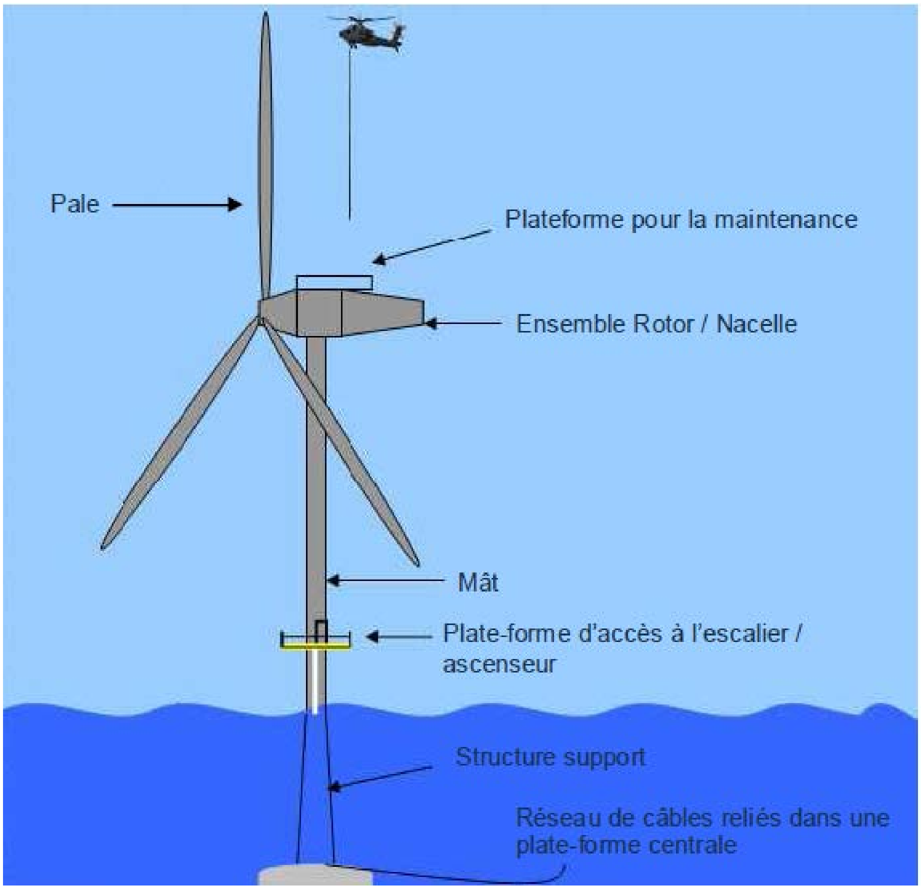
Comité Français de Mécanique des Sols et de Géotechnique

Association régie par la loi du 1.07.1901

Workgroup « Foundations of Offshore Wind Turbines »

# Recommendations for planning and designing foundations of Offshore Wind Turbines

# Part I – Field studies (temporary version)



# SUMMARY

# NOTATIONS

| | |
|---|---|
| **Bq** | Pore pressure ratio |
| **$G_{50}$** | Secant shear modulus at 50% of the ultimate strength |
| **Go or $G_{max}$** | Shear modulus at very small strains |
| **$K_0$** | Earth pressure coefficient at rest |
| **LL** | Liquid Limit |
| **LP** | Plastic Limit |
| **OCR** | Over Consolidation Ratio |
| **$q_c$** | Cone penetration resistance |
| **$q_t$** | Corrected cone resistance |
| **Rc** | Resistance to uniaxial compression (=UCS) |
| **$R_f$** | Friction ratio (cone penetration test) |
| **Vp** | Compression waves velocity |
| **Vs** | Shear waves velocity |
| **$\delta_r$** | Residual interface angle |
| **$\varepsilon_{50}$** | Axial strain of a sample at 50% of ultimate strength (triaxial test) |
| **$\varphi'$** | Effective friction angle |
| **$\varphi'_{car}$** | Phase transition angle |
| **$\varphi'_{cv}$** | Friction angle at critical state (constant volume) |

# ACRONYMS

| | |
|---|---|
| **ASTM** | American Society for Testing and Materials |
| **BRGM** | Bureau de Recherches Géologiques et Minières (Geological & Mining Research Bureau) |
| **BS** | British Standards |
| **CIRIA** | Construction Industry Research and Information Association |
| **Ifremer** | Institut Français de Recherche pour l’Exploitation de la Mer (French Research Institute for Exploitation of the Sea) |
| **ISO** | International Organisation for Standardization |
| **ISSMGE** | International Society for Soil Mechanics and Geotechnical Engineering |
| **NF** | Norme Française (French Standard ) |
| **SHOM** | Service Hydrographique et Océanologique de la Marine (Naval Hydrographic and Ocea-nographic Service) |
| **CAD** | Anisotropically consolidated, drained |
| **CAU** | Anisotropically consolidated, undrained |
| **CID** | Isotropically consolidated, drained |
| **CIU** | Isotropically consolidated, undrained |
| **CPT** | Cone Penetration Test |
| **CPTU** | Cone Penetration Test with pore pressure measurement |
| **CSS** | Cyclic direct Simple Shear |
| **DSS** | Direct Simple Shear |
| **DTS** | Desk Top Study |
| **FEED** | Front End Engineering Design |
| **GIS** | Geographical Information System |
| **HPDT** | High Pressure Dilatometer Test |
| **MASW** | Multichannel Analysis of Surface Waves |
| **MBES** | Multibeam Echo Sounder |
| **PMT** | Pressuremeter Test |
| **RQD** | Rock Quality Designation |
| **SSS** | Side Scan Sonar |
| **UHR** | Ultra High Resolution |
| **UU** | Unconsolidated, Undrained |
| **UXO** | UneXploded Ordnances |
| **VHR** | Very High Resolution |
| **VST** | Vane Shear Test |

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# FOREWORD

The « Recommendations for planning and designing foundations of offshore wind turbines», which are being developed under the aegis of the French Committee of Soils Mechanics (CFMS), deal with the geotechnical issues related to the planning and designing of the foundations of offshore wind turbines.

These recommendations aim to mitigate the absence of normative documents and official regulations regarding the design and construction of foundations for offshore structureswithin the French territorial waters.

The current document, called « Field Studies » is intended to constitute a chapter of the final document. Given the increasing pace of development of wind power off the French coasts, it has been developed as a priority. It is presented as a temporary version, which may be modified or improved before being published as a final document.

**Any comment regarding this preliminary version can be sent until June 30, 2016 to:**

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# FIELD STUDIES

## 1. INTRODUCTION

The properties of a soil below the installation site of wind turbines must be assessed using field studies complying with the applicable standards and regulations and according to the state of the art. As of today, no French official document does regulate the building of structures in offshore high seas. This document, and more particularly the present chapter, intends to specify the 'good practices' that shall be applied during field studies carried out to build offshore wind turbines.

Field studies must eventually provide all data required for a detailed dimensioning. They are usually divided into geological, geophysical and geotechnical studies. These studies will be carried out over various stages depending on the project needs and progress.

The scope of field reconnaissance and the choice of the methods to be implemented must take into account the type and size of the wind turbine structure, and must also be adapted to the anticipated geological conditions within the site (soil complexity, seabed conditions...). The surface that shall be covered by field investigations must cover the whole area of the wind farm and must take into account tolerances regarding the positioning and installation of the structures.

Offshore wind farms involve a large number of machines (tens to hundreds of units) as well as a wide surface area (tens to hundreds of $km^2$). The ground stratigraphy, the mechanical properties of materials and their lateral and vertical variability should be accurately determined at each foundation location. Furthermore, a solid knowledge of the mechanical properties of shallow sediments is required over the cable routes, between wind turbines and to the coast. The reconnaissance of landfall areas itself is not covered by the present document.

# 2. ELEMENTS TO BE PROVIDED TO THE GEOTECHNICAL ENGINEER

The data that the owner or the maître d'oeuvre shall make available to the geotechnical engineer are to a large extent depending on both the nature of the services required and the project stage. The elements to be provided must be defined for each operational stage.

The indications given below in this paragraph must be deemed as informative, and thus, as minimum.

Regardless of the nature of the contract (studies, reconnaissance services), the geotechnical engineer must be made aware of:

- the precise location of the project,
- the development state of the project (conceptual studies, pre-project, detailed project),
- the decisions previously taken and how they may evolve in terms of foundations type and installation,
- the history and results of the investigations already completed,
- the precise objectives of the geotechnical mission.

The geotechnical engineer assigned to the field reconnaissance operations must in addition have at disposal a complete overview of the site conditions, notably: bathymetry, seafloor morphology, expected geology, operational and extreme weather and sea conditions (waves, wind, current, tide).

The owner or maître d'oeuvre must share without any restriction its knowledge of geohazards and hazards caused by man (shipwrecks, cables, unexploded ordnances). In the event where unexploded ordnances would be present or suspected, the owner has the responsibility, and prior to any operations on the site, to take all necessary measures to establish the nature and level of the associated risks, as well as the appropriate preventive measures.

