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ENVIRONMENTAL GEOTECHNICS FOR PEATLAND MANAGEMENT AND RESTORATION

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Abstract

Peatlands are dynamic eco-hydrological wetland systems, increasingly under threat worldwide due to natural and anthropogenic effects, including large-scale drainage and oxidation, causing their subsidence and ecological deterioration. In Europe, the requirements for conservation, restoration and long-term sustainability of degraded active bog have been accentuated by more stringent environmental policy and legislation. This paper describes how peat bunds (dams), strategically constructed at affected areas around the bog margins, can gradually re-establish the natural peatland hydrology and peat-forming vegetation through collection, storage and controlled release of surface runoff from the high bog. For geotechnical stability, the translational-type slip failure was identified as the critical case. The analysis must account for drying out of the compacted peat during drought periods and ensuing increases in lateral and uplift hydraulic pressures and seepage pressures generated following torrential rainfall events. Various geotechnical issues, including how much the current soil mechanics framework, standard strength-measurement procedures and ways of evaluating pertinent parameters should be used in describing fibrous peat behavior, are also described. Finally, subsidence and/or restoration of peatland may occur over protracted time periods, making monitoring a challenge. In this regard, airborne LiDAR scanning and geophysical techniques provide rapid, economical topographic and depth profiling in peatlands, with the latter also providing engineering-property characterization, to augment conventional GPS surveying, auger and penetrometer methods.

Keywords: *conservation, dams, geotechnical, hydrology, monitoring, stability, subsidence, wetland*

1. INTRODUCTION

Peat deposits are encountered in many geographical areas, covering large areas of the world's land mass. These waterlogged, heterogeneous and anisotropic deposits comprise the fragmented remains of dead plant vegetation that build up over time where there is a persistent presence of water to promote new plant growth in the 0·1–0·6m deep layer (*acrotelm*) as well as maintenance of dead plant remains in underlying layers (*catotelm*), typically many meters in depth. As such, peat materials, developed over thousands of years, generally have extremely high water content, low shear strength, very high compressibility and they are relatively permeable at in-situ stress (O'Kelly 2006, 2017). Morphological differences arise from the circumstances producing the peatland formation and its plant types. Constituent organic fibers are in the forms of decomposed wood remains, leaves, stems and leave stalks, rootlets, rhizoids and any other elongated plants or plant remains. Depending on their degree of humification, the organic solids can exist as fresh (intact) fibers, slightly decomposed or ultimately fully decomposed (amorphous) material (O'Kelly and Pichan 2013).

Peatlands are dynamic eco-hydrological wetland systems, increasingly under threat worldwide due to natural and anthropogenic affects, especially over the last century. For instance, only about 19% of the 1.3 million hectare peatland resource that once covered the island of Ireland currently remains intact. Many of these peatlands are experiencing degradation due to the effects of large-scale peripheral and/or radial drainage systems that accelerate the rates of peat oxidation, adverse chemical transformations and subsequent subsidence of the peat mass which tends to propagate across the peatland. In terms of ground subsidence and ecological damage, the thinning peat and clay layer at the margins is typically where drainage and localized turf cutting for fuel have most impacted. However, their effects on bog hydrology can extend tens of meters to hundreds of meters from a cutting face towards the high bog, depending on peat substrate hydrogeological conditions and extraction techniques employed. Relatively small and localized increases in effective stress levels arising from a reduction in elevation of the natural groundwater table or alternatively due to applied surface loading can cause significant and ongoing settlements and hence reductions in the hydraulic conductivity which can have widespread impacts on the peatland morphology and hydrology (O'Kelly 2008).

More stringent environmental policy and legislation in Europe, partly following the EU Habitats and Water Framework Directives, have accentuated the requirements for conservation, restoration and long-term sustainability of degraded active bog ecosystems, particularly those that remain relatively intact. This work requires understanding and careful management of the bog hydrology and biodiversity to rebuild the fragile remnants of the original ecosystems, with the objectives of developing and sustaining the characteristic functions required for the transition to a pristine fully-functional wetland. Additionally, in the context of climate change, peatlands gain increasing attention due to their ability to absorb and store carbon, particularly if they are in a natural, undrained state.

After describing typical geomechanical properties and behavior of peat materials, including discussion of standard strength-measurement procedures and ways of evaluating pertinent parameters used in describing fibrous peat behavior, this paper turns to field investigation and monitoring techniques employed for peatlands. The dynamics of peatland morphology are described followed by various roles environmental geotechnics solutions can serve in peatland conservation and restoration, with a particular on focus geotechnical stability aspects of peat bunds (dams). The paper concludes with two field case studies that employ a network of peat bunds or a larger peat dam for the collection, storage and controlled release of surface runoff from the high bog in re-establishing the natural hydrology and peat-forming vegetation at affected areas around the margins of a degraded active raised bog site.

2. GEOMECHANICAL PROPERTIES AND BEHAVIOUR OF PEAT MATERIALS

For peat classification, the type of parent vegetation should always be reported, either by using terms such as 'moss peat', 'fen peat' or, preferably, by referring to the predominant plant type(s) present – for instance, *Sphagnum* peat or sedge peat (O'Kelly 2017). Atterberg limit tests are not appropriate for peat in that the deduced plastic range for the peat test material is notional, such that calculated liquidity index values are not reliable indicators of its consistency (O'Kelly 2015a). In assessing the likely engineering behavior of peat, a more useful suite of index tests is natural water content, organic content, fiber content and degree of humification (O'Kelly 2016).

