

O'Kelly B.C., 2007. Compressibility and permeability anisotropy of some peaty soils, *Proceedings of the 60th Canadian Geotechnical Conference, Ottawa, Ontario, 21st–23rd October, 2007*

COMPRESSIBILITY AND PERMEABILITY ANISOTROPY OF SOME PEATY SOILS

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ABSTRACT

The compressibility and permeability anisotropy of five peaty soils were studied using the oedometer and hydraulic consolidation apparatus. The one-dimensional compression, yield and creep properties measured for the vertical and horizontal directions were generally similar as the specimen sets had experienced the same mean *insitu* confining stress. The empirical correlation after Azzouz et al. (1976) was found to more reliably predict the field compressibility. The laboratory coefficient of permeability values of 10^{-9} to 10^{-10} m/s were one or two orders of magnitude lower than that expected in the field, most likely due to scale effects.

RÉSUMÉ

L'anisotropie de compressibilité et de perméabilité de cinq sols tourbeux ont été étudiées à l'aide de l'oedometer et l'appareillage hydraulique de consolidation. Les propriétés de compression, de la contrainte à la limite élastique et de fluage mesurées pour les directions verticales et horizontales étaient généralement semblables car les ensembles de spécimens avaient rencontré le même contraintes d'*insitu*. La corrélation empirique après Azzouz et al. (1976) a été trouvé à évaluer plus exactement la compressibilité de champ. Les valeurs laboratoire de la coefficient de perméabilité de 10^{-9} – 10^{-10} m/s étaient un ou deux ordres de grandeur inférieurs à cela prévu dans le champ.

1 INTRODUCTION

Peaty soil deposits are usually cross-anisotropic in their mechanical and seepage properties due to the preferred horizontal alignment of the constituent solid particles that occurs during the deposition process and the effects of subsequent consolidation under the overburden pressure. Seepage generally occurs more rapidly in the horizontal direction than in the vertical direction and the state of permeability anisotropy can be quantified in terms of the horizontal-to-vertical permeability ratio (r_k); a value of unity indicating isotropic conditions. In general, the permeability of the deposit decreases with increasing depth (decreasing void ratio), and the state of biodegradation. O'Kelly (2006) studied the compressibility, permeability and level of anisotropy of 11 undisturbed soft soils under one-dimensional loading in the vertical and horizontal directions. This paper presents the results of a similar study on five undisturbed peaty soils. The levels of compressibility measured in the laboratory are also compared with those predicted by existing empirical correlations reported in the literature.

2 TEST PROGRAM

The compression, yield and creep characteristics were studied using maintained-load oedometer consolidation tests to BS1377 (1990). The oedometer tests comprised

five load steps, applied using a stress increment ratio of unity, and covering the stress range of 12.5 to 200 kPa. two-way drainage was allowed via porous discs in contact with the top and bottom ends of the test specimens. The coefficient of permeability values in the vertical and horizontal directions were measured directly during the pause stages of consolidation tests conducted in the hydraulic consolidation (Rowe cell) apparatus. These specimens were allowed to drain to atmosphere under stresses of 20, 30 and 40 kPa (applied across the cell diaphragm) over a period of 24 h. The constant head permeability tests were each of 8 h duration and were conducted at the end of each load step. The first 6 h period of the permeability test allowed for steady flow conditions to become established under the constant head of 1.15 m applied. The quantity of flow over the following 2 h period was then measured by recording the mass of the effluent water collected in a graduated cylinder.

Duplicate sets of undisturbed test specimens, 76.2-mm in diameter and 19.0-mm in height, were prepared from adjacent sections of carefully sampled borehole cores that had been recovered in thin-walled, 100-mm diameter tubes (12 degree cutting edge and 7% area ratio) using a fixed-piston sampler. One set of specimens was carved out and tested in the vertical direction and the other set was carved out and tested in the horizontal direction. Details of the five peaty soils, identified by labels [1–5],

Table 1. Soil descriptions, index and *insitu* properties.

