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Overview, standards and recommendations for the foundations of offshore wind turbines

Geotechnical consultancy report

August 2025

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LABORATÓRIO NACIONAL
DE ENGENHARIA CIVIL

TECHNICAL STUDIES OF OFFSHORE ENERGY POTENTIAL

Geotechnical Consultancy. First Report

Overview, standards and recommendations for the foundations of offshore wind turbines

REPORT 235/**2025 – DG/Chefia**
2nd revised version, August 2025

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IPMA – Instituto Português do Mar e da Atmosfera, I.P.

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R&D GEOTECHNICS

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Title

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Overview, standards and recommendations for the foundations of offshore wind turbines

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TECHNICAL STUDIES OF OFFSHORE ENERGY POTENTIAL

Geotechnical Consultancy. First Report

Abstract

This report is part of the geotechnical consultancy requested by the Instituto Português do Mar e da Atmosfera, I.P. (IPMA) from the Laboratório Nacional de Engenharia Civil, I.P. (LNEC), within the scope of studies aimed at developing offshore energy potential in the Leixões and Figueira da Foz areas, under the Recovery and Resilience Plan (process PRR RP-C21-i07.01). Given the anticipated installation depths exceeding 50 metres, the report focuses exclusively on floating foundation solutions.

The primary goal of this document is to identify and organize the essential technical aspects needed for the development of future project phases. In this context, we will highlight the relevant national and international technical standards for designing foundations for floating offshore wind structures. Additionally, we will outline the technical and methodological criteria that should be considered for geophysical, geological, and geotechnical survey campaigns.

The technical guidelines set out herein provide a reference framework that may also support future planning, design, and contracting procedures for offshore wind farms in Portuguese waters.

Keywords: Offshore wind structures / Technical standards / Floating foundation solutions

ESTUDOS TÉCNICOS DO POTENCIAL ENERGÉTICO OFFSHORE

Consultoria Geotécnica. Primeiro Relatório

Resumo

O presente relatório enquadra-se na consultoria geotécnica solicitada pelo Instituto Português do Mar e da Atmosfera, I. P. (IPMA) ao Laboratório Nacional de Engenharia Civil, I. P. (LNEC), no âmbito dos estudos para o aproveitamento do potencial energético offshore nas zonas de Leixões e da Figueira da Foz, inseridos no Plano de Recuperação e Resiliência (processo PRR RP-C21-i07.01). Atendendo às profundidades superiores a 50 metros previstas nas áreas de implantação, o relatório incide exclusivamente sobre soluções de fundação flutuante.

O principal objetivo deste documento consiste na identificação e sistematização dos aspetos técnicos fundamentais ao desenvolvimento das fases subsequentes de projeto. Neste contexto, são identificadas as normas técnicas nacionais e internacionais aplicáveis ao dimensionamento de fundações para estruturas eólicas offshore flutuantes, bem como definidos os critérios técnicos e metodológicos a considerar na execução das campanhas de prospeção geofísica, geológica e de caracterização geotécnica.

As orientações aqui apresentadas constituem uma base técnica de referência que poderá igualmente ser utilizada em fases de planeamento, conceção e contratação de futuros parques eólicos offshore em águas portuguesas.

Palavras-chave: Estruturas eólicas offshore / Normas técnicas / Soluções de fundação flutuantes

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1 | Introduction

The Instituto Português do Mar e da Atmosfera, I. P. (IPMA) requested the Laboratório Nacional de Engenharia Civil, I. P. (LNEC) to act as geotechnical consultant and to carry out laboratory tests within the scope of technical studies for offshore energy potential included in the Recovery and Resilience Plan (process PRR RP-C21-i07.01). These studies refer to the areas of Leixões and Figueira da Foz, which cover 644 km² and 1325 km², respectively.

Regarding the geotechnical consultancy component, the Work Plan includes the following activities:

a) Identification of applicable Portuguese and international standards.
b) Definition of the terms of reference for site investigation and geotechnical characterisation work (field and laboratory).
c) The preparation of an interim report with the results of tasks a) and b).
d) Validation of geotechnical data.
e) Processing of geotechnical data.
f) Integration of the geophysical, geological and geotechnical information into a geological-geotechnical model for each area.
g) Identification of complementary studies within the scope of future micro-siting.
h) Preparation of specific thematic cartography in a GIS environment and of a final report for each spatialized area.

This report is the interim report referred to in paragraph c) of the Work Plan. It aims to be used as a technical reference for the design process for all aspects of geotechnics, foundations and ground-structure interaction. It can also be used for other phases of the Portuguese Offshore Wind Farms development, such as planning and tendering by the Issuer.

Given that the anticipated installation depths in the Leixões and Figueira da Foz areas will exceed 50 meters, this report will focus solely on floating solutions.

The presentation of various standards reflects the differences in conditions or options prevailing in the areas or countries where offshore wind farm projects were developed.

