Consulting Report

Appendix 8.4 - Peat Landslide Hazard and Risk Assessment
Millennium East Wind Farm

Highlands, Scotland
Nadara Limited

043648-D-001v02

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Prepared for
Fluid Environmental Consulting

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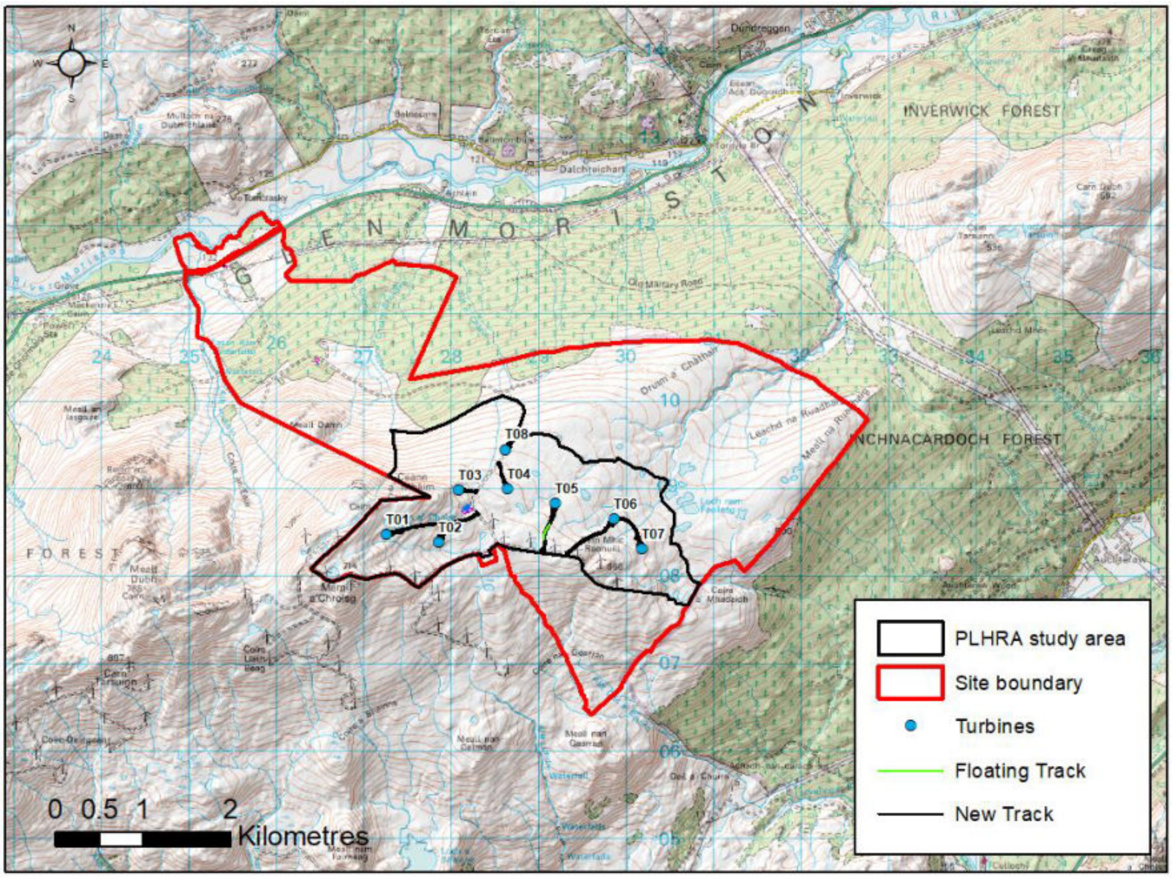
1. INTRODUCTION

1.1. Background

Nadara Limited (the Applicant) are seeking consent under Section 36 of the Electricity Act for construction of the Millennium East Wind Farm, Highlands (hereafter the 'Proposed Development').

The Site for the Proposed Development is located east of the existing Millennium Wind Farm and lies approximately 7.5 km west of Fort Augustus, 8 km north of Invergarry and 14 km southwest of Invermoriston. The Site is approximately 18.7 km^2 (c. 1,867 ha) in area (Plate 1.1). The Site is bordered to the north by commercial forestry and to the south and west by the Millennium Wind Farm.

Plate 1.1 Proposed location of Millennium East wind farm



The Proposed Development will comprise:

- Eight wind turbines of approximately 6.6 MW each, five with a maximum tip height of up to 180 m and three with a maximum tip height of up to 200 m;
- Foundations supporting each wind turbine;
- Onsite distribution sub-station and control building;
- Temporary mobilisation and construction compounds;
- A network of new on-site access tracks and associated watercourse crossings;
- A network of underground cables to connect turbines to a distribution substation; and
- Borrow pit extension.

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, 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 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; and

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

Section 1.3 of this report describes how this indicative scope is addressed.

The spatial scope of the assessment (the 'PLHRA study area', as shown in Plate 1.1) is limited to the main infrastructure area in the upper slopes, given that the Site boundary is substantially larger than the proposed development footprint.

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 provides mitigation and control measures to reduce or minimise landslide risks prior to, during and after construction.

Assessments within the PLHRA have been undertaken alongside assessments for the Outline Peat Management Plan (Appendix 8.3) and have been informed by results from the Peat Survey Report (Appendix 8.2). Where relevant information is available elsewhere in the Environmental Impact Assessment Report (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 limit equilibrium approach is that many observed relationships between reported peat landslides and ground conditions can be considered together, whereas a FoS approach is limited to consideration of a limited number of geotechnical parameters. The disadvantage of the limit equilibrium approach is that the outputs of such an approach are better at illustrating relative variability in landslide susceptibility across a site rather than absolute likelihood.

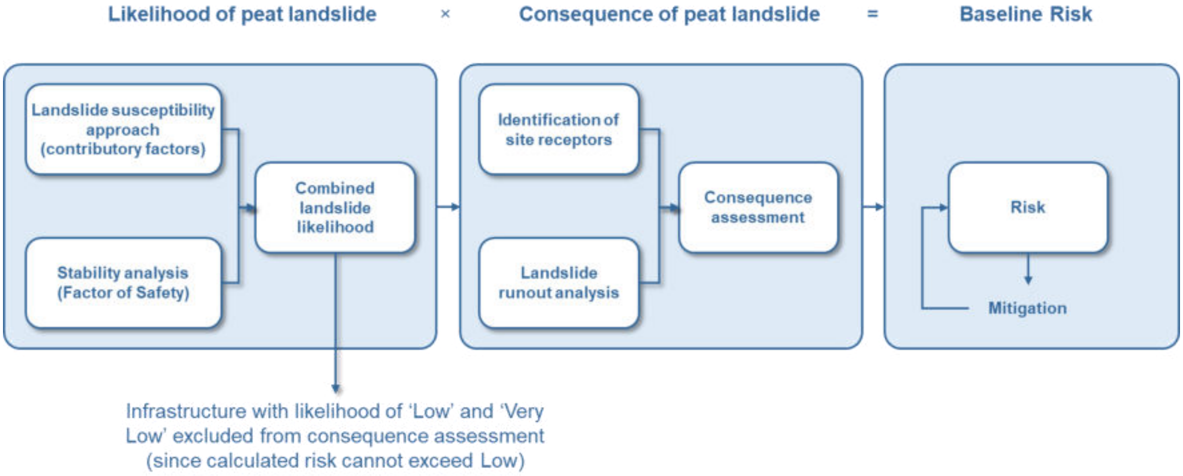
The advantage of the FoS approach is that clear thresholds between stability and instability can be defined and modelled numerically. However, in reality, there is considerable uncertainty in input parameters and it is a generally held view that the geomechanical basis for stability analysis in peat 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. Plate 1.2 shows the approach adopted for this assessment.