Geotechnical issues range from the need for a fundamental understanding of the behavior and determination of pertinent parameters for peat as an organic soil at low effective stress, to its use and development as a hydrological barrier in drain blocking or dam construction scenarios near peatland margins in order to mitigate desiccation and promote the growth of species contributing to biodiversity (Johnston and O'Kelly 2016). The in-situ effective stress levels for virgin peat deposits are generally extremely low on account of the waterlogged peat material's very low bulk unit weight of typically 9·5–10·5kN/m^3 (O'Kelly 2017). As such, wetland deposits have great potential for buoyancy generation, prompting the development of novel foundation systems that beneficially incorporate it in foundation design practice for supporting lightweight structures bearing on peaty ground (Aminu et al. 2019). As reported in Zhang and O'Kelly (2014a, 2014b), effective stress theories developed for inorganic soils are routinely applied in practice for peat material, although there are arguably fundamental issues regarding the application of conventional soil mechanics theories and approaches to peat material on account of its extremely high water content, fibrous nature and the flexible, porous (see Fig. 1) and hence permeable, and also compressible, nature of the constituent organic solids.

In Europe and elsewhere, geotechnical stability determinations for dams, dikes, embankments, foundations and slopes in peat deposits routinely involve effective stress analysis, with pertinent shear strength parameters often determined from standard triaxial testing, without special consideration given to internal tensile reinforcement provided by the fiber content and also the high compressibility of the peat material (O'Kelly and Zhang 2013). O'Kelly (2015c) presented a detailed review of current laboratory practice for measurement of the effective-stress shear strength properties of peat materials and encouraged discussion among researchers and practitioners about the best way forward for understanding and determining them. The difficulties of standard triaxial compression testing of fibrous peat material and representing its behavior in an effective-stress Mohr–Coulomb framework are also elaborated in the papers by O'Kelly and Orr (2014) and O'Kelly (2017). Various standard laboratory approaches, including fall cone, miniature vane shear and triaxial compression testing for undrained shear strength (s_u) determinations are described by O'Kelly (2017) for fibrous peats and O'Kelly (2014) for amorphous peat and other highly organic soil materials. For fibrous peats, ongoing debate among researchers concerns how much the current soil mechanics framework, standard strength-measurement procedures and ways of evaluating pertinent parameters should be used to describe their behaviors.

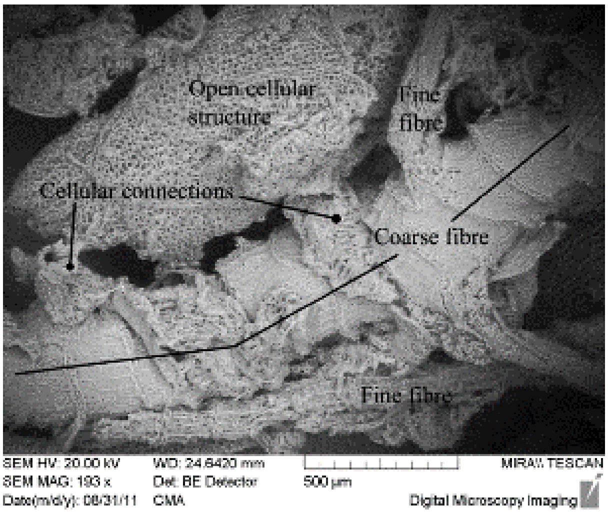

Fig. 1. Scanning electron micrograph of moderately humified organic fibres taken from an Irish *Sphagnum* peat material

Source: Brendan C. O'Kelly, Environmental Geotechnics, vol. 2, no. 1 (February 2015), p. 35.

Considering the structural anisotropy in peat, the shearing mechanism for the field scenario must be carefully considered in choosing a suitable strength apparatus and testing conditions (O'Kelly 2015c). Among the standard and routinely used laboratory strength apparatuses, the shearing mode in the direct simple shear (DSS) device more closely represents that for analysis of translational planar slides — that is, the DSS-derived strength parameter values generally correspond satisfactorily with field strength interpretations for dams, dikes and also embankments bearing on shallow peat deposits (see O'Kelly (2017)). For virgin peat, 0·46 is a representative value for the DSS-derived normalized undrained strength ratio, with 0·40 given as a tentative lower bound, and approximately 28° for its effective angle of shearing resistance value (O'Kelly, 2017).

The very high compressibility, secondary compression (creep) rate and hydraulic conductivity of fibrous peats have been well described in the papers by O'Kelly (2005a, 2005b, 2006, 2007). Secondary compression is defined as ongoing settlement for a constant effective stress level, one reasonable explanation of the phenomenon based on the gradual expulsion of pore water from micropores within the organic solids to the macropore between them (Adams 1964, O'Kelly 2014) — the so called two-level structure concept. Considering the inhomogeneity of peat material and small test-specimen sizes employed for standard laboratory testing methods, O'Kelly (2008a, 2009) developed a large consolidometer-permeameter apparatus to accurately measure both the settlement response and hydraulic characteristics of 152-mm diameter undisturbed peat test-specimens under constant-head low Reynolds Number flow conditions. Another peculiarity of the material is that since its organic fabric can absorb as well as transmit water (and nutrients), peat arguably does not behave as a conventional Darcian medium.