# 3. FIELD STUDIES OBJECTIVES

Field studies must provide the appropriate information regarding soils and rocks, up to a depth that will allow detecting the presence of weak formations, able to:

- impact the stability of the structure
- generate excessive deformations (settlements)

Field studies will usually include:

- studies of the geological context, at the scale of the site
- geophysical studies
- geotechnical studies

Geological studies must allow identifying major hazards and subsequent risks.

Geophysical studies essentially entail surveys from echosounder from side-scan sonar and from seismic reflection. The objective is to establish the bathymetry and the seafloor morphology, to define lithological units and tectonic structures, and to provide the data required to establish stratigraphic profiles. They will allow a spatial correlation with the one-off data from sampling and in-situ tests.

Geotechnical studies include geotechnical investigations and data interpretation. The geotechnical investigations include:

- reconnaissance from in-situ tests [for instance: cone penetration tests (CPT/CPTU), pressuremeter tests (PMT), dilatometer tests (HPDT)] as well as sampling followed by laboratory tests,
- data processing.

The objective of the geotechnical investigations is to obtain for each geotechnical formation the following data:

- Classification and description of the soils and rocks,
- Geotechnical parameters: shear strength and deformation properties, in-situ stress state (e.g. overconsolidation) relevant for the type of analysis planned.

The interpretation of the geotechnical parameters provided shall allow a detailed and complete dimensioning of the foundations. Lateral extend and variation of geotechnical units and geotechnical parameters are issues that should be answered.

It is of utmost importance that ground samples collected during the geotechnical reconnaissance and dedicated to laboratory testing be of a sufficient quality to allow producing the geotechnical parameters used for dimensioning.

The laboratory testing programme designed to determine the strength and deformation properties of the soil must entail tests that are adapted, and carried out in a sufficient number.

The effects of the cyclic loads generated by swell and wind on the geotechnical parameters must be taken into account throughout the dimensioning process of the foundations of offshore wind turbines.

There are several effects, and they notably concern:

- How shear strength and shear moduli may evolve due to the accumulation of loading cycles;
- How strengths and moduli may be modified in relation with loading rate.

These evolutions notably depend on how pore pressures may vary.

When combined, these effects may significantly impact the long-term response of foundations (cyclic movements, settlements, horizontal displacements). The evolution of the stiffness of the soil foundation system may affect the structure's natural period and resistance to fatigue. Specific tests are required to determine the cyclic behaviour of the soils and how the shear moduli vary with the distorsion rate.

Several steps are required to reach a sufficient level of knowledge regarding the geological and geotechnical conditions of the site (see Section 6.5). Each step must be concluded with the proposal of a ground model (see Section 6.4). While initially temporary and incomplete, this model will eventually help defining the content of the following stages and will be gradually supplemented until it becomes the final model. This final model is characterised by an accurate description of the geology over the whole site and provides geotechnical parameters profiles for the dimensioning of the foundations below each structure (wind turbine, sub-station, meteorological mast, cables).

## 3.1. ISSUES SPECIFIC TO THE FOUNDATIONS OF OFFSHORE WIND TURBINES

The main issues regarding the dimensioning of the foundations of offshore wind turbines are discussed in this section.

*Scour:* waves and currents may generate scour around the foundations (piles or gravity bases). Scouring is particularly hazardous if fine to medium sands are present, but assessing their magnitude is always difficult. Anti-scouring solutions may be necessary. Alternating tilt movements due to the waves may also generate "flushes" under the edges of the gravity bases, as well as generate erosion.

*Ultimate Capacity:* no matter what type of foundation is anticipated, the surrounding soil must be capable of bearing both the static and cyclic loads transmitted by the structure, with a sufficient safety margin regarding failure, and without any excessive displacement. For monopile or gravity foundations, loads are compressive ones. In the case of multipods or anchor foundations, loads may be tensile ones. The capacity under cyclic loading may differ from the capacity under monotonic loading. The capacity under cyclic loading must be considered carefully.

*Cyclical Degradation:* some types of soils (for instance: soft clays, sensitive clays, carbonated soils) may undergo a significant degradation of their mechanical properties due to cyclic loading. This phenomenon has consequences on the ultimate capacity and the displacement of foundations.

*Permanent Displacements:* static (permanent) loads result in initial displacements of the structure, that may be followed by further displacements over time generated by soil consolidation and creep effects. Cyclic loads due to wind and waves may also cause additional permanent displacements resulting from shear deformations and pore pressure dissipation generated by the repetition of loads in soils of low permeability. Vertical displacements or settlements must be anticipated if gravity foundations are considered. Permanent horizontal displacements are particularly critical in the case of monopile foundations as they result in permanent rotations.

*Cyclic Displacements:* cyclic loads generate cyclic and post-cyclic displacements of the foundation and of the structure. Some soils (soft or sensitive clays, loose granular materials, carbonated soils) may be particularly sensitive to these phenomena and consequently generate excessive settlements. The sum of these displacements (both permanent and cyclic) at the rotor level must remain lower than the tolerance limits associated to wear and fatigue risks.

*Cables Burial:* in the zones currently considered for the installation of offshore wind farms, protecting the cables will preferably require burial. There are several burial methods, such as ploughing, jetting, trenching. How efficient is each method entirely depends on the type of soils encountered over the burial depth required to protect the cable, or imposed by regulations. Within rocky materials, alternative protective methods may be considered, such as rock dumping or prefabricated elements. The type and features of the means to be used must be established for each application.

*Piles settlement:* the driving of metallic elements (essentially tubes) remains the most common solution used to install offshore piles. Driving large diameter monopiles (typically from 5 to 7m) is achievable. In stiff soils, it may be necessary to clear the pile plug or to drill pilot holes to assist driving. In rocky soils, drilling and grouting is a possible solution..

Specific studies are necessary to ensure: 1) that it is possible to drive the piles to the depth required to mobilise the design resistance, 2) that hammers will be appropriately selected and 3) that stresses generated by pile driving will not damage the pile elements. In stiff soils and soft rocks, particular attention should be given to risks of premature refusal, to potential damages on the pile tip in hard levels, and to potential pile collapse due to structural instability and steel fatigue generated by large numbers of blows. Preliminary tests for assuring pile driving feasibility may be required. These tests should be anticipated sufficiently early on the project schedule, either in the offshore site, or onshore on a site with proven similar geotechnical features.

*Sediments Mobility:* how the seafloor level may possibly evolve and affect the farm life cycle shall be determined by a hydro-sedimentary study, which will include potential dunes displacement, seabed erosion, accretion...

*Skirt Penetration:* it may be necessary to equip gravity bases with skirts either to ensure that foundations remain stable or to avoid phenomena such as peripheral scouring or erosion due to wash out under the base. The penetration of these elements has to be achievable down to the required level.

*Liquefaction Potential:* the risk of liquefaction (loss of mechanical resistance) of sands or silty sands, which results from cyclic loads, has to be assessed in seismic and/or strong swell zones.

*Seafloor Preparation Work:* seafloor preparation work may be required prior to installing the foundation. For instance, the seafloor may require rocks removal or ground levelling prior to installing the piles or burying the cables. In the case of gravity foundations, most of the times, it will be necessary to build an artificial flat platform by adding materials. In some cases, removing surficial sediments that are heterogeneous or of poor material properties should be considered. The stability of the added materials should be subject to a specific study.

*Foundations Stiffness:* foundations stiffness is an essential element when assessing the structure's natural frequency. Offshore wind turbines are particularly sensitive to resonance and fatigue issues. The structure's natural frequency and how it evolves over time due to cyclic loading (stiffness degradation) must be accurately assessed.

*Soil Reactions:* ground reactions under the base, due to monotonic and cyclic loads, must be accounted for in gravity base design. In the case of stiff soils, or soils with highly heterometric grain size, these reactions may be very strong.

*Overall Stability:* the overall stability of the soil units bearing the foundations has to be assured, notably in the case of submarine slopes and when foundations generate significant stress on large surfaces (e.g. gravity foundations). Specific slope stability studies may be required. They shall consider the various possible triggering issues (gravity, seismic acceleration, gas within sediments, etc.) and the effect of stresses induced by the structure.

# 3.1. Acquisition of the Parameters Required for the Dimensioning of the Foundations of Offshore Wind Turbines

## 3.2.1 Parameters Required for the Dimensioning of the Foundations of Offshore Wind Turbines

In order to answer the issues raised above, a number of information, both geological and geotechnical, should be gathered. Table 1 is a list of the basic parameters required to identify and classify soils and rocks encountered in the stratigraphic profile. The classification must be made in compliance with a recognized standard (ISO, BS, ASTM, AFNOR). Tables 2 and 3 specify the additional parameters required for specific issues, or for soil types that do not behave in a standard way, such as carbonated sands, soils of volcanic origin or chalk. These materials, sometimes called unconventional soils (ISO 19901-8), are present in both metropolitan and overseas French waters.

