

Peat Landslide Hazard and Risk Assessments:

Best Practice Guide for Proposed Electricity Generation Developments

Prepared for
Energy Consents Unit Scottish Government

Second Edition, April 2017

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Introduction

1.1 Purpose

Peat landslides represent one end of a spectrum of natural processes of peat degradation. They have the potential to damage peatland habitats, affect biodiversity and deplete the peatland carbon store, which globally represents some 30% of the carbon stored in world soils (Immirzi *et al.*, 1992). Human activity, including burning, farming (grazing), afforestation and construction may also act to damage the peat resource (e.g. Lindsay and Bragg, 2004).

In the wake of widely reported peat landslide incidents in 2003 (e.g. Dykes and Warburton, 2008; Lindsay and Bragg, 2004; Mills *et al.*, 2007) and given the number of onshore wind farms and small hydro schemes being developed, there has been an increasing focus on peatlands when considering future Section 36 applications seeking consent under the Electricity Act 1989 (Scottish Government *et al.*, 2014; SNH and FCS, 2010; Scottish Renewables and SEPA, 2012). While this guidance is primarily focused on S36 applications for electricity generation projects, the principles apply equally to S37 applications for above-ground overhead lines which pass through peatland environments. This guidance, first published in December 2006 (Scottish Executive, 2006), has been developed to provide best practice information on methods for identifying, mitigating and managing peat landslide hazards and their associated risks.

Following a ten year period of practice this guidance has been updated to reflect new research and publications. The revision takes account of practical experience of working with the guidance from developers, statutory bodies and the Scottish Government Energy Consents Unit against a backdrop of increasing efforts to safeguard peatlands via guidance documents issued in related fields (Scottish Renewables and SEPA, 2012; SEPA, 2010; Scottish Natural Heritage, 2016).

1.2 Guidance objectives

The objectives of this guidance are to:

- Promote best practice and raise awareness of potential peat landslide hazards and their associated risks;
- Provide guidance on identifying natural peat landslide hazards and elevated landslide hazard associated with construction and operation activities in relation to any proposed development;
- Provide guidance on the required scope of site investigations at various stages in the planning process for proposed electricity generation developments; and
- Provide advice on potential mitigation options for detailed feasibility assessment in the planning of upland electricity generation developments in order to reduce peat landslide hazard and risk.

1.3 Context

Blanket bog is the most widespread peatland type in Scotland, particularly in the uplands, and is the one most commonly affected by electricity generation developments. However, raised bogs, intermediate bogs and fens are also sometimes affected, directly or indirectly. All of these habitats are of high value for nature conservation due to their rarity and/or vulnerability and all are particularly susceptible to changes to their

hydrology. Blanket bog, raised bog and some types of fen are on Annex 1 of the EC Habitats Directive, meaning that some examples are worthy of designation as Special Areas of Conservation (SACs).

Lowland raised bog, blanket bog and upland flushes, fens and swamps are included on the Scottish Biodiversity List (SBL), which includes all habitats that Scottish Ministers consider to be of principal importance for biodiversity conservation in Scotland. The SBL was published in 2005 to satisfy the requirement under Section 2(4) of The Nature Conservation (Scotland) Act 2004. The list has been updated several times since its original publication to take into account changes to the UKBAP priorities list, and most recently has been revised into 'Categories for Action' which relate to the different types of activities that public bodies carry out to deliver their Biodiversity Duty.

Peat landslides are a characteristic landscape response of peat uplands to intense rainfall events, and the importance of understanding their impacts and the potential for their occurrence is now well understood. It is estimated that Scotland's peatlands hold approximately 50% of the UK's total soil carbon store (Cummins *et al.*, 2011), and as infrastructure pressure on peat uplands increases, the potential impacts of wind farm developments must be considered alongside their potential benefits.

In recent years, costs and benefits have been considered not just in terms of the stability of the peatland (this guidance), but the volumes of peat excavated, reused and potentially lost during construction (Scottish Renewables and SEPA, 2012) and the carbon balance of the wind farm (Scottish Government, 2011). In recognition of the importance of peat as a carbon store, a number of policy documents and national plans make clear the Scottish Government's intention to protect, manage and restore degraded peatlands to their natural functions, biodiversity and benefits, and in so doing create a source of carbon sequestration (Scottish Government, 2017; Scottish Natural Heritage, 2015a).

Just as wind farms and their associated infrastructure may be affected by or cause peat landslides, other infrastructure such as road networks, flood defences, drainage, power lines, residential areas and farmland may also be affected. Terrestrial habitats in the path of a peat landslide may be damaged by ground displacement and by burial by debris, and aquatic habitats damaged by incorporation of landslide debris in watercourses (McCahon *et al.*, 1987). In addition, the displacement and break-up of peaty debris after a landslide event will ultimately result in small scale depletion of the terrestrial carbon store (Nayak *et al.*, 2008).

Typically, slope instability and landslide hazard assessments have followed a standard approach, detailed in a number of statutory and guidance documents (e.g. BS5930, 1999; Department of Environment, 1990; 1996). However, previous investigations have illustrated that the geotechnical controls of peat landslides differ from landslides in mineral soils (dry peat is typically 90% - 95% organic matter) and that pre-conditions for failure are not well accounted for by site investigation methods detailed in existing documentation. For example, peat has special hydrological properties (90% water content), it has a very low density and is often very fibrous in nature (Hobbs, 1986, 1987). Therefore, this guidance has been developed to ensure that appropriate and reliable peat landslide hazard and risk assessments can be undertaken during the planning of upland electricity generation developments such as wind farms. Although the Derrybrien slide in Ireland remains the only widely publicised peat landslide event to have occurred during wind farm construction, other failures have occurred close to (but not necessarily in association with) wind farms (e.g. Long *et al.*, 2011).

1.4 Information requirement

At the project level, large engineering projects involving peat should be planned and carried out using national best practice. This includes geotechnical risk management as discussed in the joint publication by The Institution of Civil Engineers (ICE) and the Department of the Environment, Transport and the Regions (DETR) publication “Managing Geotechnical Risk” (Clayton, 2001).

The Energy Consents Unit (ECU) looks for a peat landslide hazard and risk assessment (PLHRA) that addresses the guidelines of The Electricity Works (Environmental Impact Assessment) (Scotland) Regulations, Schedule 4, “Content of an Environmental Statement”. These Regulations are intended to cover all aspects of an EIA. Part II of these regulations sets out in general terms the requirements that a PLHRA must satisfy:

- The data required to identify and assess the potential impacts that the development is likely to have on the environment;
- A description of the development comprising information on the site, design and size of the development;
- A description of the measures envisaged in order to avoid, reduce and, if possible, remedy significant potential adverse impacts.

The ECU expects developers to demonstrate that site specific peat stability information has been properly recorded, analysed and presented. For example if a developer’s site investigation/survey identifies any area of high or medium risk in relation to a potential peat landslide incident, then it is expected that the submitted information will include detailed proposals of mitigation measures that reduce those risk levels to an acceptable or manageable level (see Table 5.4). The EIA should also address the risks associated with peat landslides following construction and after restoration works are complete.

The PLHRA is carried out by the developer as part of the Environmental Impact Assessment and will be assessed on behalf of the ECU by their appointed assessor. A written assessment of the developer’s submitted PLHRA will be prepared by the ECU. This assessment is known as a ‘Checking Report’. The Assessor’s ‘Checking Reports’ will be succinct, providing clear and justified conclusions, detailing those issues which require addressing to ensure a satisfactory assessment while also providing recommendations for minor revisions to improve clarity or content where appropriate. If considered necessary by the Assessor, draft conditions of consent addressing specific recommendations will be provided as an annex to the Checking Report.

ECU acknowledges that in complex cases, some iteration of reports submitted under the guidance may be necessary to resolve technical aspects of the PLHRA. Where this is the case, clear guidance will be provided by the ECU, facilitated by the Assessor.

1.5 ECU assessment services

Most Section 36 applications will be assessed in relation to their potential to generate peat landslide risks. Exceptions would be those sites where there is no peat or where peat is highly localised and demonstrably outwith areas proposed for infrastructure. Section 37 applications should also be assessed for peat landslide risk where infrastructure is proposed in peatland areas.

The scope of each Checking Report will be relative to the scale, complexity, and topography of each development site. Information that has been referenced but not submitted will not be reviewed. A site visit may be carried out in order to help the Assessor prepare the written assessment, and will be arranged through the developer, if required.

Each Checking Report will include a summary of the findings of the developer's PLHRA and will confirm whether or not adequate and appropriate field survey, peat sampling and analytical methods have been employed to assess peat stability and associated landslide risks. The report will provide a summary outcome as follows:

- The PLHRA is considered to be **satisfactory**: the checking report has determined that the PLHRA is sufficiently robust in all respects; although some recommendations may be made for clarity, no further revisions are required.
- The PLHRA **requires minor revisions**: although much of the PLHRA is sound, one or two key elements are considered to be insufficiently robust to support the PLHRA conclusions and minor revisions are required; areas for attention will be advised in the review findings and may be progressed by the developer through either an appendix to the original submission or by clarification letter.
- The PLHRA **requires resubmission**: there are significant shortcomings throughout the PLHRA and reworking of the PLHRA report is required to support a robust assessment; areas for attention will be advised in the review findings and outline guidance offered to support the developer in preparing a satisfactory PLHRA.

Outline contents of a typical PLHRA are presented in Appendix D.

Developers should note that the Scottish Government has employed the checking services under contract. The ECU will review the Checking Reports before issuing them to each developer. Developers are asked to submit responses directly to the ECU and not to the assessment contractor acting on behalf of the Scottish Government.

ECU staff can consider brokering one-to-one dialogue between the assessment contractor and the developer, in order to discuss and clarify further information requirements and/or agree technical solutions. It is accepted that the developer must be permitted to make the decision on what data are used to support a particular development and for this reason ECU is prepared to review and comment on any approach that treats geotechnical risk management in a reasonable fashion.

1.6 Developer design team

Detailed assessments of peat landslide hazard as a precursor to risk assessment require an understanding of geology, peat hydrogeology and ecology, and the geotechnical properties of peat and the underlying materials. Accordingly, assessments of peat landslide hazard and risk require a competent, multidisciplinary team comprising at least three of the following disciplines:

- (i) Engineering geologist;
- (ii) Geomorphologist;
- (iii) Geotechnical engineer;
- (iv) Hydrogeologist/hydrologist;
- (v) Ecologist.

These team members should be led by a Competent Person who will be chartered through an appropriate professional institution (CEng, CGeol, CIWEM, MICE or equivalent) with a minimum of 5 years demonstrable experience in managing geotechnical risk and undertaking upland geohazard assessments and/or surveys, specifically in peatland environments. Given the complexity of peatlands, the qualifications and experience of the team should be clearly stated early in the developers' reports.

1.7 Checklist for peat landslide hazard and risk assessments

Figure 1.1 provides a pathway from an initial scoping study through to delivery of a detailed site assessment of peat landslide risk in the form of a PLHRA. Once the area of interest has been identified, the scoping study, supported by an initial site reconnaissance survey, should provide the basis for a first pass assessment of potential peat landslide hazards.

Should the site indicate potential for peat landslide hazards, guidance follows to assist the specification of detailed site investigation to obtain critical information to inform peat landslide hazard and risk assessment and engineering mitigation of associated risks. Exit points from the hazard and risk assessment process are provided at appropriate stages. For example, if only minimal peat cover is identified after the desk study stage and confirmed by site reconnaissance, the option to exit the hazard assessment process is made available.

The structure of this document follows the assessment process shown in Figure 1.1. A brief review of peat landslide mechanisms and indicators follows to provide context for those unfamiliar with peat landslide hazards. This is followed by detailed guidance on preparation of a front-end desk-study, initial site assessment and accompanying site reconnaissance survey, criteria for detailed ground conditions assessment thereafter, and an overview of the principles of hazard and risk assessment.

An overview of peat landslides

2.1 Peat landslides

Peat instability is manifest in a number of ways, all of which can be observed on site or remotely from aerial photography, where photo resolution allows:

- **Minor instability:** localised, small scale development of tension cracks, tears in the acrotelm (upper vegetation mat), compression ridges, or bulges and thrusts; these features may be warning signs of larger scale major instability (such as landsliding) or may simply represent a long term response of the hillslope to drainage and gravity, i.e. creep;
- **Major instability:** comprising various forms of peat landslide, ranging from collapse and outflow of peat filled drainage lines/gullies (occupying a few-10s cubic metres), to medium scale peaty-debris slides (10s to 100s cubic metres) to large scale peat slides and bog bursts (1000s to 100,000s cubic metres) (Dykes and Warburton, 2007a).

Dykes and Warburton (2007a) provide a helpful overview and classification of the various types of 'major instability' referred to above. Forms of 'minor instability' are considered further in Section 2.2.

Two broad groups of peat landslide have previously been reported (Plates 2.1 and 2.2). The term 'peat slide' is generally used to describe slab-like shallow translational failures (Hutchinson, 1988) with a shear failure mechanism operating within a discrete shear plane at the peat-substrate interface, below this interface, or more rarely within the peat body (Warburton *et al.*, 2004). The peat surface may break up into large rafts and smaller blocks which are transported downslope mainly by sliding. Rapid remoulding during transport may lead to the generation of organic slurry in which blocks are transported. Peat slides correspond in appearance and mechanism to translational landslides (DoE, 1996) and tend to occur in shallow peat (up to 2.0m) on moderate slopes (5 to 15°). A great majority of recorded peat landslides in Scotland, England and Wales are of the peat slide type.

The term 'bog burst' has been used to describe particularly fluid failures involving rupture of the peat blanket surface or margin due to subsurface creep or swelling, with liquefied basal material expelled through surface tears followed by settlement of the overlying mass (Hemingway and Sledge, 1941-46; Bowes, 1960). They are characterised by pear shaped areas of disturbed (often sunken) blanket bog, arranged in concentric tears and rafts, with little substrate revealed, and without necessarily a clear scar margin. Downslope of the area of subsidence, there is usually a block and slurry runout zone, similar in appearance to that associated with peat slides. Bog bursts correspond in appearance and mechanism to spreading failures (DoE, 1996) and tend to occur in deeper peat (greater than 1.5m) on shallow slopes (2 to 10°) where deeper peat deposits are more likely to be found (Mills, 2002). Reports of bog burst failures are generally most common in the Republic of Ireland and Northern Ireland.