1.5. Team competencies

This PLHRA has been undertaken by a chartered geologist with 27+ years experience of mapping and interpreting peatland terrains and peat instability features. A geomorphological walkover survey was undertaken by the same individual. Peat depth probing was undertaken by Fluid Environmental Consulting's highly experienced peatland survey team, and additional Site observations and photographs were made available from these surveys to the PLHRA team.

Plate 1.2 Risk assessment approach



2. BACKGROUND TO PEAT INSTABILITY

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.

2.1. 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 occurred at 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 weather system moving northeast from Ireland across Scotland. The event in Pollatomish damaged several houses, a main road and washed away part of a graveyard. Some of the landslides originated in 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 all 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. In 2020, a bog burst occurred at the Meenbog wind farm, Co. Donegal, on land undergoing construction (Morton et al, 2024). Two occurrences of instability in association with construction works on the Viking Wind Farm (Shetland) have been reported (July 2022 and May 2024), though in both cases, these have involved failure of peat or mineral spoil at track margins rather than the triggering of a new 'peat slide' by groundworks. An earlier failure in 2015 (The Shetland Times, 2015) pre-dated construction of the wind farm and was not associated 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 one reported Scottish example occurring on the Shetland Islands (Mid Kame), an area previously associated with peat instability.

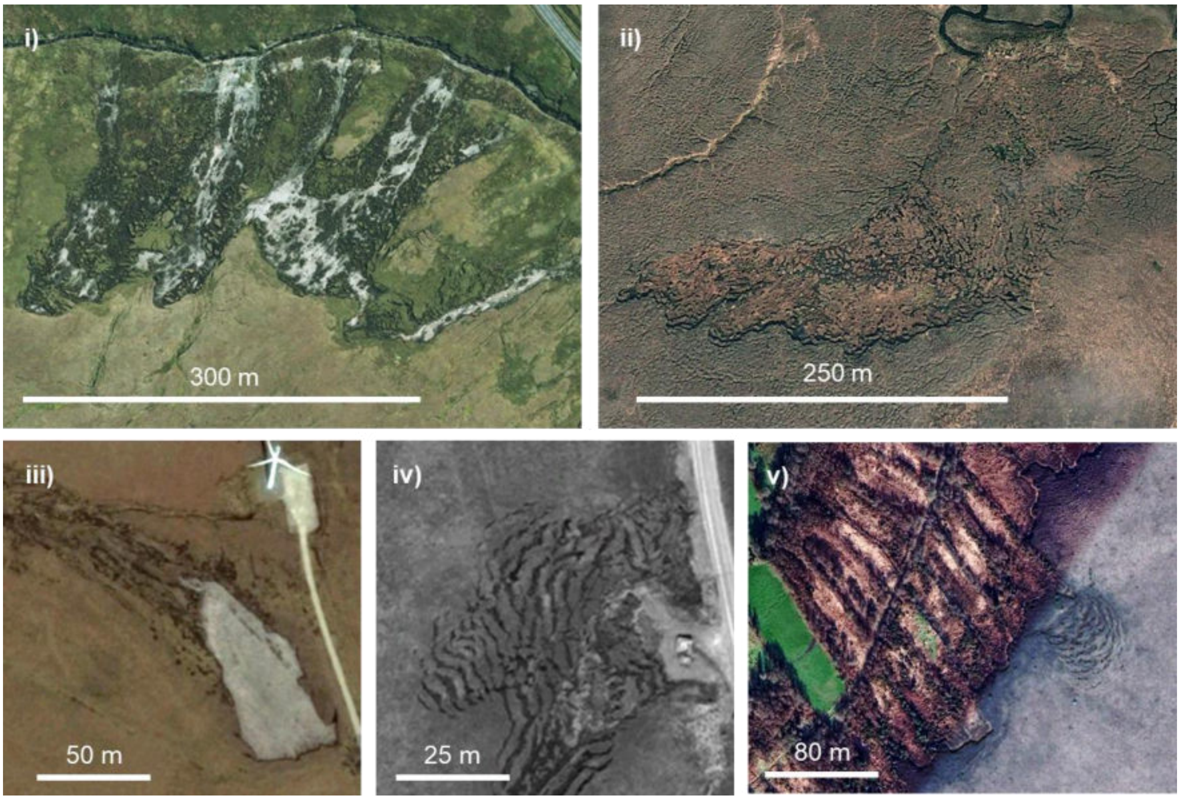


Plate 2.1 Characteristic peat landslide types in UK and Irish peat uplands: Top row - natural failures: i) multiple peat slides with displaced slabs and exposed substrate, ii) retrogressive bog burst with peat retained within the failed area; Bottom row - failures possibly induced by human activity: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

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 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).

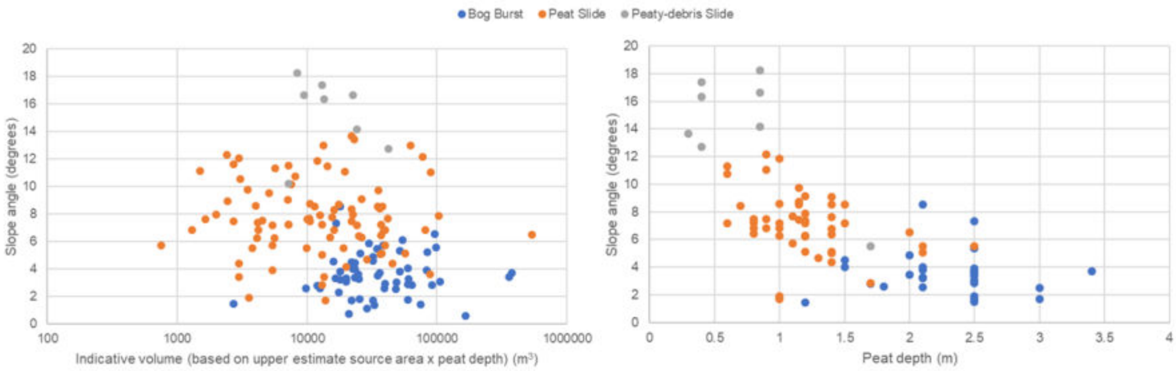


Plate 2.2 Reported slope angles and peat depths associated with peat slides and bog bursts (from literature review of locations, depths and slope angles, after Mills, 2002)

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 1.0 m and up to 10 m) 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 and there are no signs of instability or previously reported landslide events in association with the Millennium Wind Farm and Millennium Wind Farm Extension.