Table1: Parameters required for a standard characterisation of soils and rocks

| CLAY, SILT | SABLE, GRAVE | ROCHE |
|---|---|---|
| General Description<br>Lithography | General Description<br>Lithography | General Description<br>Lithography |
| Grain size distribution | Grain size distribution<br><br>Angularity | Presence of heterogeneous elements (blocks, flint, gypsum …)<br><br>Fracturation (RQD, opening and state of fractures, spacing, orientation)<br><br>Alteration |
| Water content<br>Total unit weight<br>Atterberg limits (LL and LP) | Minimum and maximum densities<br>Relative density | Total unit weight<br>Porosity, saturation<br>Weight of solid blocks |
| Organic matter content<br>Carbonate content | Organic matter content<br>Carbonate content | Carbonate content |
| Undrained shear strength<br>Drained shear strength<br>Residual and/or remoulded shear strength | Effective angle of friction (φ')<br>Undrained shear strength | Unconfined compressive strength (UCS) |
| Mineralogy | Mineralogy | Mineralogy |
| -------------------------------------<br>Stress history<br>------------------------------------- | -------------------------------------<br>Stress history<br>------------------------------------- | |

Table2: Additional parameters that could be required for specific issues

| ISSUE | PARAMETERS |
|---|---|
| **Ultimate Strength** | - Monotonic shear strength under various stress paths (strength anisotropy)<br>- Cyclic shear strength under various combinationsof average stress and cyclic amplitude for triaxial or simple shear stress paths<br>- Sand: Effective angle of friction (φ'), critical angle ($φ'_{cv}$), phase transition angle ($φ'_{car}$) |
| **Permanent Displacement** | - Compressibility<br>- Permeability<br>- Permanent strains and pore pressures generated under various combinations of average stress and cyclic amplitude for triaxial stress paths or simple shear<br>- Compressibility after cycles |
| **Cyclical Displacements** | - Cyclic shear strain versus cyclic shear stress for triaxial or simple shear stress paths<br>- Initial cyclical shear modulus |
| **Foundation Stiffness** | - Cyclic shear strain versus cyclic shear stress for triaxial or simple shear stress paths<br>- Shear modulus at very small distorsion ($G_o$ or $G_{max}$) and evolution with distorsion rate<br>- Damping |
| **Soil Reactions** | - Monotonic and cyclic shear strength<br>- Compressibility under virgin loading and reloading<br>- Permanent and cyclic strains and permanent pore pressures under various combinations of average stress and cyclic amplitude for triaxial or simple shear stress paths<br>- Seafloor topography and morphology, presence of anomalies on the seafloor |
| **Skirt Penetration** | - Undrained shear strength<br>- Remoulded shear strength (or sensitivity)<br>- Drained angle of friction (φ') - Sand<br>- Residual sand-steel or sand-concrete interface angle ($δ_r$)<br>- Cone resistance ($q_c$)<br>- Seafloor topography and morphology, presence of anomalies on the seafloor<br>- Presence of blocks in the soil |

| ISSUE | PARAMETERS |
| --- | --- |
| **Pile Installation** | - Shear strength<br>- Shear modulus ($G_{50}$) or strain at 50% of ultimate strength ($\varepsilon_{50}$) - clays<br>- Cone resistance ($q_c$)<br>- Unconfined compressive strength (UCS) - Rocks<br>- Abrasivity<br>- Clay sensitivity |
| **Liquefaction Potential** | - CPTU data ($q_c$ or $q_t$, $R_f$, Bq)<br>- Grain size and fines content<br>- Atterberg limits and water content<br>- Shear waves velocity (Vs) |
| **Scouring and Erosion** | - Grain size<br>- Permeability |
| **Cable Burial** | - Cone resistance ($q_c$) - Sands and clays<br>- Grain size and permeability – Sands<br>- Rock abrasivity<br>- Thermal conductivity<br>- Electrical resistivity<br>- Velocity of compression (Vp) and shear (Vs) waves |

Table3: Required additional parameters to characterise some non-standard soils and rocks

| TYPE OF SOIL | PARAMETERS | NOTES |
| --- | --- | --- |
| **Carbonated sands, with or without cementation** | - Compressibility (limit compressibility index)<br>- Crushability<br>- Cementation level<br>- Unconfined compressive strength if cementation | - Classification according to Clark and Walker based on three criteria: carbonate content, grain size, unconfined compressive strength<br>- See Argema: Practical guidelines for offshorestructures – “Piles in carbonated formations”. |
| **Soils of volcanic origin** | - Compressibility<br>- Others: case-by-case study | - High nature and behaviour variability<br>- Case-by-case study |
| **Clays** | - Accurate description of weathering levels<br>- Compressibility<br>- Creep<br>- Matrix permeability<br>- Soil mass permeability<br>- Water absorption | - Classification according to CIRIA (publication C574 – « Engineering in chalk ») based on density, alteration, fracturation state |
| **Organic Soils** | - Organic matter content<br>- Compressibility<br>- Creep<br>- Presence of gas | |

### 3.2.2 Relevance of the In-situ and Laboratory Methods Used to Acquire the Parameters

The relevance of the various in-situ or laboratory methods used to determine soils parameters is assessed in the following tables. There is a distinction between tests that are commonly used during usual investigations (Table 4) and specific tests that must be performed for particular applications (Table 5). A table is dedicated to tests on rocks (Table 6). The applicability level of each method is assessed over a 1 to 5 scale.

1 = weak or inappropriate

2 = acceptable for non-critical analyses

3 = moderately good

4 = good

5 = very good

Table4: Methods for usual investigations

| Soil Parameters | In-situ Tests | | | Laboratory Tests | | |
|---|---|---|---|---|---|---|
| | Type of Test | Applicability | | Type of Test | Applicability | |
| | | Sand | Clay | | Sand | Clay |
| Stratigraphy | Seismic reflection[(a)] | 2 to 3 | 2 to 3 | | | |
| Surface soils classification (seafloor) | Multibeam bathymetry<br>Side Scan Sonar (SSS) | 1<br>1 | 1<br>1 | Grain Size<br>Grain Size and fines content<br>Water content<br>Atterberg Limits | 5<br><br>2 | 2<br>4<br>3<br>5 |
| Sub-surface soils classification | CPT<br>CPTU | 2<br>4 to 5 | 2<br>4 to 5 | Grain Size<br>Grain Size and fines content<br>Water content<br>Atterberg Limits | 5<br><br>2 | 2<br>4<br>3<br>5 |
| Density in place | CPT, CPTU | 2 | 2 | Unit Weight measurement | | 4 |
| Undrained shear strength | CPT, CPTU<br>VST<br>PMT<br>Tbar, Ball probe | | 3 to 4<br>4 to 5<br>2 to 3<br>4 to 5 | Triaxial UU<br>Triaxial CIU<br>DSS<br>Fall cone, Torvane<br>Pocket penetrometer | 4 | 2 to 3<br>4<br>4<br>2<br>2 |

| Soil Parameters | In-situ Tests | | | Laboratory Tests | | |
|---|---|---|---|---|---|---|
| | Type of Test | Applicability | | Type of Test | Applicability | |
| | | Sand | Clay | | Sand | Clay |
| Effective angle of friction | CPT, CPTU | 2 to 3 | 1 | Triaxial CIU, CID*<br>Shear box | 5(b)<br>4 | 5<br>1 |
| Sensitivity | CPT, CPTU<br>VST<br>Tbar, ball probe | | 2<br>3 to 4<br>4 to 5(c) | Fall cone, lab vane<br>Triaxial UU on intact and remoulded materials | | 3 to 4<br>3 to 4 |
| Deformability ($G_{50}$, $E_{50}$) | PMT | 3 to 4 | 4 to 5 | Triaxial CIU, CID<br>DSS | 3 to 4<br>3 to 4 | 4<br>4 |
| Consolidation properties | CPTU | 1 | 3 | Oedometer | 3(b) | 5 |
| Permeability | CPTU | | 3 | Oedometer<br>Permeameter | <br>4 | 3<br>4 |

(a) needs to be a multichannel one when water height is lower or equal to the target penetration (need to erase the multiple)

(b) subject to the knowledge of the density in place

(c) only if cyclic tests are made

Table 5: Methods for specific applications

| Soil Parameters | In-situ Tests | | | Laboratory Tests | | |
|---|---|---|---|---|---|---|
| | Type of Test | Applicability | | Type of test | Applicability | |
| | | Sand | Clay | | Sand | Clay |
| Soil units interpolation | Seismic refraction<br>Electrical resistivity | 3 to 4[(a)]<br>1 to 3[(b)] | 3 to 4[(a)]<br>1 to 3[(b)] | | | |
| Identification of carbonated soils | CPT, CPTU | 4[(c)] | 3 | Carbonate content | 5 | 5 |
| Compressibility of carbonated sands | | | | Oedometer<br>Crushability | 4<br>3 | |
| Strength aniso-tropy of clays | | | | Triaxial CAUc, CAUe et DSS | | 5 |
| Cyclic response and mode of loading effect | | | | Triaxial CIU/CAU (static/cyclical) DSS/CSS | 5 | 5 |
| Thixotropy | | | | Thixotropy test | | 4 |
| Interface behaviour (piles, caissons) | | | | Ring shear (soil/soil and soil/steel)<br>Shear box(soil/soil and soil/steel) | 3 to 4<br>3 to 4 | 3 to 4 |
| Initial shear modulus $G_{max}$ | Seismic cone<br>MASW | 4 to 5<br>3 to 4 | 4 to 5<br>3 to 4 | Resonant column<br>Bender elements on Triaxial, DSS or oedometer | 4 to 5<br>4 to 5 | 4 to 5<br>4 to 5 |
| Corrosion Po- | Electrical resis- | 4 | 4 | Electrical resistivity | 4 | 4 |

| Soil Parameters | In-situ Tests | | | Laboratory Tests | | |
|---|---|---|---|---|---|---|
| | Type of Test | Applicability | | Type of test | Applicability | |
| | | Sand | Clay | | Sand | Clay |
| tential | tivity cone | | | | | |
| Liquefaction Potential | CPT, CPTU | 3to 4 | | Cyclic triaxial | 3 to 4[(d)] | |