Both peat slides and bog bursts may have extensive runout, particularly where debris is incorporated in watercourses. The low density of peat debris means that it may be transported kilometres downstream with potential impacts on in-stream engineering structures and aquatic habitats (McCahon *et al.*, 1987).

There is considerable natural variability in movement types and complex failures may result where the geotechnical properties of the peat vary. Hence there is some degree

of overlap in processes and mechanisms between different landslide types. This variability is captured in the formal classification of peat landslides by Dykes and Warburton (2007a), based on a comprehensive database of examples collated from the literature and field studies. The classes of peat landslide reflect: the type of peat deposit (raised bog, blanket bog, or fen bog), location of the failure shear surface or zone (within the peat, at the peat-substrate interface, or below), indicative failure volumes, estimated velocity and residual morphology (or features) left after occurrence. Table 2.1 shows the indicative slope angles and peat thicknesses associated with each type.

With time, the features associated with these types of landslide will soften through erosion and drying and re-vegetate, leaving only subtle scars in the landscape (Feldmeyer-Christe and K uchler, 2002; Mills, 2002). A study into vegetation recovery for several UK peat landslide sites indicated that typical features were clearly visible in the field and on aerial photographs for some 30-40 years post failure until full vegetation cover had been achieved. Thereafter, failure morphology degraded and vegetation growth continued until the scars became difficult to identify once around 100 years had elapsed since failure (Mills, 2002).

Table 2.1 Peat landslide types and key controlling parameters (after Dykes and Warburton, 2007a)

Peat landslide type	Definition	Typical slope range	Typical peat thickness
Bog burst	Failure of a raised bog (i.e. bog peat) involving the break-out and evacuation of (semi-) liquid basal peat	2 – 5°	2 – 5m
Bog flow	Failure of a blanket bog involving the break-out and evacuation of semi-liquid highly humified basal peat from a clearly defined source area	2 – 5°	2 – 5m
Bog slide	Failure of a blanket bog involving sliding of intact peat on a shearing surface within the basal peat	5 – 8°	1 – 3m
Peat slide	Failure of a blanket bog involving sliding of intact peat on a shearing surface at the interface between the peat and the mineral substrate material or immediately adjacent to the underlying substrate	5 – 8° (inferred)	1 – 3m (inferred)
Peaty debris slide	Shallow translational failure of a hillslope with a mantle of blanket peat in which failure occurs by shearing wholly within the mineral substrate and at a depth below the interface with the base of the peat such that the peat is only a secondary influence on the failure	4.5 – 32°	< 1.5m
Peat flow	Failure of any other type of peat deposit (fen, transitional mire, basin bog) by any mechanism, including flow failure in any type of peat caused by head-loading	Any of the above	Any of the above

2.2 Controls of peat instability

A number of *preparatory factors* operate in peatlands which act to make peat slopes increasingly susceptible to failure without necessarily initiating a landslide. *Triggering factors* change the state of the slope from marginally stable to unstable and can be considered as the 'cause' of failure (DoE, 1996). There are also inherent characteristics (or *preconditions*) of some peat covered slopes which predispose them to failure. These are considered further below.

2.2.1 Preparatory factors

The following are some of the transient factors which operate to reduce the stability of peat slopes in the short to medium term (tens to hundreds of years):

- (i) Increase in mass of the peat slope through progressive vertical accumulation (peat formation);
- (ii) Increase in mass of the peat slope through increases in water content;
- (iii) Increase in mass of the peat slope through growth of trees planted within the peat deposit (afforestation);
- (iv) Reduction in shear strength of peat or substrate from changes in physical structure caused by progressive creep and vertical fracturing (tension cracking or desiccation cracking), chemical or physical weathering or clay dispersal in the substrate;
- (v) Loss of surface vegetation and associated tensile strength (e.g. by burning or pollution induced vegetation change);
- (vi) Increase in buoyancy of the peat slope through formation of sub-surface pools or water-filled pipe networks or wetting up of desiccated areas; and
- (vii) Afforestation of peat areas, reducing water held in the peat body, and increasing potential for formation of desiccation cracks which are exploited by rainfall on forest harvesting.

The impacts of factors (i) and (ii) are poorly understood, but the formation of tension cracks, desiccation cracks and pipe networks have been noted in association with many recorded failures. Long-term reductions in slope stability contribute to slope failure when triggering factors operate on susceptible slopes, as described below.

2.2.2 Triggering factors

Peat landslides may be triggered by natural events and human activities. The following natural triggers have been reported in relation to peat instability:

- (i) Intense rainfall causing development of transient high pore-water pressures along pre-existing or potential rupture surfaces (e.g. at the discontinuity between peat and substrate);
- (ii) Snow melt causing development of high pore-water pressures, as above;
- (iii) Rapid ground accelerations (earthquakes) causing a decrease in shear strength;
- (iv) Unloading of the peat mass by fluvial incision of a peat slope at its toe, reducing support to the upslope material; and
- (v) Loading of the peat mass by landslide debris causing an increase in shear stress.

Factors (i) and (ii) are the most frequently reported triggers for peat mass movements in the UK. The increasing incidence of multiple peat landslide events may be associated

with increased storm frequency (Evans and Warburton, 2007), a climatic trigger considered to be more likely under climate change scenarios.

Triggers associated with human activities include:

- (vi) Alteration to natural drainage patterns focussing drainage and generating high pore-water pressures along pre-existing or potential rupture surfaces (e.g. at the discontinuity between peat and substrate);
- (vii) Rapid ground accelerations (blasting or mechanical vibrations) causing an increase in shear stresses;
- (viii) Unloading of the peat mass by cutting of peat at the toe of a slope reducing support to the upslope material (e.g. during track construction);
- (ix) Loading of the peat mass by heavy plant, structures or overburden causing an increase in shear stress; and
- (x) Digging and tipping, which may be associated with building, engineering, farming or mining (including subsidence).

Natural factors are difficult to control, and while some human factors can be mitigated, some cannot. For these reasons it is essential to identify and select locations and routes for development infrastructure that avoid the deepest peat areas and minimise the impact of the development on peatlands.

Note that Lindsay and Bragg (2004) provide a detailed review of the potential destabilising effects of forestry activities on a peatland in Ireland in association with the Derrybrien failure, including discussion of some of the anthropogenic triggers listed above. In preparing assessments of peat stability, developers should give afforested peatlands (which are often hydrologically disrupted and physically degraded) the same scrutiny as peatlands without forest, even if this may be more arduous in practice (due to concealment of the ground surface by tree cover and associated access difficulties).

2.2.3 Preconditions

The following static or inherited factors may act as preconditions to slope instability in peatlands (Evans and Warburton, 2007; Dykes and Warburton, 2007a):

- (i) Impeded drainage caused by a peat layer overlying an impervious clay or mineral base (hydrological discontinuity, especially an iron pan at the base of the peat deposit);
- (ii) A convex slope or a slope with a break of slope at its head (concentration of subsurface flow);
- (iii) Proximity to local drainage, either from flushes, pipes or streams (supply of water); and
- (iv) Connectivity between surface drainage and the peat/impervious interface (mechanism for generation of excess pore pressures).

Dykes and Warburton (2007b) note that "...areas of peat subjected to tine cutting, peat upslope of transverse ditches and thin upland peat on convex mountain slopes should be identified as potentially unstable where not obviously disrupted by previous failures or surface erosion".

2.2.4 Pre-failure indicators

The presence of preparatory or preconditioning factors prior to failure are often indicated by ground conditions that can be mapped or measured remotely or by a site visit. In many cases, sites that have experienced landslides apparently without warning could often have been identified as susceptible to failure by a suitably trained person (see

section 1.6) or through relatively inexpensive monitoring strategies. The nature and signs of instability often differ depending on the type and scale of failure. The following critical features are indicative of potential failure in peat environments:

- Presence of historical and recent failure scars and debris;
- Presence of features indicative of tension;
- Presence of features indicative of compression;
- Evidence of 'peat creep';
- Presence of subsurface drainage networks or water bodies;
- Presence of seeps and springs;
- Presence of artificial drains or cuts down to substrate;
- Concentration of surface drainage networks;
- Presence of soft clay with organic staining at the peat and (weathered) bedrock interface; and
- Presence of an iron pan within a mineral substrate.

Each of these indicators is considered below with illustrative plates to guide recognition during site visits.

2.2.4.1 Historical and recent failure scars and debris

The presence of existing landslide scars in a development area may indicate local site conditions conducive to future peat landslide activity. Plates 2.1 and 2.2 illustrate typical peatland morphology associated with historical failure sites. With increasing time since failure, exposed scars will re-vegetate. However, where a bare substrate has been revealed by sliding, full vegetation cover may take 30-40 years to develop.

Although reactivation of the debris or peat surrounding landslide scars has rarely been noted in the published literature, occurrence of peat landslides at different locations on the same hill, separated in occurrence by many years, has been identified on several occasions. Therefore, the existence of a peat landslide scar in a development area provides a strong indicator of potential future peat landslide hazard (see Dykes and Warburton (2007a) for oblique aerial photographs of the peat landslide types shown in Table 2.1).

2.2.4.2 Tension features

Cracking of the upper layers or full thickness of peat may indicate an accumulation of stress in peat soils as well as provide a route for surface water to infiltrate rapidly to basal peat layers and contribute to the generation of excess pore-water pressures. Tension features may include tension cracks, which are narrow and deep fissures, frequently infilled with water, and which may be continuous or discontinuous for several tens of metres (Plate 2.3). Alternatively, shallow tears, which are wider and shallower 'diamond' shapes may indicate tension at the surface only (Plate 2.4). Concentric tiers of arcuate tension cracks may indicate local displacement, while multiple intersecting cracks may be a precursor to fragmentation of the peat into rafts or blocks (Plate 2.5).

2.2.4.3 Compression features

Compression features usually indicate displacement upslope which has resulted in the formation of ridges (Plate 2.6), thrusts (Plate 2.7) or extrusion features (Plate 2.8). Often, related tension features will be visible at the upslope limit of peat displacement.

2.2.4.4 Peat creep

Tension and compression features can be associated with creep of the peat blanket on a slope. Zones of tension are often juxtaposed with compression ridges in response to creep of the peat mass and changes in local slope gradient. At the surface such movements can be detected by displacement of walls and boundaries and tilting of fences and posts.

2.2.4.5 Subsurface drainage networks or water bodies

Subsurface drainage pathways may enable high transient pore-water pressures to develop under conditions of enhanced water supply, e.g. during an intense rainstorm. Soil piping is widespread in upland blanket peat catchments in the UK, with pipes tending to be more prevalent at hillslope summits and footslopes and in areas of peatland subject to moorland gripping (Holden, 2004; 2005).

Such pipe drainage networks (Plate 2.9) can often only be identified on-site by the sound of running water beneath the surface. Rarely, a pipe ceiling may collapse, leaving a hole in the peat surface (Plate 2.10). If pipe networks are identified, their size and extent can be ascertained through non-intrusive ground investigation e.g. Ground Penetrating Radar (Holden, 2004; see section 4.4.3.1).

Larger subsurface water bodies, formed where pipes have become blocked or where spring lines are present below the surface, can be identified by 'trembling' at the peat surface. Continued supply of water (without release) to a subsurface water body may cause visible swelling of the peat mass over periods ranging from a few hours to several months. Evidence of drainage outlets should also be noted as these usually indicate a well-developed subsurface pipe network. The presence of sediment discharged at natural pipe outlets often indicates a deep subsurface drainage network with periodically high water pressures.

2.2.4.6 Seeps and springs

Groundwater seeps and springs are controlled by seasonal rainfall. Large fluctuations in rainfall may increase the rate of groundwater discharges and if this occurs following a period of drought there may be an increased likelihood of peat landslide occurrence.

2.2.4.7 Artificial drainage and cuttings

Moor drains in open peatlands (or grips), forest drains on afforested peatlands and cuttings (for fuel) to substrate, particularly where oriented transverse or oblique to the slope contour, may weaken a peat covered slope. The drain or cut will create a vertical discontinuity, removing tensile strength in the upper layers and enabling ponding of water.

2.2.4.8 Drying and cracking

Drying of peat caused by periods of drought or by drainage (natural or man-made) may also cause cracking, providing pathways for rapid infiltration of water to horizons at depth within the peat mass. Crack networks can also be caused by drying of a peat mass associated with forestry and the associated drawdown of the water table. These crack networks can be found both under and between lines of trees in a forest stand, although they may be hidden under a litter layer (see Lindsay and Bragg, 2004).

2.2.4.9 Concentration of natural drainage networks

Natural surface drainage pathways also provide a means of supplying water to a susceptible peat area. These may be manifest as gullies (Plate 2.11), which are typically steep sided and may have bare peat floors or be fully vegetated around a single thread sinuous stream. Alternatively, flushes (Plate 2.12) may enable significant diffuse flow of water without an obvious single thread watercourse.

Areas of peat which are already dissected by gully networks (with numerous hags and groughs) have rarely been associated with peat instability, however, flush zones are often cited as coincident with the locations of peat instability.

2.2.4.10 Soft clays

Landslides in which peat is the major part (by volume) may fail within the peat deposit, at the interface between it and the peat substrate, or within the substrate underlying the peat (Dykes and Warburton, 2007a). Glacial tills with a high clay content have been cited as the substrate for a number of failures where the shear surface was interpreted to be within the substrate. The uppermost clay layers beneath peat may be weakened by organic acids leached from the base of the peat, producing particularly soft clays. Where clays have been softened in this way, augering or probing may penetrate the clays with a similar refusal to the overlying peat, and if this occurs, it should be noted.

2.2.4.11 Iron pans

A number of studies have identified impermeable iron pans (or similar hardened horizons formed by leaching) in the upper centimetres of the mineral substrate beneath peat deposits. These pans may have smooth, almost 'polished' surfaces and provide little frictional resistance to the overlying peat.

2.3 Summary

Any of the indicators described in 2.2.4.1 to 2.2.4.11 may in isolation indicate future potential for peat landslides to occur and combinations of these features may indicate a greater susceptibility to failure. It should be noted that there are few citations in the academic literature that support the idea of increasing slope gradient and increasing peat thickness (particularly together) as the primary controls on failure. Both Evans and Warburton (2007) and Boylan *et al.* (2008) note that the majority of recorded failures are on relatively low gradients (typically 4-8°) where peat accumulation may be greater and in thin to moderate thickness peats (typically 0.5 – 2.0m deep in blanket peat, but thicker in raised bogs; Boylan *et al.*, 2008).

