Consulting Report

Appendix 9.4 - Peat Landslide Hazard and Risk Assessment
Knockcronal Wind Farm

South Ayrshire, Scotland

20-FEC-013-D-001v01

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1. INTRODUCTION

1.1. Background

Knockcronal Wind Farm Limited (the Applicant) are seeking consent under Section 36 of the Electricity Act 1989 for construction of the Knockcronal Wind Farm, South Ayrshire (hereafter the ‘Proposed Development’).

The site for the Proposed Development lies approximately 4.8 km to the south of Straiton and is approximately 5.4 km^2 (c. 540 ha) in area (see **Plate 1.1**). The site is bordered to the south and west by extensive conifer plantations and to the north and east by moderately steep open fells that fall towards the floodplain of the Water of Girvan.

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Plate 1.1 Location of the Proposed Development

The Proposed Development will comprise:

- 9 wind turbine generators of up to 200 m tip height with associated foundations and hardstandings.
- Depending on the access route selected (northern and or western) there will be approximately 5.7 to 6.2 km of new track constructed, and approximately 2.2 to 2.8 km of existing track upgraded. Approximately 0.2 km of the new track is proposed to be floated, with the remainder excavated..
- Up to 5 borrow pits.
- Temporary gatehouse and construction compounds.
- A substation and energy storage facility.
- A met mast.

The main site is relatively compact, however, there will be two access route options, one to the north and one to the west. Both have been considered and assessed as part of the EIA, but only one access route option will ultimately be selected and constructed. Over most of their routes, the two access route options will comprise upgrades to existing forestry track.

The Scottish Government Best Practice Guidance (BPG) provides a screening tool to determine whether a peat landslide hazard and risk assessment (PLHRA) is required (Scottish Government, 2017). This is in the form of a flowchart, which indicates that where blanket peat is present, slopes exceed 2° and proposed infrastructure is located on peat, a PLHRA should be prepared. These conditions exist at the Proposed Development site and therefore a PLHRA is required.

1.2. Scope of Work

The scope of the PLHRA is as follows:

- Characterise the peatland geomorphology of the site to determine whether prior incidences of instability have occurred and whether contributory factors that might lead to instability in the future are present across the site.
- Determine the likelihood of a future peat landslide under natural conditions and in association with construction activities associated with the Proposed Development.
- Identify potential receptors that might be affected by peat landslides, should they occur, and quantify the associated risks.
- Provide appropriate mitigation and control measures to reduce risks to acceptable levels such that the Proposed Development is developed safely and with minimal risks to the environment.

The contents of this PLHRA have been prepared in accordance with the BPG, noting that the guidance "*should not be taken as prescriptive or used as a substitute for the developer's [consultant's] preferred methodology*" (Scottish Government, 2017). The first edition of the Scottish Government Best Practice Guidance (BPG) was issued in 2007 and provided an outline of expectations for approaches to be taken in assessing peat landslide risks on wind farm sites. After ten years of practice and industry experience, the BPG was reissued in 2017, though without fundamental changes to the core expectations. A key change was to provide clearer steer on the format and outcome of reviews undertaken by the Energy Consents Unit (ECU) checking authority and related expectations of report revisions, should they be required.

In section 4.1 of the BPG, the key elements of a PLHRA are highlighted, as follows (Scottish Government, 2017):

i. 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.

ii. An assessment of evidence for past landslide activity and present-day instability e.g. pre-failure indicators.

iii. A qualitative or quantitative assessment of the potential for or likelihood of future peat landslide activity (or a landslide susceptibility or hazard assessment).

iv. Identification of receptors (e.g. habitats, watercourses, infrastructure, human life) exposed to peat landslide hazards.

v. A site-wide qualitative or quantitative risk assessment that considers the potential consequences of peat landslides for the identified receptors.

Section 1.3 describes how this report addresses this indicative scope.

1.3. Report Structure

This report is structured as follows:

- Section 2 gives context to the landslide risk assessment methodology through a literature based account of peat landslide types and contributory factors, including review of any published or anecdotal information available concerning previous instability at or adjacent to the site.
- Section 3 provides a site description based on desk study and site observations, including consideration of aerial or satellite imagery, digital elevation data, geology and peat depth data.
- Section 4 describes the approach to and results of an assessment of peat landslide likelihood under both natural conditions and in association with construction of the Proposed Development.
- Section 5 describes the approach to and results of a consequence assessment that determines potential impacts on site receptors and the associated calculated risks.
- Section 6 provides mitigation and control measures to reduce or minimise these risks prior to, during and after construction.

Assessments within the PLHRA have been undertaken alongside assessments for the Outline Peat Management Plan (Technical Appendix 9.3) and have been informed by results from the Peat Survey (Technical Appendix 9.2). Where relevant information is available elsewhere in the Environmental Impact Assessment Report (EIA / EIAR), this is referenced in the text rather than repeated in this report.

1.4. Approaches to assessing peat instability for the Proposed Development

This report approaches assessment of peat instability through both a qualitative contributory factor-based approach and via more conventional stability analysis (through limit equilibrium or Factor of Safety (FoS) analysis). The advantage of the former is that many observed relationships between reported peat landslides and ground conditions can be considered together where a FoS is limited to consideration of a limited number of geotechnical parameters. The disadvantage is that the outputs of such an approach are better at illustrating relative variability in landslide susceptibility across a site rather than absolute likelihood.

The advantage of the FoS approach is that clear thresholds between stability and instability can be defined and modelled numerically, however, in reality, there is considerable uncertainty in input parameters and it is a generally held view that the geomechanical basis for stability analysis in peat is limited given the nature of peat as an organic, rather than mineral soil.

To reflect these limitations, both approaches are adopted and outputs from each approach integrated in the assessment of landslide likelihood. **Error! Reference source not found.**Plate 1.2 shows the approach:

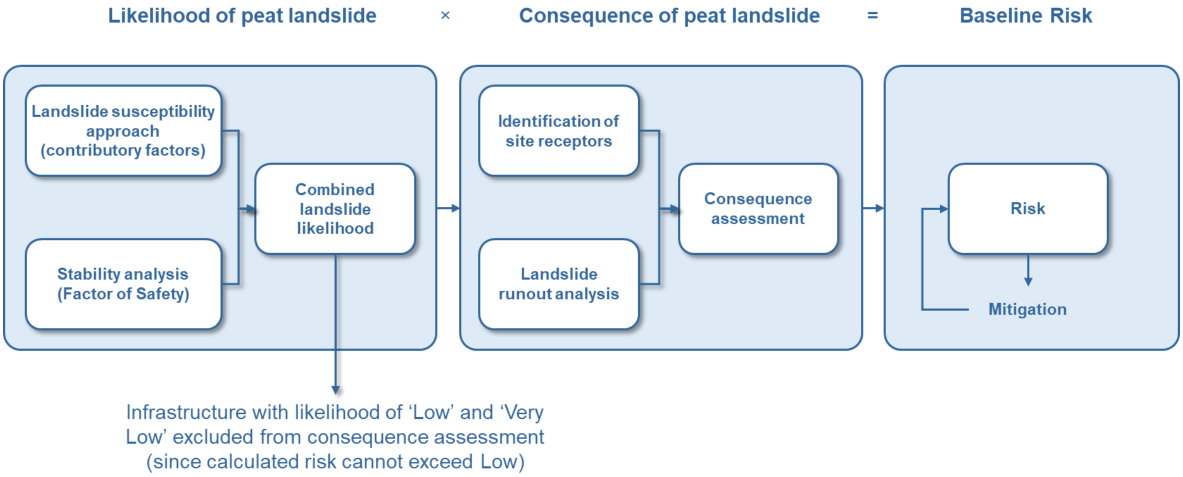

Plate 1.2 Risk assessment approach

2. BACKGROUND TO PEAT INSTABILITY

2.1. Peat Instability in the UK and Ireland

This section reviews published literature to highlight commonly identified landscape features associated with recorded peat landslides in the UK and Ireland. This review forms the basis for identifying similar features at the Proposed Development and using them to understand the susceptibility of the site to naturally occurring and human induced peat landslides.

Peat instability, or peat landslides, are a widely documented but relatively rare mechanism of peatland degradation that may result in damage to peatland habitats, potential losses in biodiversity and depletion of peatland carbon stores (Evans & Warburton, 2007). Public awareness of peat landslide hazards increased significantly following three major peat landslide events in 2003, two of which had natural causes and one occurring in association with a wind farm.

On 19th September 2003, multiple peat landslide events occurred in Pollatomish (Co. Mayo, Ireland; Creighton and Verbruggen, 2003) and in Channerwick in the Southern Shetland Islands (Mills et al, 2007). Both events occurred in response to intense rainfall, possibly as part of the same large scale large-scale weather system moving northeast from Ireland across Scotland. The former event damaged several houses, a main road and washed away part of a graveyard. Some of the landslides were sourced from areas of turbary (peat cutting) with slabs of peat detaching along the cuttings. The landslides in Channerwick blocked the main road to the airport and narrowly missed traffic using the road. Watercourses were inundated with peat, killing fish inland and shellfish offshore (Henderson, 2005).

In October 2003, a peat failure occurred on an afforested wind farm site in Derrybrien, County Galway, Ireland, causing disruption to the site and large-scale fish kill in the adjoining watercourses (Lindsay and Bragg, 2004).

The Derrybrien event triggered interest in the influence of wind farm construction and operation on peatlands, particularly in relation to potential risks arising from construction induced peat instability. In 2007, the (then) Scottish Executive published guidelines on peat landslide hazard and risk assessment in support of planning applications for wind farms on peatland sites. While the production of PLHRA reports is required for all Section 36 energy projects on peat, they are now also regarded as best practice for smaller wind farm applications. The guidance was updated in 2017 (Scottish Government, 2017).