| Soil description | Label | Origin | Depth (m) | von Post scale | w_l (%) | w_p (%) | I_p (%) | G_s | LOI (%) | <i>In-situ</i> properties | | | | |
|---------------------------------------|-------|--------------------------|--------------|-------------------|--------------|--------------|--------------|-------|------------|---------------------------|-------|----------------------------------|------------------------------------|-------------------------|
| | | | | | | | | | | w_o (%) | e_o | γ (kN/m ³) | γ_d (kN/m ³) | σ_{vo}' (kPa) |
| Soft to firm, black, peaty SILT | [1] | Alluvial/ marshland | 3.5 | - | 170 | 85 | 85 | 2.26 | - | 140 | 3.2 | 12.7 | 5.2 | 10 |
| Soft, dark grey, fibrous organic CLAY | [2] | Alluvial | 3.5 | - | 143 | 52 | 91 | 2.51 | - | 130 | 3.6 | 13.1 | 5.4 | 12 |
| Very soft, fine fibrous PEAT | [3] | Raised bog (alluvial) | 1.5 | H6 | 710 | 380 | 330 | 1.41 | 88 | 710 | 10.3 | 9.5 | 1.2 | 0 |
| Very soft, coarse fibrous PEAT | [4.1] | Blanket bog | 0.5 | H4 | 1070 | 320 | 750 | 1.35 | 95 | 1220 | 16.4 | 10.1 | 0.76 | 0 |
| Very soft, coarse fibrous PEAT | [4.2] | | 1160 | | | | | | | 15.4 | 10.1 | 0.80 | 0 | |
| Soft, coarse fibrous PEAT | [5] | Raised bog (alluvial) | 1.2 | H3 | 470 | 280 | 190 | 1.53 | - | 555 | 9.5 | 9.5 | 1.5 | 0 |

Note: w_l , liquid limit; w_p , plastic limit; I_p , plasticity index; G_s , specific gravity of solids; LOI, loss in dry mass on ignition, w_o , initial water content; e_o , initial void ratio; γ , bulk unit weight; γ_d , dry unit weight; σ_{vo}' , initial vertical effective stress.

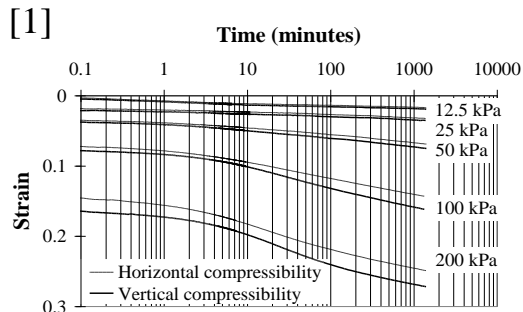
are listed in Table 1. The peaty silt [1] and clay [2] materials were obtained from alluvial deposits. The soils [3–5] were bog peat materials. The states of biodegradation were classified using the von Post (1924) humification scale. H3 indicates a very slightly biodegraded material; H4 a slightly biodegraded material; and H6 a moderately to strongly biodegraded material. The core of coarse fibrous peat [5] material was taken from a depth of within 1.0-m of the ground surface and fine root holes were generally aligned in the vertical direction along the full length of the

extruded core, although the root holes were more prevalent at shallower depths.

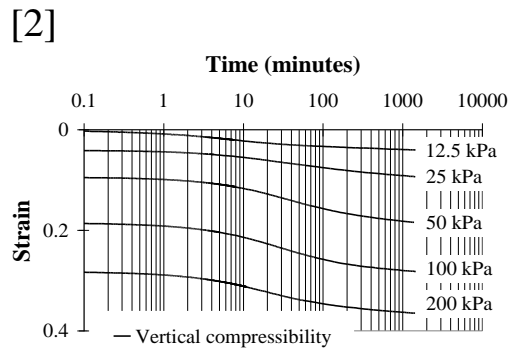
3 EXPERIMENTAL RESULTS AND ANALYSIS

3.1 Compressibility

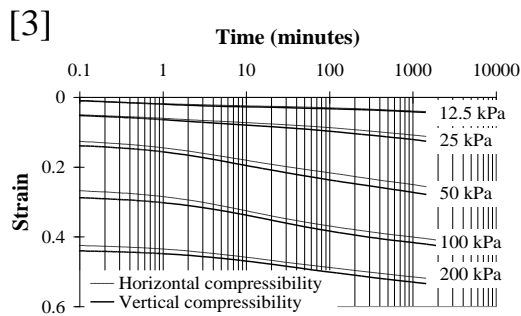
Figure 1 shows the cumulative strain versus logarithm of time data from the oedometer tests.



