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Geotechnical engineering for wind farms on peatland sites

Géotechnique des parcs éoliens sur les sites de tourbières

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ABSTRACT Ireland's commitment to renewable energy has resulted in a large number of on-shore wind farm sites being investigated and developed. The most advantageous wind conditions and locations for wind farm developments frequently coincide with upland peatland areas particularly in the west of the country. This has led to the investigation and development of sometimes difficult and sensitive peatland sites. This paper uses the experience gained from a large number of wind farm developments on peatland sites to discuss the main geotechnical engineering hazards encountered along with engineering techniques and approaches used to overcome them. The hazards, which are generally associated with low shear strength and high compressibility of peat, range from large-scale peat slides to excessive settlement.

RÉSUMÉ L'engagement de l'Irlande à l'énergie renouvelable a donné lieu à un grand nombre de sites éoliens on-shore objet d'une enquête et développé. Les conditions et les lieux de vent les plus avantageuses pour les développements de parcs éoliens coïncidents souvent avec des zones de tourbières hautes terres en particulier dans l'ouest du pays. Cela a conduit à la recherche et le développement de sites de tourbières parfois difficiles et délicates. Cet article utilise l'expérience acquise à partir d'un grand nombre de projets de développement éolien de la ferme sur les sites de tourbières pour discuter des principaux risques d'ingénierie géotechnique rencontrés avec les techniques d'ingénierie et les approches utilisées pour les surmonter . Les risques, qui sont généralement associés à faible résistance au cisaillement et compressibilité élevée de tourbe, vont de diapositives de tourbe à grande échelle à un tassement excessif.

1 BACKGROUND

Ireland's commitment to the European Union regarding renewable energy has resulted in a large number of on-shore wind farm sites around the country being investigated and developed. Following the 2009 Renewable Energy Directive (2009/28/EC) in relation to electricity consumption, Ireland has a requirement and target of 40% to be generated from renewable sources by 2020. A large number of these wind farm sites have been developed particularly along the western seaboard to take advantage of the strong Atlantic winds. This has led to the investigation and development of sometimes difficult and sensitive peatland sites which are covered with deep blanket peat on sloping ground.

The authors have been involved in over 80 wind farm developments on peatland sites in Ireland (Figure 1) and on other sites in the United Kingdom, at various stages of development. The potential power generated from the 80 sites in Ireland worked on by AGEC is estimated at over 1,200MW.

This paper discusses the geotechnical engineering hazards commonly encountered on peatland sites, along with some observations on engineering techniques and approaches used to overcome them. Hazards range from large-scale peat slides to serviceability of infrastructure on weak and compressible peat.

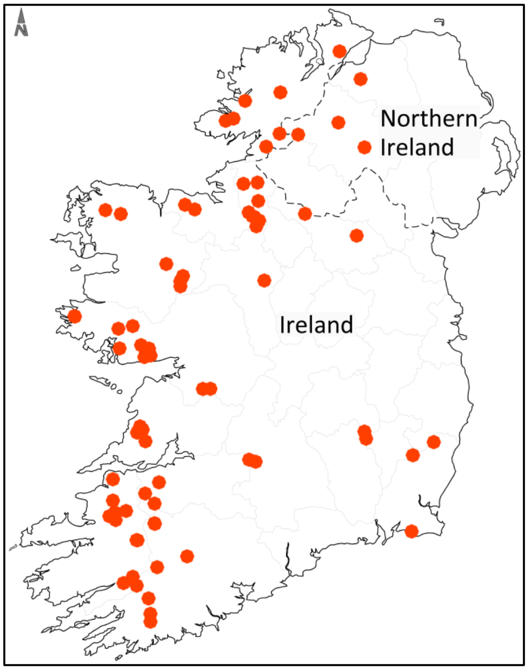

Figure 1. Plan of wind farm development sites worked on by AGEC (80 nos.)

2 PEATLAND IN IRELAND

2.1 Distribution of Peatland

Three main type of peatland, or bog, occur in Ireland namely upland blanket bog, lowland blanket (oceanic) bog and raised bog. Peatland is generally found in areas of high rainfall under conditions of poor drainage. About 21% of the land mass of Ireland is covered by peatland (Connolly et al. 2009).