(a) subject to a good calibration on in-situ tests (CPT) or on samples

(b) poor definition of interfaces; an extensive calibration on in-situ tests (CPT) or on samples is required

(c) CPT data is highly sensitive to the level of cementation

(d) subject to a sound knowledge of the density in situ

Table 6: Specific methods for investigations in rocks

| Soil Parameters | In-situ Tests | | Laboratory Tests | |
|---|---|---|---|---|
| | **Type of Test** | **Applicability** | **Type of Test** | **Applicability** |
| Stratigraphy | Videologging<br>Neutron<br>Gamma-ray | 3 to 5<br>3 to 4<br>3 to 4 | | |
| Fracturation (frequency and orientation) | Videologging<br>Eastman Camera | 3 to 4<br>4 to 5 | | |
| Density in place | Gammagraphy (gamma-gamma) | 3 to 4 | Density measure-ment | 4 to 5 |
| Strength | | | Unconfined com-pressive strength test<br>Brazilian test-<br>Franklin test | 4<br>4<br>1 or 3[(a)] |
| Stress-Strain relationships ($G_{50}$, $E_{50}$) | HPDT | 3 to 5 | Unconfined com-pressive strength test with strain gauges | 3 to 5 |
| Initial shear modulus $G_{max}$ | Seismic logging (Vp; Vs)<br>MASW | 4 to 5<br>3 to 5 | Vp and Vs measurements on cores | 3 to 4 |

(a) subject to a correlation with the unconfined compressive strength

# 4. SITE GEOLOGICAL MODEL

The large size of an offshore wind farm development (tens to hundreds of km²) coupled with the low density of foundations (on average: one structure per km²) requires designing an adequate reconnaissance strategy. It is both about obtaining a complete assessment of the stratigraphic and tectonic structures on the whole site, and determining the geotechnical parameters required for the dimensioning of the foundations of each of the wind turbines.

It is therefore necessary to develop the knowledge of geological and geotechnical conditions on both the scale of the site and the scale of the foundations. One way to reconcile both scales of knowledge is to build a geotechnical and geological model that can evolve over time. As the project progresses, the model will gather and synthesize all available information about the site.

The main objective is to eventually define geotechnical profiles of calculation. For that matter, and during the various stages of studies, one shall define:

- Firstly, geological provinces whose features (lithology, stratigraphy) may be considered as homogeneous,
- Secondly, geotechnical provinces characterised by similar features regarding the nature of soils, layer thicknesses and geotechnical hazards.

Each step of the model helps improving the schedule, nature and content of the reconnaissance campaigns by integrating the knowledge previously acquired.

The model embeds the various geological hazards that may impact the choice of the type of foundations, the dimensioning of the latter, or the construction process. Geological hazards to be taken into account are listed in the Section 5.2.

The hazards that may impact the project must be subject to specific studies. Some studies may require fields of expertise that are outside the scope of the present document.

Geological information systems (GIS) may represent efficient tools to manage data and build the geological and geotechnical model.

The main stages of the building process are described below. Each of them constitutes an improved version in regard to the previous one.

**Stage 1: Initial geological model**

The first version of the model is achieved by studying documents (bibliography, bathymetric maps, local or regional geological maps, geotechnical studies of the same area or of an adjacent one...), as detailed in Section 5.2. The quality and accuracy of this first model may highly vary depending on whether the area of interest has been previously studied or researched scientifically. It should usually allow establishing the following elements:

- General stratigraphy and lithology of the main geological formations
- Tectonic elements
- Main geological hazards and constraints

**Stage 2: Stratigraphic model (or sismo-stratigraphic)**

The second phase of the model is elaborated from preliminary reconnaissance (geophysical in particular) carried out over the whole field (Section 5.3, Table 8). Bathymetric data is used to establish a digital ground model, while data from seismic reflection is used to define the geometry of the main stratigraphic units. At this point, the transformation of seismic waves propagation is most often based on hypotheses on propagation velocities within the various layers. Thus, defining the geometry of stratigraphic units remains a rather inaccurate process.

If, at this stage, boreholes data can be obtained, the information acquired from them must be taken into account to enhance and calibrate geophysical data.

The stratigraphic model allows defining areas of similar nature and seismic features, which will provide directions for the preliminary geotechnical reconnaissance.

**Stage 3: Site geological model**

The site geological model is formed by integrating the results from the preliminary geotechnical reconnaissance (Section 5.3, Table 9) into the previous sismo-stratigraphic model. Preliminary geotechnical data will allow:

- Improving the velocity model and therefore enhancing layers geometry as well as their lateral thickness variability,
- Improving the lithological characterisation of layers,
- Assigning preliminary geotechnical parameters to these layers,
- Putting forward a draft of the geotechnical provinces.

**Stage 4: Geotechnical model**

At this point, data collected from the detailed reconnaissance (Section 5.4, Tables 10 and 11) are integrated within the model. Integrating the geotechnical data within the geological model of the site must allow defining with more accuracy the geotechnical provinces proposed previously.

This task may lead to defining geotechnical units separate from the sismo-stratigraphic units that were previously defined, for the following reasons:

- Several sismo-stratigraphic units may disclose similar geotechnical parameters,
- Conversely, some sismo-stratigraphic units may show internal variations that require defining several geotechnical units within them,
- At last, some phenomena that cannot be detected by using indirect geophysical methods (weathering in particular) may affect entirely or partially some sismo-stratigraphic units.

Geotechnical provinces allow proposing one or several geotechnical profiles of calculation, featuring similar layer thicknesses and homogeneous mechanical properties.

Each geotechnical profile shall define:

- Soils classification and description
- Shear strength and deformation properties that will be required for the planned type of analysis,
- The state of stress in-situ (OCR and $K_0$, anisotropy …)
- Geotechnical parameters offering a response to offshore wind turbines specificities (cyclic loading, fatigue …)

The geotechnical parameters that are gathered must meet the needs for a complete and detailed dimensioning of the foundations. Assessing their variability is an essential issue.

# 5. RECOMMENDED RECONNAISSANCE

## 5.1. STUDIES SCHEDULE

The objective of soils investigations (geological studies, geotechnical and geophysical reconnaissance) is to reach a level of knowledge as thorough as possible, in order to:

- build a geological and geotechnical model of the site (Section 4).
- define the type(s) of foundations that will be best suited to the established geotechnical profiles and to the project needs.

In reference to international practices, developing an offshore wind farm entails 3 main stages:

- a **preliminary stage** aiming at establishing the technical and financial feasibility of the project;
- a **project stage**, strictly speaking, which covers all steps related to designing and building the structures;
- an **operation stage** in which the client, or project operator, shall inspect and maintain the structures.

Table 7 shows a synthesis of the various stages required to develop an offshore wind farm.

i. PRELIMINARY STAGE

The French current context of public procurement implies a two steps sequence within the preliminary stage:

- the first step, called **pre-project**, follows a public tender: the tenderer is led to preselect a type of structure and its associated foundation, to perform a pre-dimensioning and to estimate a cost. The relevance of the choices made during this step and the representativeness of the estimated costs are to a large extent dependent on the representativeness of the initial geological model available at this point. It is the duty of the tenderer to define the risks associated with its bid and to decide if investing in reconnaissance operations could reduce these risks. The present document does not recommend whether performing site investigations or not is needed during this step.
- the second step, called **conceptual design** or **tender confirmation,** lasts for a duration of 1 to 2 years after the concession is awarded. In this step, the validity of the selected

technical options must be proven and financial assessments must be precised. In particular, all major geological hazards must be identified. This stage must include a significant volume of geotechnical and geophysical reconnaissance. Results from these investigations will feed the geological and seismostratigraphic models of the site. The nature and scope of the preliminary reconnaissance to be achieved during this step are both developed below, and summarised in the Section 5.3 (Tables 8 and 9).

ii. PROJECT STAGE

The project stage entails two steps: design and construction.

At the end of the project stage, the geotechnical parameters required for the final dimensioning and installation of the foundation system of each wind turbine must be gathered. The nature and scope of the reconnaissance will notably depend on the chosen type of foundationsand how heterogeneous each site is. This last criterion may be critical in the geological context of the French continental plateau.

The design stage will decide whether the final investment decision is taken or not. During this design stage, significant geotechnical hazards must be identified and the geotechnical model must be finalised. It will eventually include geotechnical profiles applicable at each wind turbine location, or by group of turbines.

During the project construction stage, additional reconnaissance may still be required to avoid minor or localised risks.

