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Geotechnical Field and Laboratory Investigation Procedures Pertinent to the Development of Commercial On-Shore Wind Farms in Ireland

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Abstract
In the last decade, both the Irish landscape and construction industry has seen a dramatic increase in the number of commercial on-shore wind farm developments. Geotechnical field and laboratory based testing procedures play a critical role in the development, design and construction of wind farms. A comprehensive knowledge of the ground conditions and soil parameters prevailing across the development footprint are necessary to facilitate a site specific infrastructure and turbine foundation design; therefore, reducing associated construction risks and ensuring that an economic construction programme can be premeditated. This paper presents some geotechnical field and laboratory based procedures pertinent to both the development and design of commercial on-shore wind farms in Ireland. The various procedures are compared in terms of suitability of the test procedure for the soil type encountered and geotechnical design soil parameters derived. Although each geotechnical site investigation scheme is both an iterative and unique process, a phased approach relating to a rough peat moor land typically encountered across wind farm sites in Ireland is presented.

Keywords: Renewable Energy, Geotechnical, Site Investigation.

1. Introduction

In 2009, the Renewable Energy Directive (2009/28/EC) set renewable energy policy targets within the European Union (EU) specifying that 20% of all energy is to be obtained through renewable sources by 2020. Ireland's agreed target was set that 16% of gross final consumption of energy, which equates to approximately 40% gross electricity consumption, should come from renewable energy sources by this date. Since Ireland's first wind farm was constructed in 1992 until early 2012, a total on-shore renewable energy capacity of approximately 1,500MW has been installed. However, in order to meet the EU 2020 target a total additional installed renewable energy capacity of at least 3,100MW is required (IWEA, 2012). It is expected that this additional energy requirement will come from a number of 'green' energy sources, including for example: off-shore wind; biomass; tidal; and solar. Nevertheless, on-shore wind farm developments will play a crucial role in ensuring that these targets are indeed adhered to

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and will help constitute a core element of Ireland's future economic growth – ensuring an independent, secure and reliable energy supply for future generations.
However, significant challenges lie ahead for the on-shore wind industry in Ireland principally due to the following non-exhaustive list: the best available sites have already been developed and/or are under developer option; planning and environmental regulations are becoming more stringent; grid connection difficulties; anti-wind lobbying groups are increasing in both strength and frequency; and the size of wind turbine components are increasing (resulting in additional turbine access delivery issues).
In order to both assess the potential feasibility of a new wind farm site and to ensure an efficient and cost effective design/construction process, it of upmost importance that all ground conditions and associated geohazards are fully identified, analysed and mitigated against for the entire project lifespan. This paper highlights the application of conventional geotechnical field and laboratory based procedures in relation to both the development and design phases of on-shore wind farm sites in Ireland. In addition, a phased approach detailing a typical geotechnical investigation procedure in an upland, peat moor land is presented.

2. Geotechnical Processes

Project Development Stage: In order to determine the feasibility of the wind farm development site, an early stage geotechnical assessment comprising of both a site reconnaissance survey and geotechnical desk study review should be conducted. The primary objectives of the desk study review are to evaluate the ground conditions based upon existing information and to plan the scope of the subsequent stages of investigation (EN 1997-2:2007). Key geotechnical desk study considerations for review include, but are not limited to, the following: topography; previous/existing land use; hydrology and hydrogeology; utilities and services; mining and mineral potential; solid/superficial geology; unexploded ordnance; and site geomorphology.
In Ireland, a large majority of upland wind farm development sites are underlain by a peat stratum of varying thickness; therefore, additional early stage development considerations analysing the risk of peat slides occurring within the development footprint should also be investigated. A Peat Slide Risk Assessment (PSRA) report should be carried out in accordance with the latest local guidelines (SEPA 2012, Scottish Executive 2006, Scottish Renewables et al, 2010), and should provide an assessment of the peat stability conditions based upon the following quantitative and qualitative analysis: a desk study review of the existing literature and map information for the site area; a subsequent site reconnaissance exercise to identify any evidence of active, incipient or relict peat instability, as well as mapping ground conditions that may influence the stability of peat on-site; and a detailed infrastructure orientated peat probing exercise to map both the extent and geotechnical characteristics of the underlying peat. In addition, a Qualitative Risk Assessment (QRA) may be compiled to ascertain a numerical assessment of the potential risk of peat instability within the development footprint. This approach is based on a system where factors and influences are multiplied together to generate risk rating scores and corresponding qualitative relative risks (i.e. low, medium or high).

Results of the early stage geotechnical works should help infer both the turbine layout and on-site infrastructure design. Conversely, if the geotechnical risks are considered too high (i.e. substantial subsurface karstic environments underlie the site) an early stage strategic exit from the project may be advisable. In order to avoid major construction issues, but also to minimise the expenditure of clients and improve bottom line financial results of companies, it is of upmost importance that all potential major geohazards are identified and communicated at project feasibility stage.