3.1 Background

Peat landslide hazard and risk assessments (PLHRAs) are generally delivered as part of the Environmental Impact Assessment (EIA) process, often as a technical annex to the geology chapter. The need for an assessment is typically determined at the scoping phase of the EIA, whereby a scoping opinion is offered by the competent authority indicating that peat stability should be one of the matters covered in environmental information.

This guidance considers that PLHRAs should be a requirement where there is peat within the application boundary of a proposed development site. This short section considers information developers might use to determine whether a PLHRA report is likely to be required.

3.2 Peat

3.2.1 Presence of peat

The presence of peat at a proposed development site can be determined in a number of ways:

- (i) By direct observation of peat during a site walkover;
- (ii) By reference to published geology or soil maps; and
- (iii) By intrusive investigation (e.g. coring).

In Scotland, organic soils are defined (Scottish Government *et al.*, 2014) in the following way:

- **Peaty (or organo-mineral soil):** a soil with a surface organic layer less than 0.5m deep;
- **Peat:** a soil with a surface organic layer greater than 0.5m deep which has an organic matter content of more than 60%;
- **Deep peat:** a peat soil with a surface organic layer greater than 1.0m deep (Bruneau and Johnson, 2014).

Depending on the geomorphology of the site (e.g. presence of gullies, hags, incised streams), it may or may not be possible to verify the presence of peat by direct observation. Organic soils as thin as 0.35m are capable of accommodating species typical of blanket bogs (such as *Sphagnum* species) which would often be assumed to indicate the presence of peat of a reasonable thickness. In these cases, intrusive investigation by hand augering can be used to provide verification of the presence of peat.

Superficial geology maps or soil maps should normally provide information on the presence or absence of peat, although these can be out-of-date or inappropriate for local scales and peat cover can be present even where not indicated.

3.2.2 Evidence of peat instability

The presence of past peat landslides or pre-failure indicators (see Section 2.2.4) indicates the need for detailed assessment of peat stability, even if slopes are generally gentle and minimal peat depth information has been obtained at the scoping stage. While assessment of these features is not expected at the scoping stage, their locations

should be noted and the features investigated in further detail during the detailed site assessment.

3.3 Slope

In the previous iteration of the guidance, the need for a PLHRA report was determined as a function of the presence of peat and the severity of slopes within the application boundary. The threshold slope was considered to be 2° such that sites with peat cover but with very gentle gradients under 2° did not necessarily require submission of PLHRA reports. This reflected reports of peat landslides in blanket bogs, which were limited to slopes >2°. However, Boylan *et al.*, 2008 note that failures on raised bogs occur on slopes of less than 2°. Accordingly, in this revised guidance, a discrimination is made between raised bogs and blanket bogs as to whether the slope threshold is applied.

3.3.1 Blanket bogs

In blanket bogs, which typically mantle hillslopes, PLHRAs should be undertaken where slopes exceed 2° reflecting published data on peat landslide source slopes for blanket bogs (Evans and Warburton, 2007; Boylan *et al.*, 2008).

3.3.2 Raised bogs

In raised bogs (which typically occur on very gentle terrain), PLHRAs should be undertaken, reflecting published data (Boylan *et al.*, 2008) which indicates the occurrence of peat landslides on very low gradients in raised bog environments.

Detailed site assessment

4.1 Overview

The content and structure of a peat landslide hazard and risk assessment (PLHRA) is ultimately the responsibility of the developer or their nominated consultant/contractor, but should have the following key elements:

- An assessment of the character of the peatland within the application boundary including thickness and extent of peat, and a demonstrable understanding of site hydrology and geomorphology;
- An assessment of evidence for past landslide activity and present-day instability e.g. pre-failure indicators;
- A qualitative or quantitative assessment of the potential for or likelihood of future peat landslide activity (or a landslide susceptibility or hazard assessment);
- Identification of receptors (e.g. habitats, watercourses, infrastructure, human life) exposed to peat landslide hazards; and
- A site-wide qualitative or quantitative risk assessment that considers the potential consequences of peat landslides for the identified receptors.

The assessment would normally comprise desk study, site reconnaissance, site mapping and probing, hazard and risk assessment and reporting. These steps are considered further below.

4.2 Desk study (review of existing information)

All development sites should be subject to a front end desk study which collates all data relevant to peat instability for the site and provides context to site based survey, mapping and peat characterisation.

The extent of the peat landslide study area should be clearly identified on all maps and plans at the outset of the desk study. The study area should not be restricted to the footprint of the proposed infrastructure but should take in any areas of the landscape that the development might impact on, or that might impact upon the proposed scheme. Typically, the study area will be determined by catchments and topography, sometimes extending downslope and upslope of the application boundary.

Once the extent of the peat landslide study area has been identified, appropriate efforts should be made to collect any and all relevant information relating to the site. The time spent in data collection and review should reflect the nature and scale of the investigation and the volume of information available for the site.

4.2.1 Sources of site information

Sources of information to be considered may include:

- (a) Previous site information including technical reports, feasibility reports, and previous ground investigation information;
- (b) Geological information, specifically the regional field guide relevant to the site in question and maps of superficial (drift) and bedrock geology;
- (c) Soil Survey of Scotland (Macaulay Institute) Soil Memoirs;
- (d) Site-wide aerial photography, both contemporary and historical;

- (e) Digital elevation data;
- (f) Academic literature and publications about the site;
- (g) Newspaper archives;
- (h) Internet searches, and
- (i) Local or site knowledge relayed by landowners, farmers and local residents.
- (j) Scotland's Soils website <http://soils.environment.gov.scot/>

a) to e) provide fundamental site information of relevance not only to peat landslide hazard and risk assessments but later stages of geotechnical design if and when consent has been granted. These should be considered essential sources for the initial assessment. f) to i) provide additional information and are often particularly informative where a history of instability at a development site has already been recognised by landowners, researchers or has been recorded by the local press.

It should be noted that maps indicating peat cover should not be taken as definitive statements on its presence or absence. The depth and extent of peat deposits may vary sharply over short distances as a function of local underlying geology, past and ongoing geomorphological activity and management history. It is for this reason that the desk-study must be informed by a site reconnaissance survey, to ensure that existing information is sufficient and reliable.

4.2.2 Desk based mapping and site modelling

Following review of the information available for the site, a base map of relevant data should be compiled. The data acquired may allow the extent of the peat deposits to be defined and basic geomorphological interpretation to be undertaken. This map would usually be sufficient to provide a basis for site reconnaissance and ground truthing. In some cases, digital datasets can be transferred to desk-based mapping tools such as handheld GPS, tablet computers or portable mapping devices.

4.2.2.1 Aerial photography

Since the previous issue of this guidance in 2006, the availability of digital aerial photography in Scotland has significantly improved. Ortho-rectified digital aerial photography is now available for a majority of the UK from a number of suppliers, including data from a major acquisition for Scotland in 2008/09. Data is readily available for inspection in Google Earth™, including in some areas for multiple time periods (or epochs). The quality of data continues to improve, but in general, 25cm ground resolution is becoming widely available, even in remote areas.

Aerial photography may be used to:

- Identify the presence of existing failure scars and the extent of debris runout;
- Identify pre-conditioning factors for failure (where visible at the resolution of the photography);
- Identify evidence of other pre-development ground conditions of relevance to ground works but not exclusively associated with landslides, including vegetation cover, drainage regime and dominant drainage pathways; and
- Identify evidence for land management practices with the potential to influence ground conditions (e.g. burning, artificial drainage, peat cutting, forestry).

While contemporary aerial photography is of value in determining current site conditions, historical photography can be particularly useful where:

- There is a requirement to identify features reported on site (e.g. landslides) that may be decades old; and
- Where the site has been subject to significant changes in land-use and where there is a requirement to understand the site conditions prior to modification (e.g. where the site has been afforested, burnt or cut over).

Digital datasets can be easily viewed in standard geographical information system (GIS) software, and compared with infrastructure layouts and other GIS based site-wide datasets such as geology and topography. When using digital aerial photography datasets, the ground resolution of the photography should be clearly stated and the date of capture of the data provided.

Mapping of peat geomorphology (including landslides and erosion), hydrology (natural drainage features), land-use (forestry, artificial drainage) and any other pertinent factors can be undertaken in GIS in order to inform subsequent site visits and the scope of detailed peat probing work.

4.2.2.2 Soil and geology maps

Geological datasets available from the British Geological Survey (BGS) are typically available for solid (bedrock) and drift (superficial) geologies. The former describe the hard rock underlying the softer overlying materials, while the latter provide detail of the overlying materials (such as alluvium, till or peat). Since issue of the previous guidance, BGS now offer access to much of this information via Geofacets, providing georeferenced geological maps which can be built into GIS and compared with other site data.

The BGS also offer landslide information via the GeoSure™ database, which incorporates landslides reported within the National Landslide Database and assigns an indicative landslide potential according to site characteristics (such as geology and slope). Information on collapsible and compressible ground is also available.

As of 2011, Macaulay Institute soils datasets became available digitally via lease or as paper copies from the James Hutton Institute, an amalgamation of the Macaulay Institute and Scottish Crop Research Institute. Data concerning a number of characteristic soil attributes for each soil type (e.g. organic matter content, bulk density) are also available.

From 2014, a consolidated carbon and peatland map for Scotland was made available by Scottish Natural Heritage. This map was modified following an extensive consultation exercise in 2016 (Scottish Natural Heritage, 2016).

When using digital geological or soil data, the reliability of the data should always be considered, as should the scale at which the map was intended to be viewed. For example, boundaries displayed at 1:250,000 scale would not generally be regarded as reliably located when viewed at 1:10,000 scale in GIS software.

4.2.2.3 Digital topographic datasets

Digital terrain models (DTMs) generated from LiDAR aerial surveys can provide detailed information on site topography including elevation, slope angle and slope aspect. These data should be used as follows:

- To characterise overall site relief e.g. steep with pronounced convex slopes, or gentle and undulating, and identify topographic controls on drainage e.g. hillslope summits and footslopes, major catchments, sub-catchments and gullies;
- To classify the site into slope classes (e.g. 0-5°, 5-10°) on the basis that certain slope ranges may be more or less susceptible to specific failure mechanisms (see Section 2.1); and

- To identify north and south-facing slopes on the basis that slopes with differing aspects may have differing hydrological characteristics in relation to sun exposure (e.g. rates of snow melt).

As with other digital datasets, digital terrain models are now widely available from a variety of suppliers, or can be flown by commission if required. Datasets are normally geo-referenced and can be layered in a GIS with the mapping and aerial photography datasets described previously.

When using digital topographic datasets, the resolution of the data should be stated (e.g. 5m) and any limitations of the data resolution for the analysis clearly stated. For example, 25m or 50m ground resolution may be insufficient to pick up small scale but critical variations in topography on sites of quite variable relief.

4.2.2.4 Other digital mapping datasets

A large number of digital mapping datasets have become available as digital data delivery has become more popular. Some of these may be relevant to the assessment of peat landslide hazards, including hydrological features, the position of existing infrastructure, the location of environmentally designated sites (such as Special Areas of Conservation or SSSIs) and forestry plans. In most cases, this data is collated as part of the wider EIA process and should be made available to the PLHRA team.

4.2.2.5 Remotely sensed imagery

Data collected by remote sensing includes aerial photographs, digital topographic datasets (e.g. from NEXTMap) and multispectral datasets illustrating ground conditions (e.g. moisture content). Until recently, earth observation applications to peat landslide investigations have relied upon the interpretation of aerial photographs, with satellite imagery lacking the spatial resolution required to provide detailed images at the scale of an individual landslide. However, increasingly satellite and airborne technology offer opportunities to investigate and map individual peat landslides, and susceptible terrain. The main satellite and aerial imagery sources which may be applicable to landslide investigations are summarised below and covered in more detail in Appendix A:

- RGB digital camera imagery and hyper-spectral imagery (Unmanned Aerial Vehicles): for high resolution photography of ground conditions, high resolution digital elevation models and assessment of water content and forest condition;
- Optical satellite imagery (Landsat thematic mapper): for identification of flow tracks, ground fissures and subtleties in peat morphology;
- Microwave (Synthetic Aperture Radar Interferometry, InSAR): for vegetation type, moisture content and collation of digital elevation models;
- Multispectral video: for mapping of groundwater systems; and
- Hyperspectral scanners: mapping of geological units in areas of poor exposure using soil moisture content as a proxy, estimation of soil thicknesses prone to landsliding.

Where pre-existing datasets are available, these can be of value in understanding site conditions. However, commissioning of such datasets for a single scheme would normally be considered cost prohibitive.

4.2.3 Listing of data sources

Given the variety of datasets available, it is important that the PLHRA provides a clear listing of all data sources referred to during preparation of the desk study, including where relevant the age of the dataset (e.g. for aerial photography) or where appropriate, its resolution. Not only does this demonstrate knowledge of the validity of the data, but

where schemes are revisited in later years (e.g. for wind farm repowering) it provides a data benchmark with which subsequent data acquisition can be compared.

4.3 Site reconnaissance survey

Site reconnaissance should be undertaken early in the EIA process to verify the features identified during the desk study, and to enable an interpretation of the site in the context of the surrounding environment. Ideally, this should be undertaken subsequent to review of aerial photographs of the site and any associated mapping.

Reconnaissance level peat depth probing should be undertaken to verify the presence of peat on published data sources (such as BGS drift maps) and check whether peat is more widely distributed than desk study data suggests, as can often be the case.

The reconnaissance survey may also provide helpful information on ease of site access (e.g. accessibility of forest stands for peat probing or the location of particularly wet or dangerous ground), information which could be of value in scoping and planning more intensive peat probing work.

On the basis of the reconnaissance survey and validation of the desk study, ground conditions assessment (or detailed site survey) can be planned and implemented.

4.4 Ground conditions assessment

Ground conditions assessment should provide sufficient information to enable peat landslide hazard and risk assessment to be undertaken. Following this work:

- Any site evidence for past landslides or incipient instability should have been accurately recorded (including details of the field evidence and the locations observed);
- Site hydrology (e.g. presence of flushes, soil pipes) and peat geomorphology (un-eroded, eroded, type of erosion) should be well understood and preferably summarised on maps, with the hydrological baseline sufficiently well understood to enable water table levels and their impact on stability to be modelled;
- The impact of land-use on natural hydrology and peat thickness should have been ascertained (e.g. maps of drain distribution or locations of forestry or cuttings);
- Sufficient peat depth data should have been collected to enable characterisation of peat depth across the site, and in further detail at infrastructure locations;
- The character of the peat (i.e. geotechnical properties, humification, wetness, nature of contact with substrate and the nature of the substrate itself) should have been determined sufficiently to enable stability analysis to be undertaken (if this approach is taken in the hazard and risk assessment).