The programmes of the detailed reconnaissance to be carried out during the project stage are developed below and summarised in the Section 5.4 (Tables 10 and 11).

iii. OPERATION STAGE

During the operation stage, inspection and maintenance works must be performed by the owner to ensure the long-term stability and safety of the installations. For instance, campaigns to inspect the seafloor or additional reconnaissances may be considered to respond to specific issues, such as risks related to scouring.

It is also recommended to set up an information feedback regarding the structure's behaviour. This feedback will entail an operational monitoring of the structures and foundations, as well as an analysis of the data gathered.

Table7: Schedule of a development project for an offshore wind farm, and organisation of the geotechnical and geophysical studies and reconnaissance

| **Project Stages** | | | **Objective of the Project Stage**<br><br>**Assessment of Geotechnical Risks** | **Geological studies, geophysical and geotechnical reconnaissance to be carried out** |
|---|---|---|---|---|
| **Prelimi-nary** | *Con-ceptual design* | Pre-project | Pre-selection of the structures and foundations types<br>Financial and technical assessment of the project | Compulsory geological (bibliographical) study (DTS)<br><br>Constitution of the initial geological model |
| | | | | Optional geophysical and/or geotechnical reconnaissance |
| | | **Project draft** | Major risks assessment<br>Confirmation of tenders in the French context<br>Validation of the technical options<br>Validation of the financial assessment<br>Drawing up of the general building principles<br>Choice of the structures and foundations type<br>Structures settlement<br>Pre-dimensioning of foundations<br>Installation feasibility of foundations and cables | Compulsory preliminary geophysical and geotechnical reconnaissance.<br>Objective:<br>- Identification of the major geotechnical hazards<br>- Definition of the stratigraphy and lithology<br>- Constitution of the stratigraphic and geological site models<br>- Definition of the geotechnical parameters for the pre-dimensioning of foundations for each geological province<br>- Preliminary characterisation of cable routes and installation conditions |
| **Project** | *Basic design FEED* | **Design** | Significant risks assessment<br>Validation of the construction means, of costs and of schedule<br>Dimensioning for each group of wind turbines<br>Investment decision and switch to construction stage | Compulsory detailed geophysical and geotechnical reconnaissance<br>Objectives:<br>- Identification of the significant hazards<br>- Definition of the stratigraphic profiles and of the geotechnical parameters profiles for the dimensioning of the foundations<br>- Constitution of the geotechnical model<br>- Definition of the cable laying |

| Project Stages | | | Objective of the Project Stage<br><br>Assessment of Geotechnical Risks | Geological studies, geophysical and geotechnical reconnaissance to be carried out |
|---|---|---|---|---|
| | | | | and burial conditions<br><br>If necessary, feasibility tests regarding installation or burial |
| | *Detailed design* | **Detailed construction studies** | Minor or localised risks assessment<br>Detailed study of each wind turbine. Dimensioning for each foundation.<br>Burial predictions.<br>Detailed installation procedures for foundations and cables.<br>Remediation procedures | Additional specific reconnaissance(s) if required<br>Objectives:<br>- Identification of minor or localised hazards |
| | *Installation* | **Installation** | Installation follow-up | Implementation of monitoring |
| **Operation** | *Inspection*<br>*Maintenance* | Inspection<br>Maintenance | Ensuring the long-term stability and safety of the structures<br>Organising the feedback regarding the behaviour of structures | Scour monitoring (bathymetry)<br><br>Instrumentation set up and data analysis |

## 5.2. STUDIES ON EXISTING DOCUMENTS

This initial study, called Desktop Study (or DTS) entails gathering and processing all existing and accessible "bibliographical" data.

The full study must allow identifying the major hazards and the associated risks. It requests various skill sets and usually consists in assembling information dealing with all environmental site conditions:

- Bathymetric conditions (water depths)
- Meteo-oceanographic conditions
- Geotechnical and geophysical conditions
- Presence of man-made elements on the site: operational or disused cables or pipes, shipwrecks, unexploded ordnances (UXO) or other obstacles, either on the seafloor or buried
- Fishing activities
- Navigation traffic
- Leisure boating activities
- Existence of wildlife/protected reserves
- Prohibited areas (military, …)

The objective of the geological and geotechnical bibliographic study is to gather as much accessible information as possible, which could highlight major hazards due to soils or define a realistic choice for a foundation solution. Data sets can directly concern the site, or its proximity.

The conclusions of the study may become critical when assessing the technical feasibility of some types of foundations and the economic consequences on the overall project. In any case, they are essential to give directions to further stages.

Particular attention should be taken to characterise more specifically the risks arising from the following issues:

- Faulting networks and their activity
- Fractured zones
- Paleo- thalwegs
- Complex hydrogeological conditions, artesian groundwater
- Seismic hazards

- Liquefaction and cyclic mobility of sands
- Shallow gas
- Slopes stability
- Karsts, cavities
- Erosion
- Mobility of surface sediments, either of natural origins, or caused by the influence of structures, substructures and foundations
- Soils with specific behaviour (carbonate, volcanic, polluted...)
- Presence of large size elements (boulders, …) or of indurated zones that could prevent building the foundations
- Presence of soils that could evolve over the scale of the structures' life cycle

These information sets will be researched using documents and technical publications from specialised organisations: Ifremer, SHOM, BRGM, etc. as well as academic and private scientific archives. Experience shows that geophysical records can be accessed and somehow re-processed. In some cases, geotechnical data acquired on the site or close to it or from formations of a similar nature may prove useful and relevant.

This bibliographic stage will lead to the design of the initial geological model and will allow defining:

- the level of knowledge regarding the geological and geotechnical features on the whole site,
- the missing critical parameters (morphological, stratigraphic orgeotechnical) needed to achieve the following stages,
- the objectives and specifications of the preliminary geotechnical and geophysical reconnaissance to be carried out.

## 5.3. PRELIMINARY RECONNAISSANCE

After the preliminary development stage, major ground hazards must have been identified, the structures and foundations types must have been defined and the pre-dimensioning of foundations must allow realistic cost estimates.

These objectives require:

- A good understanding of the geological and geophysical features of the site,
- An assessment of the geotechnical characteristics of the materials, as well as their spatial variability.

Data gathered from the preliminary geotechnical campaign must be made available as soon as possible in order to take into account the potential geological heterogeneities and to accurately specify the objectives of the geotechnical campaign that will ensue.

Preliminary reconnaissance must allow a clear definition of both the geophysical and geotechnical means that are best suited to the characterisation of the soils encountered on the site and should be later utilised for further reconnaissance.

***Geophysical preliminary reconnaissance***

**The geophysical preliminary reconnaissance** on the whole development site of the offshore wind farm must allow:

- establishing the bathymetry and seafloor morphology,
- defining lithological units and tectonic structures,
- understanding the site geology,
- putting forward a seismostratigraphic model, down to at least the influence depth of the foundations,
- providing directions for the geotechnical reconnaissance, and more particularly so that data can be acquired on all geological provinces.

Usually, the means to be used are:

- multibeam echosounder
- side scan sonar
- seismic reflection
- magnetometry

The means to be used must also allow detecting man-made obstructions (unknown shipwrecks, cables, unexploded ordnances). In the case of UXOs, it must be precised that, if the detection of magnetic anomalies related to their presence may be performed during the geophysical campaign, specifying which data must be gathered and how it must be processed falls outside the competence of the geophysicist. Magnetometer surveys are indeed usually performed during campaigns that are separate from the geophysical campaign, so they may meet specific objectives requiring a dense grid map.

Equipments specifications and implementation are described in the document « Geotechnical and geophysical investigations for offshore and nearshore developments », published by the ISSMGE.

The **recommended programme of preliminary geophysical reconnaissance** is described in the Table 8.

Indicated quantities, which comply with the state of the art, are deemed necessary. However, they may be adjusted depending on:

- available information, such as information gathered during the bibliographic study (DTS),
- proven site complexity.

Particular care shall be given to the seismic reflection methods to be implemented when carrying out geophysical reconnaissance. The two following issues must be addressed in particular:

- the choice of the type of source: there are several types of seismic sources, such as electrical (Sparker), electro-mechanical (Boomer), electro-acoustic (Pinger) sources, Chirp. Each of them offers different signal frequencies and power. These parameters will impact the accuracy of results, as well as the penetration depth. The choice of the method must therefore be adapted to the penetration and accuracy objectives of the campaign. Furthermore, several sources are often tested at the beginning of the geophysical campaign in order to determine which one will provide the best results. Implementing jointly two systems during the same campaign may prove necessary to meet different penetration and resolution objectives (e.g. Pinger system with an objective of 5 or10 m of penetration and 0.2 m of resolution; and Sparker or Boomer system with an objective of 50 m of penetration and 0.5 m of resolution)
- Single-trace or multi-trace seismic reflection (UHR). Single-trace seismic reflection is severely limited in penetration because of the phenomenon of multiple reflections between water surface and seafloor. Seafloor multiples appear at a penetration equal to 1x water height, and it becomes very difficult to identify reflectors under this limit. Penetration objectives to be reached when developing offshore wind farms being usually be-

tween 50 and 100 m, with water depths between 15 and 40 m, single-trace seismic reflection cannot allow reaching the required penetration with enough accuracy. A multi-trace seismic reflection method must usually be implemented for this type of project, since multiples can be removed digitally.