Standards should not be seen as a rigid framework that restricts innovation or dictates specific design methodologies. Rather, they are tools that establish common design criteria and ensure a defined level of safety. The development of innovative solutions is encouraged if they meet or exceed the safety conditions specified in the standards. Technical specifications complement these standards by covering topics such as analysis and design methodologies.

1.1 Received data

The following documents were made available to LNEC by IPMA, prior to completing this report:

- Ocean Infinity (2024) **105634-IPMA-OI-COM-TEN-METHOD-RE01 Leixões and Figueira da Foz**.
- Instituto Hidrográfico (2025) **Hydrographic survey and seabed remote classification offshore Leixões**. Final technical report REL TF GM 02/2025. Marine Geology Division, Element GM14IH06.
- IPMA (2024) **Bathymetric data** (provided in GeoTIFF format).
- Project RP-C21-i07.01 (2025) **Technical studies for offshore energy potential. Environmental and geotechnical analysis**. Revision 3.

1.2 Report organisation

The report is organised into five chapters, systematically structured to present the main regulatory frameworks and technical principles related to the design of foundations for floating offshore wind structures.

Chapter 1 corresponds to this introduction, which defines the scope of the report, outlines its general objectives.

Chapter 2 provides a concise overview of the main foundation solutions applicable to offshore wind structures, covering both fixed and floating technologies. Although fixed foundations do not apply to the case under consideration due to the water depths involved, their inclusion supports the justification for adopting floating solutions in the present project.

Chapter 3 presents the applicable regulatory framework for foundation design, identifying the relevant technical standards, design principles, structural safety verification criteria, external environmental conditions, loads, and their respective combinations. This chapter also addresses the structural analysis methodologies and the geological and geotechnical characterisation of the seabed soils.

Chapter 4 gives a general guidance for the execution of geophysical and geological survey campaigns, and outlines the criteria for the geotechnical characterisation of the foundation soils, aimed at obtaining the necessary parameters for foundation design.

Finally, Chapter 5 presents the main conclusions and final remarks, summarising the most relevant aspects discussed throughout the report.

2 | Foundations solutions

The development of offshore wind farms requires foundation solutions specifically adapted to the oceanographic and geotechnical conditions of the installation site. Foundations can be categorised into fixed and floating types, each incorporating distinct anchoring systems, selected according to the characteristics of the seabed or the presence of rock. The selection of the most appropriate solution requires an integrated assessment of water depth, subsurface properties, and the loads transmitted by the wind turbine, as well as the environmental and logistical constraints of the location.

2.1 Fixed foundations

Fixed foundations encompass a variety of technical solutions with differing levels of structural and constructional complexity. Their use is generally limited to shallow or intermediate water depths, typically up to 60 meters, depending on the foundation type and site-specific conditions. Representative examples of these foundation systems are shown in Figure 2-1.

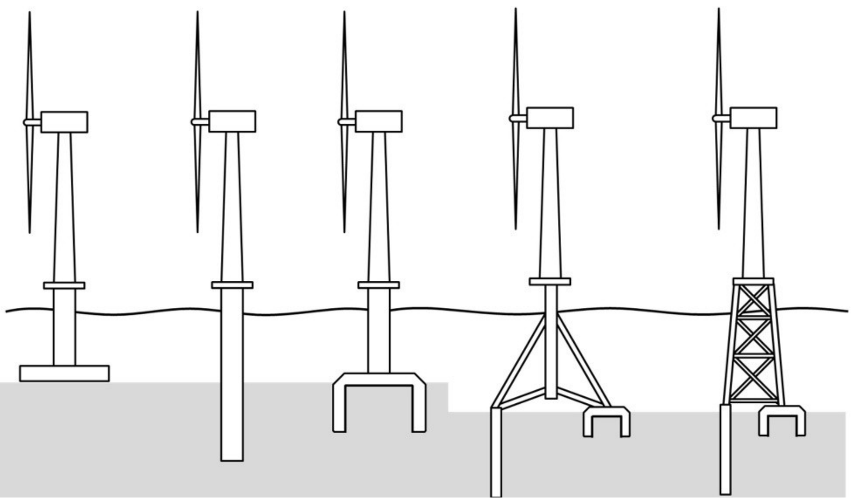

Figure 2-1 : Illustrative examples of fixed offshore wind foundations: from left to right, gravity-based, monopile, suction bucket, tripod and jacket (modified from Oh et al. (2018))

2.1.1 Gravity-based foundations

The gravity-based foundation relies on the principle of self-weight stability. These foundations typically consist of massive reinforced concrete structures placed directly on the seabed. Global stability is ensured by the dead weight of the structure, which must be calculated to resist sliding and overturning induced by environmental loads. Seabed preparation is a critical part of the process and usually involves the removal of soft or loose sediments and the placement of a levelling layer of gravel or rock fill to ensure a flat and stable bearing surface. Gravity-based foundations are prefabricated in dry docks and transported to the installation site by flotation or barge, then submerged and, where required, further stabilized with granular ballast. These systems are suitable for water depths of up to around 30 metres and are advantageous in sites where pile driving is impractical, such as in the presence of erratic boulders or shallow bedrock. However, local scour remains a significant design issue, often mitigated through protective measures such as geotextile mats or rock armouring.