Natural decomposition of the constituent organic matter produces permanent material changes, including progressive destruction of constituent fibers, disappearance of physical structure/fabric, reduction in water-holding capacity, weakening of adsorption complex, gas generation and reduction in solids volume, which significantly alter the shear strength and compression properties and behavior of fibrous peat (O'Kelly and Pichan 2013, 2014; Pichan and O'Kelly 2013). Hence, an understanding of the relationship between degree of humification and engineering properties is vital from a geotechnical perspective. Comprehensive reviews of the effects of decomposition on the compressibility of fibrous peats are presented in the papers by Pichan and O'Kelly (2012) and O'Kelly and Pichan (2013). The final stage of the decomposition process involves the conversion of humic substances into gases, including carbon dioxide and methane, or dissolved organic carbon as end-products, with the total gas void content of natural peat deposits generally ranging 5–10% (Hobbs 1986). These gases accumulate into bubbles, thereby generating a slight buoyancy effect for waterlogged peat material, before they are released from the peat mass to atmosphere through an ebullition process dependent upon ambient barometric pressures. The decomposition rate is generally extremely slow under normal subsurface conditions on account of the non-conducive environment (Pichan and O'Kelly 2013, O'Kelly and Pichan 2014). However, many peatlands are experiencing accelerated degradation due to the effects of large-scale drainage and oxidation, causing their subsidence. Numerous case studies report that the bulk of the subsidence for drained peatland is attributed to the decomposition of organics. For example, 55–80% of the subsidence that occurred for the Sacramento–San Joaquin Delta peat deposit, California, USA, was substantially caused by decomposition (Drexler et al. 2009). Beuving and van den Akker (1996) reported that in grassland on peat, almost 0·5m depth of peat layer is oxidized per 100 years. A similar subsidence rate (i.e. >150 mm over a 35-year monitoring period) reported for ombrotrophic parts of the Komosse Bog Complex, Sweden, was attributed to decomposition that occurred on account of changes in climate, hydrology and rate of nutrient supply (Franzen 2006). Subsidence may be exacerbated by underlying regional groundwater level changes.

There is a dearth of reported work on the link between geotechnical properties and the botanical constituents of peat materials. The author's opinion is that differences in botanical composition can at least partly explain differences in geotechnical behaviors for various peat materials, as substantiated by significant differences measured in field vane strength values documented for waterlogged *Sphagnum* peat underlain by fen/reed peat at the Ballydermot bog, County Offaly, Ireland (see Fig. 2).

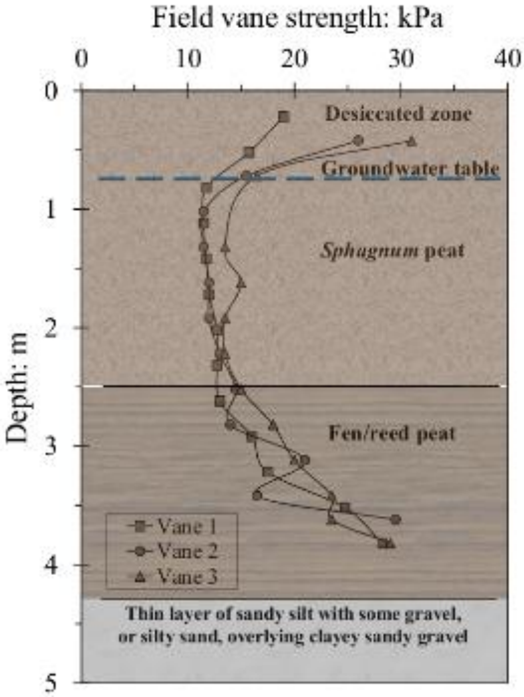

Fig. 2. Nominal undrained shear strength profiles from field vane testing for moderately to strongly humified peat deposit at cutaway section of the Ballydermot raised bog, County Offaly, Ireland

Source: Brendan C. O'Kelly, Geotechnical Research, vol. 4, no. 3 (2017), p. 140.

Careful measurements from nests of piezometers for various depths at this site also illustrated the importance of knowledge of the bog hydrology in understanding the in-situ geomechanical behavior, with the peat deposit underlain by higher permeability sub-artesian inorganic soil layers that induced downward flow and hence self-consolidation of lower fen/reed peat layers (O'Kelly, 2015b, 2017).