The quality of geophysical recordings also depends on the implementation conditions of equipments and on the characteristics of the naval support. It is commonly admitted that boat speed must remain below 4 knots and that operations must not be carried out on seas where wind exceeds a force of 4 on the Beaufort scale.

Table 8: Recommended programme of preliminary geophysical reconnaissance

R: specific recommendation  T: tolerated

| Objective | Method | Grid | Penetration | Notes |
|---|---|---|---|---|
| **Seafloor topography** | Multibeam bathymetry (MBES) | Full field coverage with a 50% to 100% overlap<br><br>T: 20% overlap | NA | Processing of MBES data by backscattering is recommended<br>Single-trace echosounder to calibrate the MBES |
| **Seafloor morphology**<br><br>**Nature of surface sediments** | Side Scan Sonar (dual frequency) | Full field coverage with a 50% to 100% overlap | NA | R: collect samples to calibrate sediments nature: grab sampler (or gravity corer) |
| **Stratigraphy** | Single- or multi-trace seismic reflection<br>Source: boomer or sparker for significant penetrations;<br>R: to be complemented with pinger/chirp for shallow penetrations | 250 m x 1000 m (cross lines) grid | Typically:<br>50 -100m<br>depending on soil/rocks conditions<br>Resolution:<br>< 1m in depth<br><br>Pinger/chirp: Resolution < 0.3m | Full field coverage<br><br>Surface seismic reflection required on all cables routes (see Chap. 6.4.5) |

***Preliminary geotechnical reconnaissance***

**Preliminary geotechnical reconnaissance** must allow establishing on the whole wind farm site a typical geotechnical profile for each geological province that was highlighted during the interpretation of geophysical data:

- stratigraphy,
- nature of soils and identification,
- basic geotechnical features: mechanical strength, deformability, stress history.

These objectives can be met by performing:

- boreholes with the acquisition of intact samples followed by laboratory tests,
- in-situ tests,
- a mix of both.

The recommended programme of preliminary geotechnical reconnaissance is described in Table 9.

Naval and reconnaissance means must meet the proposed objectives.

Equipment specifications, implementation and quality requirements are described in the documents « Geotechnical and geophysical reconnaissance for offshore and nearshore developments » from the ISSMGE, which was previously mentioned, and the ISO/DIS 19901-8 « Petroleum and natural gas industries - Specific requirements for offshore structures - Part 8: Marine soil investigations »

The campaign must be designed so that it can provide the capital elements to:

- Feed the site geological model. For that matter, boreholes penetration must be sufficient to cross all main formations and understand their configuration on the scale of the site. Depths have to be defined by the geotechnical engineer according to the local context. Typically, penetrations from 30 to 50 meters, or even deeper for some boreholes and with specific configurations, are to be considered in connection with results from geophysical data.
- Provide the geotechnical parameters required for a pre-dimensioning of the foundations considered for each geological province. It is highly recommended to mix in-situ tests and sampling. The geotechnical parameters profiles are to be established over the influence height of the foundations.
- Assess the variability of geotechnical data on the whole site.

When the number of geological provinces is low, performing twin boreholes may prove worthwhile at this step if soil conditions are favourable. Twin boreholes means boreholes with continuous coring and boreholes with continuous CPTs performed at a few metersfrom each other. This method, introduced for offshore oil and gas works (for instance, see Borel and Puech, 2010) allows a good correlation of geotechnical data, and later the extrapolation of data based on CPTs alone, faster and cheaper to perform.

In the case of highly heterogeneous sites, it may prove more relevant during the preliminary reconnaissance to multiply boreholes so that the main geological provinces are covered, by alternating sampling and in-situ tests within a same borehole.

Current international practices show that performing a number of boreholes of about 10% of the number of wind turbines to be installed allows meeting the objectives set on most of the sites. However, this percentage shall not be deemed as a restrictive, but rather as indicative, since the volume of investigations to be performed may vary in function of how heterogeneous the site is. In the case of a high number of geological provinces, the required number of boreholes may be significantly higher. It is recommended to allow for sufficient flexibility in the reconnaissance contract to adapt the final programme to the site's complexity, as revealed by the first boreholes.

In any case, the expertise of the geotechnical engineer must be utilised and integrated to improve the reconnaissance programme.

Table 9: Recommended programme of preliminary geotechnical reconnaissance

| Objective | Method | Programme | Penetration | Notes |
|---|---|---|---|---|
| • Stratigraphy<br>• Nature of soils and identification<br>• Basic geotechnical properties<br>• Typical geotechnical profile for each geological province<br>• Assessment of the geotechnical properties of materials and their spatial variability | Coring<br>+<br>Boreholes with in-situ tests, such as CPTU,<br>PMT or HPDT<br>and/or with<br>well logging<br>(natural radioactivity,<br>Vp, Vs, imaging) | Achievement of twin boreholes*:<br>- 1borehole with continuous coring/sampling<br>- 1 borehole with in-situ tests<br>At least a couple of boreholes for each geological province<br>AND/OR<br>Single boreholes such as:<br>- Alternated borehole** CPTU/coring/sampling<br>- borehole with CPTU as continuous as possible if relevant<br>- borehole with continuous coring/sampling and well logging<br>To be distributed on the whole field to establish the spatial variability of the site | Sufficient to:<br>1- cross the main formations and understand their configuration at the scale of the site<br>2- establish profiles of geotechnical parameters over the height of the influence of foundations | * Prioritise twin-boreholes if relevant and low number of provinces<br>** Alternated boreholes may prove financially attractive in the preliminary stage |

## 5.4. DETAILED RECONNAISSANCE

The project stage entails two steps:

- the design step, which must allow characterising the major hazards, and after which the geotechnical parameters must be known with enough accuracy to proceed to the dimensioning, individually or by group, of the wind turbines. Validating the construction means, costs and schedule must be made possible,
- the construction step during which construction studies will be carried out.

Detailed reconnaissance aim at meeting all the needs of the project stage. A single detailed geophysical reconnaissance and a single detailed geotechnical reconnaissance will most often meet the objectives. However, additional reconnaissance may prove necessary during the achievement stage to remove uncertainties raised from minor or localised risks.

***Detailed geophysical reconnaissance***

The detailed geophysical reconnaissance aims at completing the geophysical reconnaissance previously achieved during the project draft stage. The campaign objectives are the following:

- Provide more accurate data (bathymetry, seafloor morphology, obstructions) about the structures locations,
- Complement the existing seismic reflection data below the structures, with specific objectives of penetration and resolution,
- Provide additional data using « geophysical engineering » methods (seismic refraction, surface waves, electrical resistivity). These methods will only be used if objectives demand it.

Table 10 indicates the type of recommended programme of detailed geophysical reconnaissance.

Table10: Recommended programme of detailed geophysical reconnaissance

T: tolerated

| Objective | Method | Grid | Penetration | Notes |
|---|---|---|---|---|
| **Seafloor topography** | Multibeam bathymetry (MBES) | Coverage of each structure location with overlap of 100% | NA | Size depends on the type of structure (wind turbines, meteorological mast, transformation substations and cables) |
| **Seafloor morphology**<br>**Surface obstructions** | Side Scan Sonar (dual frequency) | Coverage of each structure location with overlap of 100% | NA | Size depends on the type of structure (wind turbines, meteorological mast, transformation substations and cables) |
| **Stratigraphy** | Single- or multi-trace seismic reflection<br>Source:<br>-boomer or sparker for significant penetrations<br>-chirp for small shallow penetrations | Two perpendicular lines for each structure | Depending on the type of foundation and on specific objectives | |
| **Measurement of the velocity of compression waves Vp by seismic refraction** | Refraction (dragged on the seaflooror static) | On structures locations: to be defined according to objectives<br>Cable route: continuous profile | 5 to 20 m depending on objectives<br>5 m | |
| **Measurement of shear wave velocity Vs by surface waves** | MASW | On structures locations: to be defined according to objectives | 5 to 15 m depending on objectives | |

***Detailed Geotechnical Reconnaissance***

The final dimensioning of the foundations and the installation studies assume the definition of a profile of geotechnical parameters applicable below each wind turbine.

By principle, it is necessary during the **detailed geotechnical campaign** to carry out at least one representative borehole for each wind turbine location regardless of the considered type of foundation.

The number of representative boreholes may be exceptionally reduced if it can be demonstrated that the site, in whole or in part, is homogeneous enough to interpolate geotechnical data at some locations. This demonstration must be founded on a high quality geological model, a detailed risk assessment, and a thorough integration process of the geotechnical and geophysical data. Methods from geostatistics may prove useful.

On sites characterised by a strong geophysical and geotechnical heterogeneity, and in the event where gravity foundations are considered, it will be necessary to carry out at least three peripheral boreholes in addition to the deep « central » borehole, to ensure that subsurface soil conditions are homogeneous over a depth of at least 10 m or until refusal (CPT). If foundations equipped with skirts are considered, it will be necessary to ensure that the investigation depth equals at least the penetrationof the skirts, plus 2 metres.