2.1.2 Monopile foundations

The monopile foundation consists of a large-diameter tubular steel element, typically ranging from 4 to 9 metres in diameter, with a wall thickness between 50 and 150 mm. The installation is done vertically using impact or vibratory methods; however, in dense or partially gravelly soils, assisted drilling may be necessary. The structural behaviour of monopiles is governed by the mobilisation of lateral resistance along the shaft and end-bearing resistance at the pile tip. This configuration effectively transfers to the seabed vertical and horizontal loads, and overturning moments generated by wind, waves, and current actions. Monopiles are viewed as a cost-effective solution for water depths of up to approximately 30 meters. They are particularly suited for geotechnical conditions where soil profiles are predominant. Their applicability in deeper waters is constrained by increasing structural demands, and in rocky substrates, installation is often infeasible due to driving limitations.

2.1.3 Suction bucket foundations

The suction bucket foundation consists of an inverted cylindrical steel structure installed via suction-induced penetration. Once positioned on the seabed, negative pressure is generated within the bucket, creating a pressure differential that draws the structure into the soil. This method enables a quiet, rapid, and environmentally low-impact installation, avoiding the need for percussive or vibratory driving. Suction buckets are particularly effective in fine soils and dense granular materials and may be deployed as standalone foundations or as anchoring solutions for floating structures. Their use is generally feasible in water depths up to approximately 50 metres. One notable advantage is the reversibility of the installation: removal can be achieved by injecting water into the bucket to neutralise the differential pressure, thus facilitating environmentally responsible decommissioning.

2.1.4 Tripod foundations

The tripod foundation consists of a central transition component connected to three inclined tubular steel legs, each anchored to the seabed with driven or bored piles. This geometry provides enhanced lateral stiffness and favourable dynamic performance under environmental loading. Load transfer is achieved through a combination of axial (compression and tension) and lateral pile resistance, allowing for a well-distributed load path. Tripod foundations are particularly well-suited for intermediate depths, ranging from 20 to 50 metres, and for soil conditions with lateral variability or interbedded weak layers. Their performance under cyclical loading and adaptability to geotechnically complex sites make them a valuable option in many offshore environments.

2.1.5 Jacket foundations

The jacket foundation is a three-dimensional lattice steel structure, inspired by offshore oil and gas platforms. It comprises multiple welded tubular elements that form braces and nodes, providing high structural redundancy and excellent stress distribution. Jackets are anchored to the seabed via piles installed at the lower corners of the structure. This solution is appropriate for water depths typically between 30 and 60 metres, and under favourable conditions, can be extended to depths approaching 80 metres. The installation process commonly involves either pre-driving the piles followed by positioning the jacket or installing the jacket and driving the piles through sleeves. The main technical challenges associated with jackets include the complexity of fabrication, the need for high-precision welding, and fatigue verification of critical connections, given the cyclic nature of offshore loading.

2.2 Floating foundations

In deep-water conditions, where fixed foundations are no longer technically or economically viable, floating foundation systems are adopted. These systems ensure structural stability through hydrostatic equilibrium and are maintained in position by dedicated station-keeping arrangements. A typical floating foundation comprises three main components: a floating substructure, mooring lines, and anchoring systems. Representative examples of such configurations are provided in Figure 2-2.

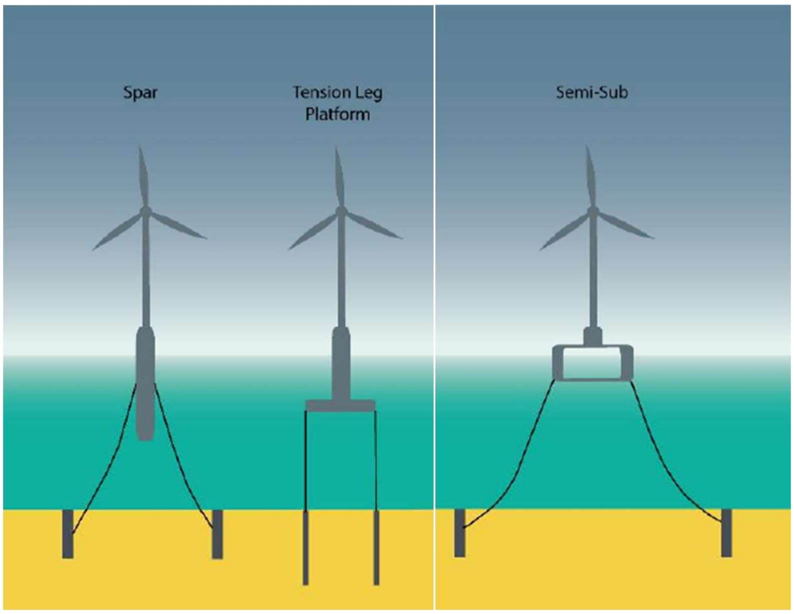

Figure 2-2 : Illustration of floating foundations (LR-RP-003:2024)

2.2.1 Spar-buoy platforms

Spar-buoy platforms are based on a long, vertically oriented cylindrical floater, with the centre of gravity located significantly below the centre of buoyancy, thereby providing inherent hydrostatic stability. This configuration is particularly well-suited to deep-water locations, typically in depths exceeding 100 metres, and is widely regarded as one of the most effective and robust solutions for installations beyond 200 metres. However, the substantial draft required for stability introduces logistical challenges, especially during transport and installation, such as the need for deep inshore waters or alternative vertical assembly methods offshore.