Upland blanket bog covers large expanses of most of the mountainous areas and would be the dominant peatland encountered on wind farm sites. In the west, due to the wetter climate, blanket bog occurs down to sea-level (oceanic bog). Raised bogs are commonly found in the midlands in generally flat areas. Raised bogs generally tend to be 3 to 12m thick. Blanket bogs would typically be 3m thick, but as the underlying surface is irregular, locally thicker deposits are commonly present. Blanket bog thickness typically thins at greater elevations.

2.2 Engineering Characteristics of Peat

The engineering characteristics of peat are covered in detail in a number of papers, for example Hanrahan (1954), McFarlane (1969), Hobbs (1986), Carlston (1988), and more recently Boylan and Long (2014).

Peat is of particular engineering concern due to its low strength and high compressibility. This is significant for wind farm construction where most of the engineering works are on sloping ground and shear failure of the peat can result in large-scale landslides.

Peat consists of the remains of decaying plant life and comprises an upper fibrous layer and lower humified layer (Figure 2). The uppermost peat layer (acrotelm), with a thickness of typically 0.3 to 1m, contains actively growing bog plants and virtually undecayed fibrous plant matter. The acrotelm has relatively high shear strength due to its fibrous nature, and whilst notably compressible, provides a supportive layer above the weaker catotelm layer.

The catotelm contains dead plant matter in various states of decay. As the catotelm is essentially a waterlogged and oxygen deficient environment plant matter slowly putrefies insitu resulting in plant matter slowly decaying (humification). The catotelm has notably low shear strength (Figure 2) and high compressibility.

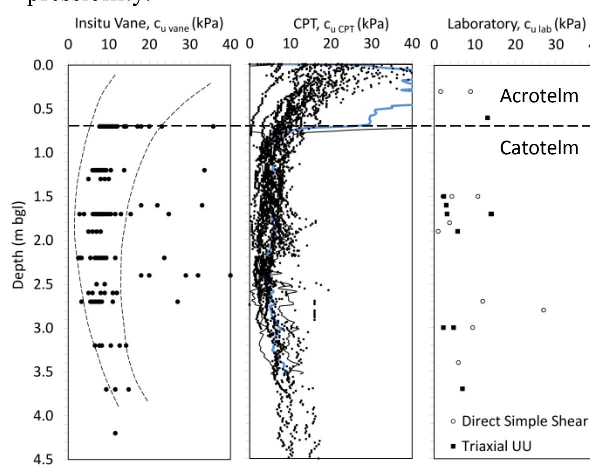

Figure 2. Undrained shear strength measurement in peat

Figure 2 shows several methods (insitu shear vane, CPT and laboratory testing) used to determine the strength of blanket peat at a site in northwest Ireland. Distinguishing between the two peat layers using

such methods can be difficult and there is invariably scatter, due to particularly fibre content.

In practice there is variation between the results of the various testing methods and careful interpretation is required. Notwithstanding, simple methods such as shear vane testing are frequently and most commonly used to determine shear strength (Boylan & Long 2014).

3 GEOTECHNICAL HAZARDS ENCOUNTERED ON PEATLAND SITES

3.1 Geotechnical Hazards

A number of typical geotechnical hazards are commonly associated with construction work on peatland sites, see Table 1.

Table 1 Typical geotechnical hazards and causes on peatland sites

Hazard	Principal Causes
Peat slide	• Unexpected area of weak ground conditions • Extended area of weak ground • Intense rainfall event • Improper construction e.g. excessive loading
Localised peat slope failure	• Unexpected localised weak ground conditions • Intense rainfall event • Improper construction e.g. loading, undercutting
Localised bearing failure	• Unexpected localised weak ground conditions • Excessive loading • Improper construction e.g. floating road, arisings
Instability of peat arisings	• Excessive rainfall • Overly softened arisings • Concentration of surface water
Excavation slope failure in peat during construction	• Unexpected weak ground • Localised slope failure • Water ingress • Loading of excavation slope crest • Slope too steep
Excessive or long term settlement of floating road in peat	• Inadequate site investigation & insufficient understanding of deformation properties of peat • Inadequate road construction • Unexpected localised weak ground conditions • Excessive loading
Failure of base of excavation e.g. liquefaction, piping, heaving	• High groundwater • Presence of sensitive soils e.g. silty sand • Inadequate design and understanding of ground • Loading/vibration/excavation • Improper construction
Flooding of excavation by groundwater	• Elevated groundwater • Interception of water-bearing soils • Unexpected ground conditions