2.2.1. Factors Contributing to Peat Instability

Peat landslides are caused by a combination of factors – triggering factors and preconditioning 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 those 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. BASELINE CONDITIONS

3.1. Topography

The Proposed Development is distributed across east and north facing slopes that fall towards Glen Moriston and the River Moriston to the north. The westernmost point in the Site is just north of Mam a Chroisg (714 m AOD), while Ceann a Mhaim (670 m AOD) forms a prominent high point in the centre of the Site (Figure 8.4.1). Turbines 1 and 2 are located on the slopes to the east of Mam à Chroisg and south of Ceann à Mhaim at elevations of 645 m AOD and 590 m AOD respectively, although there is no peat within the main hardstanding of either turbine (see section 3.5). Turbine 3 is situated just below the 600 m contour and all other turbines lie between 550 and 500 m AOD. A small named summit (Carn Mhic Raonuill, 568 m AOD) hosts one of the Millennium Wind Farm turbines that are accessed via a track running along the west-to-east aligned ridge crest that hosts an access track for the existing Millennium Wind Farm.

Plate 3.1 shows a perspective view of the Proposed Development with key geographical features identified.

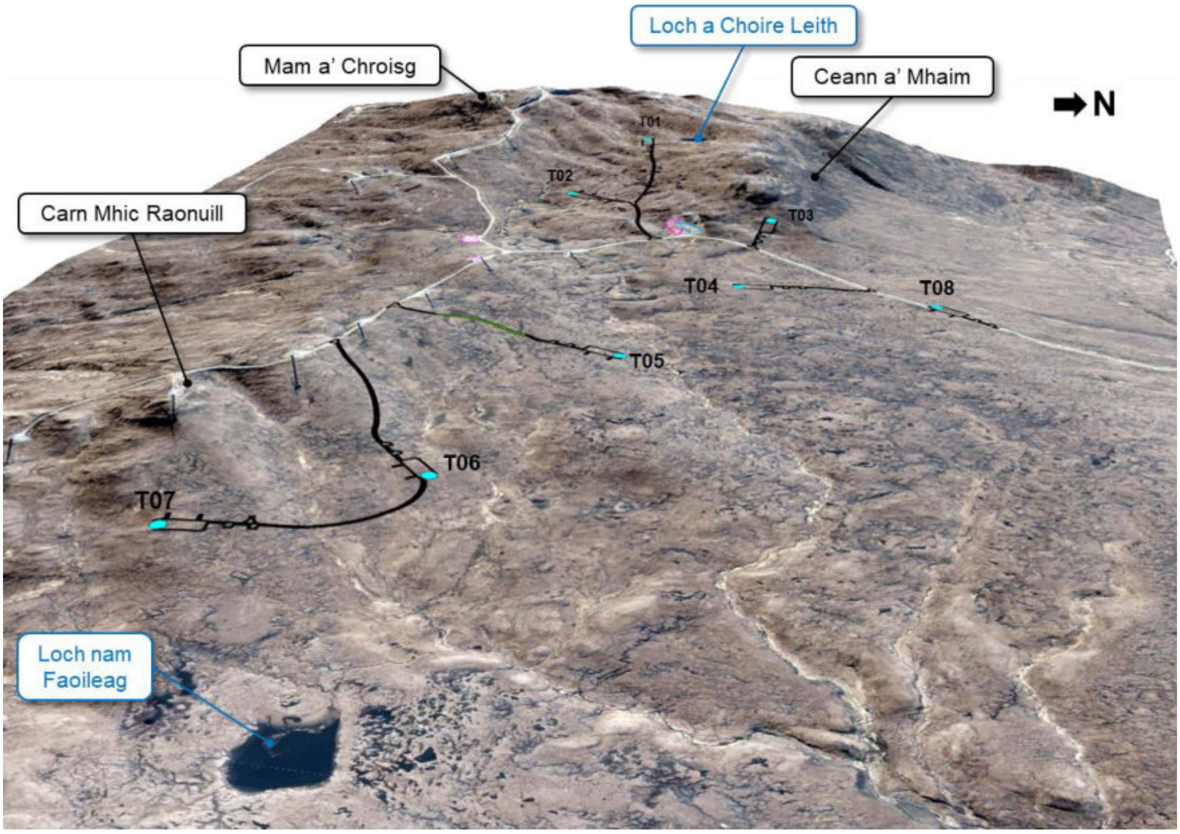


Plate 3.1 3D perspective view of Proposed Development with key geographical features highlighted

Slope angles vary from gentle (<2.5°) to moderate slopes (generally <7.5°) in the east of the Site to steeper slopes in the west in association with the named summits at higher elevations (Figure 8.4.2).

3.2. Geology

The inset panel of Figure 8.4.3 shows the solid geology of the Site mapped from 1:50,000 scale publicly available BGS digital data and indicates the Site to be entirely underlain by metamorphic Tarvie Psammite, with isolated igneous sills of granodiorite, diorite or microdiorite.

The main panel of Figure 8.4.3 shows the superficial geology of the Site, also derived from BGS digital data, indicating widespread peat on the middle and lower slopes of the study area, with peat absent at higher elevations above 600 m. Local areas of Devensian till are shown upslope of the peat beneath Ceann à Mhaim and Carn Mhic Raonuill. Bedrock is frequently visible at the surface, particularly at higher elevations and where erosion has cut peat down to the underlying geology (e.g. Plate 3.2a). A borrow pit is located at the western end the access track serving the northernmost string of turbines in the Millennium Wind Farm Extension (Plate 3.2b).