Project Design Stage: Once the development feasibility of the site is confirmed, an intrusive geotechnical site and subsequent laboratory based investigation should be carried out to inform all necessary soil parameters for infrastructure and foundation design purposes. The site investigation should be tailored in accordance with the preferred geotechnical design methods and should establish the detailed soil stratigraphy across the entire site.

Tables 1 to 4 presented hereafter list some typical, representative geotechnical field and laboratory based procedures relating to the main soil types encountered across wind farm developments in Ireland i.e. Tables 1, 2, 3 and 4 relate to peat, coarse grained soils, fine grained soils and bedrock, respectively. For additional information regarding both the test procedures and geotechnical parameters noted hereafter the relevant ground investigation and testing standards should be consulted (EN 1997-2:2007).

In addition, to the procedures noted within Tables 1 to 4, the following points are noted:-

- Groundwater monitoring should be carried out across the site to inform on: the depth, thickness, extent and permeability of water-bearing strata in the ground, joint systems in the rock, and the pore water pressure distribution;
- Specimens for chemical testing (i.e. pH value, sulphates, chloride content etc.) should be sampled at regular agreed depth intervals within the exploratory holes to determine any aggressive ground conditions. Furthermore, if it is anticipated that some spoil material will be removed off-site, additional chemical testing should be prescribed to determine any specific landfill placement requirements;
- Additional infrastructure specific peat works may be required once both the turbine layout and supporting infrastructure layout is confirmed; and
- Once the preliminary choice of foundation method is confirmed, supplementary turbine specific site investigation works will most likely be required to confirm the foundation type and derive the pertinent geotechnical parameters for input into foundation analysis design programmes.

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Table 1. Geotechnical Field and Laboratory Based Test Procedures relating to Peat

Geotechnical Parameter	**Field Test**	**Laboratory Test**
Moisture content; w (%)	–	Oven drying method$^{(d)}$
Organic content; LOI (%)	–	Loss on dry mass on ignition$^{(d)}$
Density; ρ (Mg/m^3)	–	Oven drying method$^{(d)}$
Depth; z (m, bgl)	Peat probing	–
	Ground penetrating radar	–
	Trial pitting and/or borehole investigation	–
Degree of humification	Von-Post classification	Colorimetric method$^{(d)}$
Total carbon content; TC (%)	–	Dry combustion and elemental analysis$^{(d)}$
Undrained shear strength; c_u (kPa)	Hand vane	Laboratory vane$^{(ud)}$
	Cone penetration test	Triaxial test and/or Direct simple shear test$^{(d \text{ or } ud)}$

Note: 'd' refers to a disturbed specimen; 'ud' refers to an undisturbed specimen; and '–' not applicable

Table 2. Geotechnical Field and Laboratory Based Test Procedures relating to Coarse Grained Soils

Geotechnical Parameter	**Field Test**	**Laboratory Test**
Minimum and maximum densities; e_{max}, e_{min} and I_D	–	Laboratory vibration$^{(d)}$
Particle size distribution; PSD (%)	–	Dry sieving$^{(d)}$
Bulk density; ρ (Mg/m^3)	–	Proctor compaction$^{(d)}$
Youngs Modulus; E (MN/m^2), Shear Modulus; G (MN/m^2)	Down-hole seismic testing	Consolidated triaxial compression$^{(ud)}$
Permeability; k (m/s)	Variable/Constant head test	–
	Soakaway permeability test	
California Bearing Ratio (CBR); I_{cbr}	Plate loading test	Laboratory CBR$^{(d)}$
	Dynamic cone penetration	
Depth; z (m, bgl)	Seismic refraction	–
	Trial pitting and/or borehole investigation	–

Note: 'd' refers to a disturbed specimen; 'ud' refers to an undisturbed specimen; and '–' not applicable

Table 3. Geotechnical Field and Laboratory Based Test Procedures relating to Fine Grained Soils

Geotechnical Parameter	Field Test	Laboratory Test
Water content; w (%)	–	Oven drying method(d)
Bulk Density; ρ (Mg/m^3)	–	Proctor compaction(d)
Atterberg (consistency) limits; w_P, w_L	–	Liquid and plastic limit test(d)
Particle size distribution; PSD (%)	–	Dry sieving followed by sedimentation(d)
Undrained shear strength; c_u (kN/m^2)	Hand vane	Triaxial(ud)
		Lab vane(ud)
Compression index; c_c coefficient of primary consolidation; c_v (m^2/year)	–	Oedometer (one-dimensional compressibility)(d)
Youngs Modulus; E (MN/m^2), Shear Modulus; G (MN/m^2)	Down-hole seismic testing	Consolidated triaxial compression(ud)
Drained (effective) shear strength; c' (kPa), φ' (°)	–	Triaxial(ud)
		Translational shear box(d)
Residual Shear strength; c'_R (kPa), φ'_R (°)	–	Ring shear box(d)
Permeability, k (m/s)	Variable/Constant head test	Particle size analysis(d)
	Soakaway test	Constant head test in triaxial cell(d)
California Bearing Ratio; I_{cbr}	Dynamic cone penetration	Laboratory CBR(d)
	Plate loading test	
Depth; z (m, bgl)	Trial pitting and/or borehole investigation	–
	Seismic refraction	