Since then, a number of peat landslide events have occurred both naturally and in association with wind farms (e.g. Plate 2.1). In the case of wind farm sites, these have rarely been reported, however landslide scars of varying age are visible in association with wind farm infrastructure on Corry Mountain, Co. Leitrim, at Sonnagh Old Wind Farm, Co. Galway (near Derrybrien; Cullen, 2011), and at Corkey Wind Farm, Co. Antrim. In December 2016, a plant operator was killed during excavation works in peat at the Derrysallagh wind farm site in Co. Leitrim (Flaherty, 2016) on a plateau in which several published examples of instability had been previously reported. A peat landslide was also reported in 2015 near the site of a proposed road for the Viking Wind Farm on Shetland (The Shetland Times, 2015) though this was not in association with construction works.

Other recent natural events include another failure in Galway at Clifden in 2016 (Irish News, 2016), Cushendall, Co. Antrim (BBC, 2014), in the Glenelly Valley, Co. Tyrone in 2017 (BBC, 2018), Drumkeeran in Co. Leitrim in July 2020 (Irish Mirror, 2020) and Benbrack in Co. Cavan in July 2021 (The Anglo-Celt, 2021). Noticeably, the vast majority of reported failures since 2003 have occurred in Ireland and Northern Ireland, with the one reported Scottish example occurring on the Shetland Islands, an area previously associated with peat instability.

Plate 2.1 Characteristic peat landslide types in UK and Irish peat uplands: Top row - natural failures: i) multiple peat slides with displaced slabs and exposed substrate, ii) retrogressive bog burst with peat retained within the failed area; Bottom row - failures possibly induced by human activity: iii) peat slide adjacent to turbine foundation, iv) spreading around foundation, v) spreading upslope of cutting

This section of the report provides an overview of peat instability as a precursor to the site characterisation in Section 3 and the hazard and risk assessment provided in Sections 4 and 5. Section 2.2 outlines the different types of peat instability documented in the UK and Ireland. Section 2.3 provides an overview of factors known to contribute to peat instability based on published literature.

2.2. Types of Peat Instability

Peat instability is manifested in a number of ways (Dykes and Warburton, 2007) all of which can potentially be observed on site either through site walkover or remotely from high resolution aerial photography:

- **minor instability:** localised and small-scale features that are not generally precursors to major slope failure and including gully sidewall collapses, pipe ceiling collapses, minor slumping along diffuse drainage pathways (e.g. along flushes); indicators of incipient instability including development of tension cracks, tears in the acrotelm (upper vegetation mat), compression ridges, or bulges / thrusts (Scottish Government, 2017); these latter features may be warning signs of larger scale major instability (such as landsliding) or may simply represent a longer term response of the hillslope to drainage and gravity, i.e. creep.

- **major instability:** comprising various forms of peat landslide, ranging from small scale collapse and outflow of peat filled drainage lines/gullies (occupying a few-10s cubic metres), to medium scale peaty-debris slides in organic soils (10s to 100s cubic metres) to large scale peat slides and bog bursts (1,000s to 100,000s cubic metres).

Evans and Warburton (2007) present useful contextual data in a series of charts for two types of large-scale peat instability – peat slides and bog bursts. The data are based on a peat landslide database compiled by Mills (2002) which collates site information for reported peat failures in the UK and Ireland. Separately, Dykes and Warburton (2007) provide a more detailed classification scheme for landslides in peat based on 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.

For the purposes of this assessment, landslide classification is simplified and split into three main types, typical examples of which are shown in Plate 2.1. Dimensions, slope angles and peat depths are drawn from charts presented in Evans and Warburton (2007). The term “peat slide” is used to refer to large-scale (typically less than 10,000 of cubic metres) landslides in which failure initiates as large rafts of material which subsequently break down into smaller blocks and slurry. Peat slides occur ‘top-down’ from the point of initiation on a slope in thinner peats (between 0.5 m and 1.5 m) and on moderate slope angles (typically 5°-15°, see Plate 2.2).

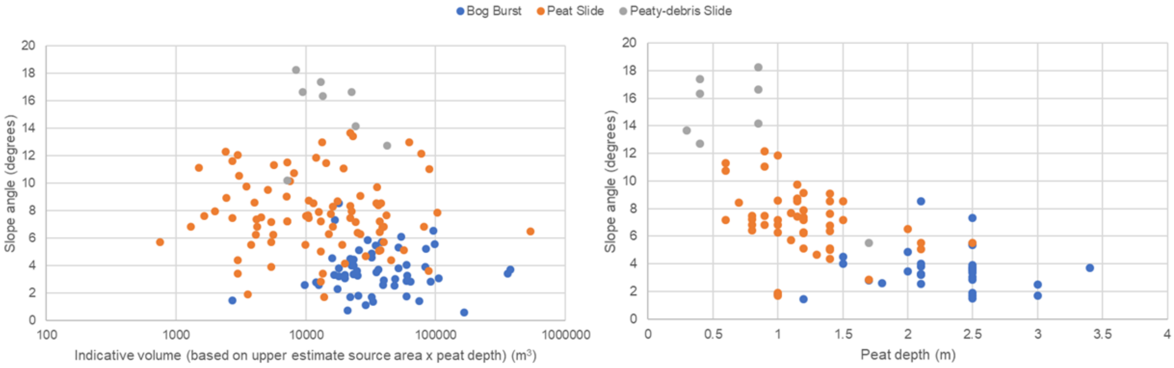

Plate 2.2 Reported slope angles and peat depths associated with peat slides and bog bursts (from literature review of locations, depths and slope angles, after Mills, 2002)

The term “bog burst” is used to refer to very large-scale (usually greater than 10,000 of cubic metres) spreading failures in which the landslide retrogresses (cuts) upslope from the point of failure while flowing downslope. Peat is typically deeper (greater than 1.0m and up to 10m) and more amorphous than sites experiencing peat slides, with shallower slope angles (typically 2°-5°). Much of the peat displaced during the event may remain within the initial failure zone. Bog bursts are rarely (if ever) reported in Scotland other than in the Western Isles (e.g. Bowes, 1960).

The term “peaty soil slide” is used to refer to small-scale (1,000s of cubic metres) slab-like slides in organic soils (i.e. they are <0.5 m thick). These are similar to peat slides in form, but far smaller and occur commonly in UK uplands across a range of slope angles (Dykes and Warburton, 2007). Their small size means that they often do not affect watercourses and their effect on habitats is minimal.

Few if any spreading failures in peat (i.e. bog bursts) have been reported in Scotland, with only one or two unpublished examples in evidence on the Isle of Lewis and Caithness. There are no published failures or news reports of landslides in proximity to the Proposed Development. Review of the nearby Hadyard Hill (c. 6 km to the west) and Dersalloch (4 km to the northeast) wind farms show no evidence of instability at infrastructure locations based on review of contemporary satellite imagery.

2.2.1. Factors Contributing to Peat Instability

Peat landslides are caused by a combination of factors – triggering factors and reconditioning factors (Dykes and Warburton, 2007; Scottish Government, 2017). Triggering factors have an immediate or rapid effect on the stability of a peat deposit whereas preconditioning factors influence peat stability over a much longer period. Only some of these factors can be addressed by site characterisation.

Preconditioning factors may influence peat stability over long periods of time (years to hundreds of years), and include:

i. Impeded drainage caused by a peat layer overlying an impervious clay or mineral base (hydrological discontinuity).

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).

iv. Connectivity between surface drainage and the peat/impervious interface (mechanism for generation of excess pore pressures).

v. Artificially cut transverse drainage ditches, or grips (elevating pore water pressures in the basal peat-mineral matrix between cuts, and causing fragmentation of the peat mass).

vi. Increase in mass of the peat slope through peat formation, increases in water content or afforestation.

vii. 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.

viii. Loss of surface vegetation and associated tensile strength (e.g. by burning or pollution induced vegetation change).

ix. Increase in buoyancy of the peat slope through formation of sub-surface pools or water-filled pipe networks or wetting up of desiccated areas.

x. 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.

Triggering factors are typically of short duration (minutes to hours) and any individual trigger event can be considered as the ‘straw that broke the camel’s back’:

i. Intense rainfall or snowmelt causing high pore pressures along pre-existing or potential rupture surfaces (e.g. between the peat and substrate).

ii. Rapid ground accelerations (e.g. from earthquakes or blasting).

iii. Unloading of the peat mass by fluvial incision or by artificial excavations (e.g. cutting).

iv. Focusing of drainage in a susceptible part of a slope by alterations to natural drainage patterns (e.g. by pipe blocking or drainage diversion).

v. Loading by plant, spoil or infrastructure.

External environmental triggers such as rainfall and snowmelt cannot be mitigated against, though they can be managed (e.g. by limiting construction activities during periods of intense rain). Unloading of the peat mass by excavation, loading by plant and focusing of drainage can be managed by careful design, site specific stability analyses, informed working practices and monitoring.

2.2.2. Consequences of Peat Instability

Both peat slides and bog bursts have the potential to be large in scale, disrupting extensive areas of blanket bog and with the potential to discharge large volumes of material into watercourses.

A key part of the risk assessment process is to identify the potential scale of peat instability should it occur and identify the receptors of the consequences. Potential sensitive receptors of peat failure are:

- The development infrastructure and turbines (damage to turbines, tracks, substation, etc).
- Site workers and plant (risk of injury / death or damage to plant).
- Wildlife (disruption of habitat) and aquatic fauna.
- Watercourses and lochs (particularly associated with public water supply).
- Site drainage (blocked drains / ditches leading to localised flooding / erosion); and
- Visual amenity (scarring of landscape).