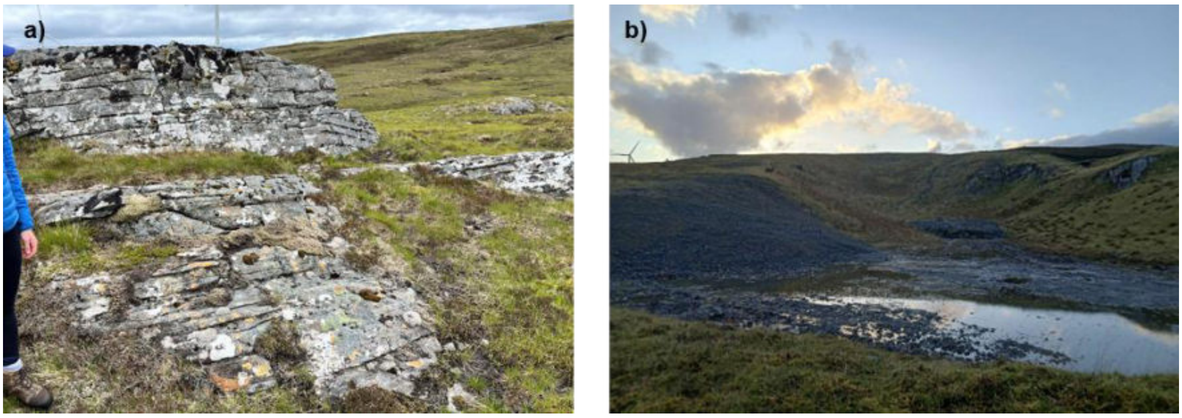


Plate 3.2 a) typical bedrock exposure on the approach to Ceann a Mhaim, b) the existing borrow pit serving the previously constructed wind farm

There are no geological designations within the study area.

3.3. Hydrology

The Site drains north towards the River Moriston via two main tributaries, the Allt a' Chaise and Allt Phocaichain (Figure 8.4.4). These tributaries are fed by a number of very minor headwater channels which originate as gullies in the upper slopes below the ridge line. Below the 540 m contour, bog pools are relatively extensive (e.g. Plate 3.3b), shown both on Ordnance Survey base layers for the Site and visible on satellite imagery (see Figure 8.4.4). Two large lochans are present to the northeast of Turbines 6 and 7, one named – Loch nam Faoileag. A number of diffuse flushes are present in the mid-slopes. There are no artificial drains on the Site.

3.4. Land Use

Land use is very limited, with the primary development on site being the previously constructed wind farm and associated ancillary infrastructure and previous excavated borrow pit.

3.5. Peat Depth and Character

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

- An initial Phase 1 100 m grid was acquired by SLR comprising 351 probes, of which 315 are within the Site boundary.
- The Phase 1 grid was extended or supplemented by Fluid Environmental Consulting (Fluid) in April 2024, adding a further 1,212 locations,
- Detailed Phase 2 probing comprising 10 m grids within infrastructure footprints and 50 m track probing with 10 m offsets was undertaken by Fluid in July and August 2024, adding a further 1,440 locations.

- Following layout review and adjustments, a second set of Phase 2 probing was undertaken BY Fluid in October 2024 adding another 266 probes.

In total, 3,223 probes characterise the Site. Full details of the survey are provided in the Peat Survey Report (EIAR Appendix 8.2). A further 25 locations were cored to determine peat characteristics and to calibrate the probing depths recorded at key infrastructure locations. 77% of probed locations indicated rock at the base of the peat and the remainder granular substrates (Table 2, Appendix 8.2).

Interpolation of peat depths was undertaken in the ArcMap GIS environment using a natural neighbour approach. This approach was selected after comparison of outputs with three other methods (inverse distance weighted, kriging and TIN). The natural neighbour approach was selected because it preserves recorded depths at each probe location, unlike some other approaches (e.g. kriging) itis computationally simple, and minimises 'bullseye' effects.

The peat depth model is shown on Figure 8.4.5 with probing locations superimposed. Peat depths can be summarised as follows:

- Peat is generally shallow or absent in the west of the Site, particularly at higher elevations where it exists on pockets, typically between bedrock ridges.
- In the east, despite the gentle gradients on the ridge line (along which the existing access track is located), peat depths are very limited, deepening downslope towards the limits of the PLHRA study area.
- Where peat is present, it is typically shallow, c. 0.5 – 1.0 m, occurring more deeply over relatively small areas, and very deeply (>3.0 m) in very isolated pockets.
- The Peat Survey Report (Appendix 8.2) notes that c. 58% of probes are <0.5 m in depth (carbon-rich soil), c. 28% are 0.5 – 1.0 m in depth and <14% are >1.0 m.

Comparison of the peat depth model with the layout indicates that the layout has been designed to minimise overlap with deeper peat deposits, with Turbines 1-3 and 6-8 largely out of peat and Turbines 4 and 5 sited in shallower peat than the surrounding areas. Access routes to the turbines provide the principle overlap with deeper deposits, though existing track infrastructure has been used as far as possible.

The inset panel on Figure 8.4.5 shows the Carbon and Peatland (2016) map categories for the Site, indicating primarily Class 1 soils over the northeastern half of the Site and Class 3 peaty-soils in the southwestern half. This correlates well with the peat depth data and interpolated peat depth model.

3.6. 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 8.4.4) was subsequently verified during a site walkover undertaken in June 2024 by a Chartered Geologist / peatland geomorphologist with over 20 years' experience of assessing peat landslides. Plates 3.2 and 3.3 show typical features identified during the walkovers.

Figure 8.4.4 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.