Most of the hazards in Table 1 are related to low shear strength and high compressibility of peat but also include high groundwater and sensitive soils below the peat. In terms of risk, a peat slide would be considered the most severe and considerable geotechnical effort would be dedicated to ensuring that a peat slide could not occur. Other hazards would be related to serviceability issues, such as excessive settlement of floating roads; whilst not considered a major risk nevertheless the operational costs to a development of impaired access roads may be financially unacceptable. A number of the geotechnical hazards are discussed below.

3.2 Peat Slides

Peat slides in Ireland have been dated at about 4200 BP (Murray, 1997), and with written accounts dating back to the 1400s (Feehan and O'Donovan, 1996). There is an estimated over 120 reported events of peat failures in Ireland (GSI, 2006) and undoubtedly a considerable number of unreported events.

Large-scale peat failures in 2003 at Pollatomish, County Mayo and Derrybrien, County Galway, which occurred during the construction of a wind farm, focused attention on to such events. It is now effectively mandatory to include a peat slide assessment as part of the planning requirements for wind farm developments. Peat failure volumes can range from a few 100m^3 to in excess of million m^3 (Boylan et al. 2008).

It is estimated that about 50% of Irish peat failures occur naturally (Dykes 2010) and the remainder are associated with anthropogenic causal factors such as peat cutting or construction activity. Based on the experience of the authors, triggering factors for peat failures typically relate to the type of terrain and peat cover. Where steeper slopes and peat thicknesses are generally thin (<1.0m), rainfall induced peat failures are more common (Figure 3). In contrast, on flatter sites where peat thicknesses are greater (>1.0m) anthropogenic activity is generally the major contributory factor (Figure 4).

A review of a number of peat slides associated with construction activity indicates that failure was generally initiated a short-time after construction activity. This would indicate that the operational shear strength is the undrained strength; for example this appeared to initiate the failure in Figure 4. Peat slides as a result of rainfall are likely controlled by effective strength parameters, this would account for the failures in Figure 3 and the 2003 failures in Pollatomish

and on the Shetland Islands (Dykes & Warburton, 2008).

Figure 3. View of a multiple landslides caused by rainfall (Croaghmoyle & Buckoogh Mountains, Co. Mayo, Ireland)

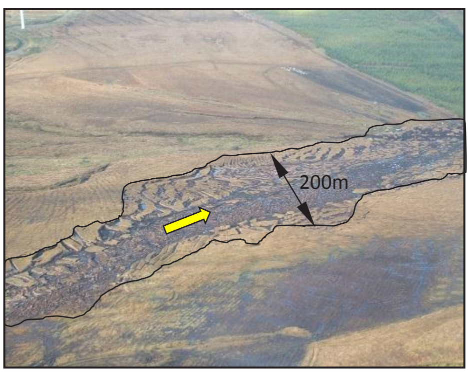

Figure 4. Oblique aerial overview of a peat failure caused by construction/ anthropogenic factors (Ballincollig Hill Wind Farm, Co. Kerry, Ireland)

Peat failures are referred to as bog bursts or more commonly bog slides, which are described (Hutchinson, 1988) as follows:

- Bog flows (or bursts): Type of debris flow which involves large quantities of water/peat debris which flow down-slope usually following existing surface water channels. In many bog flows there is likely an initial shear failure on a discrete sliding surface prior to peat rapidly breaking-down into slurry.
- Bog slides: Comprises a mass of intact peat that moves bodily downslope. Slides occur on a discrete shear plane usually located at depth in the peat. The failed peat typically breaks into smaller pieces, and commonly evolves into a flow.