The key objective of the ground conditions assessment is to obtain sufficient and reliable information in support of the PLHRA. This section provides recommendations for site mapping and ground investigation where peat is known to be present at a proposed development site. It does not cover the standard geotechnical investigations that would normally be required for development planning as specified in current standards (e.g. BS EN 1997-2:2007 (EC7-2) and associated National Annex (BSI, 2007); BS 5930:1999+A2:2010 (BSI, 2010); BS 1377 (Parts 1 to 9) (BSI, 1990).

4.4.1 Site mapping

Peat landslides and the pre-failure indicators which may suggest their future occurrence are geomorphological features, and as such should be represented on a

geomorphological map of the site. At its most basic, a geomorphological map (e.g. Cooke and Doornkamp, 1990; Griffiths, 2001) should show:

- The position of major slope breaks (e.g. convexities and concavities);
- The position and alignment of major natural drainage features (e.g. peat gullies and streams);
- The location and extent of erosion complexes (e.g. hags and grouchs, large areas of bare peat);
- Outlines of past peat landslides (including source areas and deposits), if visible; and
- The location, extent and orientation of cracks, fissures, ridges and other pre-failure indicators (see section 2.3).

In addition, non-geomorphological features can be mapped where they have relevance to peat instability:

- The position and alignment of artificial drains (or grips);
- Turbary (deep cuts in peat associated with harvesting for fuel); and
- Forest stands (and their condition).

The resulting geomorphological map, when compared with a slope angle map derived from a digital terrain model and with solid and drift geology information should provide a basis for zoning the site into areas of similar character, and where peat landslides or indicators are present, determining what site-specific factors control their distribution.

The most effective way of preparing a geomorphological map is to undertake mapping from high resolution aerial photographs in GIS software. Features mapped at the desk study stage can then be verified in the field, and any features not visible at the scale or resolution of the photography can be added to the map. Alternatively, if aerial photography is not available, or is of insufficient quality, GPS survey can be used to demarcate areas of similar ground condition (e.g. Dykes, 2009).

Preparation of these maps relies upon the skill, knowledge and experience of the interpreter in accurately recording features specifically associated with peat instability, including peat landslides themselves. Good examples of the mapping of peat landslide morphology can be found in Higgitt and Warburton (1999) and Wilson and Hegarty (1993).

4.4.2 Ground investigation

This section provides guidance on the general principles behind planning a ground investigation in support of a PLHRA, and then summarises a range of intrusive and non-intrusive approaches to characterising ground conditions within a development area.

Ground investigations (GI) in peatlands serve a number of purposes, particularly in relation to the planning and siting of wind farm infrastructure:

- Ground investigation data may be used to identify the site baseline conditions as a context to environmental impact assessment (e.g. the depth and extent of peat), and this may include association of specific habitat types with specific peat thicknesses;
- Peat depth data may be used in calculation of a mass balance for the site, i.e. quantifying the amount of peat that may be excavated as compared with the amount that may be reused (such as in a Peat Management Plan, e.g. Scottish Renewables and SEPA, 2012); and

- Geotechnical data may be used to characterise the properties of peat (and the substrate) to inform stability analysis.

Guidance in relation to characterising the geotechnical properties of soils on proposed construction sites is specified in Eurocode 7 – ‘Geotechnical design – Part 2: Ground investigation and testing’ (BS EN 1997:2-2007; BSI, 2007). Eurocode 7 defines the scope of ground investigations at three levels, corresponding to successive stages in a construction project: i) preliminary investigations for positioning and preliminary design of the structure, ii) design investigations, and iii) control and monitoring. The planning stage of a wind farm development corresponds to a preliminary investigation, the scope of which is specified in Section 2.3 of Eurocode 7. This document does not offer guidance on design investigations, which would normally occur post-consent.

A preliminary investigation should be sufficient to assess the general suitability and stability of the site, its suitability in comparison with alternative sites, suitable positioning of structures, the possible effects of works on their surroundings, identify borrow areas, consider possible foundation methods and ground improvements, and enable planning of design and control investigations. In addition, estimates of soil data including stratification, pore pressure, strength properties and presence of contaminated ground or groundwater should also be possible from the preliminary investigation.

GI sampling locations should be optimised using the findings of the site reconnaissance and geomorphological mapping and should reflect the nature and extent of the proposed construction works. The Scottish Government (Scottish Government *et al.*, 2014) provide information on the level of detail expected for site investigations on peatlands, which suggests both a site-wide density of approximately one probe per 100m (or one probe per hectare) supplemented with significant additional probing at infrastructure and along tracks.

4.4.2.1 Scoping ground investigation

A competent person should be responsible for identifying and justifying the numbers, locations and types of sample collected, and this will depend upon the size and variability of the development site. Grids, transects, random or targeted sampling strategies may be appropriate. In relation to infrastructure, sampling or probing locations should be considered for:

- All proposed turbine locations, possibly using a gridded sampling approach within the extent of the micro-siting allowance;
- Access tracks, with sampling along the centrelines and more widely within the area covered by the micro-siting allowance.
- Major areas of hardstandings (e.g. site compounds); and
- Borrow pits.

The following additional factors should be considered during scoping of the ground investigation programme:

- *Topography and morphology*: peat depths are likely to be shallower on steeper slopes, and therefore sufficient samples/probes should be taken to reflect the range of slope angles identified over the development site;
- *Vegetation*: the physical characteristics of peat will vary according to their hydrological setting, usually reflected in surface vegetation, samples should be taken to reflect the range of major vegetation types (e.g. heathers, mosses, grasses);

- *Hydrology*: the hydrology of the site should be recorded and mapped where possible including any evidence of surface and subsurface drainage pathways and the depth of water strikes encountered during peat probing; and
- *Land management*: peat will also vary according to local land management practices, with peat that has been subject to burning, draining or cutting exhibiting differing characteristics to adjacent undisturbed peat.

In general terms, sufficient sampling locations should have been investigated to produce an outline map of variability in peat depth across the development site (to inform layout iterations).

4.4.2.2 Peat depth probing and coring

Peat depths may be determined by coring and by probing. Coring involves the retrieval of material in a chambered sample (e.g. a hand auger, gouge or 'Russian' type corer, Aaby and Berglund, 1986) and enables both the depth of peat and the variation in its character with depth to be observed and logged.

Probing may be undertaken using steel (or other) rods and does not involve the retrieval of material. Typically an avalanche probe or survey poles may be used. The depth at which the peat ends and the substrate (e.g. rock or clay) begins is usually determined by a change in resistance (or rate of refusal) of the probe, or by a change in sound e.g. a granular sound as mineral material is encountered. Inevitably this is less accurate than coring for determining the depth of peat, particularly where the substrate is soft (e.g. clay) and the change in resistance is subtle. Furthermore, no insight is given into the characteristics of the peat (e.g. its humification or wetness).

The balance of probing and coring undertaken during site work should be considered during scoping of the programme. Typically, probing may be undertaken more rapidly than coring. Where time or budget is a key driver, allocating a certain proportion of sample locations to coring whilst undertaking the majority of investigation with probing may be acceptable.

Dependent on the probing technique, all materials encountered and depths of changes in strata should be logged and recorded. Logging should be undertaken on-site or samples removed from the site and logged remotely using the techniques described in Section 4.4.2.3.

Dynamic probing can also be used to provide information on peat depth and variability in strength with depth through the stratigraphy.

4.4.2.3 Logging of peat stratigraphy

Peat deposits form over many thousands of years through the slow decay and accumulation of successive layers of organic debris. As these layers build up, the prevailing climatic conditions and their influence on moisture content lead to decomposition of peat fibres (or humification), and compaction. Many UK peat uplands are characterised by fibrous upper peat layers overlying more humified amorphous basal peat, underlain by either weathered substrates of tills and/or bedrock.

The degree of organic content and the high percentage moisture content of peat materials mean that standard logging using BS5930 (BSI, 1999) is not suitable to interpret and record the detailed differences between peat layers. Instead, it is advised that logging of the peat is conducted under two logging systems:

- Troels-Smith, as outlined in Long *et al.* (1999); and,
- Modified Von Post classification, as outlined in Hobbs (1986).

Logging should be carried out using both systems wherever trial pits and augured or cored samples have been extracted and where peat sections are exposed by existing cuttings or on naturally exposed and free draining faces such as gully sidewalls. The advantage of a combined system is that Troels-Smith affords logging of mineral deposits (washed fines, till layers) where von Post does not, and hence the use of both systems enables effective characterisation of the peat, the substrate, and the peat-substrate interface, a critical layer with respect to peat instability.

Otherwise, materials identified on site that are not peat should be described in accordance with the most current and relevant British or Eurocode standard.

4.4.3 Other ground investigation techniques

4.4.3.1 Non-intrusive (geophysical) techniques

Geophysical survey techniques may provide an alternative non-intrusive method for investigating peat environments. These technologies measure the vertical and lateral variation of physical properties of the ground. They are particularly useful in areas where biodiversity and other environmental issues preclude the use of more invasive methods (such as trial pits and drilling). Geophysical methods are generally used to support more traditional intrusive techniques and should be correlated with intrusive investigation to improve confidence in results.

Variations in physical properties may be collected along horizontal profiles to identify vertical variability of a physical property, or on a grid basis to allow contour plots of data variation over the development site (and therefore identification of local anomalies or spatial continuity). Data collection techniques for geophysical survey are outlined in Appendix B.

4.4.3.2 Intrusive investigation – trial pits

Trial pits provide an opportunity to log continuous sections of peat stratigraphy and extract representative, undisturbed block samples for subsequent laboratory testing. Detailed methods for shallow and deep trial pitting are discussed in detail in BS5930 (BSI, 1999). Where possible, trial pits should be carried out using a tractor mounted excavator and should be dug to the level of the underlying substrate (if bedrock) or slightly into softer substrate materials (e.g. till) in order to identify the presence of impermeable horizons at the top of the substrate.

Frequently, issues of site access and generation of potential instability prevent the safe use of excavators. In these circumstances, trial pitting should be undertaken by hand or alternatively hand augering techniques should be used. Further details on the safety consideration for excavations are included in the AGS Safety Manual for Site Investigations (2002). Consideration should be given to the suitability of the location for infrastructure if it is not suitable for plant access. All trial pits should be logged, photographed and back filled using the appropriate methods described in BS5930 (BSI, 1999). Block samples should be taken from the walls of the trial pit where it is safe to do so. In this instance, disturbed samples may be collected from the representative excavated material. Importantly, after back filling, the surface vegetation mat must be re-laid to promote recovery of habitat

Consideration should be given to practical access routes. Peat covered areas often contain materials of variable compressive strength and vehicles may easily become stranded. Prior to the ground investigation fieldwork, the proposed access route should be checked and agreed in order to minimise damage to the peatland. The site team should be made aware of any potentially hazardous ground conditions and alerted to health and safety constraints.

4.4.3.3 Site instrumentation and monitoring

Instrumentation at the development site both during and subsequent to ground investigation can be of value in monitoring groundwater levels, characterising hydrological responsiveness of peat layers and identifying precursory slope movements at tension crack locations. Ideally a minimum twelve month cycle of monitoring is required to identify seasonal variability in hydrological conditions, and in turn, rates of slope movement. The shorter the monitoring the period, the less representative the data will be of longer-term trends and extreme responses. However while twelve months may not be possible, monitoring can continue beyond the investigation and even during determination.

The need for monitoring will depend upon ground conditions identified at the site. For example, if a planned turbine site is situated downslope of a pipe network or within a flush or particularly wet zone, groundwater monitoring may be valid. If the turbine site is situated in an area of cracking, pegs may be required to monitor potential crack displacement. A minimum monitoring period of 8 weeks would be anticipated. In areas where ground movement is possible, the monitoring would be longer and comprise a baseline survey and permanent monitoring network such that if movement were to occur, it could be accurately determined from retrospective surveys. Where the period is shorter, justification should be provided.

Appendix C identifies variables relevant to slope instability and the instrumentation available to monitor them.

4.4.3.4 Representation of peat depth data

Once peat depth data has been collected, the data can be portrayed on site plans in a number of ways:

- As colour coded points, with colours corresponding to specific depth ranges (e.g. 0.0 – 0.5m, 0.5, 1.0m, etc);
- As contour lines of peat depth (or isopachs) with each contour representing a specific peat depth (e.g. 0.5m, 1.0m, etc); or
- As filled contours of peat depth, with each shaded area representing a peat depth range between contours (e.g. 0.0 – 0.5m, 0.5 – 1.0m).

In order to derive contours or filled contours, application of an interpolation process in GIS is normally required. Interpolation uses the values from existing data points to predict values at unsampled locations. Interpolation is valuable as it provides information on likely peat depths between sampled points, and the resulting interpolated surface can be used in a GIS package alongside other data to estimate risk levels at areas of the site that have not been directly sampled for depth.

There are a number of interpolation methods available, including natural neighbour, inverse distance weighting and kriging. If these methods are applied, it is important that any user defined inputs (other than peat depth) that may influence the resulting peat model are stated, and any limitations of the model clearly outlined. The temptation to 'over-interpolate' across large distances between real data points, or to extrapolate beyond the area covered by real data should be avoided.

In order that the model be considered reliable, sufficient coverage of data points should be available in areas covered by the model, hence infrastructure targeted probing (with limited coverage elsewhere) may be inadequate to produce a site wide peat model.

4.4.4 Laboratory testing

Peat landslides generally exhibit a shear zone or shear plane within the lower layers of the peat mass, at the interface with the substrate (e.g. till or bedrock), within the

substrate, or in a combination of these layers. As such, sufficient samples must be collected to describe the geotechnical parameters of both the peat mass and the mineral substrate.