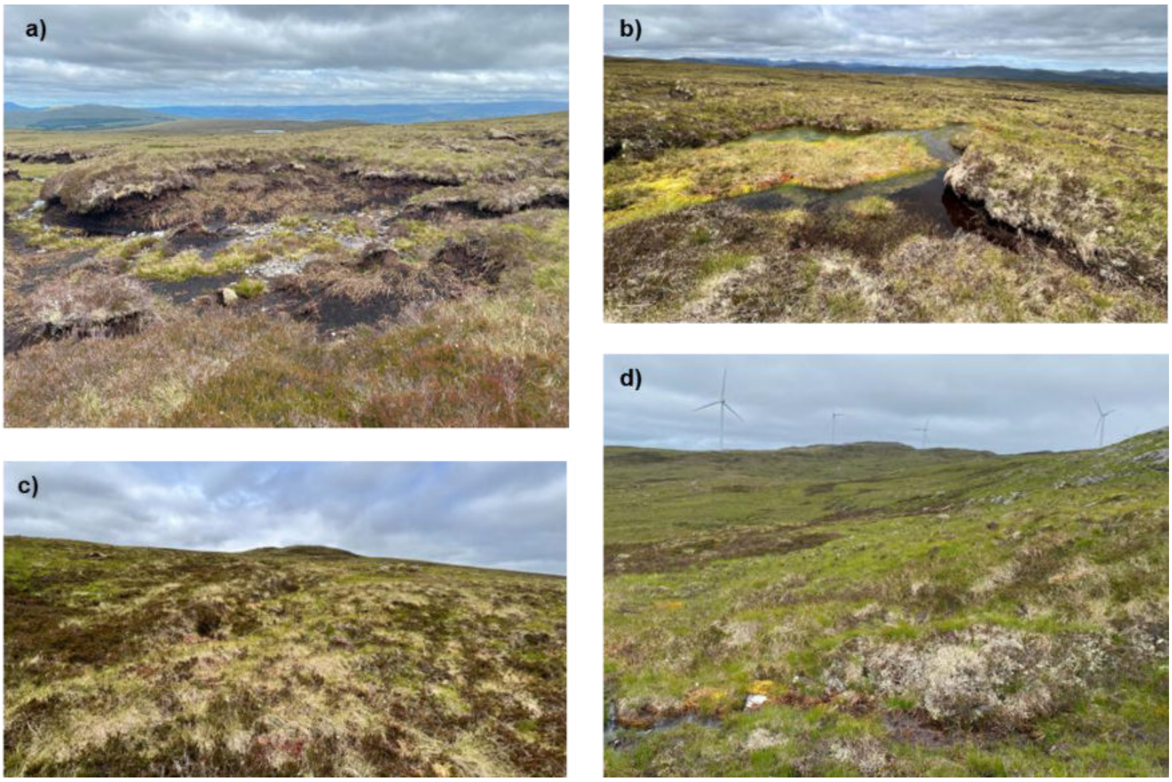


Plate 3.3 Typical site conditions: a) eroded gully floor with exposed substrate and haggs suitable for reprofiling, b) good quality bog pool habitat set within formerly eroded terrain, b) steeper slopes with peaty soil on the approach to Ceann a Mhaim, d) moderate slopes looking west towards Mam a Chroisg

The site is divided into three differing geomorphological settings, the western half of the Site north and south of Ceann a Mhaim, and the eastern half of the Site.

In the west, elevations drop quickly over relatively steep slopes descending from Ceann a Mhaim via planar peatland and minor hagging, with minor tributaries breaking up the slope. South of Ceann a Mhaim, topography is more irregular, with numerous northeast-southwest aligned ridges with thin / no peat separated by flushy and occasionally peat filled hollows. Waterbodies are scattered amongst the floors between ridges.

In the east, peatland geomorphology is more prevalent with complex pool systems or areas of erosion, some active and some relict, over much of the PLHRA study area. Flushes occasionally drain the mid slopes. Nearer the ridge line, thinner peat or soil lies over areas of bedrock.

No evidence of peat instability was observed during the walkovers.

The next section integrates the desk and field assessments described above to identify the spatial variation in landslide likelihood across the Site.

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.

Due to the combination of moderate slopes and thinner peat at this site, the most likely mode of failure is peat slides, and this is the failure mechanism considered in this report. This is in keeping with the most likely mode of failure for the peat depths and slope angles present at the site (see Plate 2.2 and Figures 8.4.1 and 8.4.5).

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' 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 much of the 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. 13,800 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. Total stress parameters are used in this undrained analysis.

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.

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 4-1 shows the input parameters and assumptions for the modified stability analysis. The analysis employs a 5.5 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.

The analysis assumes pre-loading of the peat by floating track during which the track is built in layers and pore pressures are allowed to dissipate. The combined weight of the track and peat are then modelled in an undrained analysis utilising the heaviest vehicle loads likely to use the access the track.

4.2.3. Results

The outputs of the drained analysis (effective stress) are shown for both parameter combinations in Figure 8.4.6. The more conservative combination (minimum c' and ϕ', inset panel) suggests that only the steeper parts of the Site north of Ceann a Mhaim and isolated pockets along watercourses are likely to be of marginal stability or unstable. The best estimate parameters show stability over the whole site. This is consistent with site observations and the stability of peat in general – peat landslides are very rare occurrences given the wide distribution of peat soils in England, Scotland and Wales.

Table 4-1 Geotechnical parameters for drained infinite slope analysis

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 4-2 Geotechnical parameters and assumptions for undrained 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	See Table 4-1

Parameter	Values	Rationale	Source
		increased density, so pre-load parameters are used	
Slope angle from horizontal (β)	Various	Credible slope angles for which floating tracks are proposed	See Table 4-1
Peat depth (z)	Various	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	Typical axle load for crane suitable for turbine construction.	

In order for a section of floating track to be considered a potential source zone, two or more contiguous 25 m cells must have Factors of Safety of <1.4. This reflects the tendency of regularised grids to produce single cell outliers in results. Two contiguous cells of similar value would indicate a trend more reflective of the locality.

The outputs of the undrained analysis incorporating crane loads on floating track are shown on the right inset panel of Figure 8.4.6 which indicates that the single proposed length of floating track is in an area with Factors of Safety indicating stability.

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. 11,450 facets were considered in the analysis, with an average area of c. 490 m^2 (or an average footprint of c. 22 m x 22 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), slope curvature (C), forestry (F), 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 8.4.2 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).

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.

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

Slope range (°)	Association with instability	Peat slide
≤2.5	Slope angle ranges for peat slides 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°).	0
2.5 - 5.0		1
5.0 – 7.5		3
7.5 - 10.0		3
>10 – 15.0		3
>15.0		3

Figure 8.4.7 shows the distribution of slope angle scores across the Site. Due to the relatively steep slopes in the western half of the Site, much of this area receives the highest core, as do large areas in the east where slopes are also moderate to steep.

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 8.4.5 and reflect the peat depth ranges most frequently associated with peat landslides (see Plate 2.2).

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

Peat depth range (m)	Association with instability	Peat slide
>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

The distribution of peat depth scores is shown on Figure 8.4.7. Much of the Site either lacks peat or has been in the highest score category due to the presence of moderate rather than very deep peat.

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.

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

Substrate Geology	Association with instability	Peat slide
Cohesive (clay) or iron pan	Failures are often associated with clay substrates and/or iron pans	3
Granular clay or clay dominated alluvium	Failures are more frequently associated with substrates with some clay component	2
Granular or bedrock	Failures are less frequently associated with bedrock or granular (silt / sand / gravel) substrates	1

Probing undertaken across the Site indicated primarily bedrock or granular substrates using the refusal method, and coring at 25 locations confirmed this and no iron pans were observed (see Appendix 8.2). Accordingly, the full Site is treated as if underlain by impermeable bedrock or granular glacial till (Figure 8.4.7).

4.3.5. Peat Geomorphology (M)

Table 4-6 shows the geomorphological features typical of peatland environments, their association with instability and related scores. Being an open moorland Site (rather than afforested), there is a strong degree of confidence in the identification and mapping of these features, where present.

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

Geomorphology	Association with instability	Peat slide
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
Afforested / deforested peatland	Considered within Forestry (F), see below	0

Figure 8.4.7 shows the geomorphological classes from Figure 8.4.4 re-coloured to correspond with Table 4-6. Much of the peat-covered part of the Site comprises planar peatland with local flushy

areas and has correspondingly high scores. Planar areas lacking peat and gullied areas have lower scores.