Note: 'd' refers to a disturbed specimen; 'ud' refers to an undisturbed specimen; and '–' not applicable

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Table 4. Geotechnical Field and Laboratory Based Test Procedures relating to Rock Core Specimens

Geotechnical Parameter	Field Test	Laboratory Test
Bulk Density; ρ (kg/m^3)	–	Oven drying method
Porosity; n (%)	–	Evaporation method
Swelling (%)	–	Laboratory swell test
Deformation modulus; E (MN/m^2), Poission's ratio; ν and Compressive strength; σ_C (MPa)	Down-hole seismic testing	Uniaxial compressive strength test
Strength Index; I_{s50} (MPa)	–	Point-load test
Tensile strength; σ_T (MPa)	–	Brazil test
Depth; z (m, bgl)	Borehole/trial pitting	–
	Seismic Refraction	

Note: '–' not applicable.

3. Scoping Out an Intrusive Site Investigation Procedure

Table 5 presented hereafter represents a typical, phased intrusive site investigation procedure relating to an upland peat moor land area in Ireland. However, it must be noted that, there are no hard and fast rules for determining the type, location and frequency of the intrusive exploratory locations and therefore, each wind farm site should be individually assessed by a competent geotechnical engineer in order to indentify all variations in ground stratigraphy.

4. Case Study – Castlecraig Wind Farm, Co. Tyrone, Northern Ireland

The 23 Megawatt site comprised the development of ten turbines, approximately 4.5km of new access track, a construction compound and an electrical substation. Following the development stage works, and once the project was consented by the local Planning Authority, a site specific intrusive investigation procedure was specified to help provide all necessary soil parameters for infrastructure and foundation design purposes. The investigation procedure followed the recommendations outlined within '*Project Development Stage*' in Table 5.

The intermittent spread of both trial pits and dynamic cone penetration tests along the footprint of the infrastructure helped determine: road formation depths; the suitability of subsoils for reuse; and provided geotechnical parameters for input into cut slope stability analysis. Soil infiltration (soakaway) testing was preformed within a representative number of trial pits at turbine base and at the substation locations to help infer in-situ soil permeability values.

Table 5. Example of Site Investigation Procedure

Works	Method	Depth (m, approx)	Frequency
Project Feasibility Stage			
Peat Assessment	Peat probing	up to 5m	100m² grid intervals
Project Development Stage			
Peat Assessment	Peat probing	up to 5m	At 25m intervals along both the centerline and offset 10m either line from access tracks
	Peat probing	up to 5m	10m intervals within crane hardstand areas including turbine base footprint
	Shear vane	0.25m depth intervals for full depth of peat strata	200m² grid intervals
	Von-Post	full depth of peat strata	200m² grid intervals
Review of turbine base and cranehardstand locations	Cable percussive borehole	up to 10m	3 per foundation base
	Rotary core borehole	3-to-5m of core (with total core recovery greater than say 80%)	3 per foundation base
	Dynamic cone penetration	1-to-3m	4-to-6 per crane hardstand
	Trial pits	up to 5m	3 per hardstand/foundation base footprint Note that, soil infiltration testing should be carried out within a representative number of turbine base trial pits
Review of access tracks	Trial pits	up to 5m	200m intervals (including at each junction location and/or at every change in road direction)
	Dynamic cone penetration	1-to-3m	50m intervals along centerline of access track
Review of substation location	Trial pits	up to 5m	2 per foundation footprint
	Soakaway test	1-to-3m	1 per foundation footprint
Review of met mast location	Cable percussive borehole	up to 10m	1 per foundation

Note: specimens should be taken for laboratory testing at regular agreed intervals across the site.

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Geotechnical boreholes sunk at the centre of each consented turbine base location coupled with Multichannel Analysis of Surface Wave (i.e. P and S seismic wave determination) geophysical testing provided all pertinent geotechnical design parameters to aid the gravity base foundation design.

Summary and Conclusions

Geotechnical field and laboratory based procedures pertinent to the development of commercial on-shore wind farms in Ireland has been presented. The study highlights the application of conventional geotechnical field and laboratory based testing procedures in terms of the suitability of the test procedure for the soil type encountered and geotechnical design soil parameters derived. A comprehensive knowledge of the ground conditions and soil parameters prevailing across the development footprint are necessary to facilitate a site specific infrastructure and turbine foundation design; therefore, reducing associated construction risks and ensuring that an economic construction programme can be premeditated.

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