was prevented by oil. The seepage flux v was observed against a few different pressure differences (i.e. hydraulic gradient i) at each effective stress level to calculate k. While the above procedures are very simple in principle, the nature of peat required special consideration and innovation in implementing them. Firstly, peats are very compressible, reaching the volumetric strain of 50% at 100kPa. The strain is very anisotropic in the two tested peats – the vertical strain ε_v was much greater than the horizontal strain ε_h against isotropic loading in vertically cut specimens, with $\varepsilon_h/\varepsilon_v$=0.44 for Bansui peat and 0.48 for Kitamura peat. In the horizontally cut specimens, this means the strain is different in two orthogonal radial directions (one of them corresponding to the original vertical direction; ε_{rv}, and the other to the original horizontal direction; ε_{rh}), resulting in the elliptic horizontal cross sections. The ratio $\varepsilon_{rh}/\varepsilon_{rv}$ was 0.52 on average, approximately consistent with the above. As the specimen shape at each moment is essential in computing v (as affected by the cross-sectional area) and i (as affected by the specimen height), this study adopted image analysis based on the two orthogonally located cameras for precisely computing the specimen geometry inside the triaxial cell. This allowed capturing almost the whole specimen geometry, informing the average volume and cross-sectional area, even when the deformation is non-uniform. Secondly, the very low permeability of peats at higher effective stress and the large rate of secondary consolidation mean that the seepage flux due to the hydraulic gradient and the volume compression (and hence net water emigration) due to the secondary consolidation can be in a same order of magnitude in the later stages with higher pressures. By precisely measuring the volumetric changes of the specimen, its rate was factored by 1/2 and subtracted from the outflow flux to compute the net seepage v. Only after this correction did the v – i relationship become proportional, indicating the validity of Darcy's law.

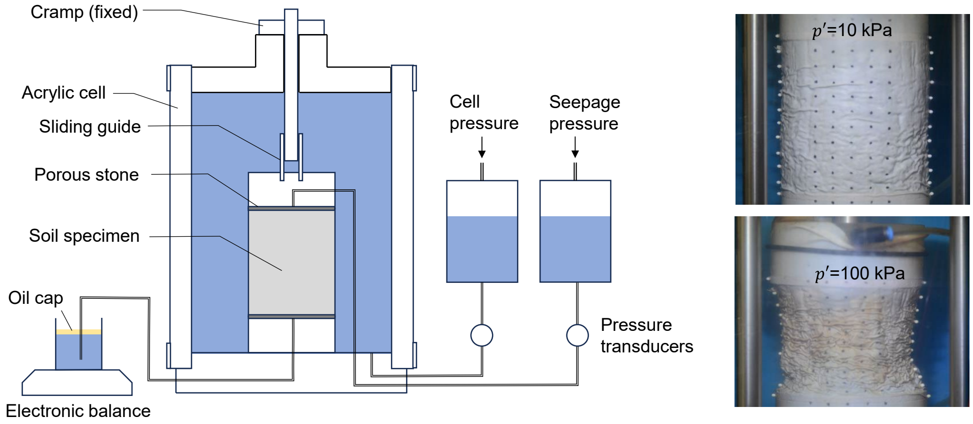
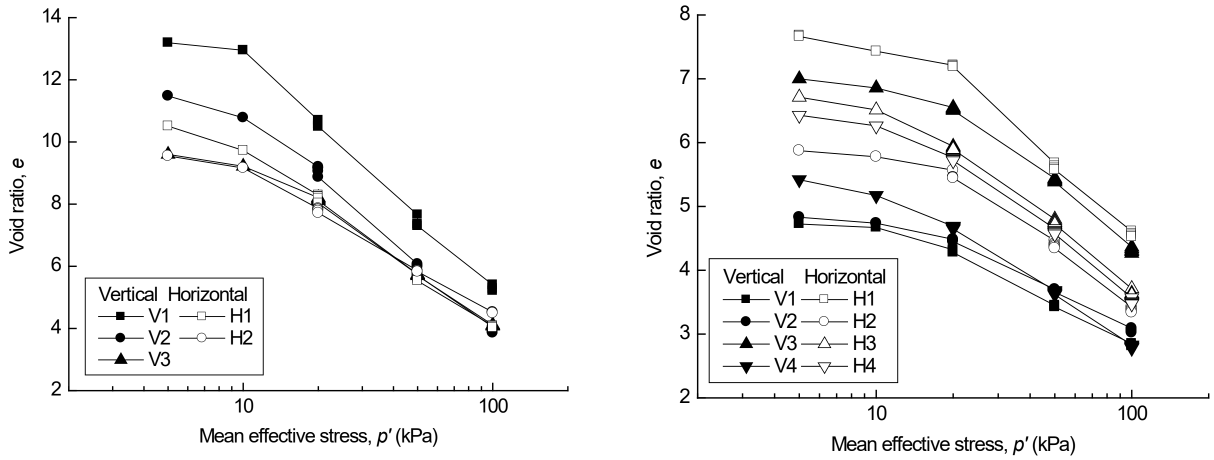


Figure 2. Apparatus for permeability measurement under isotropic pressure.