While laboratory testing for mineral soils is well understood, peat 'soils' are composed of vegetative (organic) matter in various states of decomposition, rather than mineral particles. As such, conventional geotechnical theory based on mineral soils does not apply well to peat (e.g. Gosling and Keeton, 2008). For example, the characterisation of cohesion, c , and the angle of internal friction, ϕ , is notoriously difficult due to the inherent variability in peat arising from its vegetational composition and degree of humification. Both of these values are critical in slope stability analysis, however, the behaviour of well humified peat samples can approximate the behaviour of clays (Evans and Warburton, 2007). For more fibrous peats, characterisation of geotechnical parameters is more difficult.

Section 4.4.4.1 provides a list of appropriate tests which should be considered to aid the characterisation of both the peat and underlying substrate in order that appropriate parameters can be incorporated into the site ground model.

4.4.4.1 Physical properties of peat

The following physical properties may be of value in characterising peat. Tests (iv) to (viii) are most relevant to characterising material properties of the substrate:

- (i) Moisture content;
- (ii) Bulk density;
- (iii) Organic content (Loss on Ignition);
- (iv) Plastic and liquid limit;
- (v) Specific gravity;
- (vi) Particle size distribution;
- (vii) Shear strength parameters (c and ϕ);
- (viii) Soil pH and sulphate content – (if concrete design is a consideration);
- (ix) Linear shrinkage; and
- (x) Fibre content.

Tests should be carried out in accordance with BS1377 (BSI, 1990a; 1990b) except where superseded by BS EN 1997-2:2007 (BSI, 2007). Details of the relevant standards are provided in the UK National Annex to Eurocode 7 (BSI). Note that some variations are required in certain test procedures to account for the highly organic nature of peat materials. Key variants on these tests are described below.

Drying for moisture content determinations should be undertaken at less than 50°C to avoid charring the samples. Bulk density and linear shrinkage determinations should be carried out on peat from block samples, to ensure the moisture content and volume of the peat are preserved. Organic content (loss on ignition) tests should be performed at a maximum temperature of 375°C to avoid any weight losses associated with loss of water from clay minerals (Ball, 1964).

Particle size distribution tests can give misleading results, particularly for fibrous peats, and should be treated cautiously if used in geotechnical models and calculations. The use of fibre content tests, to be carried out in accordance with ASTM D1997-13 (due to a lack of equivalent British Standard) provides an additional and useful measure of peat composition and an indicator of potential tensile strength.

All shear strength tests should be performed on undisturbed samples taken from intact block samples of peat, substrate and peat/substrate interface as considered appropriate. Soil water samples should be collected from trial pits to determine pH. Shear tests can then be conducted with water pH equivalent to the natural condition.

Hobbs (1986) provides further useful practical advice on the applicability of standard index tests to peat soils, however caution should be exercised in any interpretation of ground conditions based upon these tests.

4.4.4.2 Shear strength tests in peat

Deriving credible shear strength parameters from conventional laboratory and field testing methods has been identified as problematic (Evans and Warburton, 2007; Gosling and Keeton, 2008; Winter *et al.*, 2005). Available testing results should be analysed with reference to previously published parameters (e.g. Carling, 1986; Warburton *et al.*, 2004; Dykes *et al.*, 2008). Although shear vanes can be used to derive site specific *in-situ* results, there is some doubt as to the reliability of these tests given fibre/vane interactions during testing (see Long and Boylan, 2012).

Recent testing developments such as T-bar and ball penetrometer testing (e.g. Long and Boylan, 2012) may provide more accurate shear strength characteristics for peat materials, although these methodologies are still in their infancy. Given the uncertainties inherent in both established laboratory investigation techniques and in more recent innovative approaches to testing organic soils, this guidance does not seek to be overly prescriptive as to the types of testing to be undertaken. Rather, it is the responsibility of the competent person(s) to clearly state:

- The reasoning behind the schedule of laboratory tests;
- The uncertainties associated with the results in relation to the quality of the sample(s), the composition of the sample(s) (particularly in relation to their fibre content), and in relation to the equipment used to undertake the tests;
- How these uncertainties are accommodated in the range of parameters used in slope stability analysis, where undertaken.

The publication of the first edition of this guidance has contributed to an increased interest in geotechnical research into characterisation of peat soils, particularly in relation to stability analysis, and it is expected that further useful advances will be made subsequent to this reissue.

4.4.4.3 Selection of appropriate site plant and safe working practice

In planning any site investigation, particular attention should be paid to the safety of personnel and the public at all stages of the investigation. The implications of specific methods and their associated risk to workers and the public should be considered and accounted for during the fieldwork layout design.

Any investigation should, in the first instance, consider the results of the desk study to minimise the impact of subsequent investigation techniques on any of the peat landslide hazards identified at the site. Where practicable, the investigation methods used should have a minimal impact on the site and any arisings should be returned to their point of origin, with surface vegetation cover re-laid to promote rapid recovery of the peat surface and minimise degradation.

Similarly the impacts of the works and their potential to trigger peat landslide hazards should be considered during the planning and design of any ground investigation. Cutting of a peat slope toe to enable machinery access should be avoided where practical and similarly the loading of peat slopes by plant or by temporary peat storage areas at the slope crest should be avoided to minimise the risk of destabilising the

slope. In many cases, lightweight plant and vehicles (e.g. quad-bikes and trailers, six-wheel buggies) should be employed during the ground investigation, to avoid the impacts of heavy plant at the site. Where loading or cutting is unavoidable, efforts should be made to site the plant equipment away from slope crests and to drain the free faces of slope cuts.

The hand coring and trial pit techniques described above are most suited to areas of shallow peat cover (less than 2m). Depths greater than 2m can be achieved using hand corers, but only at the discretion of the site worker(s) in relation to ease of retrieval of samples and with regard to Health and Safety issues. Where peat depths are confirmed to exceed 2m the need for deeper ground investigation should be considered alongside the suitability of the location. A suitable combination of trial pits, boreholes and auguring/coring should be sufficient to identify variability in peat material properties across the development site.

Hazard and risk assessment

5.1 Overview

Methodologies for geotechnical hazard and risk assessment are well covered in several existing publications (e.g. Lambe and Whitman, 1979; Brunsden and Prior, 1984; Bromhead, 1986), while hazard and risk assessment for landslide investigations is thoroughly considered in Lee and Jones (2013). This revised section provides an overview of the principles of hazard and risk, with specific reference to peat landslides, and is informed by these documents and by use of the previous guidance by statutory bodies, developers and assessors.

It should be noted that examples provided in the following sections are illustrative only and should not be taken as prescriptive or used as a substitute for a developer's preferred methodology. In all cases, risk assessment methodologies should be clearly explained and incorporate consideration of the likelihood of instability and the consequences should it occur.

5.2 Hazard and risk assessment

There is no universal, agreed definition of hazard and risk that can be applied in the context of peat landslides. However, there is general acceptance in the literature that risk is 'the potential for adverse consequences, loss, harm or detriment'. Peat landslides can be considered a type of *geohazard*, i.e. 'a geological process that in particular circumstances could lead to loss or harm'.

Risk can be expressed as the product of the probability of a [peat] landslide event and its adverse consequences (after Lee and Jones, 2013; see p104), i.e.:

$$\text{Risk} = \text{Prob. ([Peat] Landslide)} \times \text{Adverse Consequences} \quad \text{Eq. 1}$$

The definition as written above is particular to peat landslides, but has the same meaning as previously presented risk definitions in Clayton (2001) (Eq. 2), and in Winter *et al.* (2008) (Eq. 3):

$$\text{Degree of Risk} = \text{Likelihood} \times \text{Effect} \quad \text{Eq. 2}$$

$$\text{Hazard Ranking} = \text{Hazard} \times \text{Exposure} \quad \text{Eq. 3}$$

The probability of a peat landslide reflects the combined influence of *preconditions*, *preparatory factors* (see Section 2.2), and *triggering factors* (see Section 2.3), or collectively 'controls', on the stability of a peat deposit. The updated version of this guidance considers peat landslide hazard as a consequence of both *natural* controls and *man-made* controls.

The addition of man-made controls (such as construction activities, alterations to peat drainage) reflects the potential destabilising effects of human activity on peatlands, and evidence from well publicised peat landslide events that human activity may exert a significant control on peat stability (e.g. Lindsay and Bragg, 2004; Dykes and Warburton, 2007a). The revised definition of risk reflects increased emphasis in this issue of the guidance on considering all potential adverse consequences.

Adverse consequences may include accidents, loss of life, environmental impacts or damage to site infrastructure and associated financial losses. The potential for adverse consequences reflects the exposure to peat landslide hazard of elements at risk within a

specific area. For example, infrastructure may always be exposed to the effects of a peat landslide, but site traffic may only occasionally be exposed.

There are various levels of risk assessment, ranging between:

- High-level qualitative assessments where the objective is to develop an approximate estimate of the risks, particularly in relative terms (e.g. low, medium and high levels of risk);
- Detailed quantitative risk assessments (or QRA) where the objective is to generate more precise measures of the risks (e.g. expressing risk as a specific magnitude of loss).

As part of the EIA submission, it is expected that a PLHRA provides sufficient estimate of risks to enable infrastructure layout (e.g. turbines, hard standings, compounds, access tracks) to avoid areas of medium or high risk, while also making full and detailed recommendations for mitigation of low and medium risks where exposure remains. In the case of peat landslides, there may also be a desire to compare economic and environmental risks associated with a particular development proposal.

The general principles of risk assessment are similar, regardless of the elements at risk (e.g. people, peat resource, development programme). The next section provides guidelines on approaches to risk assessment in relation to peat landslides.

5.3 Assessing the likelihood of a peat landslide

5.3.1 Probabilistic or factor based approaches

There are a number of approaches to estimating the likelihood or probability of a future landslide in a given area (for a full account with worked examples, see Lee and Jones, 2013):

- Use the historical frequency of landslides in the area to provide an indication as to future annual probability, i.e.:

$$\text{Annual probability (peat landslide)} = \frac{\text{Number of recorded peat landslides}}{\text{Length of record period in years}} \quad \text{Eq. 4}$$

For example, if 2 landslides have occurred in 100 years in a particular area of peatland, the annual probability is:

$$\text{Annual probability} = \frac{2}{100} = 0.02 \text{ or } 2\% \quad \text{Eq. 5}$$

A 2% annual probability of occurrence also means a 98% probability of non-occurrence in any one year.

The probability of a peat landslide event occurring in a 25 year period (a typical wind farm design life) is equivalent to (after Lee and Jones, 2013):

$$\text{Prob. (Peat landslide) in 25 years} = 1 - (1 - 0.02)^{25} = 0.39 \text{ or } 39\% \quad \text{Eq. 6}$$

The approach is relatively easy to apply where there is a historical record of landslides. However, this approach assumes that conditions in the future correspond to conditions in the past, which is not necessarily the case, for example, the construction of a wind farm may elevate likelihood through alterations to natural drainage pathways.

- Use the probability of a *landslide triggering event* as an indicator of the probability of a landslide, assuming other preparatory factors indicate peat slopes to be of marginal stability.

In the case of peatlands, a number of publications cite triggering threshold rainfall intensities in association with recorded peat instability and in association with specific

ground conditions (see Evans and Warburton, 2007; Dykes and Warburton, 2007a; GSI, 2006). Other natural triggers may be used (e.g. snowmelt), or man-made triggers can be considered (e.g. slope cutting or loading).

- c) Estimate probability through expert judgement, whereby general principles are used to assign probabilities to landslide scenarios.

Such approaches may use ranking systems that relate ground conditions to the probability of landslide occurrence, e.g. the presence or absence of instability features at the site, or combinations of scored 'hazard factors' (e.g. slope, peat depth, orientation of slope drainage) whereby higher scores indicate higher probability of future peat landslides.

Where expert judgement is used, judgements should be transparent through full documentation of sources of evidence, and the logic behind any factoring or scoring approach should be clearly detailed.

- d) Estimate probability through stability analysis, i.e. by providing a quantitative measure of slope stability incorporating consideration of slope form (slope angle), materials (shear strength), loadings (overburden) and transient parameters (e.g. pore pressure).

The results of stability analysis are generally presented in terms of a Factor of Safety (F), where:

$$F = \frac{\text{Shear strength}}{\text{Shear stress}} \quad \text{Eq. 7}$$

The probability of a peat landslide occurring should be based upon the probability of a Factor of Safety being less than 1 over the period of concern (e.g. 25 years).

A full explanation of stability analysis is beyond the scope of this guidance, however, where it has been applied (e.g. Carling, 1986; Warburton *et al.* 2004; Long and Jennings, 2006; Dykes and Warburton, 2008), the infinite slope model has provided the most informative results. A short summary is provided below.

5.3.2 Stability analysis

The likelihood of a particular slope or hillside failing can be expressed as a Factor of Safety. For any potential failure surface, there is a balance between the weight of the potential landslide (driving force or shear force) and the inherent strength of the soil or rock within the hillside (shear resistance) (Figure 5.1). Provided the available shear resistance is greater than the shear force then the Factor of Safety will be greater than 1.0 and the slope will remain stable. If the Factor of Safety reduces to less than 1.0 through a change in ground conditions e.g. through the application of a trigger, the slope will fail.

The shear force is mostly a component of the weight of the rock/soil/peat making up the potential landslide mass. The shear resistance is provided by the frictional and tensile strength of the peat, soil or rock, and the normal effective stress and influence of groundwater increasing the normal load (weight) of the sliding mass (Warburton *et al.*, 2004; Dykes and Warburton, 2007b; Dykes and Warburton, 2008). The field sampling methods and laboratory tests recommended in the previous chapter provide the means of quantifying these controlling parameters in a ground model of the development site.

Where stability analysis has been applied to peat slopes (e.g. Carling, 1986; Warburton *et al.* 2004; Dykes and Warburton, 2008), the infinite slope model has provided the most informative results. The infinite slope model assumes a planar translational failure, where the shear surface is parallel to the ground surface, and the length of the slope is large in comparison to the failure depth (hence 'shallow' failure). The nature of

detachment of peat landslides is most frequently by a translational mechanism, and since this is the failure type modelled by infinite slope analysis, it is the most appropriate analytical method.

The stability of a slope can be assessed by calculating the factor of safety F , which is the ratio of the sum of resisting forces (shear strength) and the sum of the destabilising forces (shear stress):

$$F = \frac{c' + (\gamma - m\gamma_w)z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta} \quad \text{Eq. 8}$$

where c' is the effective cohesion, γ is the bulk unit weight of saturated peat, γ_w is the unit weight of water, m is the height of the water table as a fraction of the peat depth, z is the peat depth in the direction of normal stress, β is the angle of the slope to the horizontal and ϕ' is the effective angle of internal friction.