2.2.2 Tension leg platforms (TLP)

The Tension Leg Platform (TLP) is a floating foundation anchored to the seabed by vertically tensioned tendons, which are continuously kept under tension by the platform's buoyancy. This arrangement provides a system with very high vertical stiffness, resulting in dynamic behaviour that closely resembles that of fixed-bottom structures. The mooring and anchoring systems for TLPs must be capable of withstanding high tensile loads with limited displacements, and the associated foundations must ensure adequate axial capacity. TLPs are particularly suited for intermediate to deep water sites, generally ranging from 50 to 200 metres in depth, and offer the advantage of limited vertical motion, which benefits the dynamic stability of the wind turbine.

2.2.3 Semi-submersible platforms

Semi-submersible platforms consist of multiple buoyant columns interconnected by a truss or pontoon framework. Stability is achieved through buoyancy distribution across the submerged components and an anchoring system, commonly a catenary mooring layout. This foundation type is highly adaptable, with operational depths starting at approximately 50 metres, and is especially effective in intermediate to deep waters, typically between 60 and 150 metres, with no strict upper limit. Due to their modular design, semi-submersibles are compatible with a wide range of site conditions, facilitating tow-out and installation without requiring deep-draft facilities.

2.3 Anchoring systems for floating foundations on soil substrates

Anchoring systems are critical components of floating foundation platforms, ensuring station-keeping and stability under environmental loads such as wind, waves, and currents. The selection of an appropriate anchoring solution depends on various factors, including the seabed’s geotechnical properties, water depth, and the characteristics of the floating structure. This section presents an overview of the main types of anchors used in soil-based seabed.

2.3.1 Drag embedment anchors (DEAs)

Drag embedment anchors are designed to penetrate the seabed under horizontal loading. Their holding capacity increases progressively with embedment depth, making them effective in resisting lateral forces. Variants include wedge-shaped anchors for sandy soils and plate-type anchors for clays.

These anchors are attractive due to their low cost and simple installation. However, they are less suitable for scenarios requiring substantial vertical load resistance. Performance is highly dependent on seabed conditions: in soft soils, even deep penetration may not guarantee enough resistance mobilization. In compact or rocky soils, penetration can be inadequate.

DEAs are sensitive to load direction changes, which can degrade their performance over time. Despite this limitation, they are widely employed in offshore wind applications, particularly in competent soils when horizontal loads predominate.

2.3.2 Suction anchors

Suction anchors are cylindrical steel structures that penetrate the seabed by generating a differential pressure (suction) within the anchor. This installation method reduces environmental disturbance compared to pile driving.

Suction anchors effectively resist both horizontal and vertical loads, making them particularly suitable for taut-leg mooring systems. However, their effectiveness depends on the availability of a sufficiently thick fine soil layer, typically between 10 and 15 metres, to allow effective suction generation. Their use in rocky or highly heterogeneous formations is limited.

2.3.3 Driven piles

Driven piles are conventional anchoring elements commonly used in offshore applications. They are installed by impact driving, vibration, or assisted drilling and offer robust resistance to loads acting in multiple directions.

Driven piles are known for their high reliability. However, they require specialized equipment and tend to be more expensive, especially in deepwater environments. The feasibility of these systems largely depends on achieving sufficient embedment depth, which varies according to soil type: typically, 10 to 20 meters in fine soils and 5 to 10 meters in granular soils.

2.3.4 Vertical load anchors (VLAs)

VLAs are advanced drag anchors designed to manage both horizontal and vertical forces. They are deeply embedded and then rotated to a position perpendicular to the load, enhancing their efficiency and stability.

This type of anchor is particularly effective for taut-leg mooring systems, providing a high holding capacity relative to its weight. The required stiff soil stiffness generally ranges between 5 and 10 metres, depending on soil strength and anchor design.

2.4 Anchoring systems for floating foundations on rock substrates

When the seabed consists mainly of rock, conventional soil-penetrating anchoring systems become ineffective. Instead, specialized anchoring solutions are necessary to ensure reliable fixation and resistance to multidirectional environmental loads. This section outlines key technologies adapted to rocky substrates.

2.4.1 Drilled anchors

Drilled anchors involve boring into the rock to insert and secure the anchor using mechanical or chemical bonding techniques. These anchors are capable of resisting both horizontal and vertical loads and are highly effective in competent rock formations.