While peat failures may cause visual scarring of the peat landscape, most peat failures revegetate fully within 50 to 100 years and are often difficult to identify on the ground after this period of time (Feldmeyer-Christe and Küchler, 2002; Mills, 2002). Typically, it is short-term (seasonal) effects on watercourses that are the primary concern or impacts on public water supply.

3. DESK STUDY

3.1. Topography

The Proposed Development lies on gentle to moderate slopes falling from Clashverains (306 m AOD) and Knockbuckle (315 m) at the southern limit of the site to the north towards the Water of Girvan (see **Figure 9.4.1**). Turbine infrastructure is generally located above 200 m on rolling slopes in the southern half of the site. Knockcronal, a distinct topographic high (286m AOD) in the middle of the site sits adjacent to Big Benyaw (313 m AOD, **Plate 3.2a**), the latter a prominent craggy summit. Slopes steepen fairly rapidly to the north of Knockcronal and Big Benyaw, and only the access track is proposed to traverse this area. Plate 3.1 shows a perspective view of the Proposed Development with key geographic features annotated.

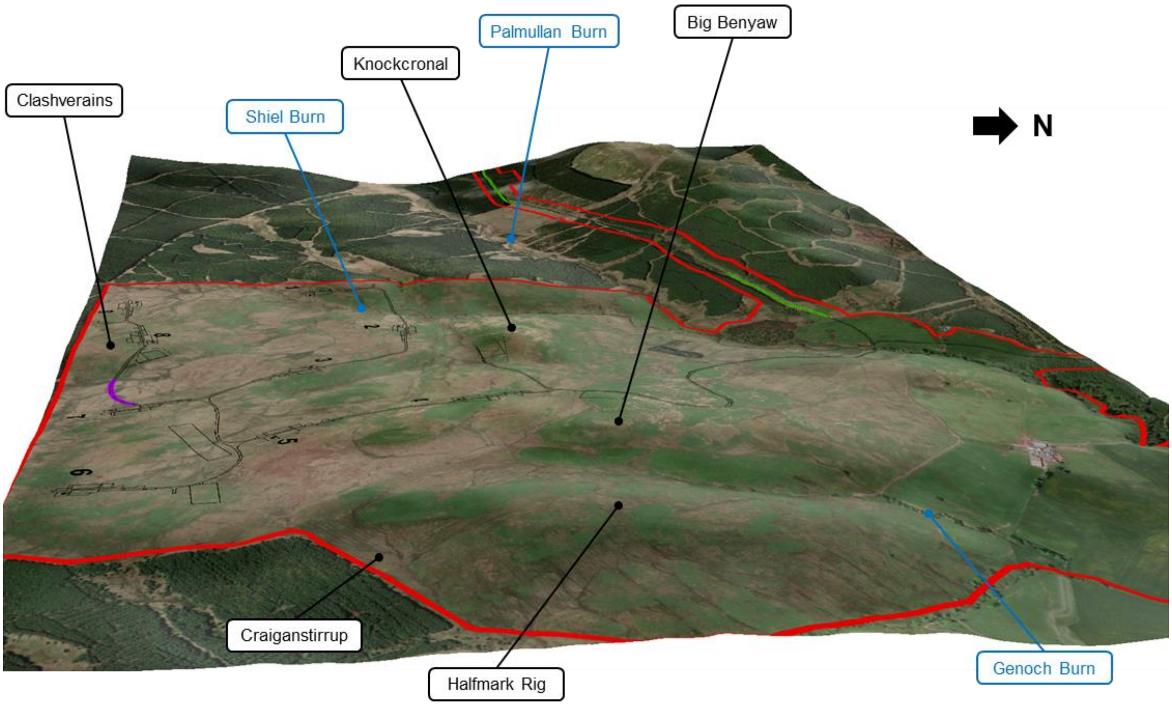

Plate 3.1 Perspective view of site

Within the main development area, slope angles are generally gentle (< 5°) over undulating topography at the summit (see **Figure 9.4.2**). Locally, around turbines 8 and 7, slope angles are slightly greater, but it is likely that groundworks for turbine construction will address these local topographic irregularities. The approach for the access track between Palmullan Burn and Big Benyaw is relatively steep for the upper few hundred metres, traversing slopes between 7.5 and 15°.

3.2. Geology

Figure 9.4.3 shows the solid geology of the site mapped from 1:50,000 scale publicly available BGS digital data and indicates the main turbine area to be broadly divided between Duneaton Volcanic basaltic andesite in the southwest and Swanshaw Sandstone in the northeast. There are localised igneous intrusions within the sandstones in the northeast and west-to-east bands of sandstone within the volcanics in the west. The southern edge of the site beneath turbines 8 and 9 comprises Southern Midland Valley felsite sills.

Figure 9.4.4 shows the superficial geology of the site, also mapped from 1:50,000 scale publicly available BGS data with Carbon and Peatland 2016 Map carbon-rich soils, deep peat and priority peatland habitats classes also shown. BGS data shows till on the lower slopes, alluvium in the Palmullan Burn valley floor and a small pocket of peat running southeast of Big Benyaw towards Knockbuckle.

The Carbon and Peatland 2016 Map shows two small areas of Class 1 peat, one overlapping the BGS peat area to the southeast of Big Benyaw above Craiganstirrup and the second lying in a hollow between Clashverains and Big Benyaw. Both areas have been largely avoided in design of the wind farm infrastructure. Elsewhere, Classes 3, 4 and 5 are indicated with mineral soils on the lower slopes towards Palmullan Burn. NVC surveys (refer to Chapter 8) indicate M17a on Clashverains and in the Class 1 area to the northeast and M17a (M25a) and M17a/M25 in association with the Class 1 area above Craiganstirrup. Otherwise, NVC surveys do not generally indicate high quality blanket bog habitats.

Plate 3.2 a) Big Benyaw from Halfmark Rig, b) minor tributary of Shiel Burn (with culvert outlet), c) spurs separating Shiel Burn from minor tributaries, d) *Juncus* dominated flush over revegetated drains

3.3. Hydrology

The site is drained by a number of minor watercourses that are confluent with Palmullan Burn on the northern limit of the main development area. Palmullan Burn then drains via a relatively narrow valley into the Water of Girvan approximately 1 km downstream. Shiel Burn passes through the central turbine area to join Knockoner Burn, which falls through the western half of the site. An un-named watercourse to the east of Big Benyaw and west of Halfmark Rig flows north to join Genoch Burn which has its confluence with the Water of Girvan roughly half a kilometre downstream of the confluence with Palmullan Burn.

The watercourses are generally of very small dimensions (<0.5m wide, see **Plate 3.2b** and **3.2c**) in the upper part of the site where turbines are proposed and are unlikely to have the capacity to convey landslide materials downstream for more than a few tens to hundreds of metres.

Interpretation of aerial imagery indicates numerous land drains cut into the ground surface (**Figure 9.4.5**), most of which are overgrown (e.g. **Plate 3.2d**). Drains tend to have been cut in flushed areas which now show extensive reed cover.

Neither the Palmullan Burn nor Water of Girvan are designated. Other than Tairlaw Burn, a surface water DWPA which lies to the east of the site, Private Water Supplies (PWS) are generally confined to lower elevations (see Chapter 9 and Figure 9.6).

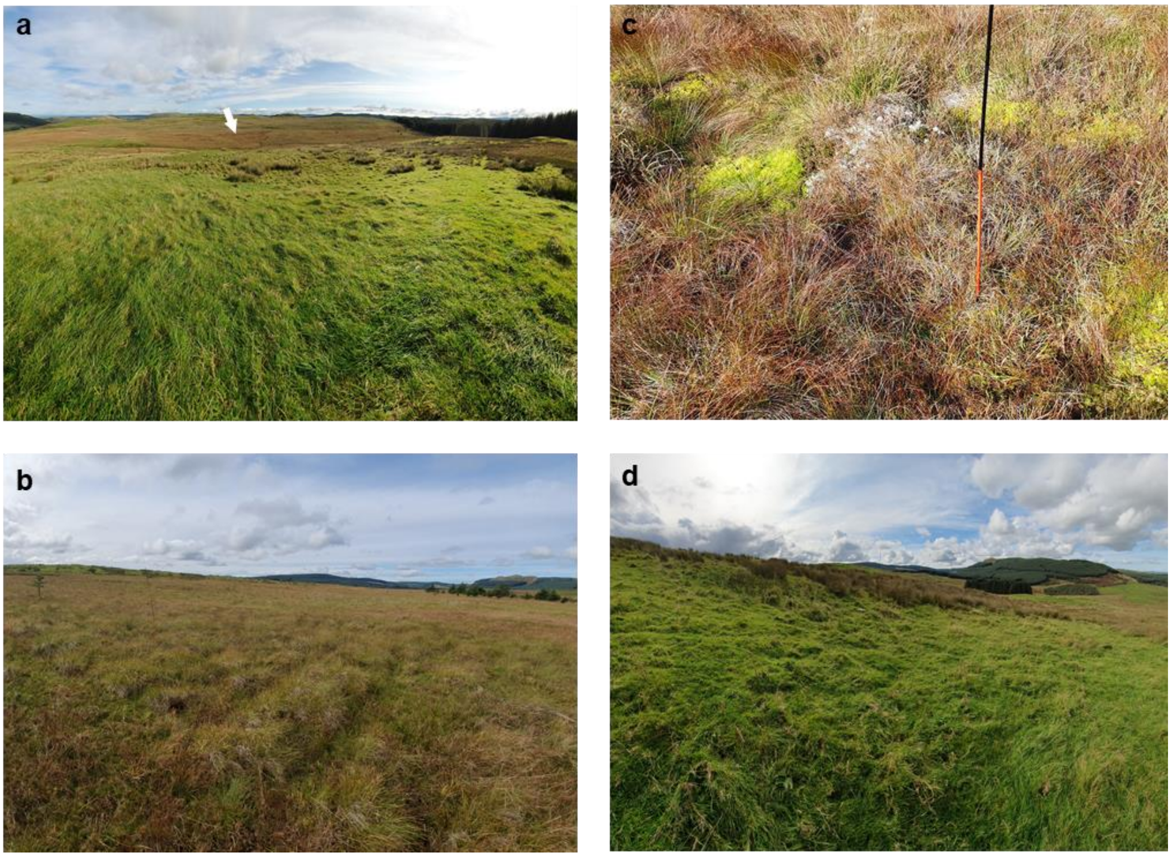

Plate 3.3 a) saddle with deeper peat (looking NE from Clashverains), b) typical bog vegetation on deep peat area above Craiganstirrup, c) *Sphagnum* in deep peat area east of Clashverains, d) typical non-peat grassland on middle and lower slopes below main turbine area