Values of $F < 1$ indicate a slope would have undergone failure under the conditions modelled; values of $F > 1$ suggest conditions of stability.

The infinite slope model can be modified to allow use of 'slices' in the slope (Craig, 1997). These slices allow sections of the slope with differing characteristics, such as peat depth or slope angle, to be treated individually. By considering the length of the slices, a residual mobilising force from one slice, if unstable, can be brought to bear on the slice below and taken into account in the stability analysis of the lower slice. Slices are not modelled as providing restraining forces to the slices below, as this is highly unlikely to happen in practice.

Sufficient slope stability analysis should be undertaken to represent the range of material, topographic and hydrological conditions at the development site. Spatial variability in Factor of Safety can then be used as a key input into hazard zoning or for calibration of other approaches to estimating landslide probability (such as factor based approaches).

5.3.3 Summary

Ultimately, under the assumption that peat landslide probability is spatially variable over a proposed development area, and assuming that this spatial variability reflects site conditions, probability ranges can be assigned to different areas of the site (see Table 5.1). When compared with the potential for adverse consequences in the same polygon, a risk value can be determined for that specific location in the proposed development area.

The table below provides an illustration of how qualitative descriptions of likelihood might relate to the probability of a landslide occurring. The developer *should not* consider these examples as prescriptive and should determine any likelihood scale (if used) according to their own understanding of the site conditions and with respect to the hazard and risk assessment methodologies they have chosen.

Table 5.1 Peat landslide probability ranges for the lifetime of a proposed development

Scale	Likelihood	Probability of occurrence
5	Almost certain	> 1 in 3
4	Probable	1 in 10 – 1 in 3
3	Likely	1 in 10 ² – 1 in 10
2	Unlikely	1 in 10 ⁷ – 1 in 10 ²
1	Negligible	< 1 in 10 ⁷

5.4 Assessing adverse consequences

Potential adverse consequences, in the event that a peat landslide does occur, should be estimated. The intention should be to represent consequences as a range that can be applied to specific areas of the development site. For example, the consequences of a landslide occurring for a watercourse may depend on how far the landslide is from it, or on the importance of a watercourse from a habitat perspective, e.g. it may be designated as a Special Area of Conservation (SAC).

Consequences could include but are not limited to the following elements:

- The potential for harm to life during construction;
- The potential economic costs associated with lost infrastructure, or delay in programme;
- The potential for reputational loss associated with occurrence of a peat landslide in association with construction activities;
- The potential for permanent, irreparable damage to the peat resource (both carbon stock and habitat) associated with mobilisation (and ultimately loss) of peat in a landslide; and
- The potential for ecological damage to watercourses subject to inundation by peat debris.

A magnitude of adverse consequence should be attached to each element for each area to which a peat landslide probability has been assigned (see Table 5.2).

Table 5.2 Degree of adverse consequence for elements exposed to peat landslide hazard (example shown here relates to financial cost)

Scale	Adverse consequences	Impact as % damage to (or loss of) receptor
5	Extremely high	> 100% of asset (e.g. infrastructure or habitat)
4	Very high	10% - 100%
3	High	4% - 10%
2	Low	1% - 4%
1	Very Low	< 1% of asset (e.g. infrastructure or habitat)

Consequence analysis is a key element of risk assessment, since without it only landslide potential or hazard is assessed. When determining receptors at risk, care should be taken to identify designated environmental features both within the application boundary and within a reasonable distance of it (since the effects of peat landslide debris may be felt off-site if debris is incorporated within watercourses).

5.5 Determining risk

Once all areas within the site have been assigned a peat landslide probability and a degree of adverse consequence, a risk level can be estimated for each area, and peat landslide risk maps prepared for the development site. Table 5.3 shows how the qualitative descriptors for likelihood and adverse consequences can be simply combined to produce risk levels.

Risk maps can be produced for individual elements at risk (e.g. environment, infrastructure) or a summary risk map which sums the risks associated with all exposed elements within the development area can be presented.

The need for further investigation or specification of mitigation measures should be a function of the risk level present on the site (see Table 5.4).

Table 5.3 Indicative risk levels

		Adverse consequence				
		Extremely High	High	Moderate	Low	Very Low
Peat landslide probability or likelihood	Almost certain	High	High	Moderate	Moderate	Low
	Probable	High	Moderate	Moderate	Low	Negligible
	Likely	Moderate	Moderate	Low	Low	Negligible
	Unlikely	Low	Low	Low	Negligible	Negligible
	Negligible	Low	Negligible	Negligible	Negligible	Negligible

Where the risk level for a zone is medium or high, avoidance or specification of mitigation measures would normally be the only means by which project infrastructure could be considered acceptable within that zone at the proposed development site.

Table 5.4 Risk ranking and suggested actions

Risk Level	Action suggested for each zone
High	Avoid project development at these locations
Medium	Project should not proceed unless risk can be avoided or mitigated at these locations, without significant environmental impact, in order to reduce risk ranking to low or negligible
Low	Project may proceed pending further investigation to refine assessment and mitigate hazard through relocation or re-design at these locations
Negligible	Project should proceed with monitoring and mitigation of peat landslide hazards at these locations as appropriate

It is accepted that for some locations, further detailed ground investigation may be required to better quantify risks. If these locations are of concern, the developer should consider offering assurances through specification of these additional works in conditions of consent.

Possible mitigation measures in relation to peat instability are considered below.

5.6 Mitigation

The extent of mitigation required will depend upon the scale of the project, the nature of the risk and estimated risk level. A combination of options may be required to reduce the risks to an acceptable level for a given scheme.

5.6.1 Avoidance

Areas exhibiting medium or high risk levels associated with peat landslides should be avoided, for example by relocating infrastructure within the development area or by relocating to an alternate site. Where avoidance is not possible, the proposed design should be modified to incorporate engineering measures to reduce or eliminate the assessed risk.

5.6.2 Engineering mitigation measures to minimise landslide occurrence

Many of the site specific (e.g. peat depth, slope angle) and site independent variables (e.g. weather) that contribute to the incidence of natural peat landslides are beyond engineering control without significant damage to the peat itself. However, a number of engineering measures exist to minimise the risks associated with potential triggers (such as short term peaks in hydrogeological activity).

5.6.2.1 Installation of drainage measures

Installation of targeted drainage measures would aim to isolate areas of susceptible peat from upslope water supply, re-routing surface (flushes/gullies) and subsurface (pipes) drainage around critical areas. Surface water drainage plans should be considered as a useful way of accounting for modified flows created by construction, which in turn may affect peat stability, pollution and wildlife interests. Drainage measures need to be carefully planned to minimise any negative impacts.

5.6.2.2 Construction management

Site specific procedures aimed at minimising construction-induced peat landslide hazards should be identified and implemented and followed rigorously by site construction personnel. These may include work method statements subject to an environmental check to monitor compliance. These checklists should incorporate a weather forecast to avoid peat working during heavy rain and to allow environmental mitigation measures to be put in place where construction work is on-going. Weather forecasts can be obtained using data available from numerous web-sites or provided at a cost by commercial organisations or the Met Office. Particular care should be taken in relation to storage of excavated peat deposits on site, with loading of intact peat by excavated deposits avoided wherever possible.

Further guidance in relation to the construction of tracks on peatlands, and the management of peat on construction sites is provided by SNH and SEPA (Scottish Natural Heritage, 2015b; Scottish Renewables *et al*, 2015).

5.6.3 Engineering mitigation measures to control landslide impacts

A number of engineering measures are available for reducing the impacts (or exposure) associated with peat landslide hazards.

5.6.3.1 Catch wall fences

Where the potential for peat landslides has been identified, catch fences positioned downslope of the suspected or known landslide prone area can slow or halt runout (Tobin, 2003). Catch fences should be engineered into the peat substrate. Fencing may require periodic inspection for removal of debris.

5.6.3.2 Catch ditches

Similarly, ditches may also slow or halt runoff, although it is preferable that they are cut in non-peat material. Simple earthwork ditches can form a useful low-cost defence. Paired ditches and fences have been observed (Tobin, 2003) to slow peat landslide runoff at failure sites.

5.6.4 Monitoring and review

Risks identified in the PLHRA should be included in either a specific peat landslide hazard management plan or be included within the Geotechnical Risk Register for the site. These documents should be prepared by the developer or contractor undertaking the assessment, and passed on post-consent to the design and build contractor at the earliest opportunity. The implementation of measures in these documents (and update, if required) is as critical to safe site development as is their preparation.

It should be noted that factors that affect the likelihood of peat landslides and their consequences may change with time. Thus, ongoing review of the peat hazard management plan is essential. Design of stabilisation measures may be reviewed and risks may be reassessed during construction as the process of construction yields further data.

5.7 Post construction and restoration works

The PLHRA must also consider the risks (residual and new) following construction, and on completion of restoration works for the site, particularly where proposing to re-use excavated peat (Scottish Renewables and SEPA, 2012). Restoration proposals should aim to restore the water table of the peatland to ensure that the peatland becomes active again and therefore stores carbon. Otherwise, potentially significant changes to the hydrology of the peat bog may result in irreversible changes to the physical characteristics and structure of the peat that could both increase the likelihood of peat landslides and lead to long term degradation of the peat resource. Further Reading

5.8 Further Reading

This document has provided a brief overview of peat landslide hazards, the means by which they may be identified, the risks associated with their occurrence, and the measures that might be considered to mitigate these risks. A considerable range of published material, much of which is referred to herein, is available that may be of use to developers in undertaking the works described in this document.

The form, mechanisms and causes of peat landslides are considered in detail in a paper by Dykes and Warburton (2007a), and in two books that consider wider issues of peat degradation (Evans and Warburton, 2007; Martini *et al.* 2006).

The geotechnical properties of peat are well described in a chapter on organic soils by Bell (1999), with detailed discussion of peat physical and chemical properties provided by Hobbs (1986).

Methodologies for landslide investigation and management are provided in Department of Environment (1996), while landslide hazard and risk assessment is considered in detail in Lee and Jones (2013).

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Figures and Plates

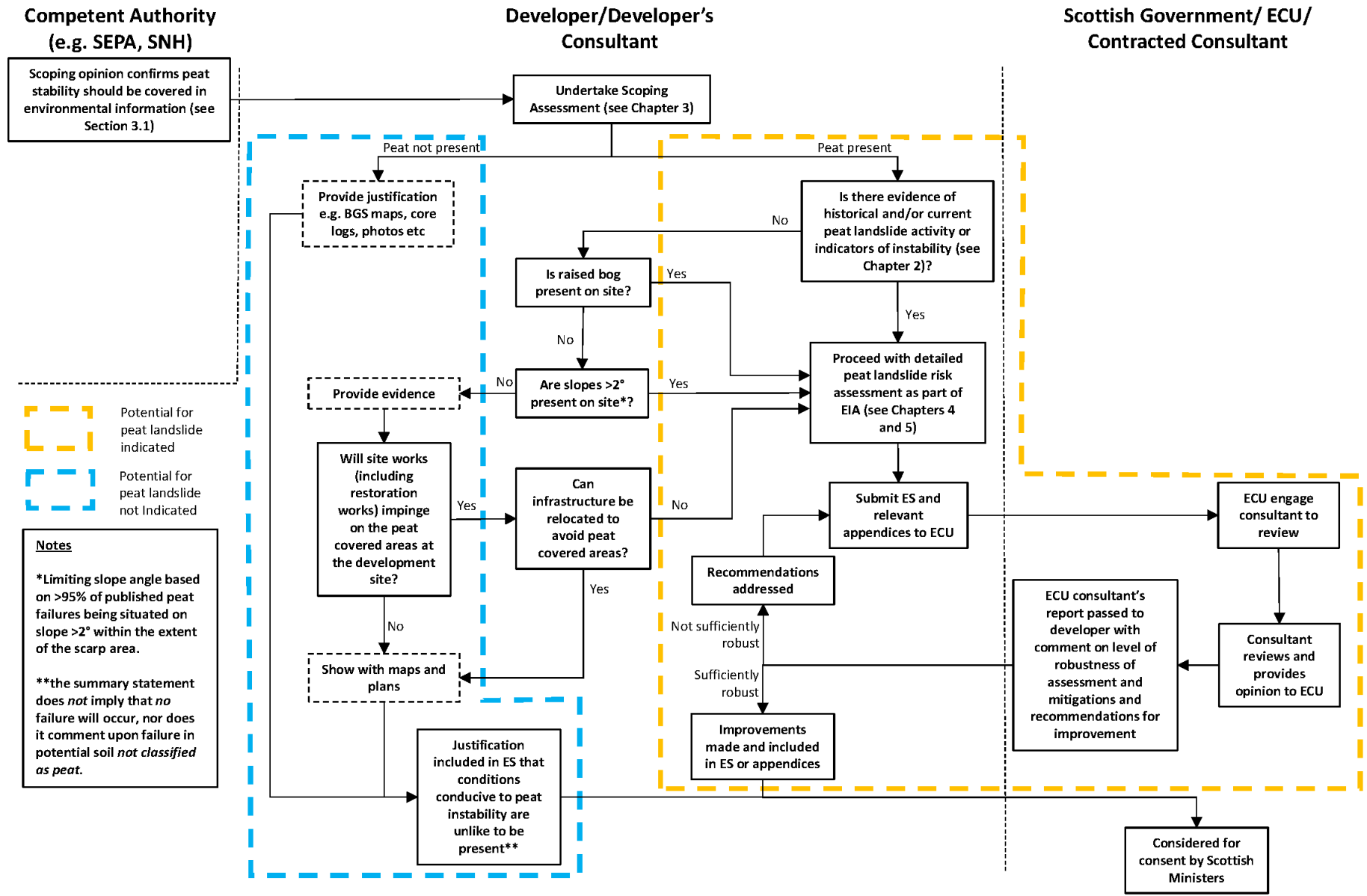
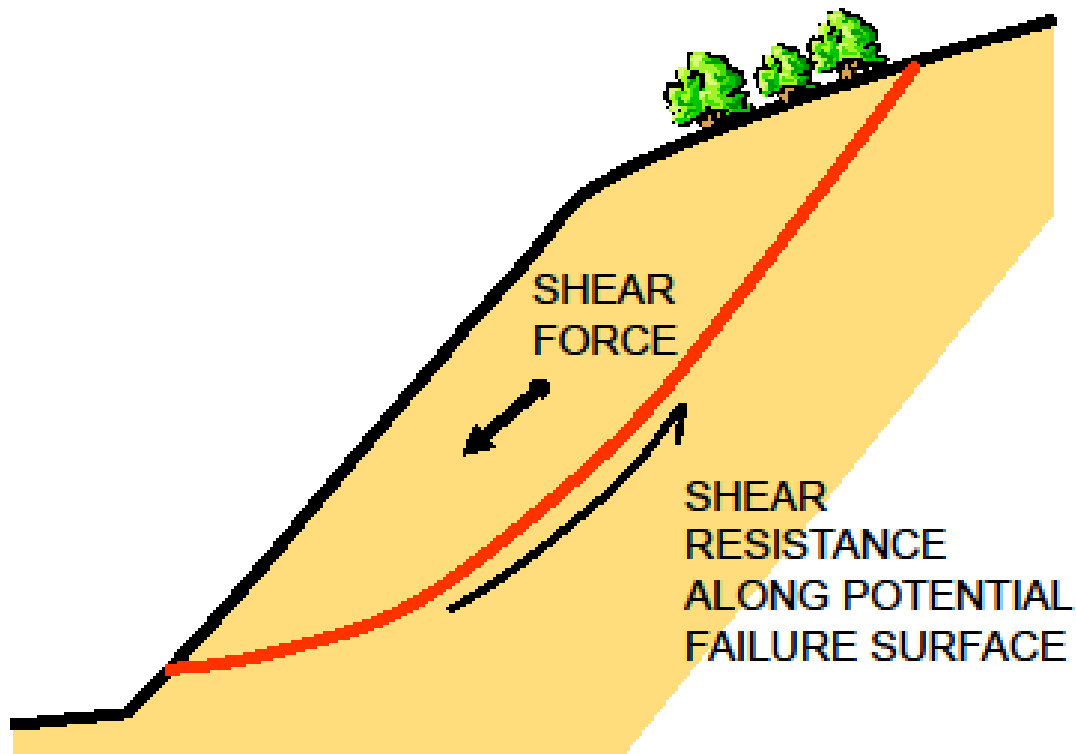