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.

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

Drainage Feature	Association with instability	Peat slide
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

The effect of drainage lines is captured through the use of a 30 m buffer on each artificial drainage line (producing a 60 m wide zone of influence) present within the peat soils at the Site. 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 8.4.7.

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.

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

Profile Curvature	Association with instability	Peat slide
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

Profile Curvature	Association with instability	Peat slide
Concave Slope	Peat failures are occasionally reported in association with concave slopes	1

The 5 m digital terrain model was used to identify areas of noticeable slope convexity across the Site. An ArcGIS geoprocessing model was used to calculate slope curvature into concave, convex and rectilinear slopes and 'flat' areas, i.e. those with minimal rate of gradient change on subdued terrain. Curvature scores are shown on Figure 8.4.7 in accordance with Table 4-8 above.

4.3.8. Forestry (F)

Table 4-9 shows forestry classes, their 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.

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

Forestry Class	Association with instability	Peat slide
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
Windblown	Windblown trees have full disruption to the underlying peat and residual hydrology due to root plate disturbance	0
Not afforested	No influence on stability	0

None of the Site is afforested and therefore the full Site receives a zero score for this factor (see Figure 8.4.7).

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.

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

Land Use	Association with instability	Peat slide
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

Land Use	Association with instability	Peat slide
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

There is minimal land use on Site with the potential to reduce stability and hence the Site has a zero score (Figure 8.4.7).

4.3.10. Generation of Slope Facets

The eight contributory factor layers shown on Figure 8.4.7 were combined in ArcMap to produce approximately 11,450 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).

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

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 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 exceeding both the worst case peat depth and slope angle scores summed (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 8.4.8 shows the outputs of the landslide susceptibility approach for peat slides. The results indicate that almost the entire Site has 'Low' or Very Low likelihoods with only minor areas of Moderate likelihood.

4.3.12. Combined Landslide Likelihood

Figure 8.4.9 the combined landslide likelihood results from the preceding analysis, comprising Moderate or higher likelihood scores and areas with Factor of Safety <1.4 from the Best Estimate and floating track assessments. None of these areas overlap with infrastructure, and therefore there are no potential source zones associated with the Proposed Development.

In order for there to be a "Medium" or "High" risk, likelihoods must be "Moderate" or higher (see Plate 4.1 below) and hence this provides a screening basis for the likelihood results. There are no areas of infrastructure overlapping Moderate likelihoods of equivalent factors of safety (i.e. those <1.4). As a result, risks can be no greater than Low and site-wide good practice should be sufficient to manage these risks and further reduce to Negligible. Section 5 of this report details appropriate good practice measures.

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

		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 in MEDIUM areas 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 in LOW areas to refine risk level and/or mitigate any residual hazards through micro-siting or specific design measures
1 - 4	Negligible	Project should proceed with good practice monitoring and mitigation of ground instability / landslide hazards at these locations as appropriate

5. RISK MITIGATION

5.1. Overview

A number of mitigation opportunities exist to further reduce risk associated with peat landslides 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.

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. Sections 5.2 to 5.4 provide information on good practice pre-construction, during construction and post-construction (i.e. during operation).

5.2. Good Practice Prior to Construction

Site safety is critical during construction, and it is strongly recommended that detailed intrusive site investigation and laboratory analysis are undertaken ahead of the construction period in order to characterise the strength of the peat soils in the areas in which excavations are proposed, particularly if these fall in areas of Moderate (or greater, if present) likelihood. These investigations should be sufficient to:

1. Determine the strength of free-standing bare peat excavations.
2. Determine the strength of loaded peat (where excavators and plant are required to operate on floating hardstandings or track, or where operating directly on the bog surface).
3. Identify sub-surface water-filled voids or natural pipes delivering water to the excavation zone, e.g. through the use of ground penetrating radar or careful pre-excavation site observations.

A comprehensive Geotechnical Risk Register should be prepared post-consent, but pre-construction, detailing sequence of working for excavations, measures to minimise peat slippage, design of retaining structures for the duration of open hole works, monitoring requirements in and around the excavation and remedial measures in the event of unanticipated ground movement. The risk register should be considered a live document and updated with site experience as infrastructure is constructed. Ideally, a contractor with experience of working in deep peat should be engaged to undertake the works.

5.3. 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 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 floating tracks:

- Allow peat to undergo primary consolidation by adopting rates of road construction appropriate to weather conditions.
- Identify ‘stop’ rules, i.e. weather dependent criteria for cessation of track construction based on local meteorological data.
- Run vehicles at 50% load capacity until the tracks have entered the secondary compression phase.
- Prior to construction, setting out the centreline of the proposed track to identify any ground instability concerns or particularly wet zones.

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:

- The geotechnical risk register prepared prior to construction should be 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.

5.4. 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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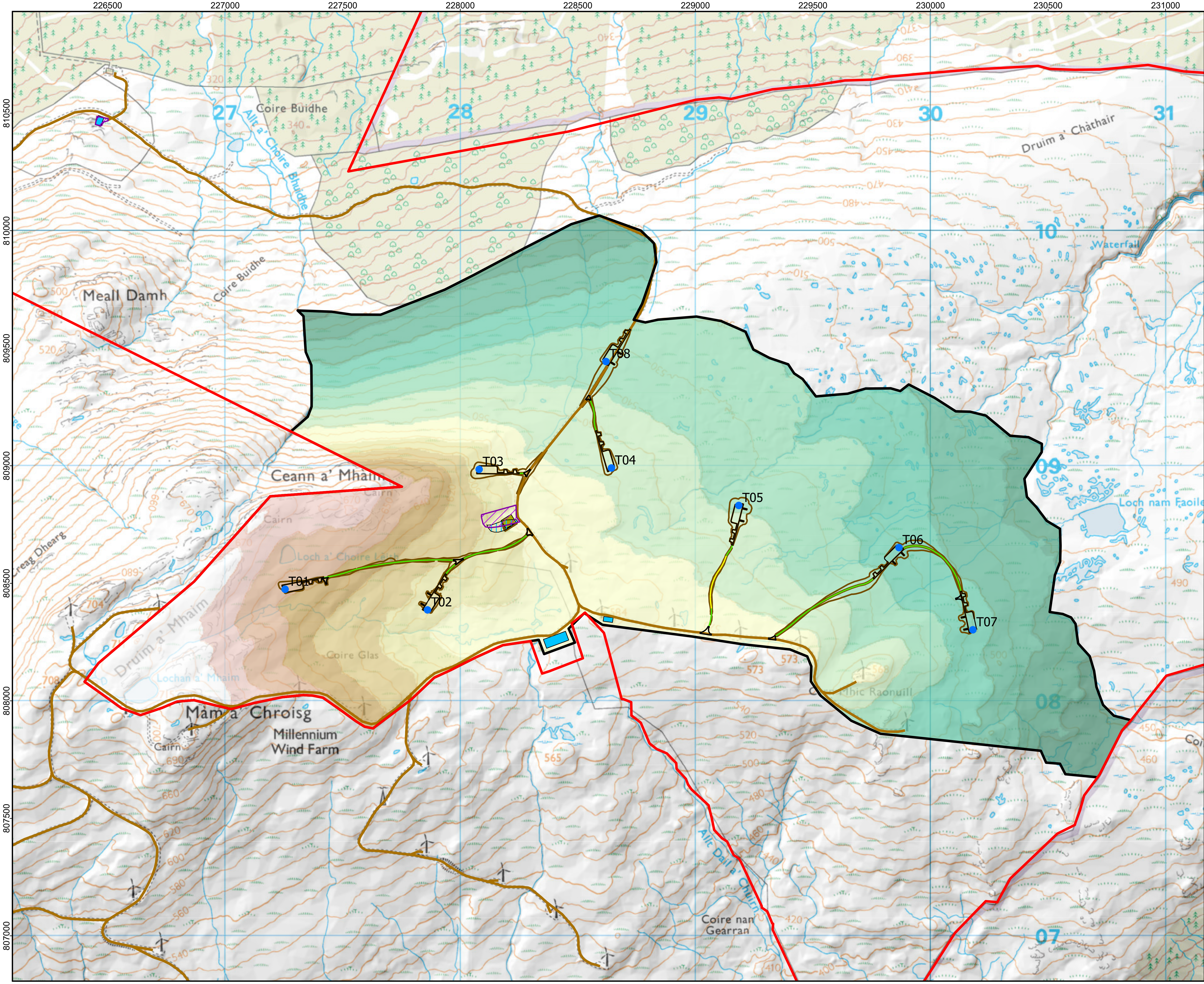
FIGURES



