Development of a large consolidometer apparatus for testing peat and other highly organic soils

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Bogs are dynamic eco-hydrological systems. Relatively small and localised increases in effective stress, either due to an applied load or a reduction in the natural phreatic level, can cause significant long-term settlements and hence reductions in the hydraulic conductivity which can have widespread impacts on the bog morphology and hydrology. This paper presents the development of a large consolidometer apparatus, which incorporates a lubricated floating-ring confining cell, in order to accurately measure both the settlement response and hydraulic characteristics of organic soils under increasing effective stress. Maintained-load compression tests are carried out on first-class quality, undisturbed test-specimens (152 mm in diameter and up to 300 mm in length; i.e. mini-structural scale), along with intermittent direct measurement of the hydraulic characteristics under constant-head low Reynolds Number flow conditions. Proving tests were conducted using floating- and fixed-ring setups in the new consolidometer and these test data are evaluated against the results of conventional oedometer tests.

Key words: hydraulic conductivity, laboratory testing, peat, settlement.

Introduction

Background

Peat is a heterogeneous, anisotropic and low shear strength material (Long 2005, O'Kelly 2005a, 2006, 2007, Mesri & Ajlouni, 2007) that is highly compressible and with a typical hydraulic conductivity of between 0.1 and 0.01 m/d reported from field measurements in slightly to moderately decomposed Sphagnum peat deposits (Hobbs 1986). Relatively small and localised increases in effective stress, either due to an applied surface load (e.g. a roadway (Osorio et al. 2008)) or a

reduction in the natural phreatic level, can have widespread impacts. Note that the effective stress (σ'), which acts across the contacts between the constituent solid particles, is estimated as the difference between the total normal stress (σ) and the porewater pressure (u) in the saturated voids (Terzaghi 1943).

Significant long-term settlements (due to the characteristic low consolidation and high creep rates), and hence reductions in the hydraulic conductivity of the peat deposit, can adversely affect the natural groundwater regime and the finely balanced eco-hydrological system. For

example, measurable and long-lasting impacts have been observed to occur within a ten-year period, up to 600 m distant from a cutaway area on a raised bog in the Irish midlands (ten Heggeler et al. 2004). Hence, it is important that the full impact of a change in the state of effective stress on the bog morphology and hydrology can be accurately estimated.

Geotechnical volume-change theory

The volume change mechanisms in peatlands are (Kennedy and Price 2005):

1. Shrinkage; the contraction of the peat layers above the groundwater table due to the development of negative porewater pressures as the peat dries.

2. Peat oxidation; causes irreversible subsidence due to mineralization of carbon to water and CO_2.

3. Compression; attributed to changes in the state of effective stress for the peat layers below the groundwater table.

Compression comprises primary consolidation (ΔH_c) and secondary compression (ΔH_s) settlement components. Primary consolidation can be described by classical 1D consolidation theory (Terzaghi 1943), whereby the change in the peat volume (assumed in a fully saturated condition) corresponds to the change in its porewater volume. The void ratio is defined as the volume of the pore voids to the volume of the solids, and the change in void ratio (Δe) can be predicted by (Fig. 1):

$$\Delta e \quad = \quad C_c \ \log \frac{\sigma_{vo}'+\Delta\sigma_v}{\sigma_{vo}'} \qquad (1)$$

where C_c, primary compression index (gradient of the void ratio–logarithm effective stress curve); σ_{vo}', initial vertical effective stress; $\Delta\sigma_v$, increase in vertical effective stress (i.e. applied stress).

At effective stresses greater than the material's pre-consolidation pressure, irreversible structural changes occur, and the primary consolidation settlement, ΔH_c, can be estimated as:

$$\Delta H_c \quad = \quad H_o \frac{\Delta e}{1+e_o} \quad = \quad H_o \frac{C_c}{1+e_o} \ \log \frac{\sigma_{vo}'+\Delta\sigma_v}{\sigma_{vo}'}$$

$$(2)$$

where e_o, initial void ratio; H_o, initial thickness of saturated peat layer.

Secondary compression settlement, ΔH_s, is attributed to the gradual degradation and the re-arrangement and compression of the constituent solids under the increased effective stress into a more stable configuration, following the primary consolidation phase, and is a time dependent process expressed by:

$$\Delta H_s \quad = \quad H_o \ C_{\text{sec}} \ \log \frac{t_1}{t_2} \qquad (3)$$

where C_{sec}, coefficient of secondary compression; t_1, time period for substantial completion of the primary consolidation phase; t_2, time period that extends into the secondary compression phase ($t_2 > t_1$).

Laboratory practice and effects of test-specimen size and aspect ratio

The validity of the compression and hydraulic conductivity values determined from representative, high-quality, undisturbed laboratory test-specimens in relation to the actual field response is largely dependant on the specimen scale and related boundary effects. For example, friction develops along the side wall of the standard oedometer confining cell causing an uneven strain response over the specimen length. Hence, the standard specimen size has a small aspect (length-to-diameter) ratio of typically 1:4 (BS1377 1990b), although the high compressibility of peat and other organic soil specimens is such that the wall friction can still be significant.

For all soils, since the porewater has no shear resistance, the friction that develops along the interface between the cell wall and specimen is proportional to the effective normal force (i.e. effective normal stress times circumferential shear area). In the fixed-ring confining cell routinely used in the oedometer apparatus, the bottom end
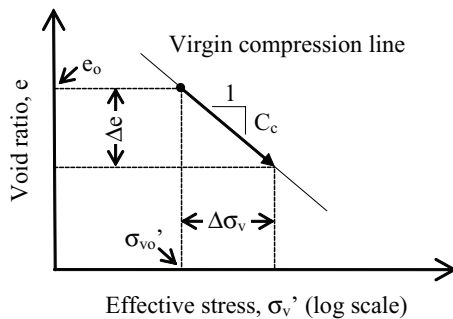
Fig. 1. Theoretical soil consolidation plot. Note: e_o, initial void ratio; σ_{vo}', initial vertical effective stress; Δe, void ratio reduction due to increase in vertical effective stress, $\Delta\sigma_v$, C_c, primary compression index.