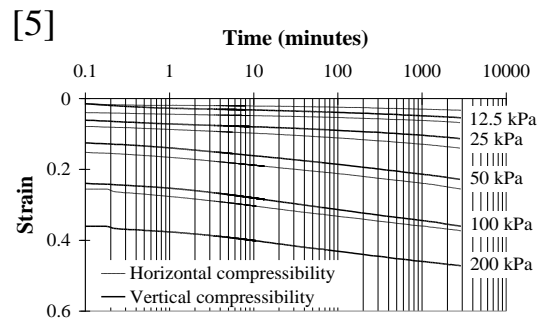
(a) Soft to firm peaty silt.



(b) Very soft, H6 peat material.



(c) Soft organic clay.



(d) Soft, H3 peat material.

Figure 1. Strain versus time data from oedometer tests.

The initial compression of the specimens measured at the start of the different load stages was negligible indicating that the specimens were in a fully saturated state. The specimens sets also had similar initial water content, bulk density and void ratio values (Table 1), which indicated that they were physically identical.

Figure 2 shows the void ratio versus logarithm of effective stress ($e-\log \sigma'$) plots for the different soils tested. The values of the primary compression index C_c , calculated from the slope of the $e-\log \sigma'$ curves, and the primary compression ratio C_c^* (Eq. 1) are listed in Table 2. The ratios of the horizontal-to-vertical primary compression indices are also listed in Table 2.

$$C_c^* = \frac{C_c}{1 + e_0} \quad [1]$$

where e_0 is the *insitu* void ratio, and C_c is the primary compression index.

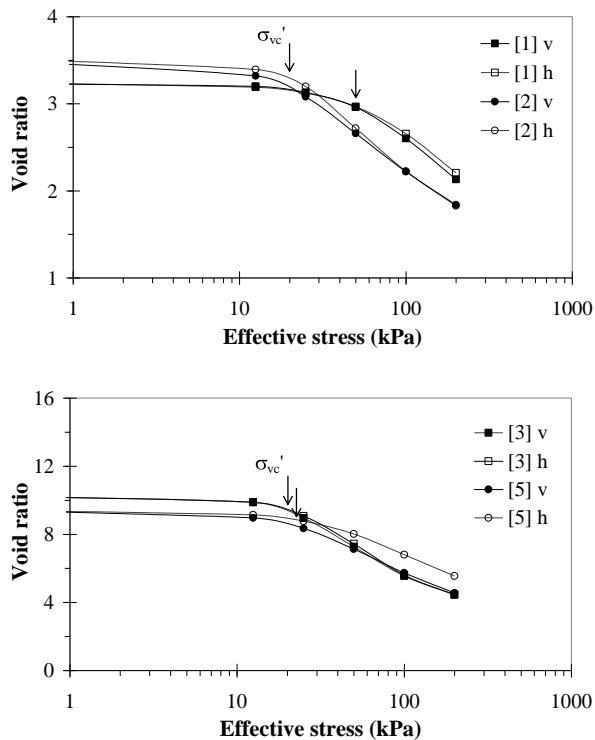


Figure 2. Void ratio versus logarithm effective stress. Note: v, vertical direction; h, horizontal direction.

The soils were highly compressible. Although slightly more compressible in the vertical direction than in the horizontal direction, the state of compressibility was similar overall for practical purposes. The exception was the structured, coarse fibrous peat [5] material which was strongly cross-anisotropic.