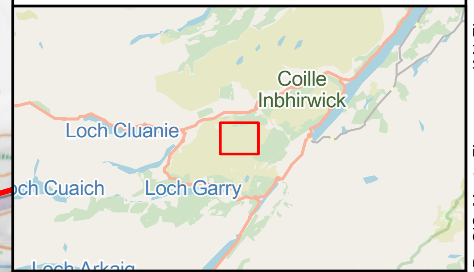
Legend:

- Site Boundary
- Assessment Area
- Proposed Turbine Locations
- Existing Borrow Pits
- Borrow Pit Extension
- Existing Wind Farm Track
- Floating Track
- New Track
- Temporary Mobilisation and Construction Compounds
- Substation
- Earthworks

Elevation (m)

- <= 460
- 461 - 480
- 481 - 500
- 501 - 520
- 521 - 540
- 541 - 560
- 561 - 580
- 581 - 600
- 601 - 620
- 621 - 640
- 641 - 660
- 661 - 680
- 681 - 700

Coordinate System: British National Grid
Projection: Transverse Mercator
Datum: OSGB 1936



Rev	Date	Description	Drn	Chk	App
01	06/06/2025	Second Draft	NT	AM	DS

Millennium East Wind Farm

RSK nadara

TITLE: Figure 8.4.1
Elevation

ID:P664052_A3_MNE_PLHRA_L1_Elevation

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Kilometres
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REV 00

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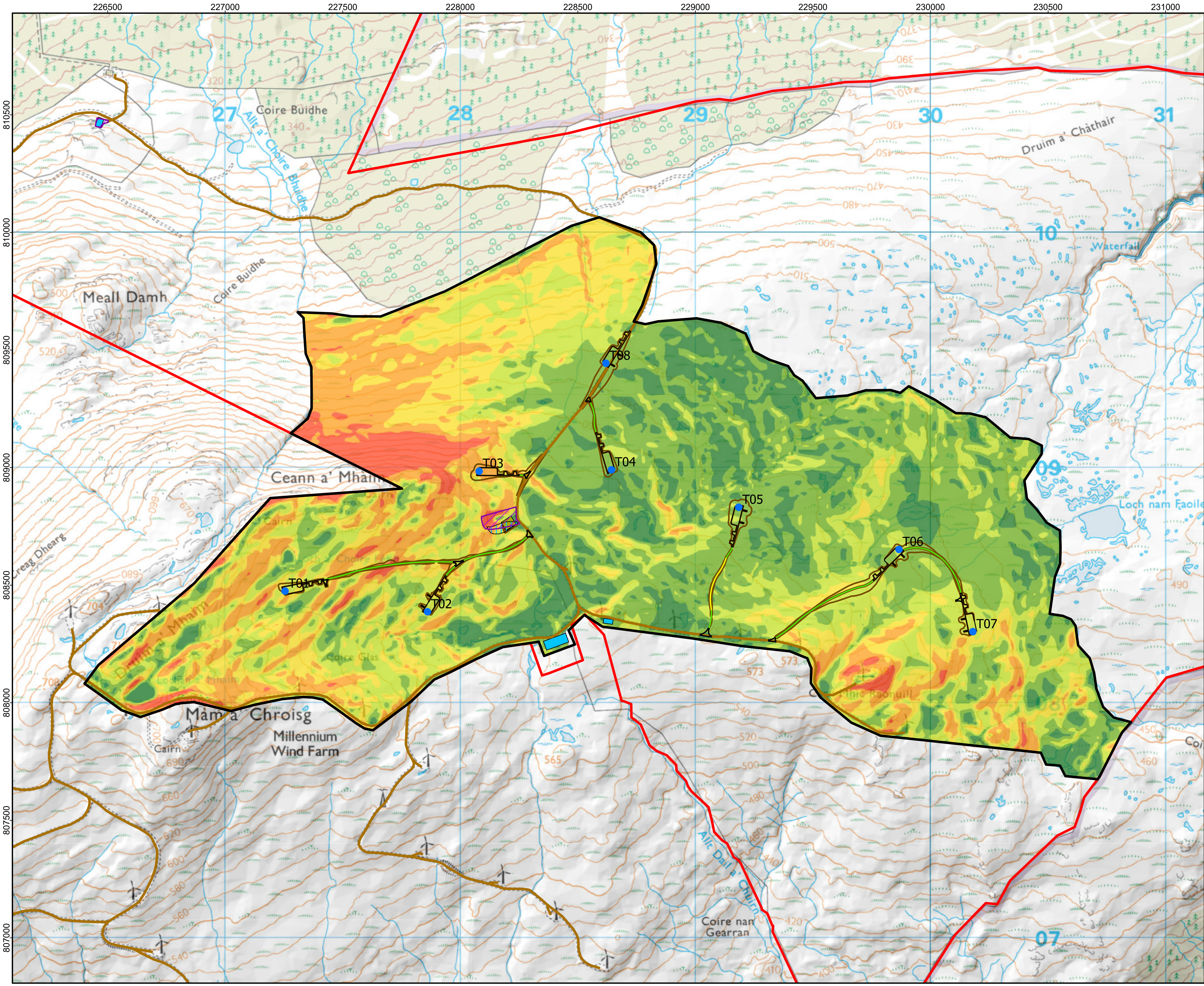