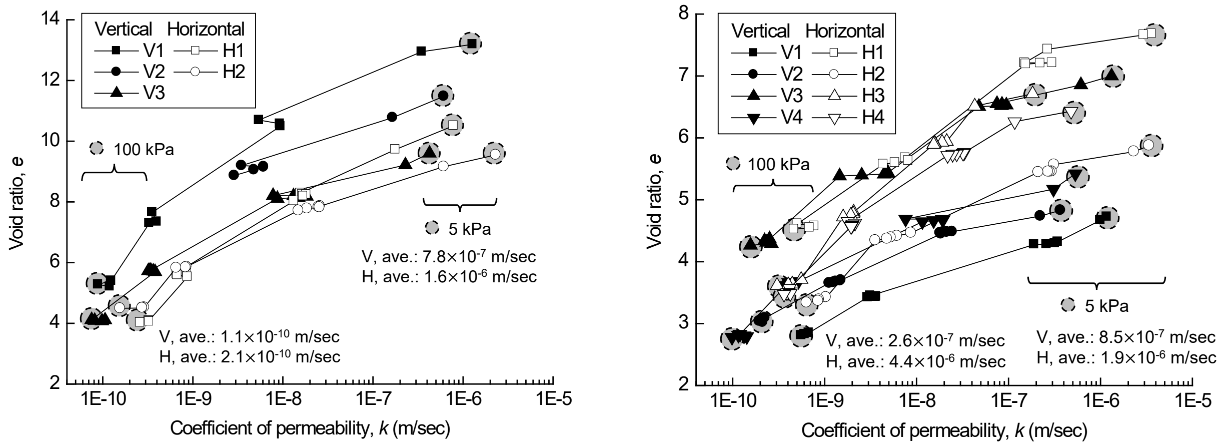
4 Permeability characteristics of peats

The compression curves of the two tested peats are shown in Figure 3. The yield stress seemed to be around 10 kPa in Bansui peat and 20 kPa in Kitamura peat. The test cases showed a great variability in the void ratio at the initial (the mean effective principal stress p'=5kPa) states, while the yield stresses were relatively consistent. The coefficients of permeability in the vertical (k_v) and horizontal (k_h) directions are shown in Figure 4 for both peats. Note that multiple data points are shown for each stress level, taken during the creep period. The initial values of neither k_v nor k_h are correlated well with the initial void ratio. Despite the very wide range of initial void ratio (9.6-13.2 for Bansui peat and



(a) (b)

Figure 3. Isotropic compression curves of tested peats: (a) Bansui peat and (b) Kitamura peat.



(a) (b)

Figure 4. Changes of coefficient of permeability with void ratio: (a) Bansui peat and (b) Kitamura peat.

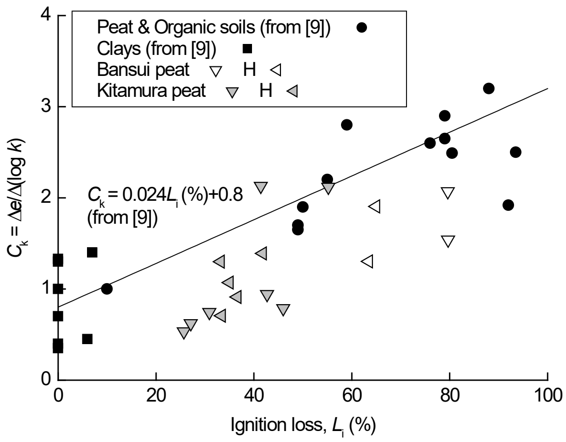


Figure 5. Correlation of $C_k = \Delta e/\log k$ with ignition loss (some additional data from Kitamura site are shown).

4.7-7.7 for Kitamura peat), the initial k_v and k_h values are approximately within a same order. Both k_v and k_h decrease rapidly with compression, eventually decreasing to the order of 10^{-10} m/s or smaller. The $e - \log k$ relationships appear to be slightly nonlinear, particularly for Bansui peat, with initially more rapid decrease of k against e. This may represent closure of the macropores as seen in Figure 1. This process may explain why the variability of k_v and k_h is smaller at p'=100 kPa than at p'=5 kPa.

When the permeability anisotropy is evaluated in terms of the average of the multiple test cases, k_h/k_v was 2.1 at p'=5 kPa and 1.9 at p'=100 kPa in Bansui peat. Similarly, k_h/k_v was 2.0 at p'=5 kPa and decreased slightly to 1.7 at p'=100 kPa in Kitamura peat. Despite the limited number of test cases, the anisotropy appears to become only modestly smaller as the consolidation proceeds. The anisotropy at higher stresses is likely to reflect the seepage channel through the micropores, as the macropores close first at lower stresses. Yamazoe et al. [2] estimated k_h/k_v=2 in their numerical back analysis of the PVD-assisted consolidation of peat ground (although their case did not involve vacuum consolidation but only embankment loading). This estimation can be justified from this study's observation. Figure 5 compares $C_k = \Delta e/\log k$ evaluated from the stress range beyond the yield, plotted against the ignition loss L_i, along with existing data from the literature [9]. When the C_k values from this study are consistent with the trend but slightly lower on the whole.

5 Concluding remarks

This study presented laboratory investigation of permeability characteristics under isotropic stresses in two peats from Hokkaido, Japan, with particular focus on the anisotropy and density-dependence of the coefficient of permeability in the vertical and horizontal directions (k_v and k_h). The anisotropy ratio k_h/k_v was around 2, seemingly decreasing as being consolidated to higher stresses. Some technical consideration and innovation were described. The study provided many other insights not discussed in this paper due to space shortage. They include the comparison of the permeabilities assessed at each stress stage (i.e. by constant-head seepage) and between the stages (i.e. by transient seepage due to the excess pore water pressure dissipation), accuracy of the volume measurement by image analysis, deformation anisotropy, etc.

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