Historical accounts of bog bursts suggest that many bursts originated as slides. Indeed, inspection of many peat failure scars suggests that initial movement occurs as sliding on a discrete plane within the peat. To this end, many geotechnical peat slide assessments use an infinite slope analysis (e.g. Skempton & DeLory 1957). The use of the infinite slope analysis also explains a common observation of peat failures; that is the sliding surface occurs at depth and close to/at the base of the peat. Figure 5 shows the calculated factor of safety (FoS) at various depths for a peat slope for a range of insitu strength profiles (actual & simplified). This clearly shows that the lowest theoretical FoS, and most likely depth of the shear plane, always occurs at the greatest depth.

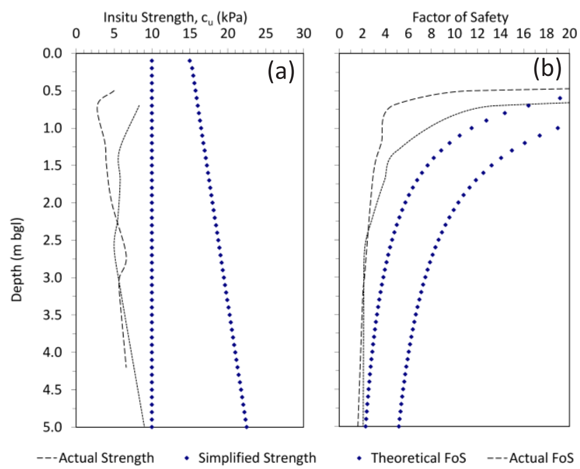

Figure 5. Range of insitu strength profiles (a) and corresponding calculated factor of safety (b) at various depths for a peat slope

For large-scale (run-away) failures to develop there is normally a large body of weak peat present that is set in motion by a triggering event, such as excessive loading. A good indicator for potential areas of weak peat is the fact that there is quaking bog, bog pools or saturated mechanically cut peat on site. Quaking bog is common in level areas and is indicative of highly saturated peat with low strength. The buoyancy effect of the peat is as a result of a body of sub-surface water present at typically the base of the peat.

To provide a relative measure of the scale of weak peat on a site then insitu strength measurement using

a shear vane can be invaluable. Figure 6 shows the results of envelopes of insitu vane testing at a number of sites. The darker shaded envelopes are from Scottish bogs which have been drained; the results clearly show the effect of consolidation and increase in strength with depth. The lighter hatched envelopes are from Irish blanket bog sites which have not been drained and are prone to or have failed.

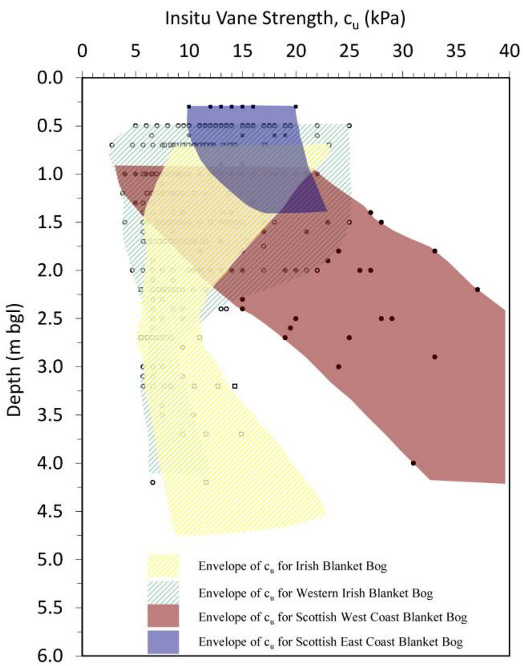

Figure 6. Insitu shear vane results used to indicate the potential for peat slides at a site

Experience suggests that sites prone to large peat slides have a higher proportion of undrained strength at or below about 4kPa, though other factors need to be taken into account, most notably topography. For detailed assessment of peat sliding a combination of peat testing methods should be used; notwithstanding results are invariably scattered and detailed careful interpretation is required. Occasionally, weak sensitive soils may underlie peat; there are a few examples of shear surfaces developing in underlying weaker soils, for example Garvagh Glebe, Ireland 2008.