A review of the main soil constitutive models that have been developed and applied for modelling the complex geomechanical behavior of peat and other highly organic soil materials is presented by Zhang and O'Kelly (2013). At present, predictions of the geomechanical behavior of these soils for design practice is mostly based on constitutive theories developed for fine-grained inorganic soils, with adjustment to consider the large-strain problems typically encountered in dealing with peat deposits (Zhang and O'Kelly 2013, 2014). Several plausible conceptual models of peat consolidation have been proposed, such as the two-level structure concept mentioned earlier, and micromechanical models developed accordingly. The state-of-the-art includes employing specialized creep models that combine (modified) Cam-Clay with the isotache description of soil compressibility in simulating the soft and viscous nature of peat material; for example, using the Soft-Soil Creep model implemented in the PLAXIS® finite-element code. As recommended by O'Kelly and Orr (2014) and O'Kelly (2015c), there needs to be further development of existing and new specific material models to simulate more accurately the general cross-anisotropic fabric and reinforcement provided by fibers in peats with low humification. In this regard, Zhang et al. (2017) extended a hyperviscoplastic constitutive model proposed for peat to account for structural cross-anisotropy, which was modelled with a fiber layer characterized by a vector field.

3. FIELD INVESTIGATIONS AND MONITORING OF PEATLANDS

Conventional profiling of peat deposits employs auger devices (see O'Kelly (2015b)) and penetrometer methods, including the cone penetration test (CPT), piezocone and full-flow probes — ball-piezometer and perhaps also the T-bar (see Long and Boylan (2012)). Geophysical electrical resistivity tomography, ground penetrating radar and multi-channel analysis of surface waves (MASW) techniques are now used extensively for rapid, economical profiling and engineering-property characterization in peatlands, as well as for the underlying soil layers (Long and Boylan 2012). Linking to an accurate global positioning system (GPS) allows spatial relocation to GPS co-ordinates, as well as providing topographic information. Using the current penetrometer and field-vane testing methods in-situ to determine the undrained shear strength of fibrous peat seems not suitable, in so far as capturing its behavior and shear strength where there is some type of reinforcement acting due to the constituent fibers and where also tensile strength is an important factor (O'Kelly, 2017).

In terms of peatland conservation and restoration, understanding the site-specific hydrological and hydrogeological conditions is essential. Hydrological gradients over the site area can be determined from monitoring of chemical parameters and water levels (e.g. using networks of standpipe piezometers and phreatic tubes). Data on the vertical hydraulic gradients and seepage patterns can be obtained from nests of piezometers, each installed for different monitoring depths.

The processes of subsidence or rehydration of peatland may occur over protracted time periods, making monitoring a challenge. In this regard, use of airborne light detection and ranging (LiDAR) scanner data is considered effective, particularly for hydro-ecological and morphological research of peatlands and in planning improvement projects for peatland habitats. As described in O'Kelly et al. (2007), the advantages of airborne LiDAR surveys are to get the morphology of large areas quickly, more easily and potentially more accurately since there is no intervention between the measurement system and the peatland surface which can easily move underfoot during conventional GPS surveying.

4. DYNAMICS OF PEATLAND MORPHOLOGY

Peatland morphology changes annually, with the in-situ peat material absorbing water and thereby swelling during the wintertime and then releasing water (usually through evapotranspiration) during the summertime, producing typical ground surface elevation changes of 30–50cm (O'Kelly et al. 2007, O'Kelly 2008b). The dynamics of peatland morphology are critical in understanding its hydrological functioning and for effectively supporting the hydroecology. For instance, the sustainability of healthy *Sphagnum* mosses, key species in the *acrotelm* layer for active raised bogs, depends on the availability of sufficient rainwater, with their growth becoming stunted, disrupting the natural growth pattern, when the mean groundwater level drops about 10cm below the ground surface elevation and/or the surface gradient increases beyond approximately 1:30 (Schouten 2002, O'Kelly 2008b) — that is, rainwater runoff occurs rather than infiltration and swelling of the peat deposit on the annual cycle.

The health of a raised bog can be measured according to expected vegetation species in the high bog and bog margins, healthy ones having a naturally high groundwater table usually coincident with the ground surface. Perimeter ditches and local cutaway areas cause lowering of the naturally high groundwater level leading to ground subsidence that tends to propagate towards the high bog. Once the *acrotelm* layer has regained contact with the new equilibrium groundwater table, the *Sphagnum* mosses can naturally regenerate in time.

5. GEOTECHNICS FOR PEATLAND CONSERVATION AND RESTORATION

Restoration of degraded active raised bog has, to date, focused on rebuilding the fragile remnants of original ecosystems by manipulating and restoring ecosystem structure and management of hydrology and biodiversity to develop and sustain the characteristic functions required for the transition to a pristine fully-functional peatland. The development of a management plan that embraces the hydrological regime, biogeochemical cycling, macro- and micro-topography in combination with monitoring and analysis of data over many decades are necessary for achievement of these aims.

Understanding the hydrological and hydrogeological supporting conditions required for active raised bog to survive and predicting its behavior under drainage or rewetting form the cornerstone of conservation and restoration program research. Various engineering solutions have been successfully implemented to gradually re-establish the natural peatland hydrology and peat-forming vegetation, including: blocking existing drains; placing hydrological barriers within the bog to reduce overall seepage rates; strategically constructing peat dams and/or networks of peat bunds at affected areas around the bog margins for the collection, storage and controlled release of surface runoff from the high bog. For better results, it is important that ponded water levels behind these structures remain at near full capacity throughout the year. Should the ponded water dissipate (e.g., as a result of excessive seepage, a breach in the bund network/dam or during drought), as discussed later in the paper, ensuing reductions in self-weight for drying out of the bund peat may have serious knock-on effects in terms of their overall lateral stability. The engineering measures described here can be used independently or integrated, depending on the site conditions and extent of the treatment area.