They are ideal for sites where vertical loads are substantial and where traditional anchors cannot achieve the required embedment. Generally, a rock thickness of 5 to 10 metres is required to ensure stability and performance, depending on the local geological conditions.

2.4.2 Rock expansion anchors

Rock expansion anchors consist of devices inserted into predrilled holes that expand to generate friction against the cavity walls. This expansion mechanism provides high resistance to both horizontal and vertical loads.

They are particularly advantageous in fractured or jointed rock formations where drilled anchors may not achieve full effectiveness. As with drilled anchors, a minimum competent rock thickness of 5 to 10 metres is typically necessary to ensure safe and efficient operation.

2.4.3 Driven piles in rock masses

Driven piles can also be applied in rock masses, particularly in weathered or fractured zones that permit penetration. These piles offer high resistance to environmental forces and are well suited to mooring applications requiring multidirectional load resistance.

Their effectiveness depends on rock properties and their ability to achieve adequate embedment depth. Typical penetration depths range from 10 to 20 meters in fractured rock, though installation in intact rock may require advanced techniques and greater effort.

3 | Standards and technical specifications for foundation of offshore wind turbines (FOWT)

3.1 Preliminary considerations

In the offshore wind sector, technical standards are developed by classification societies or by national or international consensus-based organisations such as IEC, ISO or API. Additionally, companies often develop their corporate standards, as is customary in the oil and gas (O&G) industry.

The variety of available standards reflects the differences in environmental conditions, regulatory frameworks, and technical approaches prevailing in the regions or countries where offshore wind farm projects are implemented.

Standards should not be regarded as rigid frameworks that constrain innovation or mandate specific design methodologies. Rather, they serve as instruments for establishing common design criteria and ensuring a clearly defined level of safety. The development of innovative solutions is encouraged, if they maintain safety levels equivalent to, or higher than, those stipulated in the standards. In this context, technical specifications complement standards by addressing topics such as detailed analysis and design methodologies, reflecting industry's best practices and recommended approaches.

As specified in section 2.4 of Ramboll (2021), a defined hierarchy must be observed when addressing conflicting requirements. Requirements from lower levels in this hierarchy only apply if they do not contradict those at higher levels. A possible structure of this hierarchy is outlined below:

1. National and regional laws
2. European standards
3. Project-specific requirements and specifications (e.g., design basis).
4. Owner's technical and professional requirements (e.g., for design, construction, transport and installation (T&I), operation, maintenance and decommissioning).
5. Codes and standards.
    a. Overruling status (e.g., IEC standards).
    b. Governing status (e.g., DNV standards).
    c. Mandatory status (i.e., "shall" requirements in ISO or API codes).
6. Industry best practices and recommendations.

In Portugal, there are no specific regulations for the foundations of floating offshore wind turbines (FOWTs) under the first three hierarchy levels, particularly regarding design, construction, installation, operation, maintenance, and decommissioning. As such, it is recommended that the development of project specifications for floating offshore wind structures should carefully address the following key topics:

- **General**: Information concerning the applicability of the selected standards to FOWTs and their station-keeping systems, as well as general requirements for the integrated wind turbine system mounted on the floating substructure.
- **Environmental and geotechnical conditions**: Requirements for relevant site data, including wind conditions (accounting for cyclones and hurricanes where applicable), wave effects (including extreme and breaking waves), water level variations, seismicity, ocean currents, ice conditions (where applicable), marine growth, and seabed geotechnical characteristics necessary for the design of floating offshore wind structures and their anchoring systems.
- **Safety level and safety concepts**: Definitions of the safety concept or philosophy underlying the standards, including the target reliability levels and the robustness criteria applied to structural and system designs. It also establishes the general safety level expected when designing in compliance with applicable standards.
- **Design methods and loads**: Comprehensive description of the methodologies adopted by the standards as the basis for formulating design requirements. This includes the identification and specification of design loads, load cases, and load combinations, including coupled aero-hydro-servo-elastic effects unique to floating wind systems.
- **Stability**: Provisions for the intact and damaged stability of floating wind turbine structures in compliance with applicable offshore floating standards. This encompasses static and dynamic stability assessments, wind heeling moments, restoring moments from buoyancy and mooring systems, and survivability analysis under extreme sea states.
- **Ultimate limit state (ULS)**: Requirements defining the necessary input data for ULS assessments, including design load cases (DLCs), analysis procedures, and safety factors applied to loads and materials. The ULS criteria aim to ensure structural integrity under extreme environmental conditions and accidental scenarios without unacceptable risk of failure.
- **Serviceability and Accidental Limit States (SLS and ALS)**: Requirements concerning the input data, load cases, and calculation methods for SLS (which ensures the structure’s operational performance without undue deformation or vibration) and ALS (which assesses the structure’s capacity to withstand accidental events such as mooring line failure or vessel collision). In this section, load and material safety factors applicable to these limit states shall be defined.
- **Fatigue limit state (FLS)**: Requirements addressing the assessment of fatigue damage caused by cyclic loading over the structure's operational lifetime. This includes the necessary input data (e.g., environmental scatter diagrams), calculation methodologies, fatigue design load cases (FDLCs), material S-N curves, and partial safety factors for fatigue assessment of critical components such as mooring lines, tendons, and welded joints.
- **Station-keeping systems and anchoring foundations**: Requirements for the design, analysis, and qualification of station-keeping systems, including catenary, taut-leg, and semi-