Table 2. States of compressibility anisotropy.

| Soil label | Compression index | | | Compress-ion ratio C_{cv}^* | Preconsolidation pressures (kPa) | |
|------------|-------------------|----------|-----------|----------------------------------|----------------------------------|----------------|
| | C_{cv} | C_{ch} | h-v ratio | | σ_{cv}' | σ_{ch}' |
| [1] | 1.6 | 1.6 | 1.0 | 0.37 | 50 | 51 |
| [2] | 1.5 | 1.7 | 1.1 | 0.33 | 20 | 21 |
| [3] | 6.0 | 6.3 | 1.0 | 0.53 | 20 | 22 |
| [4.1] | - | - | - | - | - | - |
| [4.2] | - | - | - | - | - | - |
| [5] | 4.7 | 4.2 | 0.9 | 0.45 | 21 | 32 |

Note: v, vertical direction; h, horizontal direction.

3.2 Yield Behavior

The preconsolidation pressure values measured for the vertical (σ_{vc}') and the horizontal (σ_{hc}') directions listed in Table 2 were determined using the construction of compression curves after Casagrande (1936). Although the specimens had been anisotropically loaded *insitu*, the preconsolidation pressures, which were measured for the orthogonal directions, were similar overall since the specimen sets had experienced the same mean *insitu* confining stress.

3.3 Secondary Compression

The oedometer curves in Fig. 1 did not exhibit the characteristic S-shape form of the theoretical curves given by Terzaghi consolidation theory. Secondary compression was dominant. Table 3 lists the rates of creep in terms of the secondary compression index $C_{\alpha e}$, which was calculated as the change in the void ratio that occurred over one logarithm cycle of time during the secondary compression phase. Apart from the coarse fibrous peat [5] material, the load stages were only of 24 h duration and definitive conclusions regarding the creep behavior would have required load stages in excess of 48 h duration.

Nevertheless, the $C_{\alpha e}$ values calculated for the vertical and horizontal directions were similar overall for the same applied effective stress. Again, the exception was the coarse fibrous peat [5] material which had a initial value of 0.6 for the horizontal-to-vertical $C_{\alpha e}$ ratio, although this material became progressively more isotropic with increasing effective stress due to the development of its new stress-induced fabric. The mean $C_{\alpha e}/C_c$ ratio values (Table 3) agreed with the findings of Mesri and co-workers (see for example Mesri et al. (1995)) with $C_{\alpha e}/C_c$ typically between 0.05 and 0.06.

Table 3. States of secondary compression anisotropy.

| Soil label | Stress range (kPa): | | | | | | | | | | Mean h-v ratio | Mean $C_{\alpha e} - C_c$ ratio |
|------------|---------------------|-----------|----------------|-----------|----------------|-----------|----------------|-----------|----------------|-----------|----------------|---------------------------------|
| | 0 to 12.5 | | 12.5 to 25 | | 25 to 50 | | 50 to 100 | | 100 to 200 | | | |
| | $C_{\alpha e}$ | h-v ratio | $C_{\alpha e}$ | h-v ratio | $C_{\alpha e}$ | h-v ratio | $C_{\alpha e}$ | h-v ratio | $C_{\alpha e}$ | h-v ratio | | |
| [1] | 0.011 | 0.9 | 0.020 | 1.0 | 0.051 | 1.0 | 0.121 | 1.2 | 0.103 | 1.0 | 1.0 | 0.06 |
| [2] | 0.023 | 0.8 | 0.050 | 1.0 | 0.074 | 1.2 | 0.067 | 1.1 | 0.054 | 1.2 | 1.1 | 0.04 |
| [3] | 0.068 | 1.0 | 0.267 | 1.0 | 0.412 | 0.9 | 0.332 | 1.0 | 0.304 | 1.1 | 1.0 | 0.05 |
| [4.1] | - | - | - | - | - | - | - | - | - | - | - | - |
| [4.2] | - | - | - | - | - | - | - | - | - | - | - | - |
| [5] | 0.058 | 0.6 | 0.096 | 0.6 | 0.254 | 0.6 | 0.336 | 0.8 | 0.309 | 1.0 | 0.7 | 0.06 |

Note: $C_{\alpha e}$, secondary compression index; C_c , compression index; h, horizontal direction; v, vertical direction.