6. GEOTECHNICAL ASPECTS OF PEAT DAM AND DIKE STABILITY

For peat bund, dam and dike structures, translational-type slip failure involving lateral displacement of a large intact peat block is generally the critical case for geotechnical instability (van Baars 2005, McInerney et al. 2007, O'Kelly 2008b, 2017) — that is, geotechnical designs based on the factor of safety approach against circular-slip type failure are invariably grossly non-conservative. Unexpected structural breaches for peat dams and dikes include a 3m-high peat dam at Raheenmore raised bog, County Offaly, Ireland (O'Kelly et al. 2007, O'Kelly 2008b), and sections of the Grand Canal embankment near Edenderry, County Offaly, Ireland (Pigott et al. 1992), and canal dike at Wilnis, the Netherlands (van Baars 2005). The Raheenmore peat dam failure is described in the next section.

The Grand Canal embankment, which transverses the Bog of Allen, was constructed by compacting air-dried peat material in 0.5m lifts after which a channel ranging 13–16m wide was excavated into the top of the embankment to form the line of the canal. Referring to Fig. 3(a), the embankment failure involved the lateral displacement of a large intact peat block (225×105m in plan area and up to10m high) through a distance of up to 60m, with the slip plane inclined at an angle of 2·5° below the horizontal, extending into the in-situ peat foundation. Referring to Fig. 3(b), the Wilnis canal dike breach involved the lateral displacement of a 60m-long intact peat block through a distance of 10m and occurred at the end of the warmest and driest summer period recorded in 50 years.

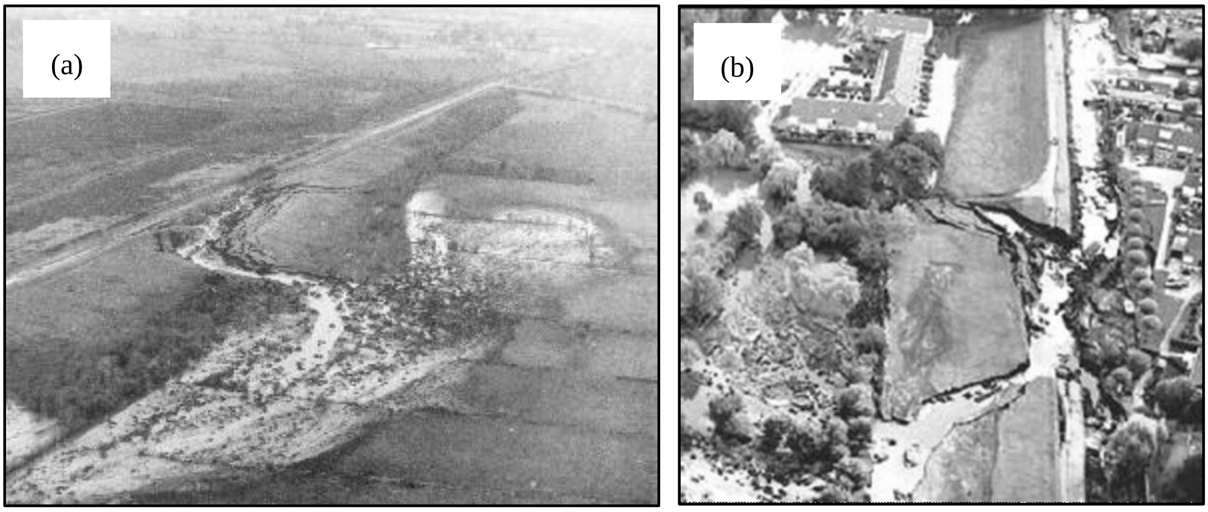

Fig. 3. Translational-slip failure mode for peat dikes: (a) Grand Canal embankment; (b) Wilnis dike

Source: Fig. 3(a), P.T. Pigott et al., Proceedings of the Institution of Civil Engineers – Water, Maritime and Energy, vol. 96, no. 3 (1992); Fig. 3(b), S. van Baars, Géotechnique, vol. 55, no. 4 (2005).

Principal contributing factors identified for these breaches were drying out of the peat material near the downslope crest and formation of tension cracks in the underlying peat layer during the preceding drought period. The former had the effect of reducing the dike self-weight and hence ultimate shear-resistance capacity mobilizable over the dike base area in response to sudden increases in lateral and uplift hydraulic pressures acting through rising water levels following torrential rainfall events (O'Kelly et al. 2007). In other words, geotechnical design for lateral stability of these structures must consider the effects of seasonal drying by evapotranspiration of the construction peat material, especially near the downslope crest, combined with sudden increases in lateral and uplift hydraulic pressures and seepage pressures acting beneath their base areas.