taut mooring configurations. The design must ensure adequate global performance, redundancy, and compliance with fatigue and ULS criteria. Furthermore, anchor foundations (such as drag anchors, suction caissons, and driven piles) must be designed to transfer loads from mooring lines or tendons to seabed soils or rock masses, following appropriate geotechnical design standards and site investigation data.

3.2 Recommended standards for floating offshore wind structures

It is recommended that the design, construction, operation, and decommissioning of floating offshore wind structures be guided by the consolidated body of standards issued by the following internationally reference organisations: the International Electrotechnical Commission (IEC), the American Bureau of Shipping (ABS), Bureau Veritas (BV), Det Norske Veritas (DNV), and Lloyd’s Register (LR).

The International Electrotechnical Commission (IEC) is the globally recognized standardization body for wind energy systems, including floating offshore wind technology. IEC TS 61400-3-2:2025 sets out the specific design requirements for floating systems. While the reference list in this specification is comparatively concise, it draws extensively on other IEC and ISO standards (Table 3-1). For aspects concerning design methodologies and station-keeping systems, it refers to American Petroleum Institute (API) Recommended Practices (RPs).

Table 3-1: List of specifications included in the IEC TS 61400-3-2:2025 framework (Ramboll; 2021)

Topic/ Issue	Specification/ Standard	Topic/ Issue	Specification/ Standard
General	IEC 61400-1 IEC 61400-3-1	Station-keeping system and anchor	API RP 2T ISO 19901-4 ISO 19901-7 ISO 19904-1
Environmental and soil conditions	API RP 2FPS IEC 61400-1 IEC 61400-3-1 ISO 19900 ISO 19901-1 ISO 19901-4 ISO 19904-1 ISO 19906	Ultimate limit state	IEC 61400-3-1 ISO 19904-1
Materials and construction	ISO 19901-7 ISO 19905-1	Serviceability and accidental limit state	ISO 19904-1
Safety levels and safety concepts	IEC 61400-3-1 ISO 19904-1	Fatigue limit state	IEC 61400-1 IEC 61400-3-1 ISO 19904-1
Design methods and loads	API RP 2FPS API RP 2T IEC 61400-1 IEC 61400-3-1 ISO 2394 ISO 19900 ISO 19901-2 ISO 19901-4 ISO 19901-7 ISO 19904-1 ISO 19906 ITTC 7.5-02-07-3.8	Transport and installation	IEC 61400-3-1 ISO 19901-6
Stability	IMO MSC.267(85)	Commissioning, surveys and O&M	IEC 61400-3-1 ISO 19901-6 ISO 19904-1

The **American Bureau of Shipping (ABS)** is a maritime classification society founded in 1862 and headquartered in the United States. It is the primary classification authority for the offshore oil and gas industry in the country, and it is expanding its involvement in offshore wind energy as well. The ABS Guide for Building and Classing Floating Offshore Wind Turbines (ABS; 2020) outlines a structured framework that references various ABS rules, guides, and guidance notes. In addition, it incorporates cross-references to key US standards from organisations such as API, NACE, ACI, and ASTM, along with international IEC and ISO standards relevant to environmental conditions, design practices, and load modelling.

Bureau Veritas (BV), the French classification society, has issued BV NR572:2024, which outlines requirements for floating wind turbine systems. This standard primarily references various Bureau Veritas documents and incorporates standards from IEC, ISO, EN, IMO, API, AISC, AWS, ASTM, and NORSOK, thereby reflecting best practices across the sector (Table 3-2).

Table 3-2: List of specifications included in the BV NR 572:2024 framework (Ramboll; 2021)

Topic/ Issue	Specification/ Standard		Topic/ Issue	Specification/ Standard
General	BV NR445 BV NR571 BV NR578	ISO 19902 API RP 2A API RP 2T	Station-keeping system and anchor	BV NR493 BV NR578 BV NI604 BV NI605 API RP 2T
Environmental and soil conditions	BV NR493 BV NI605 IEC 61400-3-1 IEC 61400-3-2 ISO 19901-1 ISO 29400	EN 1997-1 EN 1997-2 IMO MSC/Circ.884 IMO A765(18)	Ultimate limit state	API RP 2A
Materials and construction	BV NR216 BV NR426 BV NR445 BV NR467 BV NR526 BV NI594 API RP 2T	ISO/IEC 17021-1 ISO 9001 ISO 19903 EN 1992-1-1 AISC (2024) AWS D1.1	Serviceability and accidental limit state	BV NR445
Safety levels and safety concepts	BV NR493		Fatigue limit state	BV NR493 BV NR578 BV NI604 BV NI611 API RP 2T
Design methods and loads	BV NR426 BV BR445 BV NR467 BV NR493 BV NR571 BV NR578	BV NI611 IEC 61400-3-1 IEC 61400-3-2 API RP 2T ISO 19901-2 ISO 29400 EN 1993-1-1	Transport and installation	BV NR526 ISO 29400 API RP 2A IMO MSC/Circ.884 IMO A765(18)
Stability	BV NR445 BV NR578 ISO 29400	IMO MSC/Circ.884 IMO A765(18) IMO Res MSC.267(85)	Commissioning, surveys and O&M	BV NR445