3.4. Land Use

The majority of the site lies within a working farm with the open fells used for rough grazing of cattle and sheep. The western access track follows an existing commercial forestry road while the northern access runs through commercial forestry and farmland.

The fells have been extensively cut with drains, although these are more apparent on aerial photography than on the ground (see **Figure 9.4.5**), where they are generally overgrown. There is no evidence of cutting of peat, quarrying, or burning.

3.5. Peatland Geomorphology

Satellite imagery available as an ArcGIS Basemap layer was used to interpret and map features within the site boundary. Additional imagery from different epochs available on both Google Earth™ and bing.com/maps was also referred to in order to validate the satellite imagery interpretation. The resulting geomorphological map (**Figure 9.4.5**) was subsequently verified during a site walkover undertaken in September 2020 by a Chartered Geologist / peatland geomorphologist with over 25 years' experience of assessing peat landslides. **Plates 3.2a to d** and **3.3a to d** show typical features identified during the walkovers.

Figure 9.4.5 shows the key features of the site. The presence, characteristics and distribution of these features are helpful in understanding the hydrological function of a peatland, the balance of erosion and peat accumulation (or condition), and the sensitivity of a peatland to potential land-use changes.

Much of the site lacks geomorphological features typical of blanket bog uplands, primarily due to the thin peat and organic soils that dominate the site (see Section 3.6 below). Exceptions are two areas with localised *Sphagnum* lawns and pools in a saddle between Clashverains and a small topographic high underlying Turbine 3 and in the saddle above Craiganstirrup. Here the ground surface is sufficiently gentle in slope that deeper deposits have developed and habitats are of higher quality. These are the areas identified as Class 1 on the Carbon and Peatland 2016 Map, which provides a relatively good fit with ground conditions for this site. There is minor patterning of the deeper peat consistent with the macrotopography found in good quality blanket bogs. Elsewhere, where peat is thinner, the terrain is largely planar with little evidence of gullying and shallow water flow suggested by *Juncus* flushes that drain towards the minor watercourses.

There was no evidence of shallow instability, tension cracks or other incipient instability features anywhere on site. Review of historical satellite imagery extending back to 2004 indicate no features visible over this period. For the limited peat depths on site and lack of extensive blanket bog, peat slides are considered the most likely form of instability and are the failure mechanism considered in this analysis.

3.6. Peat Depth and Character

Peat depth probing was undertaken in 2 phases in accordance with Scottish Government (2017) guidance:

- Phase 1 probing on a 100 m grid undertaken in August 2020 comprising 467 locations.
- Phase 2 probing comprising 50 m spacings with centrelines and 10 m offsets for all tracks and 10 m grids for all turbine foundations and compounds, undertaken in May 2021 and totalling a further 3,715 locations.
- In total, 4,182 probes have been used to characterise the site, with a mean peat depth across the full probing dataset of 0.28 m and a maximum peat depth of 4.9 m.

A peat survey report (Technical Appendix 9.2) documents the findings of these site investigations and summarises peat depth variation over the site.

Figure 9.4.6 shows the positions of Phase 1 and Phase 2 peat probing and an interpolated peat depth map for the Proposed Development. Interpolation of peat depths was undertaken in the ArcMap GIS environment using a natural neighbour approach. This approach was selected because it preserves recorded depths at each probe location, unlike some other approaches (e.g. kriging), is computationally simple, and minimises ‘bullseye’ effects. The approach was selected after comparison of outputs with three other methods (inverse distance weighted, kriging and TIN).

The peat depth map indicates the following:

- Peat is largely absent over much of the site, particularly below 250 m AOD, with deeper peat (> 1.0 m) present in pockets in topographic lows such as saddles and headwater valleys.
- The deepest peat is found above Craiganstirrup (a large deposit c. 0.5 km x 0.3 km and up to 5.0 m deep), and on the west facing gentler slopes between Clashverains and Knockcronal.
- There is no peat on the northern access route and very limited peat on the western access route, the latter comprising an existing track with small areas of Proposed Development in afforested terrain adjacent to the track.

Comparison of the peat depth model with the layout indicates that significant efforts have been made during layout design to site infrastructure out of the deepest peat areas and to route access tracks onto shallower peat. All of the deepest peat deposits have been avoided and there are only minor crossings of relatively deep peat (>0.5 m) by access tracks in areas where avoidance would not be possible without greatly increasing track lengths and land take.

Given the lack of peat on the northern access route, this route is not considered further in the PLHRA since there cannot be instances of peat instability where no peat is present. For the western route, only the land adjacent to the existing track where peat is present is considered.

Coring undertaken as part of the probing exercise at representative locations indicates that gritty silt, sandy silt or bedrock underly peat in most locations (Appendix 9.1). Von Post logging shows moderately decomposed catotelm, rarely exceeding H7 (i.e. fibrous rather than pseudo-fibrous).

4. ASSESSMENT OF PEAT LANDSLIDE LIKELIHOOD

4.1. Introduction

This section provides details on the landslide susceptibility and limit equilibrium approaches to assessment of peat landslide likelihood used in this report. The assessment of likelihood is a key step in the calculation of risk, where risk is expressed as follows:

Risk = Probability of a Peat Landslide x Adverse Consequences

The probability of a peat landslide is expressed in this report as peat landslide likelihood, and is considered below.

4.2. Limit Equilibrium Approach

4.2.1. Overview

Stability analysis has been undertaken using the infinite slope model to determine the Factor of Safety (FoS) for a series of 25 m x 25 m grid cells within the Proposed Development boundary. This is the most frequently cited approach to quantitatively assessing the stability of peat slopes (e.g. Scottish Government, 2017; Boylan et al, 2008; Evans and Warburton, 2007; Dykes and Warburton, 2007; Creighton, 2006; Warburton et al, 2003; Carling, 1986). The approach assumes that failure occurs by shallow translational landsliding, which is the mechanism usually interpreted for peat slides. Due to the relative length of the slope and depth to the failure surface, end effects are considered negligible and the safety of the slope against sliding may be determined from analysis of a ’slice’ ‘slice’ of the material within the slope.

The stability of a peat slope is assessed by calculating a Factor of Safety, F, which is the ratio of the sum of resisting forces (shear strength) and the sum of driving forces (shear stress) (Scottish Government, 2017):

$$F = \frac{c' + (\gamma - h\gamma_w) z \cos^2 \beta \tan \phi'}{\gamma z \sin \beta \cos \beta}$$

In this formula c’ is the effective cohesion (kPa), γ is the bulk unit weight of saturated peat (kN/m^3), γw is the unit weight of water (kN/m^3), z is the vertical peat depth (m), h is the height of the water table as a proportion of the peat depth, β is the angle of the substrate interface (°) and ϕ’ is the angle of internal friction of the peat (°). This form of the infinite slope equation uses effective stress parameters, and assumes that there are no excess pore pressures, i.e. that the soil is in its natural, unloaded condition. The use of cut and fill foundations and tracks across almost the whole construction footprint suggest this is an appropriate approach. The choice of water table height reflects the full saturation of the soils that would be expected under the most likely trigger conditions, i.e. heavy rain.

Where the driving forces exceed the shear strength (i.e. where the bottom half of the equation is larger than the top), F is < 1, indicating instability. A factor of safety between 1 and 1.4 is normally taken in engineering to indicate marginal stability (providing an allowance for variability in the strength of the soil, depth to failure, etc). Slopes with a factor of safety greater than 1.4 are generally considered to be stable.

There are numerous uncertainties involved in applying geotechnical approaches to peat, not least because of its high water content, compressibility and organic composition (Hobbs, 1986; Boylan and Long, 2014). Peat comprises organic matter in various states of decomposition with both pore water and water within plant constituents, and the frictional particle-to-particle contacts that are modelled in standard geotechnical approaches are different in peats. There is also a tensile strength component to peat which is assumed to be dominant in the acrotelm, declining with increasing decomposition and depth. As a result, analysis utilising geotechnical approaches is often primarily of value in showing relative stability across a site given credible and representative input parameters rather than in providing an absolute estimate of stability. Representative data inputs have been derived from published literature for drained analyses considering natural site conditions.