Kuva 1. Teoreettinen maan painumisen kuvaaja. e_o, huokos-luvun alkuarvo; σ_{vo}', vertikaalisen jännityksen alkuarvo; Δe, huokosluvun pieneneminen vertikaalisen jännityksen ($\Delta\sigma_v$) kasvaessa; C_c, puristusindeksin alkuarvo.

of the specimen is restrained whereas the specimen top end moves relative to the confining cell. Hence, the magnitude of the wall friction that develops is proportional to the specimen height (H). However, in the floating-ring cell, equal but opposite frictional forces develop in the top and bottom halves of the confining cell since both the specimen top and bottom ends move by equal amounts away from the ends of the confining cell, although, in this case, the absolute magnitude of the wall friction is halved overall (i.e. theoretically no relative movement occurs at the specimen mid-height).

Scale effects, which in a geotechnical-laboratory context concern the effects of the microstructural fabric on the geo-engineering properties, can also have a significant bearing on the validity of the measurements in relation to the actual field response. For example, the drainage response of peat at low levels of effective stress is dominated by its constituent fibres, which act as preferential flow conduits, particularly in the case of smaller laboratory test-specimens. In practice, the degree of anisotropy and hence the measured hydraulic conductivity are scale dependent (Kruse et al. 2008), generally reducing with decreasing specimen size. For example, O'Kelly (2007) re-

ported that the hydraulic conductivity values of between 10^{-4} and 10^{-5} m/d determined from constant-head seepage tests on a saturated, slightly decomposed peat specimen in the small hydraulic consolidation (Rowe) cell were at least one or two orders of magnitude lower than that expected for the field deposit.

Furthermore, hydraulic conductivity values determined indirectly by applying standard curve-fitting techniques (Casagrande & Fadum 1940, Taylor 1942) to the strain responses measured in maintained-load compression tests are unreliable since peat and other highly organic soils, including for example municipal water treatment residues (O'Kelly 2008, O'Kelly & Quille 2009), violate many of the fundamental assumptions of Terzaghi (1943) consolidation theory, namely: the specimen strains are large; the constituent solids are themselves compressible; and the hydraulic conductivity decreases significantly during each load stage.

Water treatment residues are the slurry by-products comprising organic clay-sized particles derived from the treatment processes used in the production of potable water (Twort et al. 2000). These slurry residues must be adequately dewatered at the municipal treatment works, usually achieved by mechanical means, in order to facilitate their efficient and safe landfill disposal (O'Kelly 2004). Again, the compressibility and hydraulic conductivity of these residues must be determined in order to select an appropriate mechanical dewatering system for the treatment works and to engineer the landfill site to safely contain the dewatered residue.

Aims and scope of this study

This paper presents the development of a large consolidometer apparatus, which incorporates a lubricated floating-ring confining cell, to accurately measure the compression and hydraulic characteristics of slurries and undisturbed, soft soil cores over low-to-medium levels of vertical effective stress ($\sigma_v' \leq 40$ kN/m^2). The confining cell accommodates a much larger specimen (152 mm in diameter and typically up to 300 mm in height; i.e. mini-structural scale) than current standard laboratory consolidation apparatus and is therefore

more representative of the in-situ conditions. The hydraulic conductivity is measured directly under constant-head low Reynolds Number (laminar) flow conditions, for which Darcy's Law has been shown to be valid (Hemond and Goldman 1985, Waine et al. 1985). The longer flow path through the test specimen is also on the mini-structural scale and, hence, is more representative of the in-situ conditions. Proving tests are conducted on saturated specimens of undisturbed peat and municipal water treatment residues using floating- and fixed-ring setups in the new consolidometer and these test data are benchmarked against the results of standard oedometer tests.

New consolidometer apparatus

Figure 2 shows the newly-developed consolidometer apparatus. The confining cell comprises commercially-available smooth uPVC tubing (inner and outer diameters of 152 and 161 mm; nominally 400 mm in length) that is completely sealed at both ends by aluminium cover plates, which are bolted together by four 12-mm diameter stainless-steel tie rods. The 20-mm deep boss on the cover plates incorporates a rubber O-ring seal that push-fits inside the ends of the uPVC tubing.

The 5-mm thick, aluminium, top and bottom platens comfortably fit inside the uPVC tubing (with an even gap of about 2 mm between the outer platen rim and the inner tube surface), and the platens contact against the ends of the test specimen. Hollow, stainless-steel loading and reaction pistons, each 300 mm in length, are securely fastened to the top and bottom platens, respectively. Unlike the standard oedometer setup, the fixed piston-to-platen connections prevent the potential for tilting and jamming of the platens against the inner tube surface, which may otherwise occur during tests on very soft materials (O'Kelly 2005b). Wiper seals located in the tube cover-plates, seal the entry of the 40-mm diameter pistons to the confining cell. Vertical movement of the floating-ring cell is guided by an outer cage comprising four 15-mm -diameter vertical steel bars, which are bolted to the loading bench. Split-ring clamps locate around the loading and reaction pistons.
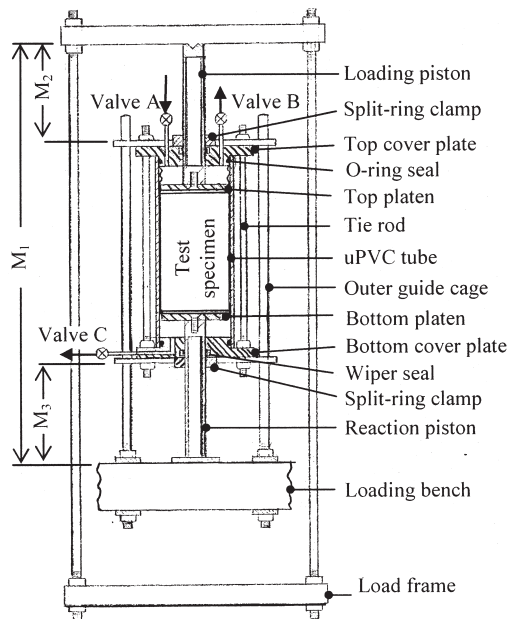

Fig. 2. Schematic design of the new consolidometer apparatus.
Kuva 2. Kaavio kehitetystä painumamittauslaitteistosta.