7. FIELD CASE STUDY

7.1. Raheenmore raised bog, County Offaly, Ireland

Raheenmore bog is a 162-hectare designated nature reserve (Special Area of Conservation) and a classic example of an active raised bog, with characteristic well-developed dome shaped relief (central peat depths of up to 15m) that has risen above the surrounding countryside. The micro-relief of this bog comprises undulating hummock and hollow systems (approximately 10–30cm in height differential), with some ponding of runoff water in the hollows. Although its margins have been arterially drained and some turf cutting had also occurred in the past, the Raheenmore bog, having slope gradients of between 1:50 and 1:100, remains remarkably intact and was identified as one of the few active raised bogs in Ireland where the restoration of the lagg zone around the bog margins was feasible. Initial measures at re-establishing the natural groundwater balance at this site involved blocking existing radial surface drains at approximately 10m intervals along their length, although this measure alone was not sufficient to arrest the propagation of the subsidence trough.

7.1.1. Cascade network of peat bunds constructed in 1994–1995

Following a series of geological and hydrological appraisals by the Irish–Dutch Raised Bog Study (Streefkerk and Zandstra 1994), a desiccated area near the south-eastern bog margin, with sparse vegetation cover and typical slope gradient of 1:20, was identified for the construction of a semi-concentric peat bund network. This employed a cascade system to pond surface runoff water over large sections of the treatment area (see Fig. 4), manipulating the hydrology to replicate an hydraulic gradient of less than 1:30, so as to arrest the propagation of the subsidence trough, restore the natural groundwater balance and create conditions conductive to re-colonization of the affected areas by indigenous plants over time.

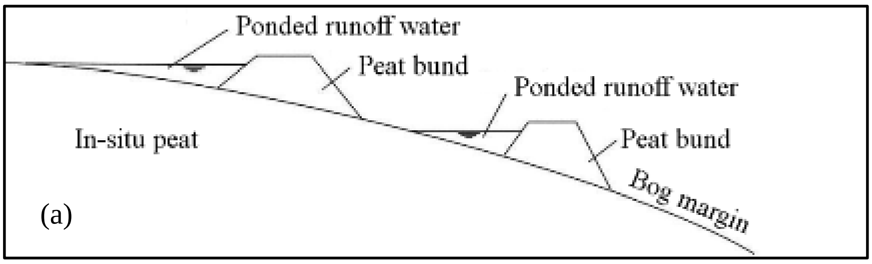

Fig. 4. Cascade network of peat bunds near south-eastern margin of Raheenmore raised bog, County Offaly, Ireland: (a) schematic diagram; (b) terrestrial image

Source: Fig. 4(b), Google Earth.

Based on experience gained in the construction of similar structures at the Bargerveen Nature Reserve, the Netherlands, the south-eastern bund network at the Raheenmore bog was constructed during the summers of 1994 and 1995 using locally sourced air-dried peat material. Individual bunds were up to approximately 306-m in length, 0·5–3m in height which increased closer to the bog margin, with crown widths of 1·5–5m, and 1:1 side slopes. With a crown width of 5·0m, the 3m-high peat bund (dam) had the largest cross-sectional area of approximately 20m^2.

The cascade system approach allows almost complete submergence of a sizeable area of more steeply sloping ground, whilst limiting lateral and uplift hydraulic pressures acting on the peat bunds, as well as destabilizing seepage pressures, to acceptably low levels. In manipulating the in-situ hydraulic gradient, it is important that the bund design height and overflow level take into account the annual cycle of swelling and shrinkage of the peat deposit and hence accompanying rise and drop in elevation of the bunds themselves. Additionally, the compression of the underlying peat layer as a result of the surcharge pressure provided by the bunds' self-weights must be considered.

The ponded water depth was greatest for the outermost 3m-high bund, with a maximum retained water depth along its length of 2·5m, and was controlled by a network of overflow pipes that passed horizontally through the bund, discharging some distance beyond its toe. Radial cross-bunds compartmentalized complete and incomplete sections of the bund network during its construction over the two consecutive summer periods. As mentioned earlier, to achieve better results, ponded water levels need to remain at near full-capacity throughout the year, although this may not be achievable where excessive seepage occurs or for drought periods. The increased head produced by the ponded water increases rates of seepage, either by way of underlying in-situ peat material or, depending on the site hydrogeology, vertical exfiltration of the groundwater to underlying higher-permeability lacustrine clay or glacial till layers. For the latter case, ponded water levels are generally controlled by vertical seepage and exfiltration of groundwater under the head difference between them and the water level in the perimeter ditch that often penetrate underlying higher permeability inorganic deposits. Seepage rates through the bunds themselves are reduced by constructing them using strongly-decomposed compacted air-dried peat material — that is, compared to fibrous peat, more strongly decomposed peat has significantly lower hydraulic conductivity (O'Kelly 2006, O'Kelly and Pichan 2013). Seepage rates through the underlying in-situ peat, especially for the relatively higher permeability *acrotelm* layer, were substantially reduced by inserting high-density plastic membranes, running from beneath the center of the smaller bunds vertically into the in-situ peat during their construction.

In December 1998, a section of the outer 3m-high peat bund was breached, with discharge water and peat debris flooding approximately 0·36 hectares of neighboring land. The breach involved the lateral displacement by up to 1·5m of a largely intact peat block on a slip plane coincident with the surface of the desiccated in-situ peat layer and inclined at approximately 3·5° below the horizontal (Bennett 1998). The ground surface was observed to have risen locally ahead of the advancing peat block. Meteorological records indicated an extended drought period at the site, with the slip-failure preceded by a torrential rainfall event, although it was not exceptional.