Det Norske Veritas (DNV), the Norwegian classification society founded in 1864 and merged with Germanischer Lloyd (GL) in 2013, has published DNV-ST-0119:2021, which defines design principles and performance requirements specific to floating offshore wind. This standard makes extensive reference to DNV's broader suite of standards and recommended practices, alongside external standards from IEC, ISO, EN, IMO, IACS, API, PTI, British Standards (BS), Eurocodes, EEMUA, and NORSOK (Table 3-3). Additional rules applicable to floating wind systems, particularly regarding certification, surveys, and inspections, are provided in DNV-RU-OU-0512:2020.

Table 3-3: List of specifications included in the DNV-ST-0119:2021 framework (Ramboll; 2021)

Topic/ Issue	Specification/ Standard	Topic/ Issue	Specification/ Standard
General	DNV-ST-0126 DNV-ST-0376 DNV-RP-A203 IEC 61400-1 IMO MSC/Circ. 1023-MEPC/Circ.3 92	Station-keeping system and anchor	DNV-ST-0126 DNV-ST-C501 DNV-OS-C105 DNV-OS-E301 DNV-OS-E302 DNV-OS-E303 DNV-OS-E304 DNV-RP-C207 DNV-RP-C212 DNV-RP-E301 DNV-RP-E302 DNV-RP-E303 DNV-RP-E305 DNV-RU-OU-0102 EN 1537 EN 1997-1 NORSOK M-001 PTI DC35.1-14
Environmental and soil conditions	DNV-ST-0126 DNV-ST-0437 DNV-RP-C205 DNV-RP-C207 DNV-RP-C212 IEC 61400-1 ISO 19901-2	Ultimate limit state	DNV-ST-0126 DNV-RP-C202 EN 1993-1-1 EN 1993-1-8 NORSOK N-004
Materials and construction	DNV-ST-0126 DNV-ST-C501 DNV-ST-C502 DNV-OS-B101 DNV-OS-C103 DNV-OS-C105 DNV-OS-C106 DNV-OS-E301 DNV-OS-E302 DNV-OS-E303 DNV-OS-E304 DNV-RP-E304 DNV-RP-E305 ISO 13628-5 ISO 898-1 EN 1992-1-1 EN 1992-2 EEMUA (2019)	Serviceability and accidental limit state	
Safety levels and safety concepts	DNV-ST-0126	Fatigue limit state	DNV-ST-0126 DNV-OS-C401 DNV-OS-E301 DNV-OS-E303 DNV-RP-E305 DNV-RP-F401 DNV-CG-0129 DNV-RP-C203 BS 7910
Design methods and loads	DNV-ST-0126 DNV-ST-0437 DNV-ST-C501 DNV-ST-N001 DNV-OS-C101 DNV-OS-C103 DNV-OS-C105 DNV-OS-C106 DNV-OS-C401 DNV-OS-D101 DNV-OS-E301 DNV-OS-E303 DNV-OS-F201 DNV-OTG-13 DNV-OTG-14 DNV-RP-C103 DNV-RP-C104 DNV-RP-C201 DNV-RP-C205 DNV-RP-C208 DNV-RP-F205 IEC 61400-3	Transport and installation	DNV-ST-0437 DNV-ST-N001 DNV-RP-N101 DNV-RP-N103
Stability	DNV-OS-C301 DNV-RP-C205	Commissioning, surveys and O&M	DNV-ST-0126 DNV-OS-E301 DNV-OS-E303

Lloyd's Register (LR), the UK's renowned classification society, adopts a slightly distinct approach by consolidating its requirements into a unified framework. Rather than issuing multiple topic-specific documents, covering design criteria, load assessments, and safety factors, the standard LR-RU-003:2024 serves as their principal reference.

NORSOK standards, developed by the Norwegian petroleum sector, remain valuable references in areas such as material selection, structural design, fabrication, and marine operations. Although originally intended for offshore oil and gas installations, many NORSOK standards – such as NORSOK N-003:2017 and NORSOK N-006:2015 – are widely adopted as best practice references within the offshore wind sector, especially for projects operating in harsh and challenging environmental conditions.