Two loading mechanisms can be fitted to the rectangular load-frame depending on the initial level of vertical stress, σ_v, namely: a series of slotted weights placed on a load hanger ($\sigma_v < 10$ kN/m^2) or a second-class type lever system (i.e. fulcrum and dead-weight hanger are located at opposite ends of the lever arm, 200 mm in overall length) providing a 5:1 mechanical advantage when higher stresses must be applied. A seating stress as low as 0.5 kN/m^2 (arising from the deadweight alone of the loading piston and platen assembly) can be applied to the top end of the specimen. The deadweight of the confining cell itself applies a mean shear stress of about 1 kN/m^2 over the specimen wall-surface area. A counterbalance system is used in cases where this boundary shear stress is considered excessive. Three long-stroke displacement transducers measure the overall specimen compression (M_1), and the relative movements between the ends of the confining cell and the loading and reaction platens (M_2 and M_3, respectively, shown in Fig. 2).

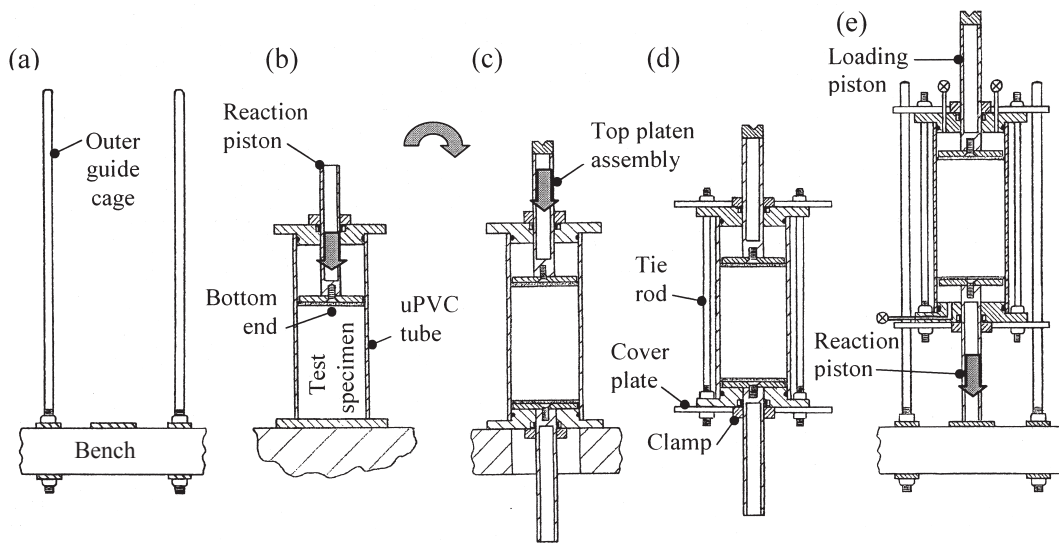An adjustable constant-head water reservoir,

Fig. 3. Assembly sequence for the consolidometer apparatus: (a) Outer guide cage secured to loading bench; (b) Reaction piston fitted to tube containing test-specimen; (c) Top platen fitted after inverting tube; (d) Confining cell sealed by bolting cover plates together; (e) With test-specimen located centrally and pistons clamped in position, the assembly is located around outer cage and lowered into position.

Kuva 3. Painumamittauslaitteiston kokoonpano: (a) Uloin ohjainkehikko, (b) Maanäytekammion vastusmäntä, (c) Yläpuristuslevy ylösalaisin käännetyssä laitteistossa. (d) Suljettu kammio, joka tiivistetty pultatuilla levyillä, (e) Maanäyte (keskellä) kammiossa ja puristusmännät lukittu mittausasentoon.

which in the current setup was located at an elevation of 1.15 m above the bottom platen level, generates an hydraulic gradient of between four and five, and hence low Reynolds Number (laminar flow) conditions across the specimen length. The water enters and exits the confining cell via the on/off valves A, B and C that are located in the top and bottom cover plates (Fig. 2). Perforations in the top and bottom platens allow uniform downward seepage to occur through the test specimen. Manometer tapings thought the wall thickness of the uPVC tubing are equi-spaced at 45 mm centres along the lower half of the confining cell. Standpipes are connected to these tapings in order to locally measure the actual head loss; the hydraulic gradient; and hence the level of heterogeneity over the specimen length.

The stages in the consolidometer assembly are shown schematically in Fig. 3. The outer guide cage is bolted to the bench (Fig. 3a). With the uPVC tube (and test-specimen inside) resting upright on a flat working surface, the reaction platen is guided down into the tube until contact-

ing against the bottom end of the specimen (Fig. 3b). The system is then carefully inverted, after which, the top platen assembly is guided into the top end of the tube until contacting against the top end of the specimen (Fig. 3c).