3.3 Localised Bearing Failure

Where in particular floating roads are constructed there is a reliance on the peat to act as a bearing stratum. Peat characteristics can be spatially variable which can result in localised changes in strength and hence the ability to bear the load of a floating road. Some visual indicators of change in peat strength are for example:

- Quaking peat - common in level areas and is indicative of highly saturated peat with low strength. The buoyancy effect of the peat is as a result of a body of sub-surface water present at typically the base of the peat.
- Bog pools - encountered in level areas with peat in the pool margins notably weak and saturated.
- Changes in topography - subtle changes in surface topography can result in changes in peat strength due to variations in say bog plants, degree of humification, peat depth and groundwater.
- Drainage - commonly drained peatland will result in an increase in peat strength (see Figure 6) but poorly maintained drainage can allow softening of peat and provide potential for tension cracks. Tension cracks are potential signs of peat movement or failure.
- Mechanical peat cutting (harvesting) - results in cutting of the acrotelm layer where most of the intrinsic strength of peat lies.

It is not possible to account for all changes in peat strength by visual indicators alone and detailed site investigation is essential. Site investigation points should be as close as possible; and should be towards the closer spacing recommended in EC7 for linear structures.

3.4 Instability of Peat Arisings

A large volume of excavated peat can be generated during the construction of wind farm infrastructure. Disturbed peat strength can be 50% or less of its peak strength and in many cases behaves as a viscous material that will readily flow particularly when affected by rainfall.

Excavated peat requires appropriate engineered retention/storage measures to prevent potential flow failure and run-off. Disturbed peat can be spread thinly and left to dry on the surface but needs to be suitably shaped and drained to avoid saturation by rainfall. Monitoring of peat storage areas for a period after completion is considered good practice, particularly for peat stored on the surface.

3.5 *Excessive Settlement of Floating Infrastructure*

Peat is highly compressible with notable creep settlement. A review of peat settlement (Long & Boylan 2013) showed that consolidation theory provides a reasonable prediction of settlement, which the authors generally found to be the case in practice. In order to predict settlement detailed investigation with high quality peat sampling and testing is required. As a rule of thumb, under typical floating road loading conditions the underlying peat can consolidate by up to one third of its thickness. However, there are many localised instances where continued excessive creep and unpredicted settlement occurs. As such, it is always prudent to include for maintenance of floating infrastructure on peatland.

4 CONCLUSIONS

(i) In pursuit of Ireland's commitment to renewable energy targets a large number of on-shore wind farm sites have been investigated and developed in locations which invariably coincide with upland peatland.
(ii) Upland blanket bog covers large expanses of most of the mountainous areas and is the dominant peatland type encountered on wind farm sites. Peat depths are typically 3m but can vary significantly.
(iii) There is a combination of specific geotechnical hazards commonly associated with construction work on peatland sites (Table 1), which are as a result of the low shear strength and high compressibility of peat. Hazards range from peat slides to excessive settlement.
(iv) The general types of peat slides, failure mechanisms and analysis are discussed. Slide shear surfaces generally occur at the base of the peat layer and as such site investigation should notably target this depth. Occasionally shear surfaces can develop in underlying weak soils.
(v) Peat strength and compressibility characteristics need to be carefully selected from a thorough ground investigation. Test results are invariably scattered and detailed interpretation based on experience is required. Some guidance is provided in Boylan & Long (2014).
(vi) Due to the natural variability of peat, site investigation points should be as close as possible, especially where floating roads are envisaged. There are many localised instances where there are serviceability problems due to continued excessive and unpredicted settlement. Allowance should be included for inspection and maintenance of infrastructure during the operational phase of any wind farm on peatland.
(vii) The selection of a particular technique or approach for a given wind farm development requires careful planning and consideration and the engagement of experienced personnel. Given the variability of ground conditions on peatland sites a particular technique or approach cannot be universally applied to all sites.

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