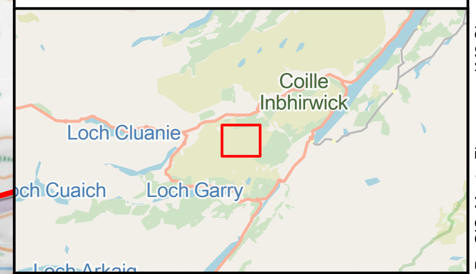
Legend:

- Assessment Area
- Site Boundary
- Proposed Turbine Locations
- Turbine Hardstanding
- Junction or Turning Head
- Existing Borrow Pits
- Borrow Pit Extension
- Existing Wind Farm Track
- Floating Track
- New Track
- Temporary Mobilisation and Construction Compounds
- Substation
- Earthworks

Slope (degrees)

- 0.0 - 2.5
- 2.5 - 5.0
- 5.0- 7.5
- 7.5 - 10.0
- 10.0- 15.0
- > 15.0

Coordinate System: British National Grid
Projection: Transverse Mercator
Datum: OSGB 1936



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01	06/06/2025	Second Draft	NT	AM	DS

Millennium East Wind Farm

RSK nadara

TITLE: Figure 8.4.2
Slope Angle

ID:P664052_A3_MNE_PLHRA_L2_Slope

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Kilometres
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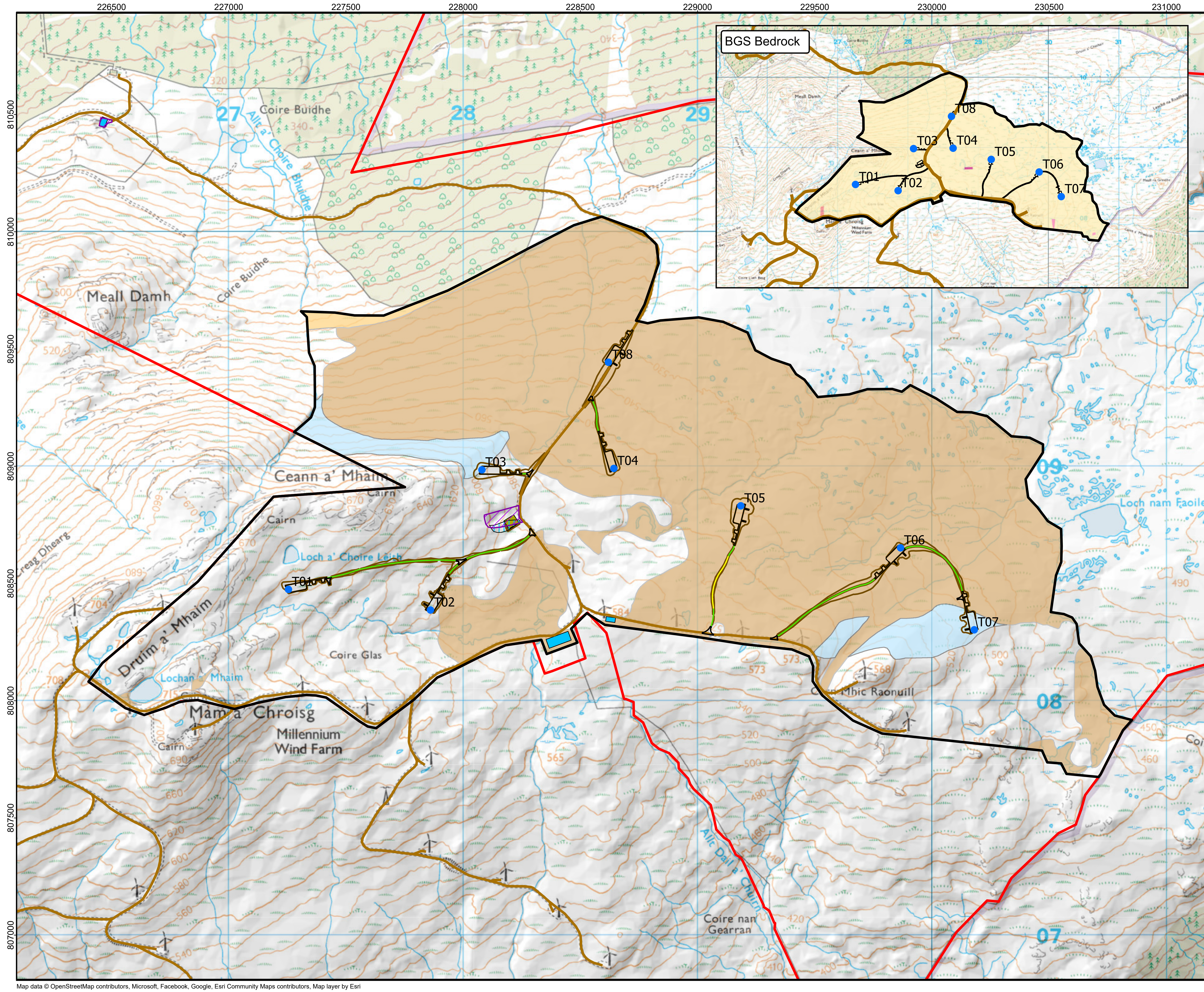

Legend:

- Assessment Area
- Site Boundary
- Proposed Turbine Locations
- Turbine Hardstanding
- Junction or Turning Head
- Existing Borrow Pits
- Borrow Pit Extension
- Existing Wind Farm Track
- Floating Track
- New Track
- Temporary Mobilisation and Construction Compounds
- Substation
- Earthworks
- Fill Footprint

Superficial Geology (BGS)

- Alluvium / Glacial - Silt, sand and gravel
- No deposits
- Peat
- Till, Devensian - Diamicton

Bedrock Geology (BGS)

- Metamorphic - Tarvie Psammite
- Igneous - Granodiorite, Diorite or Microdiorite

Coordinate System: British National Grid
Projection: Transverse Mercator
Datum: OSGB 1936

Loch Cluanie
Coille Inbhirwick
Loch Cuaich
Loch Garry

Rev	Date	Description	Drn	Chk	App
01	06/06/2025	Second Draft	NT	AM	DS

Millennium East Wind Farm

RSK nadara

TITLE: Figure 8.4.3
Geology

ID:P664052_A3_MNE_PLHRA_L3 Geology

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Kilometres
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