The specimen ends are separated from the top and bottom platens by 5-mm thick layers of uniformly graded sand. Fine, wire gauze prevents the sand grains from falling through the perforations in the bottom platen. Next, the confining cell is completely sealed by bolting the top and bottom cover plates together using the four tie rods (Fig. 3d); the test-specimen is located centrally along the uPVC tube; and the loading and reaction pistons are locked in position using the split-ring clamps (Fig. 3d). The assembly is located around the outer cage and, guided by the cover plates, is lowered into position until the entire assembly is supported by the clamped piston which reacts against the bench (Fig. 3e). Finally, the load frame is connected to the loading piston.

The water from the constant-head reservoir is allowed to enter the confining cell via valve A in

the top cover plate (Fig. 2) in order to bleed any air bubbles that may have become trapped in the void above the specimen via valve B. The water is then allowed to permeate downward through the specimen, typically over at least a 12-h period, in order to achieve full saturation of the confining cell and allow steady flow conditions to become established, with the permeant exiting via valve C, through the cell base plate, to atmosphere.

Proving tests

Materials

The test materials were a very soft, saturated, fine fibrous peat and two municipal water treatment residues (Table 1). A series of standard classification tests were carried out in accordance with BS1377 (1990a) to categorize these test materials, and included the measurement of the consistency limit values:

1. Liquid limit (w_L); the water content at which a remoulded soil changes from the plastic to the liquid state, measured using the cone penetrometer method.

2. Plastic limit (w_p); the water content at which a cohesive soil changes from the plastic to the solid state, measured by the rolling of soil threads method.

3. Plasticity index, $I_p = w_L - w_P$.

In this paper, the amount of porewater was quantified using the geotechnical definition of water content, defined as the mass of the porewater to the mass of the dry solids, expressed as a percentage. The water content was determined using the oven drying method, in which the dry solids mass corresponds to the equilibrium mass achieved after oven drying the test specimen at a temperature of 105°C for a period of 24 h. The specimens were fully saturated (saturation ratio = 100%), and the bulk and dry density values were calculated as the total wet mass and dry mass per unit volume, respectively. The loss-in-dry-mass on ignition values, which are a reflection of the organic content, were determined by igniting dry powered specimens in a muffle furnace at 440°C. The geo-engineering properties of these municipal water treatment residues have been reported elsewhere by O'Kelly (2008) and O'Kelly & Quille (2009).

Peat

Two undisturbed, core samples of moderately decomposed Sphagnum peat (H5 level of degradation on the scale of von Post (Landva & Pheeney 1980)) were obtained from a raised bog in the Irish midlands. The core sampling technique minimised, as much as possible, the disturbance due to preloading (vertical compaction) of the cores, dragging of peat fibres and smearing of pores during coring. The phreatic level at the bog was within 10 cm of the bog surface.

The sample pair was taken from the same location and at a depth of 1.0 m below the bog surface by carefully pushing two uPVC tubes

Table 1. Some properties of the test materials (peat and water treatment residues) of the constructed consolidometer apparatus.

Taulukko 1. Kuvatulla painumamittarilla testattujen turve- ja vedenpuhdistamolietenäytteiden ominaisuuksia.

	Peat	Water treatment residue	
		Works 1	Works 2
Water content (%)	1035	580	600
Saturation ratio (%)	100	100	100
Liquid limit (%)	1110	550	430
Plastic limit (%)	355	260	220
Plasticity index	755	290	210
Bulk density (1000 kg m⁻³)	0.96	1.08	1.07
Dry density (1000 kg m⁻³)	0.08	0.17	0.16
Specific gravity of solids	1.48	1.99	1.90
Loss in dry mass on ignition (%)	98	45	46
Void ratio	16.1	10.9	11.1
Undrained shear strength (kN m⁻²)	10	1.5	< 1

(of the confining cell dimensions) to a depth of 0.4 m below the base of a shallow trench. The trench had been freshly dug in the bog with a spade, removing the intensely-rooted zone (uppermost layer about 0.2 m in thickness), thereby preventing roots from being displaced down with the tubes, which would have otherwise damaged the structure of the deeper peat layers. The tubes were slowly rotated as they were inserted through the saturated *catotelm* and the thin wall and sharpened cutting-edge of the tubes minimised the preloading effect on the peat cores during sampling (O'Kelly 2005a, 2006, 2007). The difference between the peat surface level inside and outside the fully inserted tubes was less than 2 cm. The sharp cutting edge was located along the outer circumference in order that the peat volume, displaced by the introduction of the tube, is compressed outwards; leaving the peat core that enters the smooth tube in an undisturbed state. Note that the sample quality is related to the soil volume displaced by the sampling tube, expressed as a percentage of the core volume, and is traditionally quantified using the area ratio, C_a:

$$C_a = \frac{d_o^2 - d_i^2}{d_i^2}(x\,100) \quad (\%) \tag{4}$$

where d_o and d_i, outer and inner diameters of sampling tube, respectively.

Other factors being equal, smaller area ratio values imply less sampling disturbance will occur, and *visa versa*. The area ratio of 12% for the uPVC tubes is comparable with that of the 100 mm diameter, thin-walled samplers ($C_a \cong 10\%$) routinely used in practice to obtain first-class quality, core samples of soft to firm clays and plastic silts.

Next, the surrounding peat was carefully excavated from around the uPVC tube. The peat core was cut flush with the lower end of the tube using piano wire in order to prevent an expansion of the core on lifting the tube. Both ends of the tube were hermetically sealed using caps and waterproof tape, preserving the saturated condition during transportation and storage in the geotechnical laboratory. The ends of the peat core

were extruded, in turn, from the tube and carefully trimmed back using piano wire in order to reduce the specimen length to between 250 and 300 mm (i.e. aspect ratio = 1:0.51 to 1:0.61). Note that unlike knives, piano wire minimises smearing of pores and dragging of peat fibres during cutting (Kruse et al. 2008). The saturated specimen pairs, which remained undisturbed throughout the sample preparation procedure, were found to have the same physical properties and consistency limit values.