Figure 1.1 Flow diagram checklist for peat landslide hazard and risk assessment



$$\frac{\text{SHEAR RESISTANCE}}{\text{SHEAR FORCE}} = \text{FACTOR OF SAFETY}$$

Figure 5.1 Balance of slope forces

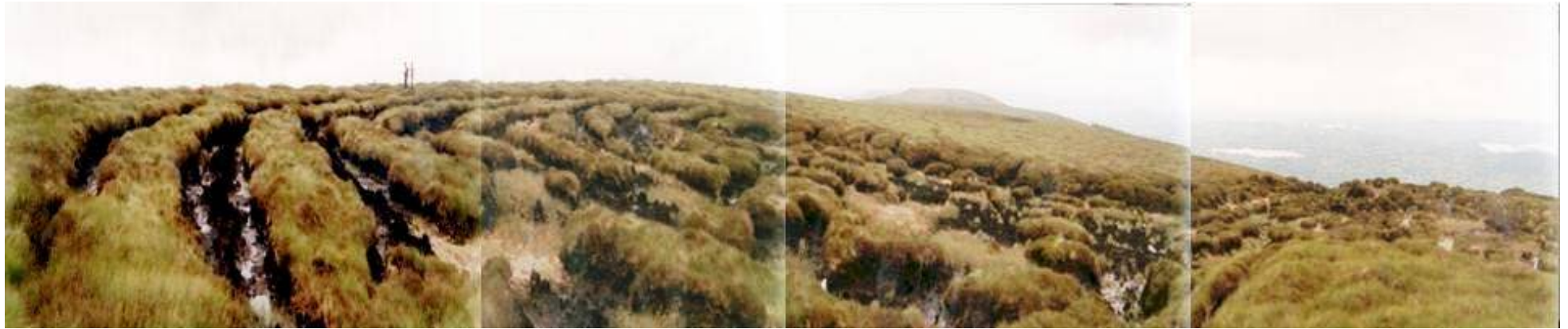


Plate 2.1 - Bog burst, a spreading failure in peat with pear-shaped area of disturbance with concentric rafts and tears and little substrate exposed



Plate 2.2 - Peat slide, a shallow translational slide failure in peat with large slab-shaped raft visible (right) and extensive exposed substrate (left)



Plate 2.3. Long and semi-continuous tension crack



Plate 2.4. Diamond shaped tears



Plate 2.5. Multiple intersecting cracks



Plate 2.7. A section of thrusting peat



Plate 2.6. Compression ridge



Plate 2.8. Extrusion features



Plate 2.9. Pipe outlet in exposed peat scarp



Plate 2.10. Collapsed piping



Plate 2.11. Gullies, and pools and hummocks



Plate 2.12. Flushes and soakaways

Appendix A

Appendix A Sources of Satellite Imagery

Satellite imagery

Several data capture techniques based on satellite and aerial imagery were available at the time of publication. An overview of the main techniques is provided below. It is expected that these techniques will be revised and superseded with advances in satellite technology, and therefore that this list should not be considered exhaustive.

Optical Satellite Imagery (Thematic Mapper)

The Landsat series of satellites operates the Thematic Mapper instrument. Unfortunately, the 30m pixel size has limited its applications for individual peat slide investigations. However, Landsat-7 now offers a 15m resolution panchromatic band which enables mapping scales to 1:25,000. Furthermore the Indian, IRS-1C with 5m pixels improves mapping scales to 1:10,000. The IKONOS satellite, available since early 2000, offers data which provides 1m ground resolution imagery and enables mapping scales of 1:2,000 or greater. The French SPOT satellite provides 10m resolution panchromatic data and the ability to acquire stereo image pairs. At these scales individual flow lobes, ground fissures and subtle morphology indicative of potential peat landslides may be resolvable.

Microwave (Synthetic Aperture Radar Interferometry, InSAR)

Radar imagery, at different wavelengths and polarisation, can be obtained from both satellite and aircraft. Radar data can be acquired during the night or day and effectively 'sees' through cloud. Currently available SAR (synthetic aperture radar) data includes ERS with 25m spatial resolution, RADARSAT with 10-15m spatial resolution and stereo capability, and JERS with 18m spatial resolution. These data enable interpretation at a range of scales from regional, to local and include vegetation type, moisture content, debris sizes etc. Synthetic Aperture Radar Interferometry (InSAR) can create digital elevation model data and detect subtle changes in elevation to the accuracy of the centimetre scale. This is particularly useful for identifying changes in topography such as subsidence and precursory ground movements on slopes.

Multispectral Video

Multi-spectral video cameras operate at the visible to near infra-red portion of the spectrum and can be mounted on low-flying aircraft. They can generate pixels of less than 1m ground resolution and are therefore suitable for large mapping scales. Field spectra obtained from in-situ measurements are used to determine different classes of iron oxide precipitates from the air and, by inference, the different pH levels of drainage systems. This may be particularly useful for the mapping of peat landslide groundwater systems.

Hyperspectral Scanners

Airborne hyperspectral scanners are much more complicated and expensive instruments than multispectral video. They can be mounted on low-flying aircraft. Remotely sensed multi-spectral data have been shown to be of considerable use for landslide investigations. Uses include the mapping of geological units in areas of poor exposure through estimation of soil moisture content, the estimation of soil thickness prone to landslides and the mapping of geomorphological features of landslides at the regional scale and the local scale.

Unmanned Aerial Vehicles (UAVs)

UAVs (commonly referred to as drones) are increasingly being used to provide site specific high resolution photography and digital elevation data (Hackney and Clayton, 2015). Good quality data acquisition is reliant on accurate and precise ground control and careful survey planning. In the UK, the Civil Aviation Authority (CAA) define operating regulations (CAP393; CAP722) which constrain survey areas to within c. 500m 'line of sight' of the operator and c. 400m altitude. A license is required to use drone acquired data for commercial purposes.

Appendix B

Appendix B Geophysical Survey Techniques

List of Figures

Figure B.1. Plan showing the location of geophysical traverses on a proposed turbine base for the Farr Wind Farm, Scotland. These included Ground Penetrating Radar (GPR), resistivity R and P-wave Seismic

Figure B.2. Results of a GPR Survey, Farr Wind Farm, showing peat stratigraphy. Fibrous peat overlies amorphous peat (yellow line) which in turn overlies compacted glacial till (red line)

Figure B.3. Results and interpretation of resistivity and P-wave seismic geophysical survey undertaken at Farr Wind Farm, Scotland, showing a horizontally stratified sequences (verified by drilling and trial pitting)

Geophysical survey techniques

Geophysical survey techniques may provide an alternative non-intrusive method for investigating peat environments. These technologies measure the vertical and lateral variation of physical properties of the ground. They are particularly useful in areas where biodiversity and other environmental issues preclude the use of more invasive methods (such as trial pits and drilling), although in general, geophysical methods should be used to support more traditional intrusive techniques.

The type of instrument, methodology and resulting interpretation will depend upon the anticipated physical properties of the peat, underlying geology, anticipated depth of the peat-substrate interface, topography, hydrogeology, and the presence of fences, cables and underground utilities which may cause geophysical noise.

Ground Penetrating Radar (GPR)

This consists of a radar antenna transmitting electromagnetic energy in pulse form. Measurements are taken of the time taken for the radar pulse to be reflected from a stratigraphic interface. Partial reflections occur at interfaces with different geoelectrical properties (within the solid and superficial geology). Information is provided on the depth to bedrock (i.e. thickness of peat and superficial deposits). In general, clay-rich and water saturated soils have a lower penetration than gravel and dry soils. However, signal penetration and resolution limits are also influenced by the frequency of the transmitted electromagnetic pulse. High frequencies give better resolution and shallow penetration. Lower frequencies give lower resolution and deeper penetration.

Electrical resistivity

This method measures small changes in the electrical resistance of the ground between an electrode array; this provides an indication of the depth to the base of the peat. For example, the two-dimensional Wenner resistivity array may be used, whereby four electrodes are placed in a line in the ground and a current is passed through the two outer electrodes. The potential difference is measured across the two inner electrodes and the resistivity is calculated.

P-wave seismic refraction

This method measures the velocity of refracted seismic waves through superficial deposits and bedrock. The sonic pulse is artificially introduced into the ground. Readings are taken using geophones connected via a multi-core cable to a seismograph. This determines the depth to, and nature of the superficial

deposit/bedrock interface. Stiffer and stronger materials usually have higher seismic velocities, while soft, loose or fractured deposits have lower velocities.

Magnetometry

The magnetometry method involves the measurement of variations in the magnetic field of the Earth caused by local differences in the magnetisation of the subsurface rocks, for instance where the minerals magnetite or hematite are present. The standard instrument is the proton magnetometer. The instrumentation has a microprocessor control to record the data for downloading to a computer at suitable points in the survey. Other types of magnetometer include magnetic balance, fluxgate and nuclear resonance. A magnetic survey is rapid and easy to carry out and a site can be surveyed with a close grid spacing (often 1m) at low cost.

Electromagnetic (EM)

Electromagnetic surveying methods make use of the response of the ground to the propagation of electromagnetic fields, which are composed of an alternating electrical intensity and magnetising force. The primary fields are generated by passing alternating current through a small coil made of many turns of wire through a large loop of wire. The response of the ground is the generation of secondary electromagnetic fields. The resultant field may be detected by a receiver coil. The depth of penetration of an electromagnetic field depends upon its frequency and the electrical conductivity of the medium through which it is propagating.

Gravity

The gravity method involves the measurement of variations in the gravity field of the Earth caused by local differences in the density of the subsurface rocks. Microgravity surveys, using the La Coste Romberg system, have been used in the detection of natural cavities and voids (or pipes).

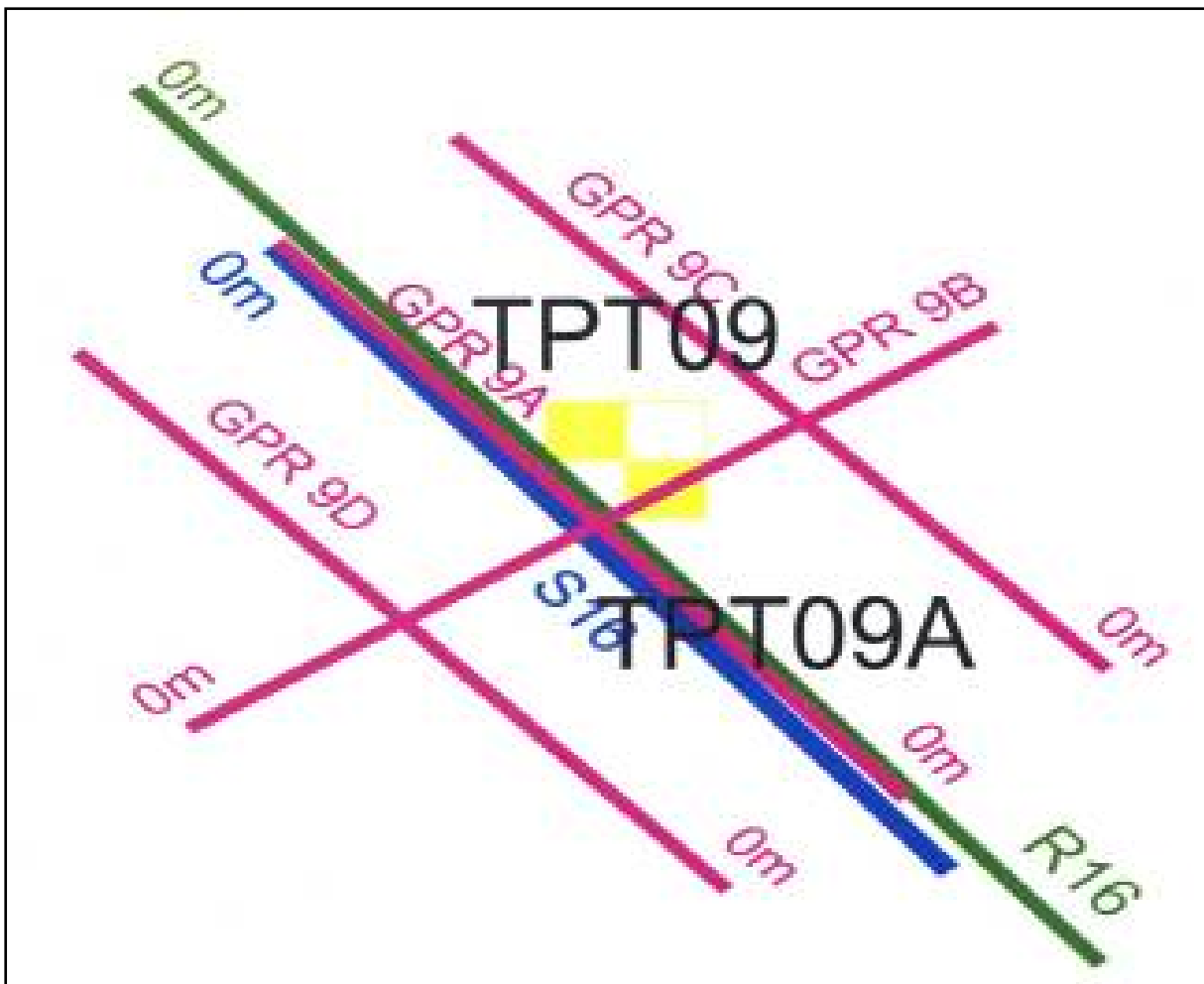


Figure B1. Plan showing the location of geophysical traverses on a proposed turbine base at the Farr Wind Farm, Scotland. These included Ground Penetrating radar (GPR), resistivity (R) and P-wave Seismic.