4.2.2. Data Inputs

Stability analysis was undertaken in ArcMap GIS software. A 25 m x 25 m grid was superimposed on the full site extent and key input parameters derived for each grid cell. In total, c. 9,340 grid cells were analysed. A 25 m x 25 m cell size was chosen because it is sufficiently small to define a credible landslide size and avoid ‘smoothing’ of important topographic irregularities.

Two forms of analysis have been undertaken:

i. **Baseline stability:** input parameters correspond to undisturbed peat, prior to construction, and under water table conditions typically associated with instability (i.e. full saturation). Effective stress parameters are used in a drained analysis.

ii. **Modified (loaded) stability:** input parameters correspond to disturbed peat, subsequent to construction, with peat loaded by floating track and typical vehicle loads; areas where peat has been excavated (e.g. the excavated peat itself and the peat upslope of the excavation) have not been modelled since it is assumed that safe systems of work will include buttressing of / support to excavations. Total stress parameters are used in this undrained analysis.

Table 4.1 shows the input parameters and assumptions for the baseline stability analysis. The shear strength parameters c' and ϕ’ are usually derived in the laboratory using undisturbed samples of peat collected in the field and therefore site specific values are often not available ahead of detailed site investigation for a development. Therefore, for this assessment, a literature search has been undertaken to identify a range of credible but conservative values for c' and ϕ’ quoted in fibrous and humified peats. FoS analysis was undertaken with conservative ϕ’ of 20° and values of 2 kPa and 5 kPa for c’. These values fall at the low end of a large range of relatively low values (when compared to other soils).

Table 4.2 shows the input parameters and assumptions for the modified stability analysis. The analysis employs a 5 m wide floating track, and assumes representative loads for a multi-axle crane with maximum axle load of 16 t moving over the floated surface. For this analysis, input data correspond to two representative cases for the single section of floating track specified (between Turbines 7 and 8) – a 5° slope with 1.0 m deep peat and a 2.5° slope with 1.0 m deep peat. The resulting vehicle loaded (or modified) analysis was then checked against the baseline stability described above.

4.2.3. Results

The outputs of the drained analysis (effective stress) are shown areas with peat for the Lower Bound parameter combination in **Figure 9.4.7**. Even this very conservative parameter combination indicates that a significant proportion of the site that has peat cover is stable (F > 1.0) with only isolated areas of marginal stability (F < 1.4). Only one location is coincident with proposed infrastructure, on access track to the north of Borrow Pit W. These results are consistent with observations of peat instability in the UK – peat landslides are very rare occurrences given the wide distribution of peat soils in England, Scotland and Wales.

Parameter	Values	Rationale	Source
Effective cohesion (c')	2, 5	Credible conservative cohesion values for humified peat based on literature review	5, basal peat (Warburton et al., 2003) 8.74, fibrous peat (Carling, 1986) 7 - 12, H8 peat (Huat et al, 2014) 5.5 - 6.1, type not stated (Long, 2005) 3, 4, type not stated (Long, 2005) 4, type not stated (Dykes and Kirk, 2001)
Bulk unit weight (γ)	10.5	Credible mid-range value for humified catotelmic peat	10.8, catotelm peat (Mills, 2002) 10.1, Irish bog peat (Boylan et al 2008)
Effective angle of internal friction (ϕ')	20, 30	Credible conservative friction angles for humified peat based on literature review (only 20° used in analysis)	40 - 65, fibrous peat (Huat et al, 2014) 50 - 60, amorphous peat (Huat et al, 2014) 36.6 - 43.5, type not stated (Long, 2005) 31 - 55, Irish bog peat (Hebib, 2001) 34 - 48, fibrous sedge peat (Farrell & Hebib, 1998) 32 - 58, type not stated (Long, 2005) 23, basal peat (Warburton et al, 2003) 21, fibrous peat (Carling, 1986)
Slope angle from horizontal (β)	Various	Mean slope angle per 25 m x 25 m grid cell	5 m digital terrain model of site
Peat depth (z)	Various	Mean peat depth per 25 m x 25 m grid cell	Interpolated peat depth model of site
Height of water table as a proportion of peat depth (h)	1	Assumes peat mass is fully saturated (normal conditions during intense rainfall events or snowmelt, which are the most likely natural hydrological conditions at failure)	

Table 4-1 Geotechnical parameters for drained infinite slope analysis

Parameter	Values	Rationale	Source
Undrained shear strength (Su)	5	Published values show undrained shear strength is typically very similar to effective cohesion (c')	4-30, medium and highly humified (Boylan et al, 2008) 4, more humified (Boylan et al, 2008) 5.2, peat type not stated (Long et al, 2005) 5, Irish bog peat (Farrell and Hebib, 1998)
Bulk unit weight (γ)	10.5	Reduction in volume under floating road is balanced by increased density, so pre-load parameters are used	See Table 4-1
Slope angle from horizontal (β)	2.5, 5.0	Credible slope angles for which floating tracks are proposed	See Table 4-1

Parameter	Values	Rationale	Source
Peat depth (z)	1.0	Reduction in volume (i.e. depth) under floating road is balanced by increased density, so pre-load parameters are used	See Table 4-1
Crane axle load (t)	16 t	Maximum haul weight that is not considered an "abnormal load"	Typical upper axle load limit (pers. comm.)

Table 4-2 Geotechnical parameters and assumptions for undrained infinite slope analysis

Relative to the baseline case for the same peat depths and slope angles under drained conditions, the calculated FoS declines from 9.1 to 3.4 for the 1.0 m / 2.5° case and from 4.6 to 1.7 for the 1.0 m / 5° case under undrained (loaded) conditions. This demonstrates that while there is a reduction in stability from loading, it is not a large reduction and falls within acceptable bounds for length of floating track in question.

4.3. Landslide Susceptibility Approach

4.3.1. Overview

The landslide susceptibility approach is based on the layering of contributory factors to produce unique ‘slope facets’ that define areas of similar susceptibility to failure. These slope facets vary in size and are different to the regular grid used for the FoS approach. The number and size of slope facets varies from one part of the site to another according to the complexity of ground conditions. In total, c. 5,900 facets were considered in the analysis, with an average area of c. 700 m^2 (or an average footprint of c. 25 m x 25 m, consistent with smaller to medium scale peaty soil or peat slides reported in the published literature.

Eight contributory factors are considered in the analysis: slope angle (S), peat depth (P), substrate geology (G), peat geomorphology (M), drainage (D), forestry (F), slope curvature (C) and land use (L). For each factor, a series of numerical scores between 0 and 3 are assigned to factor ‘classes’, the significance of which is tabulated for each factor. The higher a score, the greater the contribution of that factor to instability for any particular slope facet. Scores of 0 imply neutral / negligible influence on instability.

Factor scores are summed for each slope facet to produce a peat landslide likelihood score (S_{PL}), the maximum being 24 (8 factors, each with a maximum score of 3).

$$S_{PL} = S_S + S_P + S_G + S_M + S_D + S_C + S_F + S_L$$

In practice, a maximum score is unlikely, as the chance of all contributory factors having their highest scores in one location is very small. The following sections describe the contributory factors, scores and justification for the Proposed Development.

4.3.2. Slope Angle (S)

Table 4-3 shows the slope ranges, their association with instability and related scores for the slope angle contributory factor. Slope angles were derived from the 5 m digital terrain model shown on **Figure 9.4.2** and scores assigned based on reported slope angles associated with peat landslides rather than a simplistic assumption that ‘the steeper a slope, the more likely it is to fail’ (e.g. **Plate 2.2**). A differentiation in scores is applied for peat slides and bog bursts reflecting the shallower slopes on which the latter are most frequently observed.

Note that the slope model is a TIN (interpolated from irregularly spaced measures of elevation) and these sorts of slope model tend to simplify slopes into triangular surfaces – this can have the effect of steepening or shallowing slopes relative to their actual gradients.

Slope range (°)	Association with instability	Score (S)
≤2.5	Slope angle ranges for peat slides and bog bursts are based on lower and upper limiting angles for observations of occurrence (see **Plate 2.2** and increase with increasing slope angle until the upper limiting angle e.g. peat slides are not observed on slopes <2.5°, while bog bursts are not observed on slopes > 7.5°). It is assumed that beyond 7.5° the mode of failure will be peat slides.	0
2.5 - 5.0		1
5.0 – 7.5		3
7.5 - 10.0		3
10 – 15.0		3
>15.0		3

Table 4-3 Slope classes, association with instability and scores

Figure 9.4.8 shows the distribution of slope angle scores across the site. In the main turbine area, a majority of the site is on slopes < 5° although there are local areas crossed by track that exceed this value (and therefore have the highest score).

4.3.3. Peat Depth (P)

Table 4-4 shows the peat depths, their association with instability and related scores for the peat depth contributory factor. Peat depths were derived from the peat depth model shown on **Figure 9.3.8** and reflect the peat depth ranges most frequently associated with peat landslides (see Plate 2.2).

Peat depth range (m)	Association with instability	Score (P)
>1.5	Bog bursts are the dominant failure mechanism in this depth range where basal peat is more likely to be amorphous	1
0.5 - 1.5	Peat slides are the dominant failure mechanism in this depth range where basal peat is less likely to be amorphous	3
<0.5	Organic soil rather than peat, failures would be peaty-debris slides rather than peat slides or bog bursts and are outside the scope	0

Table 4-4 Peat depth classes, association with instability and scores

The distribution of peat depth scores is shown on **Figure 9.4.8**. Due to the spatially limited presence of peat, much of the site has a score of 0, with only the pockets of peat above 250 m AOD having the higher scores, with a majority of these falling between rather than overlapping with infrastructure.