Water treatment residue

Slurry residues were obtained from two of the larger municipal water treatment works in Ireland. Similar dosages of alum coagulant and polyelectrolyte (Chemifloc 4140® and Magnafloc LT25®, respectively) had been added to the source waters at the treatment works in order to encourage coagulation of the colloidal particles into flocs that settled out more readily during the treatment processes. The slurry residues mainly comprised organic matter (evident from the relatively high loss-in-dry-mass on ignition values of 45% and 46%), and are classified as high-plasticity organic clays on the basis of their very high liquid limit (550% and 430%) and plasticity index (290 and 210) values. The slurry residues were mixed to a uniform consistency and the test-specimens were prepared by simply pouring the slurry into the consolidometer cell, with vigorous roding to remove any air voids.

Experimental method

Load stage

A series of maintained-load compression tests were carried out on the peat and water treatment residue specimens under two-way drainage conditions in the consolidometer floating-ring setup, and including a lubricated membrane wrapped around the specimen wall surface in order to minimise wall friction. The lubricated membrane comprised low density, polyethylene cling-film (about 10 to 11 µm in thickness) that had been saturated in oil.

In the case of the peat, the specimen wall-surface was wrapped in three layers of cling film after the specimen, which was stiff enough to stand unsupported in an upright position, had been fully extruded from the uPVC tube. The peat structure was studied and the peat core was checked for cracks (preferential flow pathways). Next, the wrapped specimen was carefully fitted back inside the tube with the minimum amount of handling, after oil had been generously smeared over the inner tube surface. The cling-film membrane, which protruded beyond the top end of the specimen, was clamped between the top end of the tube and the cell top cover plate in order to prevent water from flowing along the inner tube surface during the seepage tests. The membrane protrusion was sufficient to accommodate the anticipated vertical movements of the confining cell and the specimen during the load stages.

Standard fixed-ring oedometer tests with two-way specimen drainage were carried out on smaller, undisturbed peat specimens (76.2 mm in diameter and 19.0 mm in length) as a basis for validating the strain responses measured for the consolidometer setup. A second peat specimen was also compressed using the fixed-ring consolidometer setup, but without wrapping the specimen in a lubricated membrane. The absence of the lubricated membrane allowed a direct comparison of the fixed-ring oedometer and consolidometer data and, hence, the effects of the specimen scale and different aspect ratios. All of the compression tests were conducted at ambient laboratory temperature of 20°C.

The test specimens were loaded in the consolidometer by releasing the piston clamps (see Fig. 2). In the case of the floating-ring setup, the split-ring clamps were released from both the loading and reaction pistons so that the uPVC tube could move relative to both the top and bottom platens. However, in the case of the fixed-ring setup, the tube and the bottom platen remained clamped together.

Valve A from the constant-head reservoir, as well as the valves on the manometer tapings spaced along the specimen length, remained closed during the load stages. Manometer standpipes are not fitted to the uPVC tube when the specimen is wrapped in a lubricated membrane.

Valves B and C in the top and bottom cover plates (Fig. 2) were opened fully allowing both specimen ends to drain freely to atmosphere (two-way specimen drainage). The standard stress-increment ratio of unity was used for all of the compression tests. The load stage durations were typically three to four days and seven days for the peat and water treatment residue specimens, respectively. The displacements M_1, M_2 and M_3 (see Fig. 2) were continuously measured by the displacement transducers.

Hydraulic conductivity

Constant-head seepage tests were carried out over a period of four to five days at the end of each load stage. The split-ring clamps located around the loading and reaction pistons were fully secured during the seepage tests so that the specimen length, and hence the void ratio, remained constant. Valve A located along the line from the constant-head reservoir, and valve C that passes through the cell base-plate (Fig. 2), were fully opened in order to allow vertical downward seepage to occur thought the specimen. The bleed-valve B, located on the top cover plate, was temporarily opened before the start of each seepage test in order to purge any gas that may have been generated due to the natural biodegradation of the specimen during the preceding load stage. Next, steady seepage conditions were allowed to establish through the specimen. The permeant volume that exited via valve C was determined from periodic measurements of the mass of water that collected in a graduated cylinder. The seepage tests were terminated after successive measurements gave consistent hydraulic conductivity values.

Leakage along the side wall of the confining cell was not significant since the very soft test specimens (undrained shear strength ≤ 10 kN/m^2), and enclosing lubricated membrane, were pressed against the inner tube surface, thereby blocking any preferential flow paths that may have initially existed along the specimen boundary. The confining cell was dismantled after completing the final seepage test. The compressed specimen was carefully removed, subdivided over its length, and tested in order to determine the uniformity of the final water content and hence the material dry density.

Experimental results and analysis

Figure 4 shows the cumulative strain versus logarithm of elapsed time responses for the peat and water treatment residue specimens measured using the fixed- and floating-ring consolidometer setups and the standard oedometer apparatus.

As expected, the test materials were highly compressible, deforming at slow but steady rates, and with the strain–time curves exhibiting the characteristic S-shaped form in the semi-logarithmic plots (Fig. 4). Standard curve-fitting analysis indicated that the primary consolidation phase (due to the dissipation of the excess porewater pressure) was substantially complete by the end of each load stage and that the ongoing secondary compression was significant. The initial specimen compression measured at the start of the load stages (Fig. 4) was negligible, confirming that the specimens were in a fully saturated condition. Significant initial compression would have been expected had biogenetic gas bubbles been present within the specimen pore voids.