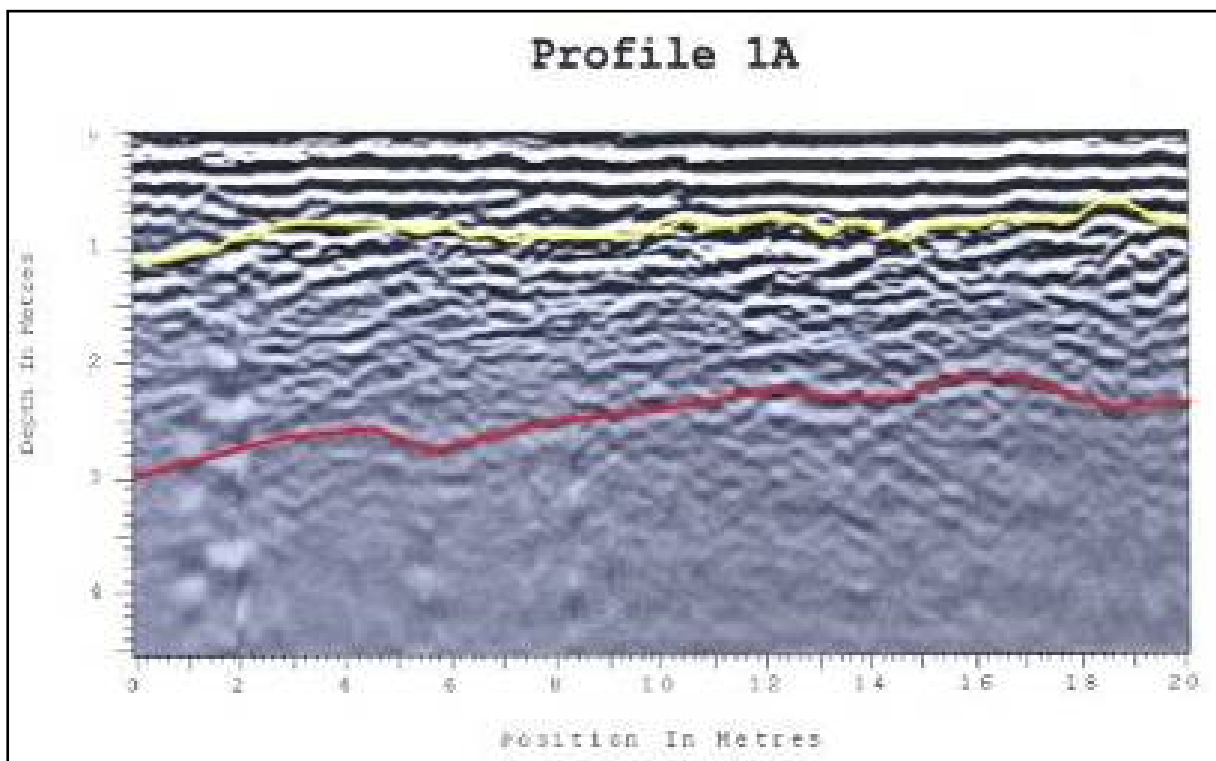


Figure B.2. Results of a GPR Survey, Farr Wind Farm, showing peat stratigraphy. Fibrous peat overlies amorphous peat (yellow line) which in turn overlies compacted glacial till (red line).

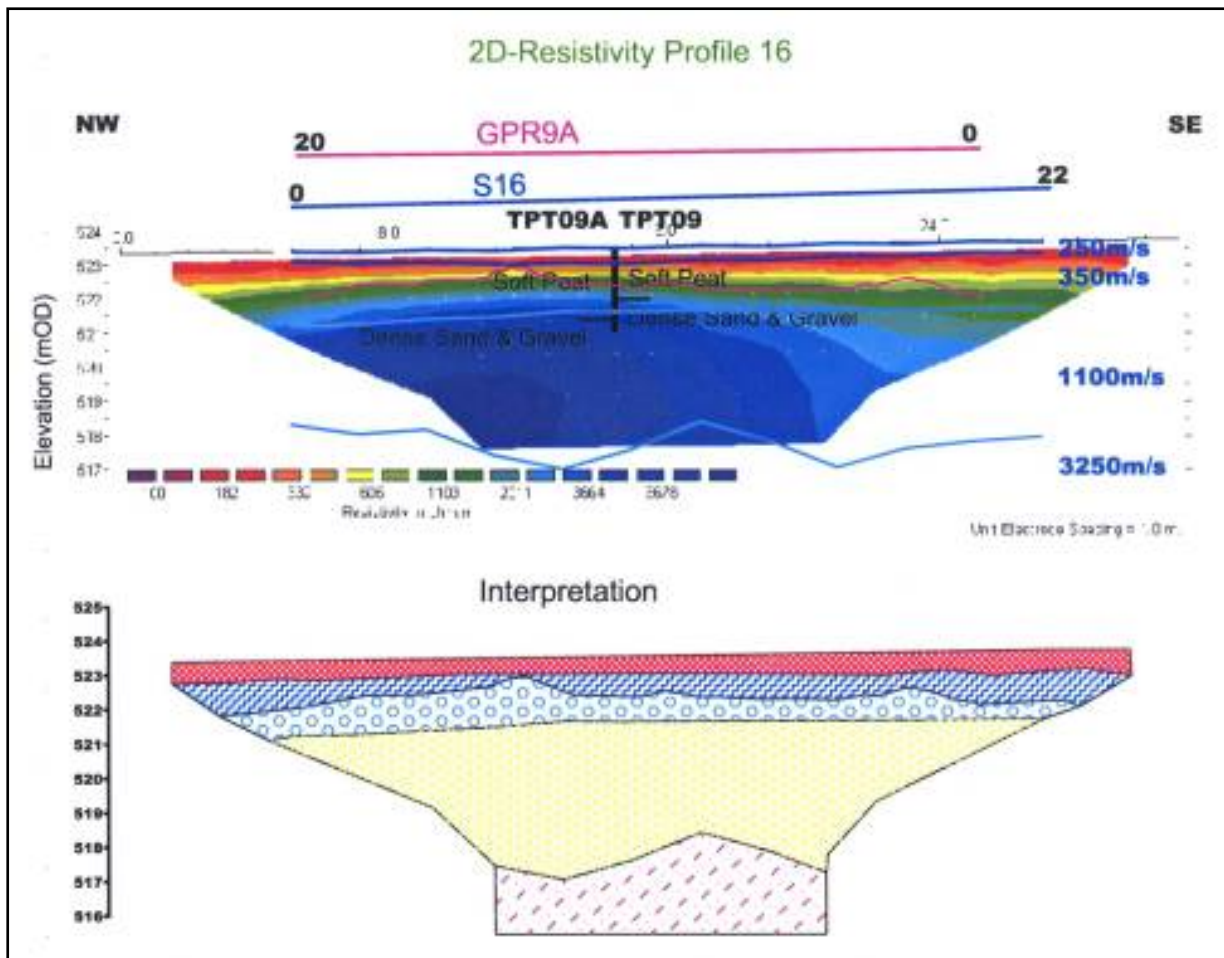


Figure B.3. Results and interpretation of resistivity and P-wave seismic geophysical surveys undertaken at Farr Wind Farm, Scotland, showing a horizontally stratified sequences (verified by drilling and trial pitting).

Appendix C

Appendix C Site Monitoring Instrumentation

Site monitoring and instrumentation

Various types of instrumentation can be considered for installation on site to allow monitoring of groundwater levels, overland flow (run-off) characteristics, slope movement at tension crack locations and rainfall. The following instruments may be installed:

Variable to be monitored	Instrumentation	Description and purpose
Groundwater	Standpipes	Installed to monitor groundwater level. Use of data loggers can be helpful in remote sites and also for detailed assessment of how groundwater levels respond to particular rainfall events, which are difficult to interpret from spot water level readings.
Pore water pressure	Piezometers	Installed to monitor groundwater pressure at a particular depth.
Overland flow	Crest stage tubes	Installed to monitor overland flow/run-off from the slopes after periods of heavy rainfall.
Rainfall	Rain gauges	Installed to collect rainfall data via either automated or regularly monitored systems.
Ground movement	Tension crack pegs	Installed either side of existing tension cracks and regularly monitored to determine rates and frequencies of crack extension and ground movement.
Detailed ground movement	Extensometers	Automated systems that can be installed in existing tension cracks to establish both the nature and rate of ground movement. Automated systems allow for data collection on ground movement at regular intervals (e.g. every 3 hrs) and therefore allow collation of ground movement with groundwater and rainfall characteristics on a given site.
Shear surface movement	Inclinometers	Installed in deep peat landslides (+ 2.5m) in locations where the depth of the shear surface is known to monitor rates of deformation at the shear surface. Where inclinometers may not be appropriate slip indicator methods can be used; Simple polythene tubing which is installed in the peat slope and probed regularly. The depth of deformation in the tubing indicates the potential position of the shear surface.

Table C1 Site instrumentation recommendations

Appendix D

Appendix D Reporting

Reporting

The multi-disciplinary team responsible for reporting the PLHRA should prepare a report as part of the Environmental Impact Assessment (EIA). This should include a factual report of the investigations undertaken as an appendix. Recommendations as to the contents of these reports follow.

Factual report structure

The following is a suggested structure for the factual report, detailing the minimum content:

- (i) **Introduction:** a brief statement indicating who the work has been carried out for, a summary of the site location and extent, and a brief summary of the scope and purpose of the investigation;
- (ii) **Design of Ground Investigation:** an explanation of the size and scale of the investigation, a rationale of why the locations and methods have been selected and a statement on the measures undertaken to mitigate and/or reduce potential site risks;
- (iii) **Field investigation and testing:** a summary of the field work undertaken including, detailed mapping, detailed site investigation plans, and length of time taken to carry out the field investigation. A summary of the logging procedure and a summary of the different peat types identified onsite. Details of the samples taken and the procedures used should be included and the location and reasons for any installations should be included;
- (iv) **Laboratory testing:** a summary of the laboratory testing that has been undertaken including summary tables of physical, chemical and geotechnical properties of each peat layer identified onsite. The information displayed should be sufficient to populate any slope stability model used in stability analysis;
- (v) **Appendices:** A detailed series of appendices should be included to present all of the supporting information for the above sections. At a minimum this should include:
 - A desk study summary plan for the site summarising all supporting mapping and observations;
 - Details on the sites investigation locations including logging sheets, elevations, photos of excavation;
 - A list of all samples taken including sample reference numbers, dates taken and the tests undertaken on each sample, and
 - All supporting laboratory results that have been used to characterise the specific site materials and their geotechnical properties.

EIA reports

The following is a suggested structure for the EIA report, detailing the minimum content:

- (i) **Introduction:** a statement indicating for whom the work was done, the nature and scope of the investigation, and a summary of the site location and extent;
- (ii) **Initial Assessment:** a detailed description of the site based on the observations made by the Competent Person during their site review and site reconnaissance.

It should be referenced to plans and maps of the site showing national grid coordinates and to a scale no smaller than 1:2,500 (this can be submitted digitally to avoid printing or presentation restrictions);

- (iii) **Ground Conditions:** descriptions of the ground conditions found during the investigation and an interpretation of their relevance to the stability of the site and surrounding area should be provided, informed by the factual report. Anomalies in any of the data collected should be noted and their impact on confidence in interpretation clearly stated. The following items should be discussed where appropriate: geological conditions; local climate and hydrology/hydrogeology; history of past landslide events and ground movement rates; soil and peat properties, land-use history and natural environmental change. They should be supported by interpretative geological cross sections of the peat environment;
- (iv) **Hazard and risk assessment:** the stability of the site and relevant adjacent areas should be evaluated with respect to the proposed development components (structures, communications) and any associated stabilisation measures. It is expected that particular attention be paid to the gradients of cut slopes and fills, drainage measures, retaining structures, failure mechanisms and the design criteria applied; The risks post construction and during restoration should also be presented;
- (v) **Discussion regarding mitigation measures:** A detailed discussion should be presented of the main conclusions of the investigation and of the resulting mitigation measures that are recommended for each infrastructure component. This should include details of the recommendations to ensure both the long term peat stability of the site (taking account of the anticipated life of the development) and the short term peat stability of the site during construction. Peat landslide hazard zonation plans should be included and peat landslide hazard management plans referred to with appropriate mitigation measures, this should be achieved by the use of a risk register. It is expected that particular reference be made to matters such as: provision for free drainage of groundwater; minimising drainage diversions and specification of drain linings where site conditions require them; avoidance of natural drainage pathways (e.g. gullies, soakaways) and provision of flexible jointed pipes capable of sustaining small movements without leakage;
- (vi) **Conclusion and Recommendations:** Conclusions and recommendations should be presented stating the outcome of the above discussion.

Assessors Report

The assessment report by the Assessor will take account of the following work areas:

- Schedule of work;
- Site selection;
- Sampling equipment and strategy;
- Techniques and methodology;
- Sample analysis;
- Risk assessment/register;
- Recommendations on mitigation measures;
- Proposals for further investigation;
- Summary of requirements;
- References used.



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