4.3.4. Substrate Geology (G)

Table 4-5 shows substrate type, association with instability and related scores for the substrate geology contributory factor. The shear surface or failure zone of reported peat failures typically overlies an impervious clay or mineral (bedrock) base giving rise to impeded drainage. This, in part, is responsible for the presence of peat, but also precludes free drainage of water from the base of the peat mass, particularly under extreme conditions (such as after heavy rainfall, or snowmelt).

Peat failures are frequently cited in association with glacial till deposits in which an iron pan is observed in the upper few centimetres (Dykes and Warburton, 2007). They have also been observed over glacial till without an obvious iron pan, or over impermeable bedrock. They are rarely cited over permeable bedrock, probably due to the reduced likelihood of peat formation.

Substrate Geology	Association with instability	Score (G)
Cohesive (clay) or iron pan	Failures are often associated with clay substrates and/or iron pans	3
Unknown	Failures often associated with clay	2
Granular or bedrock	Failures are less frequently associated with bedrock or granular (silt / sand / gravel) substrates	1

Table 4-5 Substrate geology classes, association with instability and scores

Probing undertaken across the site indicated primarily bedrock or granular substrates using the refusal method, and coring confirmed this. No iron pans were observed. Accordingly, the full site is treated as if underlain by impermeable bedrock or granular glacial till (**Figure 9.4.8**).

4.3.5. Peat Geomorphology (M)

Table 4-6 shows the geomorphological features identified across the site, their association with instability and related scores. The vast majority of the site is planar with no other features, with the exception of localised flushes in the southwest of the site.

Geomorphology	Association with instability	Score (M)
Incipient instability (cracks, ridges, bulging)	Failures are likely to occur where pre-failure indicators are present	3
Planar with pipes	Failures generally occur on planar slopes, and are often reported in areas of piping	3
Planar with pools / quaking bog	Bog bursts are more likely in areas of perched water (pools) or subsurface water bodies (quaking bog)	2
Flush / Sphagnum lawn (diffuse drainage)	Peat slides are often reported in association with areas of flushed peat or diffuse drainage	3
Planar (no other features)	Failures generally occur on planar slopes rather than dissected or undulating slopes	2
Peat between rock outcrops	Failures are rarely reported in areas of peat with frequent rock outcrops	1
Slightly eroded (minor gullies)	Failures are rarely reported in areas with gullying or bare peat	1
Heavily eroded (extensive gullies) / bare peat	Failures are not reported in areas that are heavily eroded or bare	0

Table 4-6 Peat geomorphology classes, association with instability and scores

Figure 9.4.8 shows the geomorphological classes from **Figure 9.4.5** re-coloured to correspond with **Table 4-6**.

4.3.6. Artificial Drainage (D)

Table 4.7 shows artificial drainage feature classes, their association with instability and related scores. Transverse (or contour aligned) / oblique artificial drainage lines may reduce peat stability by creating lines of weakness in the peat slope and encouraging the formation of peat pipes. A number of peat failures have been identified in published literature which have failed over moorland grips

(Warburton et al, 2004). The influence of changes in hydrology becomes more pronounced the more transverse the orientation of the drainage lines relative to the overall slope.

Drainage Feature	Association with instability	Score (D)
Drains aligned along contours (<15 °)	Drains aligned to contour create lines of weakness in slopes	3
Drains oblique (15-60°) to contour	Most reports of peat slides and bog bursts in association with drainage occurs where drains are oblique to slope	2
Drains aligned downslope (<30° to slope)	Failures are rarely associated with artificial drains parallel to slope or adjacent to natural drainage lines	1
No / minimal artificial drainage	No influence on stability	0

Table 4-7 Drainage feature classes, association with instability and scores

The effect of drainage lines is captured through the use of a 25 m buffer on each artificial drainage line (producing a 50 m wide zone of influence) present within the peat soils at the site. The spacing of the drains in many parts of the site means that these areas are almost entirely affected by these buffer zones. Each buffer is assigned a drainage feature class based on comparison of the drainage axis with elevation contours (transverse, oblique or aligned, as shown in **Table 4-7**). Buffers are shown on **Figure 9.4.8**.

4.3.7. Slope Curvature (C)

Table 4-8 shows slope (profile) curvature classes, association with instability and related scores. Convex and concave slopes (i.e. positions in a slope profile where slope gradient changes by a few degrees) have frequently been reported as the initiation points of peat landslides by a number of authors. The geomechanical reason for this is that convexities are often associated with thinning of peat, such that thicker peat upslope applies stresses to thinner 'retaining' peat downslope. Conversely, buckling and tearing of peat may trigger failure at concavities (e.g. Dykes & Warburton, 2007; Boylan and Long, 2011). However, review of reported peat landslide locations against Google Earth elevation data indicates that the majority of peat slides occur on rectilinear (straight) slopes and that the reporting of convexity as a key driver may be misleading. Accordingly, rectilinear slopes are assigned the highest score.

Profile Curvature	Association with instability	Score (C)
Rectilinear Slope	Peat slides are most frequently reported on rectilinear slopes, while bog bursts are often reported on rectilinear slopes	3
Convex Slope	Peat slides are often reported on or above convex slopes while bog bursts are most frequently associated with convex slopes	2
Concave Slope	Peat failures are occasionally reported in association with concave slopes	1

Table 4-8 Slope curvature classes, association with instability and scores

The 5 m digital terrain model and OS contours were used to identify areas of noticeable slope convexity and concavity across the site (**Figure 9.4.8**) and 25 m buffers (upslope to downslope) applied to each mapped concavity and convexity zone. Scores were then assigned in accordance with **Table 4-8** above. Due to the undulating nature and topographic complexity of the site, there is high variability in scores across the Proposed Development (**Figure 9.4.8**).

4.3.8. Forestry (F)

Table 4-9 shows forestry classes, association with instability and related scores. A report by Lindsay and Bragg (2004) on Derrybrien suggested that row alignments, desiccation cracking and loading (by trees) could all influence peat stability.

Forestry Class	Association with instability	Score (F)
Deforested, rows oblique to slope	Deforested peat is less stable than afforested peat, and inter ridge cracks oblique to slope may be lines of weakness	3
Deforested, rows aligned to slope	Deforested peat is less stable than afforested peat, but slope aligned inter ridge cracks have less impact	2
Afforested, rows oblique to slope	Afforested peat is more stable than deforested peat, but inter ridge cracks oblique to slope may be lines of weakness	2
Afforested, rows aligned to slope	Afforested peat is more stable than deforested peat, but potentially less stable than unforested (never planted) peat	1
Not afforested	No influence on stability	0

Table 4-9 Forestry classes, association with instability and scores

Only small pockets of the site are afforested, mainly in the non-peat area in the north of the main site and alongside the western access track (see **Figure 9.4.8**).

4.3.9. Land use (L)

Table 4-10 shows land use classes, association with instability and related scores. A variety of land uses have been associated with peat failures (see 2.2.1). While it is hypothesised that burning may cause desiccation cracking in peat and facilitate water flows to basal peat (and potential shear surfaces), there is little evidence directly relating burnt ground to peat landslide events.

Land Use	Association with instability	Score (L)
Machine cutting	Machine cutting may compartmentalise slopes, but has been reported primarily in association with peat slides	3
Quarrying	Quarrying may remove slope support from upslope materials, and has been observed with spreading failures (bog bursts)	2
Hand cutting (turbary)	Hand cutting may remove slope support from upslope materials, and has been reported with raised bog failures	1
Burning (deep cracking to substrate)	Failures are rarely associated with burning, but deep desiccation cracking will have the most severe effects	2
Burning (shallow cracking)	Failures are rarely associated with burning, shallow desiccation cracking will have very limited effects	1
Grazing	Failures have not been associated with grazing, no influence on stability	0

Table 4-10 Land use classes, association with instability and scores

Grazing is the primary land use on site, other than forestry along the access track alignments. Scores for land use are shown on **Figure 9.4.8**.

4.3.10. Generation of Slope Facets

The eight contributory factor layers shown on **Figure 9.4.8** were combined in ArcMap to produce approximately 5,900 slope facets. Scores for each facet were then summed to produce a peat landslide likelihood score. These likelihood scores were then converted into descriptive 'likelihood classes' from 'Very Low' to 'Very High' with a corresponding numerical range of 1 to 5 (in a similar format to the Scottish Government BPG).

Summed Score from Contributory Factors	Typical site conditions associated with score	Likelihood (Qualitative)	Landslide Likelihood Score
≤ 7	Unmodified peat with no more than low weightings for peat depth, slope angle, underlying geology and peat morphology	Very Low	1
8 - 12	Unmodified or modified peat with no more than moderate or some high scores for peat depth, slope angle, underlying geology and peat morphology	Low	2
13 - 17	Unmodified or modified peat with high scores for peat depth and slope angle and / or high scores for at least three other contributory factors	Moderate	3
18 - 21	Modified peat with high scores for peat depth and slope angle and several other contributory factors	High	4
> 21	Modified peat with high scores for most contributory factors (unusual except in areas with evidence of incipient instability)	Very High	5

Table 4-11 Likelihood classes derived from the landslide susceptibility approach

Table 4-11 describes the basis for the likelihood classes. A judgement was made that for a facet to have a moderate or higher likelihood of a peat landslide, a likelihood score would be required equivalent to both the worst case peat depth and slope angle scores (3 in each case, i.e. 3 x 2 classes) alongside three intermediate scores (of 2, i.e. 2 x 3 classes) for other contributory factors. This means that any likelihood score of 13 or greater would be equivalent to at least a moderate likelihood of a peat landslide. Given that the maximum score attainable is 24, this seems reasonable.