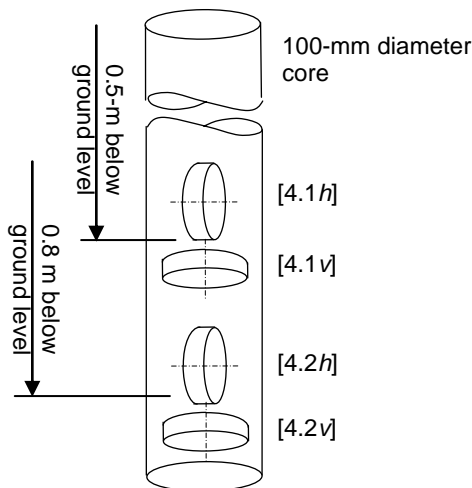


Figure 3. Orientations of test specimens.

3.4 Permeability

The constant head permeability tests were conducted on duplicate specimen sets of the slightly biodegraded (H4) peat material [4.1 and 4.2] in the hydraulic consolidation (Rowe cell) apparatus. The specimens had been axially compressed by about 14, 22 and 30% strains at the end of the 20, 30 and 40 kPa load steps (Fig. 3). The coefficient of permeability values of 10^{-9} – 10^{-10} m/s at ambient laboratory temperature of 20°C were calculated using Darcy’s Law. These laboratory-measured values were one or two orders of magnitude lower than had been expected in the field, which most likely occurred due to scale effects.

Figure 4 shows the values of the coefficient of permeability and the void ratio plotted against logarithm of effective stress for the H4 peat [4.1 and 4.2] material. Again, the levels of compressibility for the vertical and horizontal directions were similar. As expected, the void ratio and the coefficient of permeability values decreased with increasing effective stress. Least-square best-fit regression lines indicated

an inverse logarithm k to logarithm σ_v' relationship (after Lambe and Whitman, 1979).

Table 4 lists the values of the horizontal-to-vertical permeability ratio r_k , for the peat [4.1 and 4.2] material. In general, r_k was greater than or equal to unity for the normally consolidated deposits.

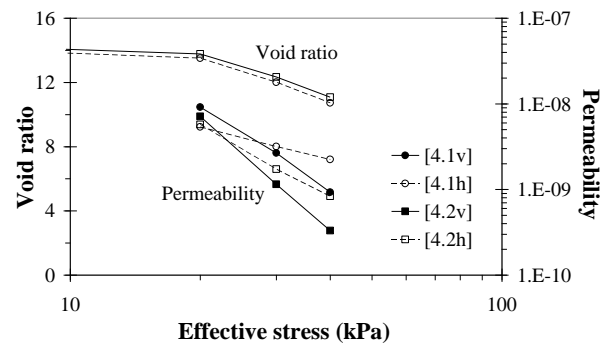


Figure 4. Void ratio and coefficient of permeability versus logarithm effective stress.

Table 4. Horizontal-to-vertical permeability ratios.

| Specimen | Anisotropic ratio (k_h/k_v) | | |
|------------------------|---------------------------------|-----|-----|
| | 20 | 30 | 40 |
| Specimen [4.1] | 0.6 | 1.2 | 2.4 |
| Specimen [4.2] | 0.8 | 1.5 | 2.5 |
| Effective stress (kPa) | 20 | 30 | 40 |

Note: k_h , coefficient of permeability for the horizontal direction; k_v , coefficient of permeability for the vertical direction.

The anomaly of the r_k value less than unity at an effective stress of 20 kPa (indicating permeability greater in the vertical direction than in the horizontal direction) most likely occurred due to preferential flow through the vertically aligned root holes present in the

peat structure. The closure of the root holes and the tendency for the constituent fibers to realign in a general horizontal direction with increasing effective stress caused more significant reductions in the permeability for the vertical direction than for the horizontal direction. The values of the r_k ratio were also greater for peat [4.2] that was sampled from a greater depth (fewer root holes present). The r_k values measured at the higher effective stress values are consistent with that expected of soft normally consolidated soils.

4. EMPIRICAL CORRELATIONS

The final part of the study assessed the level of reliability of existing empirical correlations (namely, Eqs. 2 to 4) in predicting the compressibility of peaty deposits.

$$C_c = 0.009 (w_l - 10) \quad [2]$$

(after Terzaghi and Peck, 1967)

$$C_c = 0.0065 w_o \quad [3]$$

(after Hobbs, 1986)

$$C_c = 0.0115 w_o \quad [4]$$

(after Azzouz et al. 1976)

where w_l and w_o are the values of the liquid limit and *insitu* water content, respectively.