For piled foundations, the influence height of the foundations is at least equal to the pile penetration (height of the shaft) increased by the influence zone of the tip. The latter is usually estimated at 3 diameters for piles of common diameters (< 2m). For monopods with piles of very wide diameter, where capacity is essentially ensured by friction, the influence zone under the pile may be limited to half of the pile diameter.

For gravity foundations, the influence zone related to the bearing capacity may be limited to the depth of the deepest failure line matching the characteristics (inclination) of the maximum applied load. The influence zone in regards to settlements may be significant in compressible soils and reach up to 1.5 times the foundation diameter. In any case, in the presence of a substratum, the influence zone may be limited to the depth of this substratum.

Table 11 indicates the type of recommended programme of detailed geotechnical reconnaissance

Table11: Recommended programme of detailed geotechnical reconnaissance

<table>
<tr><th>Objective</th><th>Method</th><th>Type of foundation</th><th>Programme</th><th>Penetration</th></tr>
<tr><td rowspan="5"><ul><li>Final dimensioning of foundations</li><li>Installation studies</li></ul></td><td rowspan="5">Coring/sampling boreholes<br><br>Boreholes with in-situ tests such as CPT/CPTU<br><br>Boreholes with in-situ deformation tests (PMT, HPDT)<br><br>Mixed boreholes with alternating coring/sampling and in-situ testing</td><td>PILED</td><td>1 borehole at the centre of each wind turbine location</td><td>Anticipated piles lengths + 3D minimum</td></tr>
<tr><td>MONOPILE</td><td>1 borehole at the centre of each location</td><td>Anticipated monopiles lengths + 0.5D minimum</td></tr>
<tr><td>GRAVITY BASE</td><td>1 borehole at the centre of each location<br>+<br>3 boreholes on the periphery **</td><td>1.5 x foundation width or penetration of at least 2m in the substratum<br><br>At least 10m penetration or until refusal (CPT)</td></tr>
<tr><td>SHALLOW WITH SKIRTS</td><td>1 borehole at the centre of each location<br>+<br>3 CPT boreholes on the periphery</td><td>1.5 x foundation width or penetration of at least 2m in the substratum<br><br>Skirts height + 2 m; min. 5m</td></tr>
<tr><td>ANCHORING</td><td>1 borehole at each anchor location</td><td>Depending on the anchor type and nature of soils</td></tr>
</table>

** in case of a strong geological or geotechnical heterogeneity

When foundations on piles are considered for soils where no proven dimensioning solution is available (for instance: carbonated or volcanic soils, chalks, soft rocks), it may be relevant to carry out one or several loading tests on one or several test piles beforehand. The test pile(s) will be installed using the method considered for the wind turbines foundations. Ideally, tests will be carried out on the same site as the one of the wind turbines. However, given the high cost of offshore tests, it may be relevant to carry out the tests on a land site showing similar features and at a reduced scale.

When pile driving in rocky or hard formations is considered, it may be relevant to carry out one or several feasibility tests beforehand, to make sure that driving the piles will be possible and to guarantee their structural integrity. Ideally, tests will be carried out on the same site as the one of the wind turbines. However, given the high cost of offshore tests, it may be appropriate to carry out the tests on a land site field showing similar features and a reduced scale.

In the case where tests are considered (onshore or offshore) at a lesser scale, scale effects must be taken into account. In geotechnics, scale effects arise from not respecting the stress conditions between the scale model and the actual foundation, and/or not respecting the relative size of soil elements in regards to the model's dimensions. The consequences are distortions on the stress and/or on the strain measured on the model that simply cannot be extrapolated to the actual foundation. In the case of field tests of lesser scale (onshore or offshore), the soil material for the scale model and for the foundation are deemed identical. One should ensure that the model dimensions are close enough to the ones of the foundation, in order that stress levels and the relative dimensions of the model are not too distorted so that a direct extrapolation of the observed phenomena and measured quantities is possible. For most of the issues considered, a scale reduction from 1/2 to 1/3 may be deemed acceptable. The pile must have geometrical (ratio of driving length/diameter) and structural (ratio of pile diameter/tube thickness) properties that are compatible with the nature of phenomena resulting from driving (plug formation, risks of structural instability).

## 5.5. CABLES ROUTES

Cables routes are spread out between wind turbines on the wind farm itself, and between the wind farm and the coast. Cables are most often buried (within the limits of technical/financial constraints) so that their protection is ensured, their stability is guaranteed and/or the seafloor remains free of obstructions. Burial depths will usually not exceed 2 metres, except, for instance, on vessel anchorage areas or in the influence zone of maintained channels.

Reconnaissance for cables routes will be carried out in two steps.

The first step aims at:

- providing directions for the orientation of cables corridors,
- assessing the risks incurred by the cables and define their protection level,
- defining the target depth of burial,
- determining the feasibility of the laying and buryingmeans.

This first step usually occurs during the Project Draft (Table 7). It is composed of a geophysical reconnaissance complemented by a light geotechnical reconnaissance.

***First Step Reconnaissance***

In principle, the **first step reconnaissance** should entail:

- bathymetric recordings and side scan sonar surveys on the entirety of the wind farm settlement and planned cables routes areas,
- sub-surface seismic surveys on a few standard lines, selected because of their particular interest (wind turbines alignment, planned cables route between the site and the coast, etc.).

The means to be implemented are, in nature, similar to the ones used for the preliminary geophysical reconnaissance on the site. A single preliminary geophysical campaign is usually carried out that must allow meeting the objectives set for the cables routes. However, seismic reflection means must be selected so that accuracy, rather than penetration, is prioritized for the first meters below seafloor.

Geophysical reconnaissance must be completed by a direct characterisation of the materials present on the first meters of seabed. Depth will range between 1 and 5 metres, with a common target depth of 3 metres. In addition to the information gathered during deep boreholes, the preliminary determination of the physical and mechanical properties of both surface and subsurface soils may be obtained by using light geotechnical tools, i.e. those that do not require significant naval means (or that can be achieved onboard the ship used for geophysical reconnaissance):

- Grab-sampler (limited to identifying surface soils)
- Gravity corer
- Vibrocorer
- CPT operated from a seabed frame
- Rotary corer operated from a seabed frame (in the case of a rocky seafloor)

Strictly speaking, the sampling frequency must depend on the lateral variability of sediments. At this point, the latter remains a priori unknown. It can be assumed that a statistical assessment of the properties of the soils concerned by cables burial may be approached by obtaining a few tens of boreholes. These boreholes must be adequately spread, either on the whole windfarm site and the assumed site to shore route if precise cables routes are not defined at this point, or more directly on the routes themselves if they have been pre-established. Determining the number of boreholes and their locations must be done on the basis of the geophysical recordings. Information gathered from the deep boreholes locations may be used, but will not necessarily provide relevant data over the first few meters.

Thermal conductivity measurements, which are usually required for the dimensioning of power cables, can complement the geotechnical reconnaissance. They may be carried out either in-situ or in laboratory on cores.

Table 12: Recommended programme of preliminary reconnaissance for cables routes

| Objective | Method | Grid | Penetration | Notes |
|---|---|---|---|---|
| **Seafloor Topography** | Depending onTable 8 | | | |
| **Seafloor Morphology**<br><br>**Nature of surface sediments** | Depending on Table 8 | | | |
| **Stratigraphy** | Depending on Table 8<br><br>Prioritize accuracy over penetration on the first 5 to 10 meters | | | |
| **Characterisation of the nature and strength of soils and rocks over the anticipated depth of cables burial** | Depending on context:<br><br>Gravity coring, vibrocoring, , CPT/CPTU rotary coring carried out from a seabed frame | Typically: 20 to 30 borehole locations for a 100km² site | Most often: 2 to 3 meters depending on the planned burial depth; exceptionally: up to 5 meters | Often carried out during the geotechnical preliminary reconnaissance |
| **Thermal Insulation** | Thermal conductivity measure: made in-situ by using a probe set by push penetration or on sampled cores | A few measures for each geological province | Most often: 2 to 3 meters depending on the planned burial depth | |

***Second Step Reconnaissance***

The **second step** aims at:

- enabling cables routing within corridors previously defined,
- confirming / specifying the burial target depths in function of the desired protection, as well as their variations along the route,
- determining the burial tools that are best suited to soils conditions (adequate method, type of tools and machines, required power),
- forecasting operational conditions (notably: rate of progress) and their variations along the cables route,

- identifying areas requiring specific processes (rock outcrop, obstruction to avoid, etc...).

This **second step** will occur during the design stage:

It is unavoidably composed of:

- a geophysical reconnaissance using high resolution seismic reflection on the cables corridors previously defined,
- a specific geotechnical reconnaissance along the defined cable route.

This step may possibly be followed by burial tests aiming at demonstrating if a particular method can be implemented, or at comparing the efficiency of several methods.

Routing will preferably be carried out prior to geotechnical reconnaissance, so that borehole locations are precisely localised on the planned route.

If an UXO constraint exists on the site, UXO reconnaissance could be (with reserves related to how valid it is over time) carried out prior to the routing, so that the number of magnetic anomalies to be identified can be optimised during routing.