Overall, the strain responses measured for the peat specimens in the floating-ring consolidometer and the standard oedometer apparatus (Fig. 4a, b) were in agreement, despite the significant differences in specimen size and aspect ratio values of 1:0.61 and 1:4, respectively. For example, the 18% strain achieved by the end of the final load stage at $\sigma_v = 40$ kN/m^2 in the floating-ring consolidometer was in line with that measured in the oedometer apparatus, indicating that both specimens had experienced relatively similar wall-friction effects. In contrast, the strains achieved in the fixed-ring consolidometer were consistently smaller (e.g. only 15.5% strain was achieved under the same final vertical stress, Fig. 4a) suggesting that the boundary effects had been significantly greater.

Figure 5 shows the M_2 and M_3 displacements measured between the ends of the floating-ring consolidometer cell and the loading and reaction platens, respectively, during the maintained-load tests on the peat specimen that had been enclosed in a lubricated membrane.

Given that the peat specimen was relatively homogeneous, the M_2 and M_3 displacements would have been expected to be similar, and equal
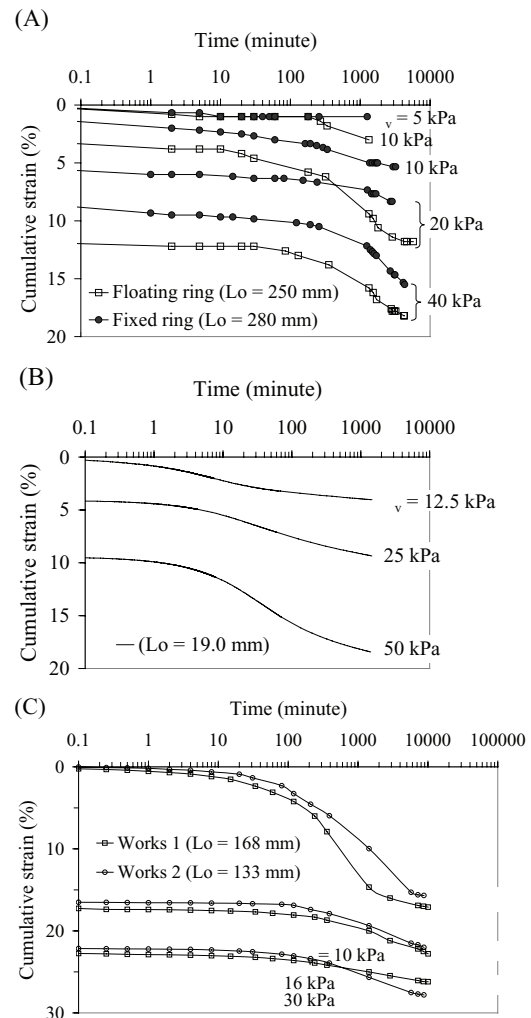

Fig. 4. Cumulative strain versus time in peat tested with the developed consolidometer (a), peat in standard oedometer (b) and water treatment residue in consolidometer (c). Note: L_o, initial specimen length; Σ_v, total vertical stress.

Kuva 4. Kumulatiivinen jännitys ajan suhteen turvenäytteessä, jota on testattu tässä tutkimuksessa esitellyllä laitteistolla (a), standardilla odometrilla (b) sekä kumulatiivinen jännitys laitteistolla testatussa vedenpuhdistuslietteessä (c). L_o = alkuperäinen näytteen pituus; Σ_v = vertikaalisen jännityksen kokonaismäärä.

to half of the total specimen compression (i.e. $M_1/2$, as shown in Fig. 6), for the development of a uniform strain response across the specimen length.

Figure 5 indicates that the floating-ring conso-lidometer cell had slipped downwards marginally relative to the specimen, but only during the first and second load stages, under the action of the cell deadweight (equivalent to an applied boundary shear stress of about 1 kN/m²). The slippage of the confining cell produced a relative increase in the measured M_3 (bottom end) displacement value and an equal reduction in the measured M_2 (top end) value. However, by the end of the second load stage at 20 kN/m², the relative downward movement at the specimen mid-height was only 3.3 mm, and no slippage occurred during the final load stage at 40 kN/m².

Figure 7 shows the actual water content reduc-tion, and hence the increase in density, achieved across the length of the peat specimens by the end of the final load stage in the consolidometer tests. A comparison of the water content distri-butions indicates that a more uniform specimen compression was achieved for the floating-ring setup that also included a lubricated membrane. In contrast, the greater wall friction in the fixed-ring setup, compounded in this test by the ab-sence of a lubricated membrane, had the effect of reducing the degree of specimen compression with depth; evident from the greater increase in density nearer the top end, rather than the bottom end, of the specimen. The water content distribu-tions for both the fixed- and floating-ring setups indicate that full primary consolidation had not been achieved near the specimen mid-height by the end of the final load stage under the two-way specimen drainage conditions. The non-uniform compression responses may also be related, in part, to some heterogeneity of the natural peat deposit with increasing sampling depth.

Figure 8 shows the saturated hydraulic conductivity values, corresponding to ambient laboratory temperature of 20°C, which were calculated using Darcy's equation (5). Steady seepage conditions generally became established within a 6-h period from the start of the hydraulic conductivity test.
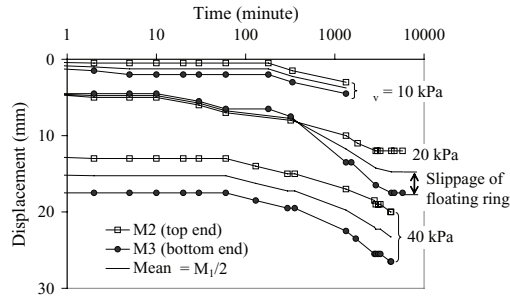

Fig. 5. Maintained-load stages for peat specimen in floating-ring consolidometer. Note: M_1, total specimen compression; M_2 and M_3, relative movements between ends of confining cell and the loading and reaction platens, respectively.