Table 5 compares empirically derived values of the field compression index and those calculated from the laboratory-measured data. The laboratory values of the primary compression ratio C_c^* are also plotted against logarithm of the *insitu* water content in Fig. 5.

Table 5. Empirically derived values of the field compression index.

| Soil label | Measured C_c value | Predicted compression index (C_c) values | | |
|------------|----------------------|--|--------------|----------------------|
| | | Terzaghi & Peck (1967) | Hobbs (1986) | Azzouz et al. (1976) |
| [1] | 1.6 | 1.4 | 0.9 | 1.6 |
| [2] | 1.5 | 1.2 | 0.8 | 1.5 |
| [3] | 5.8 | 6.3 | 4.6 | 8.2 |
| [4.1] | – | 9.5 | 7.9 | 14.0 |
| [4.2] | – | 9.5 | 7.5 | 13.3 |
| [5] | 4.6 | 4.1 | 3.6 | 6.4 |

The data points for the H6 course fibrous peat material [5] located outside the 15% correlation line (after Lambe and Whitman, 1979) suggesting that preloading

of the soil cores had occurred, most likely during sampling. The preloading effects may also explain the unusually high values that were measured for the preconsolidation pressure (Table 2). After considering the effects of sampling disturbance, the data in Table 5 tend to suggest that the correlation after Azzouz et al. (1976) would give more reliable predictions for the compressibility of peaty deposits.

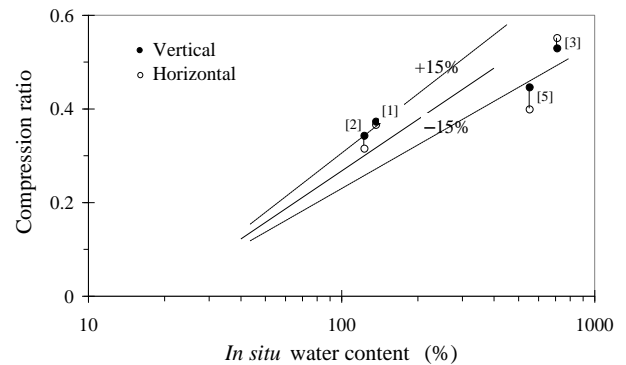


Figure 5. Primary compression ratio versus *insitu* water content.

5. SUMMARY AND CONCLUSIONS

The compressibility and permeability of five peaty materials were studied under one-dimensional loading in the vertical and horizontal directions. The materials were highly compressible, and secondary compression was the dominant mechanism. Although anisotropically consolidated *insitu*, the compression, yield and creep properties measured in the orthogonal directions were similar overall since the specimens sets had experienced the same mean *insitu* confining stress. The exception was the structured, coarse fibrous peaty material which was strongly cross-anisotropic. The empirical correlation after Azzouz et al. (1976) was found to most reliably predict the compressibility of the field deposits.

The values of the coefficient of permeability that were measured for the slightly biodegraded (H4) peat material were of the order of 10^{-9} to 10^{-10} m/s; which were one or two orders of magnitude lower than had been expected in the field, most likely due to scale effects. The measured permeability values were found to be inversely proportional to the state of effective stress on a log-log plot.

At low effective stresses in the peat structure, the horizontal-to-vertical permeability ratio (r_k) was found to be less than unity (permeability greater in the vertical direction than in the horizontal direction), which most likely occurred due to preferential flow along the vertically aligned root holes present. The permeability ratio was found to increase with increasing effective stress ($r_k = 2.5$ at $\sigma' = 40$ kPa) due to the closure of

these root holes and the development of a new stress-induced soil fabric.

ACKNOWLEDGEMENTS

The author would like to kindly acknowledge the work of Martin Carney, Liam McManus and Darren Gavin (Trinity College Dublin) in performing the geotechnical laboratory tests.

The paper was written when the author was on sabbatical leave at the Urban Institute Ireland, University College Dublin.

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