4.3.11. Results

Figure 9.4.9 shows the outputs of the landslide susceptibility approach for peat slides. The results indicate that the majority of the areas of the site with peat have a 'Low' or 'Very Low' likelihood of instability, with only small pockets of 'Moderate' instability.

Areas of 'Moderate' likelihood are typically located on moderate slopes, adjacent to drains and in areas of deeper peat. There are no areas identified with 'High' or 'Very High' landslide susceptibility. When compared with the stability analysis approach, the outputs of this approach indicate slightly more of the site to be at lower stability under natural conditions.

Review of the proposed layout indicates three areas of overlap between infrastructure and areas of landslide susceptibility of Moderate (or higher):

- A 17 m section of cut and fill track adjacent to the turning head between Turbines 8 and 9 where prevailing slopes are very gentle (< 4°) and peat is shallow (c. 0.65 m).
- A 13 m section comprising the tip of the same turning head and a small area of hardstanding for the met mast located in a gentle hollow to the west of Clashverains; since this source is part of the same infrastructure element as that for the preceding source zone, the two locations are combined in the runout assessment; and
- A small area at the proposed gatehouse compound location within forestry at the entrance to the western access track from the existing road – shallow peat (c. 0.55 m) in this area has already been ploughed and disrupted by forestry activities.

These sections of infrastructure are highlighted in purple on **Figure 9.4.10**. In order to calculate risk associated with these potential source zones, it is necessary to identify the potential consequences of instability, should it occur. **Plate 4.1** shows risk levels as a product of landslide likelihood (susceptibility) and consequence. Section 5 of this report describes the consequence assessment and risk calculation for all areas where infrastructure intersects "Moderate" likelihood of a peat landslide.

		Adverse Consequence (scores bracketed)				
		Very High (5)	High (4)	Moderate (3)	Low (2)	Very Low (1)
Peat landslide likelihood (scores bracketed)	Very High (5)	High	High	Medium	Low	Low
	High (4)	High	Medium	Medium	Low	Negligible
	Moderate (3)	Medium	Medium	Low	Low	Negligible
	Low (2)	Low	Low	Low	Negligible	Negligible
	Very Low (1)	Low	Negligible	Negligible	Negligible	Negligible

Score	Risk Level	Action suggested for each zone
17 - 25	High	Avoid project development at these locations
11 - 16	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
5 - 10	Low	Project may proceed pending further post-consent investigation of specific contributory factors to refine assessment and/or mitigate hazard through relocation or re-design at these locations
1 - 4	Negligible	Project should proceed with monitoring and mitigation of peat landslide hazards at these locations as appropriate

Plate 4.1 Top: risk ranking as a product of likelihood and consequence; Bottom: suggested action given each level of calculated risk

5. ASSESSMENT OF CONSEQUENCE AND RISK

5.1. Introduction

In order to calculate risks, the potential consequences of a peat landslide must be determined. This requires identification of receptors and an assessment of the consequences for these receptors should a peat landslide occur. This section describes the consequence assessment and then provides risk results based on the product of likelihood and consequence.

5.2. Receptors

Peat uplands are typically host to the following receptors: watercourses and associated water supplies (both private and public), terrestrial habitats (e.g. groundwater dependent terrestrial ecosystems or GWDTEs) and infrastructure, both that are related to the wind farm and other infrastructure, e.g. roads and power lines. These are considered for the Proposed Development below.

5.2.1. Watercourses

The Proposed Development site is drained by a handful of minor / unnamed watercourses draining to Palmullan Burn and ultimately to the Water of Girvan. Neither of these watercourses are designated or are private water supplies. Tairlaw Burn surface water DPWA lies to the east of the site but is not hydrologically connected to either of the source zones identified. Therefore, a consequence score of 2 has been assigned to reflect the possibility of short term increase in turbidity from peaty debris and possibility of fish kill. The Water of Girvan is over 5 km from the potential source zones in the south of the site, and the watercourses on the upper slopes are too minor to convey runout debris to Palmullan Burn in any significant volume. The one PWS located within the main turbine area lies in the Genoch Burn catchment (see Chapter 9, Figure 9.6) and is well away from any potential source zones.

5.2.2. Habitats

While blanket bog habitats are valuable, they generally recover from instability events through revegetation over a matter of years to decades, and therefore a consequence score of 3 is assigned for all open blanket bog habitats within the Proposed Development site (**Table 5-1**). This includes areas of M17a and M17a(M25a); M17a/M25. However, vegetation in the southwest of the site where the potential source zones are located does not indicate priority peatland habitats, and is therefore of lower value, and has been assigned a score of 2. Assessment of groundwater sources on site does not support the presence of GWDTEs in the areas in which potential source zones have been identified.

5.2.3. Infrastructure

The Proposed Development site is relatively isolated with no infrastructure other than private tracks associated with farming and forestry.

Infrastructure that would be most affected in the event of a peat landslide would be the Proposed Development infrastructure. These effects would be most likely during construction, at which time personnel would be using the access track network or be present at infrastructure locations for long periods. While commercial losses would be important to the Applicant, loss of life / injury would be of greater concern, and a consequence score of 5 is assigned for any infrastructure locations subject to potential peat landslides (**Table 5-1**). However, risks to life can be mitigated through safe systems of working. These infrastructure risks are not considered to be ‘environmental’ risks and are not explicitly considered in the consequence assessment below.

Receptor and type	Consequence	Score	Justification for Consequence Score
Watercourses (aquatic habitats)	Short term increase in turbidity and acidification, potential fish kill	2	Undesignated watercourse, no sensitive species noted
Watercourses (water supply)	Short term increase in sediment load with no effect on offtakes due to lack of transmission	2	No long term effects
Terrestrial habitats	Short to medium term loss of vegetation cover, carbon release from drying landslide runout	2	Habitats near source zones are not priority peatland habitats, long term effects unlikely following revegetation
Wind farm infrastructure (Project)	Damage to infrastructure, injury to site personnel, possible loss of life	5	Loss of life, though very unlikely, is a severe consequence; financial implications of damage and re-work are less significant

Table 5-1 Receptors considered in the consequence analysis

5.3. Consequences

5.3.1. Overview

A consequence assessment has been undertaken by determining the potential for landslides sourced at infrastructure locations with a Moderate natural likelihood of peat instability to impact the receptors identified above. For example, if a turbine is located in a Moderate (likelihood score of 3) area of open slope and is located 50 m from a watercourse (with a consequence score of 5), it is probable that a landslide triggered during construction would reach that watercourse. The calculated risk would be a product of the likelihood and consequence scores (likelihood: 3 x consequence: 5 = risk: 15, see **Plate 4.1**) and be equivalent to a “Medium” risk.

Figure 9.4.10 shows in purple all infrastructure locations that overlap with moderate likelihoods, based on the combined landslide likelihood scores described in Section 4. In order to determine the likelihood of impact on watercourses and infrastructure, ‘runout pathways’ have been defined that show the estimated maximum footprint of the landslide. Runout pathways are divided in a downslope direction into 50 m, 100 m, 250 m and 500 m zones on the basis of typical runout distances detailed in Mills (2002). The likelihood of runout passing from one runout zone to the next (e.g. from the 50 m zone into the 100 m zone) is based on the proportion of the published peat landslide population that reaches each runout distance shown on **Plate 5.1** (0-50 m: 100%, 50-100 m: 87%, 100-250 m: 56%, 250-500 m: 44%). The first 50 m includes the landslide source area.

5.3.2. Local limits on runout (watercourses)

Where runout pathways terminate at “blue line” watercourses (those shown on 1:10,000 scale Ordnance Survey maps), an assessment has been made of the ability to convey landslide material along the watercourse. This reflects the significant variability in dimensions of “blue line” watercourses on the ground such that some may be several metres wide and metres deep (and therefore able to transmit materials kilometres downstream) where others may be <0.5 m in width, highly sinuous and sometimes discontinuous (disappearing under the peat surface) and therefore unable to convey landslide material. A walkover survey of the minor watercourses within the open fells in the main turbine area showed them to be small in cross-section and likely unable to transmit materials any significant distance downstream, although localised watercourse impacts may be felt from fine sediments and temporary blockages.

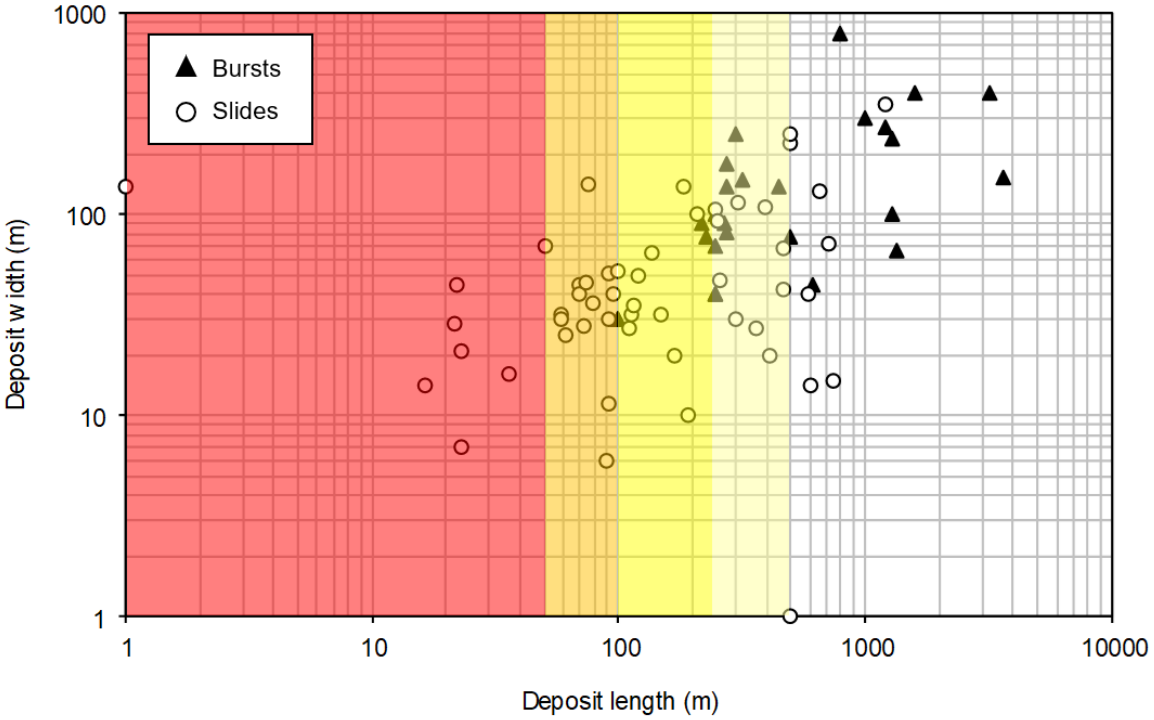

Plate 5.1 Runout distances for published peat landslides (after Mills, 2002), colours on the plot correspond to runout pathway zones on Figure 9.4.10