Kuva 5. Turvenäytteeseen kohdistetut voimat kelluvakam-mioisessa painumamittarissa. M_1= näytteen puristumisen kokonaismäärä, M_2 ja M_3= kammion pään sekä kuormitus ja vastavoimalevyjen välisen etäisyyden suhteellinen muutos.

$$k = \frac{QL}{\Delta H A t} \tag{5}$$

where Q, volume of water that passed though the specimen during a given time period, t; A, specimen cross-sectional area (181.5 cm²); ΔH, head loss that occurred across the length (L) of the compressed specimen.

The void ratio values of the test specimens are plotted in the conventional manner against logarithm effective stress in Fig. 9. Also included are the hydraulic conductivity data, which exhibit the characteristic inverse log-log relationship with increasing effective stress (after Lambe & Whit-man 1979). As expected, the test materials were highly compressible, and the level of compression was quantified in terms of the primary compres-sion index, C_c, and the primary compression ratio C_c^*:

$$C_c^* = \frac{C_c}{1 + e_o} \tag{6}$$

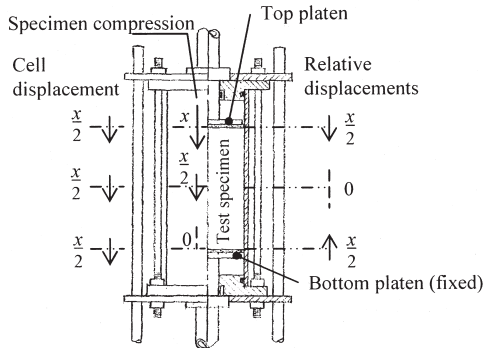where e_o, initial void ratio.

Fig. 6. Displacement measurements in floating-ring consolidometer.

Kuva 6. Kammion siirtymän mittaaminen painumamittarissa.

Discussion

Despite the significantly different test-specimen sizes and aspect ratios, the strain response and hence the level and uniformity of the compression response measured for the Sphagnum peat using the floating-ring consolidometer was similar when benchmarked against the standard fixed-ring oedometer data (Figs. 4 and 9a), with high primary compression index ($C_c = 4.7$ and 5.0, respectively) and primary compression ratio ($C_c^* = 0.27$ and 0.29, respectively). Note that for most clay soils, $C_c < 1.0$. However, the same peat experienced a significantly lower level of compression ($C_c = 3.5$; $C_c^* = 0.20$) in the fixed-ring consolidometer indicating greater specimen boundary effects, which reduced the level of compression, particularly nearer the fixed specimen end.

Being relatively well-decomposed *catotelm* (H5), the effect of biogenic gas bubbles on the water-conducting pores, and hence the seepage rates, was negligible. As expected, the saturated hydraulic conductivity values measured in the floating-ring consolidometer reduced significantly with relatively small increases in effective stress (Fig. 9a), but more importantly, the laboratory-measured values were consistent with field measurements of between 0.1 and 0.01 m/d reported for H5 Sphagnum peat by Hobbs (1986).

Although the two water treatment residues had been obtained from different municipal works, and
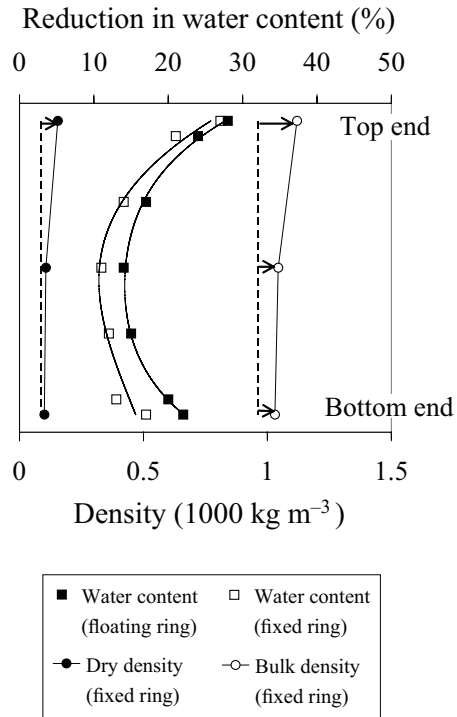
Fig. 7. Non-uniform compression of peat specimens in fixed-ring setup.

Kuva 7. Turvenäytteen epäyhtenäinen puristuminen kiinteäkammioisessa painumamittarissa.

allowing for some natural variability of the source waters entering the treatment plants, the sludge residues were found to have similar engineering properties (Table 1; Figs. 4c, 9b). In particular, the slurry residues from works 1 and 2 were highly compressible, with $C_c = 2.8$ and 3.1, respectively, and $C_c^* = 0.19$ and 0.22, respectively. Again, a uniform level of compression was achieved across the specimen length. The new floating-ring consolidometer has been used in other studies by O'Kelly (2008) and O'Kelly & Quille (2009) in order to consolidate slurry residues and form saturated homogeneous cakes from which smaller, duplicate sub-specimens have been carved out and prepared, using standard techniques, for further geotechnical-laboratory testing. Similar C_c and C_c^* values have been measured for the consolidometer slurry and the pressed sub-specimens tested using the standard oedometer apparatus,
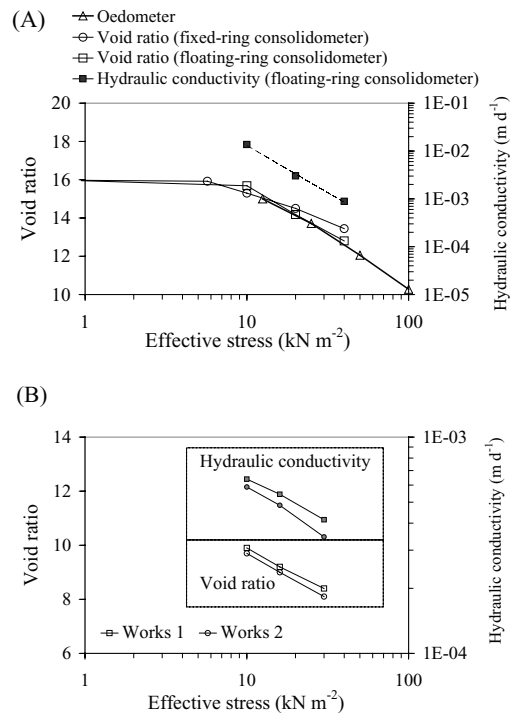
(A)

(B)

Fig. 9. Void ratio and saturated hydraulic conductivity versus effective stress in peat (A) and in water treatment residue (B).