**Geophysical reconnaissance** will include performing bathymetry and investigations using a high resolution side scan sonar. If required, they may be complemented by shallow seismic reflection and by the acquisition of "engineering geophysic" data (surface seismic refraction).

**Geotechnical reconnaissance** will include boreholes on the axis of the cables routes, using CPTs and/or coring boreholes (or vibrocoring), adequately alternated or twinned, so that a geotechnical profile can be obtained for each location on the first three meters of penetration. Boreholes frequency must be adapted to the conditions of the site. A spacing of 500 to 1000 m can be acceptable on sites deemed homogenous. On sites with complex subsurface geology, gathering information every 300 m may be relevant. Data collected, whether it is of a geotechnical or geophysical nature, must then be correlated in order to produce a ground model as continuous as possible along the route and over the burial depth.

Geophysical measurement systems using seismic refraction and dragged on the seafloor allow characterising soils in terms of compression waves velocities (Vp). Obtaining a continuous profile of velocities along the cables routes greatly facilitates the integration of data, and the constitution of the ground model. Implementing these methods is particularly recommended when soils conditions are deemed difficult regarding cables burial, notably when rocks or shallow hard layers are expected.

Particular attention should be given to the following:

- if conditions of hard soils are present at surface or close to the surface, geophysical methods based on seismic reflection will not allow defining soils conditions with a sufficient accuracy for the needs of a burial study,
- An irrelevant or insufficient reconnaissance will most often result in operational difficulties, loss of time and significant costs overruns during the burial works.

Table 13: Recommended programme of additional standard reconnaissance for the second step of cables routes

| Objective | Method | Grid | Penetration | Notes |
|---|---|---|---|---|
| **Seafloor Topography** | Multibeam bathymetry (MBES) | 200m corridor* centred on the cable axis, with a 50% to 100% overlap | NA | *Corridor width to be defined in function of the heterogeneity of the subsurface geology and of density of obstructions |
| **Seafloor Morphology**<br><br>**Nature of surface sediments if appropriate signal processing (backscattering )** | Side Scan Sonar | 200m corridor* centred on the cable axis, with a 100% overlap | NA | * Corridor width to be defined in function of the heterogeneity of the subsurface geology and of density of obstructions |
| **Stratigraphy** | HR seismic reflection Source: to be defined depending on geology (pinger /chirp) | One run on the cable axis and two runs at a 100m distance from each other. Even transversal cross-checks (about 300m to 500m) | Prioritize accuracy on the first 3 to 5 meters | |
| **Characterising continuously the soils conditions over the burial depth by using sound velocities (Vp, Vs)** | VHR seismic refraction implemented very close to the seafloor (system dragged on the seafloor or towed just above seabed)<br><br>Optional: mix seismic refraction and MASW measurements | One run on the cable axis | 3 to 5m | Seismic streamers will be of the short type (typically: 24m) with a minimum of 24 geophones spread so that they will collect as many information as possible on the first 2 to 3 meters |
| **Characterising punctually the nature and strength of soils and rocks over the foreseeable burial depth** | CPT/CPTU carried out from a seabed frame<br><br>Gravity coring, vibrocoring, rotary coring from underwater boreholes | One borehole every 300 to 1000 m depending on the complexity of the sub-surface's geological | Most often: 2 to 3 meters, depending on the planned burial depth Exceptionally: up to 5 meters | |

| | | | | |
|---|---|---|---|---|
| **Thermal insulation** | Thermal conductivity measurements: in-situ with a probe installed by push penetration or on samples | A few measurements for each geological province | Most often: 2 to 3 meters, depending on the planned burial depth | |

* if needed and not obtained during the preliminary stage

## 5.6. SUB-STATION

A network of submarine cables allows interconnecting turbines and carrying the whole production towards one (or several) sub-stations located within, or next to, the wind farm. The role of a sub-station is to centralise production and to recondition it so that it can be exported onshore by cable.

Sub-stations are relatively heavy structures (transformers) that are usually made of jackets founded on piles (driven or drilled).

Geophysical and geotechnical reconnaissance of soils for the installation of sub-stations may be combined with the various other campaigns (preliminary and detailed ones) achieved for the wind turbines. Tables 8 to 11 provide indications on that matter. The methodology and means to be implemented are identical.

Depending on the soils complexity at the sub-station location, defining the profile of soil parameters for the engineering of the stations foundations must be based at least on data sets acquired from an alternated borehole (in-situ tests and sampling with laboratory tests) or from two twinned boreholes: one with in-situ tests and the other with coring and laboratory tests.

## 5.7. METEOROLOGICAL MAST

Installing a meteorological mast on a wind farm site is common, but not mandatory. A meteorological mast is usually constituted of a light latticed structure.

The foundations of the meteorological mast are most often constituted of a monopile or of a latticed structure secured by piles. In the event where the meteorological mast would be installed very early in the development process of the wind farm, it may be used as a test bench for the future turbines foundations.

Planning for reconnaissance to be carried out for the installation of a meteorological mast is usually incompatible with the ones for turbines.

Most often, it will be necessary to schedule a specific geotechnical campaign targeting the area selected for the mast installation. This campaign will be similar to the preliminary geophysical campaign designed for wind turbines (see Section 5.3 andTable 8) and will include bathymetric recordings, surveys made using a side-scan sonar on an area of about 1 $km^2$, and seismic surveys of subsurface on a few lines crossing on the planned location of the support.

Furthermore, it should be ensured that at least one alternated geotechnical borehole is made at the mast location (in-situ tests and sampling with laboratory tests). The penetration of this borehole will depend on the planned type of foundation (see Section 5.4 and Table 11).

In the event where the meteorological mast would be installed during later stages, the corresponding reconnaissance could be integrated within the preliminary reconnaissance stage of wind turbines.

# LEXICON

## Crushability:

Sensitivity of soil grains to break under stress. This phenomenon is particularly significant in carbonate sands.

## Field Studies:

Field studies comprise all geological, geophysical and geotechnical studies. They include all operations carried out on the field or at the office that allow establishing geological and geotechnical models of the study area.

## Geological Hazard:

Geological event whose possible occurrence could generate unfavourable effects on the project objectives.

## Geological Province:

A part of the site characterised by the same sequence of geological units. The notion of geological province can evolve during the project, notably in function of the seismostratigraphic data.

## Geological Unit:

A soil or rock formation defined by its lithology and geological history.

## Geotechnical Engineer:

The geotechnical engineer is the physical person or legal entity in charge of performing geotechnical investigations or geotechnical engineering services.

## Geotechnical Profile:

A sequence of geotechnical units with defined thicknesses.

## Geotechnical Province:

A part of the site characterised by the same geotechnical profile, or several geotechnical profiles featuring the same sequence of geotechnical units.

## Geotechnical Unit:

A soil or rock formation defined by homogeneous geotechnical parameters: identification parameters, state parameters and mechanical parameters.

## Influence Height:

The influence height of a foundation is characterised by the depth under the surface beyond which the properties of encountered materials are no longer able to impact the behaviour of the foundation, in terms of both the bearing capacity and the displacements under cyclic or long-term loads (settlements due to consolidation and creep).

## Investigations:

Investigations include all operations made to collectand process data.

## Landfall:

Area where a submarine cable comes onshore.

## Major Geotechnical Risk:

Risk that can jeopardise the whole project.

## Minor Geotechnical Risk:

Risk that can justify adaptations during the achievement stage

## Reconnaissance:

All operations carried out on the site to collect geological, geophysical and geotechnical data sets on the rocks and soils, such as nature, composition, structure, spatial breakdown as well as physical, chemical, geo-mechanical and hydro-geological features. These operations can be intrusive (use of drilling and surveying equipment, geotechnical measurements and testing done both in-situ and in laboratory) or indirect (geophysical measurements)

## Representative Borehole:

A borehole can be considered to be representative in regards to a specific geotechnical issue if it can bring elements that meet the requirements in terms of depth and data content.

Note 1. The borehole must be deep enough to provide data on a height equalling at least the planned burial depth of a cable, the penetration of a skirt or the influence height of a foundation.

Note 2. Geotechnical parameters that have been collected must allow bringing probative elements in regards to the raised geotechnical problem. For instance, a simple drilling with parameters recording can be deemed representative for a cavity search, or similarly, a cone penetration test to assess the penetrability of a skirt. However, to be deemed as representative for a foundation study, a borehole must provide information with sufficient quantity and quality to allow establishing a profile of geotechnical parameters.

## Risk:

Unfavorable consequence of an uncertainty or hazard on the project objectives.

## Routing:

All studies allowing optimising the route of a submarine cable by taking into account the nature and topography of the seafloor, as well as obstructions or constraints both natural or man-made.

## Seismostratigraphic Unit:

A soil or rock formation defined from seismic reflection data, characterised by a seismic facies and de-limited by reflectors.

## Significant Geotechnical Risk:

Risk that can justify significant changes during the design stage.

## Stratigraphic Profile:

A sequence of stratigraphic units defined by their lithology and thickness.

## Substratum:

In this document, and taking into account the dimensions of the foundation and the loads applied to it, substratum means a formation whose mechanical characteristics do not allow failure lines to develop, and with a compressibility that is sufficiently low to be ignored during the settlement calculations of the foundation.

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