Landslide runout may be “supply-limited” by the availability of peat material generated in the failure or source zone. Typically, mobilised material thins with increasing distance from the source zone as rafts of landslide material break down into blocks, and blocks become abraded and roll, breaking down further into a blocky slurry. Following identification of runout zones, additional analysis has been undertaken to approximate this effect. The analysis assumes a source volume equivalent to the source footprint (0 m - 50 m zone) multiplied by the average peat depth in this source zone (from the peat depth model). This volume is then distributed over the full runout pathway (i.e. mobilised volume / runout area) to generate an average thickness of deposit. As the runout length and area increases, the volume thins, in keeping with observed peat landslide deposits. Where deposits fall below 0.2 m in thickness, it is assumed that runout will stall due to the roughness of surface vegetation relative to the thickness of landslide material. If the thickness is calculated to be 0.2 m or less in the zone adjoining a watercourse, then it is judged that there will be no significant impact on that watercourse (even if a landslide occurs).

Where topographic (or other) barriers exist to runout, these are also factored into the runout analysis. While neither source zone has a topographic barrier downslope, source zone 2 is within existing forestry, and it is considered very likely that the existing treeline to the west of the minor road (and cattle grid) would arrest any mobile materials, further reducing the likelihood of its entry to headwater gullies feeding the Shiel Burn.

5.3.3. Results of runout analysis

Based on the source and runout zones shown on Figure 9.4.10:

- Runout from source zone 1 will not reach local watercourses even if occurring over the full 0.5 km runout length shown on the map, only non-priority open fell habitats will be affected.
- Runout from source zone 2 will not affect good quality habitats (since there are none under the afforested canopy) and is unlikely to affect local watercourses due to the screening effect of the existing treeline.

Runout zone 1 crosses the turning head between Turbines 8 and 9. It is important that good engineering practice and careful monitoring of ground conditions (see section 6) is applied during construction in order to minimise health and safety incidents associated with potential instability at this location.

5.4. Calculated Risk

Risk levels have been calculated as a product of likelihood and consequence and are shown on **Table 5-2** below, with key receptor identified, citing the key receptor, the depth of runout at the receptor (based on reduction in debris thickness as the runout area increases downslope and the landslide becomes exhausted of debris) and the calculated risk.

ID	**Infrastructure**	**Landslide Thickness (m)**		**Receptor**	**Likelihood**	**Consequence**	**Risk**
		Source	**Receptor**				
1	T8 / T9 Turning head	0.65	0.65 - 0.13	Open fell below Clashverains	Moderate	Low	Low
2	Gatehouse (western access track)	0.55	0.18	Unnamed tributary of Shiel Burn (West)	Moderate	Very Low (due to stalling of debris on thinning)	Negligible

Table 5-2 Source locations, runout thicknesses environmental receptors and risks

For source zone 1, the low quality open fell habitats would be impacted throughout the runout zone, and therefore a risk of Low has been calculated. For source zone 2, only the watercourse is a receptor, and even were runout to pass through the treeline it would be less than 0.2 m thick in the 100 – 250 m runout zone and would therefore stall before reaching the stream, giving a risk of Negligible.

Based on the calculated risks shown on **Table 5-2**, site-wide good practice measures should be sufficient to manage and mitigate any construction induced instability risks. This is considered in the next section.

6. RISK MITIGATION

6.1. Overview

A number of mitigation opportunities exist to further reduce the risk levels identified at the Proposed Development site. These range from infrastructure specific measures (which may act to reduce peat landslide likelihood, and, in turn, risk) to general good practice that should be applied across the site to engender awareness of peat instability and enable early identification of potential displacement and opportunities for mitigation.

Risks may be mitigated by:

i. Post-consent site specific review of the ground conditions contributing to Moderate likelihoods which may result in a reduced likelihood, and in turn, further reduction in risk; examples include tension cracks along the peat escarpment and artificial drains aligned oblique to contour.

ii. Precautionary construction measures – including use of monitoring, good practice and a geotechnical risk register relevant to all locations.

Based on the analysis presented in this report, risks are calculated to be “Low” or “Negligible” across the site, and site-specific mitigation is not required to reduce risks pre-consent. Section 6.2 and Section 6.3 provide information on good practice during construction and post-construction (i.e. during operation).

6.2. Good Practice During Construction

The following good practice should be undertaken during construction:

For excavations:

- Use of appropriate supporting structures around peat excavations (e.g. for turbines, crane pads and compounds) to prevent collapse and the development of tension cracks.
- Avoid cutting trenches or aligning excavations across slopes (which may act as incipient back scars for peat failures) unless appropriate mitigation has been put in place.
- Implement methods of working that minimise the cutting of the toes of slope, e.g. working up-to-downslope during excavation works.
- Monitor the ground upslope of excavation works for creep, heave, displacement, tension cracks, subsidence or changes in surface water content.
- Monitor cut faces for changes in water discharge, particularly at the peat-substrate contact.
- Minimise the effects of construction on natural drainage by ensuring that natural drainage pathways are maintained or diverted such that there is alteration of the hydrological regime of the site is minimised or avoided; drainage plans should avoid creating drainage/infiltration areas or settlement ponds towards the tops of slopes (where they may act to both load the slope and elevate pore pressures).

For cut tracks:

- Maintain drainage pathways through tracks to avoid ponding of water upslope.
- Monitor the top line of excavated peat deposits for deformation post-excavation.

- Monitor the effectiveness of cross-track drainage to ensure water remains free-flowing and that no blockages have occurred.

For storage of peat and for restoration activities:

- Ensure stored peat is not located upslope of working areas or adjacent to drains or watercourses.
- Undertake site specific stability analysis for all areas of peat storage (if on sloping ground) to ensure the likelihood of destabilisation of underlying peat is minimised.
- Avoid storing peat on slope gradients >3° and preferably store on ground with neutral slopes and natural downslope barriers to peat movement.
- Monitor effects of wetting / re-wetting stored peat on surrounding peat areas, and prevent water build up on the upslope side of peat mounds.
- Undertake regular monitoring of emplaced peat in restoration areas to identify evidence of creep or pressure on retaining structures (dams and berms).
- Maximise the interval between material deliveries over newly constructed tracks that are still observed to be within the primary consolidation phase.

In addition to these control measures, the following good practice should be followed:

- A geotechnical risk register should be prepared for the site following intrusive investigations post-consent and location-specific stability analyses (if identified as required) – the risk register should be considered a live document and updated with site experience as infrastructure is constructed.
- Full site walkovers should be undertaken at scheduled intervals to be agreed with the Local Authority to identify any unusual or unexpected changes to ground conditions (which may be associated with construction or which may occur independently of construction).
- All construction activities and operational decisions that involve disturbance to peat deposits should be overseen by an appropriately qualified geotechnical engineer with experience of construction on peat sites.
- Awareness of peat instability and pre-failure indicators should be incorporated in site induction and training to enable all site personnel to recognise ground disturbances and features indicative of incipient instability.
- A weather policy should be agreed and implemented during works, e.g. identifying ‘stop’ rules (i.e. weather dependent criteria) for cessation of track construction or trafficking.
- Monitoring checklists should be prepared with respect to peat instability addressing all construction activities proposed for site.

It is considered that taken together, these mitigation measures should be sufficient to reduce risks to construction personnel to Negligible by reducing consequences to minor injury or programme delay (i.e. Moderate consequences) with a Very Low likelihood of occurrence.

6.3. Good Practice Post-Construction

Following cessation of construction activities, monitoring of key infrastructure locations should continue by full site walkover to look for signs of unexpected ground disturbance, including:

- Ponding on the upslope side of infrastructure sites and on the upslope side of access tracks.
- Changes in the character of peat drainage within a 50 m buffer strip of tracks and infrastructure (e.g. upwelling within the peat surface upslope of tracks, sudden changes in drainage behaviour downslope of tracks).
- Blockage or underperformance of the installed site drainage system.
- Slippage or creep of stored peat deposits.
- Development of tension cracks, compression features, bulging or quaking bog anywhere in a 50 m corridor surrounding the site of any construction activities or site works.

This monitoring should be undertaken on a quarterly basis in the first year after construction, biannually in the second year after construction and annually thereafter; in the event that unanticipated ground conditions arise during construction, the frequency of these intervals should be reviewed, revised and justified accordingly.

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