Various post-failure site investigation and testing and back-calculations were performed in order to understand the cause(s) of the breach event. The bulk unit weight of the strongly-decomposed compacted air-dried peat material used to construct the bund core was measured as 10·5kN/m^3, whereas partially dried out material at 1·0m depth below the downslope crest had a significantly lower value of approximately 5·0kN/m^3 (O'Kelly 2008b). Piezometer measurements indicated that the phreatic level beneath the down crest typically ranged 0·5–1·7m below crown level. Using the van Baars (2005) method and the numerical finite-element package PLAXIS®, McInerney et al. (2006, 2007) and O'Kelly (2008b) back-analyzed the breached section at which the ponded water depth was controlled at 1·5m by the pipe-overflow network. Their preliminary findings confirmed that for the worst-case combination of significant reductions in bulk unit weight of the downslope-crest peat material and ensuing increases in lateral and uplift hydraulic pressures acting on the bund arising from the 1·5m depth of ponded runoff water accumulated following torrential rainfall events produced an unstable translational-slide condition. That is, for the case of the ponded water at the pipe-overflow level, the factor of safety against the likelihood of a translational-slip failure occurring reduced from approximately 2·7 to less than unity when saturated peat material near the downslope crest had dried out during the extended drought period preceding the failure event (O'Kelly 2008b).

For bunds located near the bog margins, characteristic thinning and increases in elevation of the in-situ peat and of the underlying lower hydraulic conductivity lacustrine clay layer occur, locally altering the flow dynamics. Significant pressure heads arising from the ponded water increase destabilizing upward seepage pressures acting near the bund toe, which must be considered in the analysis. Tension cracks observed in the in-situ peat around the location of the breach would have provided preferential flow pathways, possibly causing piping beneath the bund toe and hence another destabilizing effect.

In light of the lessons learned, the remaining bunds at this location were strengthened by driving 5-m long wooden poles vertically into them to penetrate the underlying in-situ peat. The poles function as shear dowels, thereby increasing the ultimate lateral shear-resistance capacity of these bunds. Moreover, future design should aim, at a minimum, to maintain retained water levels in the peat as close as possible to any reconfigured surface topography.

7.1.2. Peat dam constructed in 1997

In 1997, a 3m-high peat dam was constructed along a cutaway section near the northern perimeter of the Raheenmore bog to retain 2·5m depth of ponded runoff water (see Fig. 5), building on earlier experience gained in constructing the bund network at the south-eastern margins of the same bog.