Kuva 9. Huokosluku ja hydraulinen johtavuus saturoituneissa olosuhteissa suhteessa turvenäytteeseen (a) ja vedenpuhdistuslietenäytteeseen (b) kohdistettuun jännitykseen.

providing further evidence that the boundary effects in the floating-ring consolidometer and oedometer apparatus are comparable.

Saturated hydraulic conductivity values of the order of 10^{-4} m/d were measured for the water treatment residues (significantly lower than that for the more structured, fibrous peat) using constant-head seepage tests in the floating-ring consolidometer. These very low hydraulic conductivity values arose due to the tendency for the free and interstitial water in the pore voids to become trapped and absorbed due to the intricate microstructure of clay-sized organic particles that constituted the residue flocs and the electro-valent character of the alum coagulant that had been added to the slurry at the municipal works (O'Kelly 2008, O'Kelly & Quille 2009).
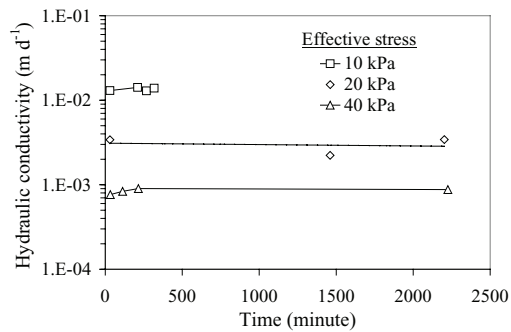

Fig. 8. Constant-head hydraulic conductivity tests on peat in consolidometer.

Kuva 8. Turvenäytteen hydrauliset johtavuudet vakio painekorkeudessa.

Summary and conclusions

The development of a large consolidometer to accurately measure the consolidation response and representative hydraulic characteristics of slurries and undisturbed organic soils under increasing levels of effective stress has been presented. The new apparatus, which has a simple and robust design, incorporates a lubricated, floating-ring confining cell in order to minimise the boundary effects during large-strain consolidation conditions. Large, first-class quality, undisturbed core samples (152 mm in diameter and typically up to 300 mm in length; i.e. mini-structural scale) are obtained by pushing the uPVC tubing of the confining cell directly into the soft ground. Maintained-load compression tests were carried out in the floating-ring consolidometer, over low-to-medium applied stress levels, along with intermittent hydraulic conductivity measurements under constant head, low Reynolds Number flow conditions.

Proving tests on saturated, undisturbed Sphagnum peat specimens indicated that when benchmarked against the standard fixed-ring oedometer apparatus, practically identical strain responses were measured using the large floating-ring consolidometer (indicating similar boundary effects), despite the significantly different specimen scale and aspect ratios of 1:0.5 and 1:4, respectively. However, the distinct advantage of the consolidometer is that the much larger

specimen size is more representative (compared to standard oedometer and Rowe-cell tests) of the inherently heterogeneous and anisotropic peat deposit, which is demonstrated by the fact that the laboratory hydraulic conductivity measurements were consistent with field measurements reported in literature.

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Tiivistelmä:

Turpeen ja muiden orgaanisten maiden painumisen mittaaminen uudella mittaustekniikalla

Suhteellisen pienet ja paikalliset muutokset maahan kohdistuvassa jännityksessä voivat aiheuttaa suolla merkittävää turpeen pitkäaikaista painumista ja edelleen sen hydraulisen johtavuuden pienenemistä. Tyypillisiä turpeen painumisen aiheuttajia ovat pohjavedenpinnan tason lasku tai maan pintaan kohdistuva mekaaninen paino. Turpeen painumisella voi usein olla merkittäviä muutoksia suon pinnan morfologiaan ja hydrologiaan. Tässä selvityksessä kuvataan orgaanisen maan painumisen tutkimiseen kehitetyn uuden mittalaitteiston kokoonpano ja toimintaperiaate sekä esitetään laitteistolla tehtyjä testituloksia. Laite on varustettu kelluvalla näytekammiolla ja se mahdollistaa tavanomaista suurempien häiriytymättömien turveäytteiden rakenteen ja hydraulisten ominaisuuksien muutosten tarkan mittaamisen. Laitteen mittaustarkkuutta testattiin laadukkailla häiriytymättömillä turvenäytteillä ja testauksissa mitattiin turpeen hydraulisia ominaisuuksia virtausolosuhteissa, joissa Reynoldsin luku oli pieni ja painekorkeus pidettiin vakiona. Testaukset suoritettiin käyttämällä sekä kiinteä- että kelluvakammioista laitteistoa ja saatuja tuloksia verrattiin perinteisellä odometrillä tehtyihin testituloksiin. Tulokset osoittivat, että kehitetyllä laitteistolla mitattavien maanäytteiden suuri koko (läpimitta 152 mm ja pituus 300 mm) säilyttää pientä näytettä paremmin tekstuurin rakennetta ja siten sillä on mahdollista muita menetelmiä tarkemmin mitata turvemaiden ja muiden orgaanisten maiden painumista *in situ* olosuhteissa .