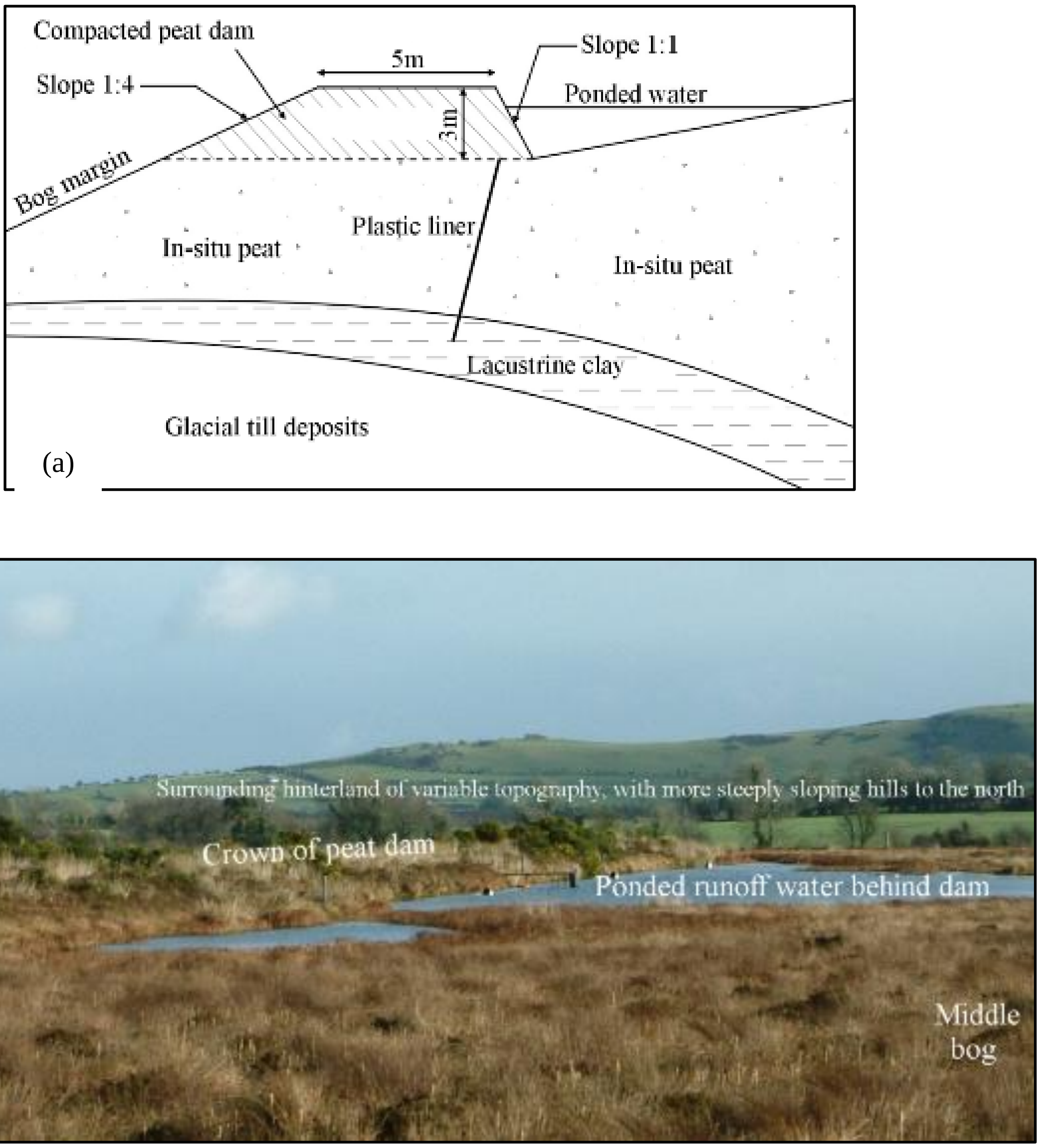

Fig. 5. Peat dam near northern margin of Raheenmore raised bog, County Offaly, Ireland: (a) schematic cross-section diagram; (b) photograph taken from high bog

Compared to the 3m-high peat bunds constructed at the south-eastern boundary in 1994–1995, the cross-sectional area of this dam was substantially greater at approximately 38m^2 on account of the much reduced gradient of four horizontal to one vertical adopted for the downside slope. The increased base width allowed easier compaction of the strongly decomposed air-dried peat material by tracking with machine plant as it was placed in lifts to construct the dam. In terms of lateral stability, the increased cross-sectional area produced greater self-weight and base contact area with the underlying in-situ peat, thereby increasing the dam’s ultimate lateral shear-resistance capacity and overall factor of safety on geotechnical instability for the worst-case scenario combination of events to satisfactory values.

The seepage rate and hence seepage pressures acting beneath the dam were substantially reduced by installing a high-density plastic membrane, running from the dam heel and keyed into the underlying lacustrine clay layer (ref to Fig. 5(a)), which tends to suppress the downward exfiltration rate. This 3m-high peat dam has performed satisfactorily in terms of its geotechnical stability over the intervening 20 years. An option meriting investigation for future peat dam construction is capping of the crown and side slopes using imported clay or high-density plastic membrane protected with imported sod peat material in order to reduce seepage losses and also prevent drying out of the compacted peat material which can potentially have a detrimental effect for its lateral stability. The ultimate lateral shear resistance capacity can also be substantially increased by incorporating a shear key between the dam structure and underlying in-situ peat deposit during construction.

Further, and importantly, extensive monitoring of the morphology and hydrology over many years using both GPS surveying and airborne LiDAR has demonstrated the effectiveness of the described approach in restoring the natural hydrology and in rehabilitating affected areas of the bog — that is, over the six-year period following the northern dam construction, the desiccated surface layer of peat material in the area behind the dam had become fully re-saturated, the bog surface had steadily risen by up to 1·0m and natural rejuvenation of indigenous *Sphagnum* mosses had begun to recolonize and infill along the edges of the ponded water (Bennett 1998, Kawisso 2003, O'Kelly et al. 2007). Swelling on re-saturation of the peat material tends to close existing tension cracks, thereby further reducing seepage rates through the *catotelm* layers.

8. SUMMARY AND CONCLUSIONS

Peat is considered as a challenging geomaterial, many aspects of its behavior seemingly remaining enigmas, including how much the current soil mechanics framework, standard strength-measurement procedures and ways of evaluating pertinent parameters should be used in describing the geomechanical behavior of fibrous peats.

Airborne LiDAR scanning and geophysical techniques provide rapid, economical topographic and depth profiling as well as engineering-property characterization for peatlands to complement conventional GPS surveying, auger and penetrometer methods.

Restoration of degraded active raised bog focuses on manipulating and restoring ecosystem structure and careful management of hydrology and biodiversity to develop and sustain the characteristic functions required for the transition to a pristine fully functioning peatland. Peat bunds (dams) strategically constructed at affected areas around the bog margins for the collection, storage and controlled release of surface runoff from the high bog have proved effective means of arresting the propagation of the subsidence trough, restoring the natural groundwater balance and creating conditions conductive to re-colonization by indigenous plants, provided the local hydrogeology is taken into account.

For more steeply sloping ground, a cascade system of peat bunds can be employed to achieve an hydraulic gradient of less than 1:30. Substantial reductions in seepage rates and destabilizing upward seepage pressures acting near the bund toe are achieved by placement of a high-density plastic membrane, running from the heal of the peat dam through the in-situ peat and keyed into the underlying lacustrine clay layer. Close management of the depths of ponded water is also necessary to promote recolonization by bog vegetation.

The critical case for geotechnical instability of peat bunds (dams) is translational-type slip failure, and its analysis must consider drying out of the compacted peat during drought periods combined with ensuing increases in lateral and uplift hydraulic pressures acting on the bund, and seepage pressures beneath its base, generated following torrential rainfall events.

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