The **International Organization for Standardization (ISO)** complements these frameworks through its globally recognised standards governing offshore structures (e.g., ISO 19900) and specific requirements (e.g., ISO 19901 series). ISO standards provide a neutral, consensus-based framework that is frequently adopted to harmonise and supplement sector-specific requirements in offshore wind projects.

Finally, it is important to highlight the contributions of internationally recognised institutions such as the API (American Petroleum Institute), ISSMGE (International Society for Soil Mechanics and Geotechnical Engineering), and CFMS (Comité Français de Mécanique des Sols). These organisations have developed key technical documents and guidelines for the design of offshore structures.

Considering the prevalence of Eurocodes (EN 1990 to EN 1998) in Portugal, and the absence of applicable legal standards for offshore wind structures, LNEC recommends prioritising the use of standards defined by Bureau Veritas (BV) since they impose the use of Eurocodes in the topics where these are applicable. Furthermore, BV standards incorporate various other entities' standards to ensure completeness. In cases where BV standards are silent, referring to the remaining standards mentioned is recommended.

3.3 Design principles and safety verifications

3.3.1 General requirements

Floating offshore wind turbines (FOWTs) are exposed to complex environmental, geotechnical, and electrical conditions that may affect their structural loading, durability, and operational performance. These include site-specific wind and marine conditions, seabed characteristics, and the influence of nearby turbines within the wind farm layout. To ensure the appropriate safety and reliability levels throughout the asset's lifecycle, these conditions shall be considered in the design process and explicitly documented on the design basis. Environmental conditions are typically categorised as:

- Wind conditions – including mean and extreme values, turbulence, and direction.
- Marine conditions – e.g. waves, sea currents, water level variations, sea ice, marine growth, scour, and seabed movement.
- Other environmental conditions – e.g. temperature, salinity, and bathymetry.

Seabed geotechnical parameters are fundamental for the design of the anchoring and station-keeping systems.

The design must be robust against events that could cause human injury, environmental damage, or significant economic loss. The methodology is based on the safety partial factor formulation, whereby actions and resistances are factored to meet predefined reliability levels.

Designers must ensure global structural stability and local component integrity under all relevant operating conditions, including transient, extreme, and accidental events.

3.3.2 Safety classes

The assignment of a safety or consequence class to the FOWT support structure is a key step in defining the applicable design requirements. According to LR-RP-003 (2024), the safety class adopted for the floating substructure may differ from that of the station-keeping system. The classification shall result from a project-specific risk assessment, which must consider:

- The safety of personnel working on or near the unit.
- The capacity of the mooring system to prevent drift, collision, or interference with adjacent assets or boundaries of the wind farm.
- The hydrodynamic stability and buoyancy performance of the floating substructure.
- The integrity and operability of dynamic and inter-array power cables, and the continuity of power generation.
- The potential for environmental damage in the event of structural failure or loss of position.
- Project insurability and financial viability.

Section 5.3 of IEC 61400-3-1:2019 defines two safety classes for offshore wind turbines:

- A standard safety class applies when failure risks human life, injury, or significant economic or societal impact.
- A special safety class applies when safety regulations are established by national or regional laws and/or by agreement between the manufacturer and the project developer or client.

For systems designed following IEC standards, the partial safety factors applied in structural assessments are specified in IEC 61400-1:2019. The selection of the appropriate consequence class directly influences these safety factors, affecting both ultimate limit state (ULS) and fatigue limit state (FLS) evaluations for the station-keeping system and the anchor holding capacity (LR-RP-003; 2024).

3.3.3 Limit states

Design verification shall consider all relevant limit states as defined by LR-RP-003 (2024) and other applicable standards. These include:

- Ultimate Limit States (ULS): considered to guarantee structural integrity under extreme loading, including loss of equilibrium (e.g. capsizing), failure of primary components, collapse, excessive deformation, instability, or failure of the station-keeping system.
- Serviceability Limit States (SLS): aiming at ensuring safe and functional operation of the FOWT under normal conditions. As per IEC 61400-3-1:2019, SLS evaluations are conducted through specific design load cases (DLCs) addressing accessibility, comfort, and functional performance.
- Fatigue Limit States (FLS): related to safety concerning damage accumulation from repeated loading during manufacturing, transport, installation, operation, and decommissioning. Fatigue must be assessed for all relevant components across the turbine's full lifecycle.
- Accidental Limit States (ALS): safeguard safety during rare or accidental events. Design must ensure sufficient robustness of the floating structure and mooring system under such conditions, particularly in cyclone-prone areas. ALS scenarios should include environmental loads with a 500-year return period, potentially combined with loss of control or yawing capacity. For robustness checks, all partial safety factors are taken as unity.

As stated in LR-RP-003 (2024), additional serviceability performance criteria may include:

- Operational limits on platform motion for personnel access and workability.
- Evaluation and mitigation of dynamic instabilities such as vortex-induced vibration (VIV), blade flutter, negative damping effects, and other aero-hydro-elastic phenomena.
- Offset limits (mean and dynamic) for intact cable configuration.
- Offset limits for damaged cable and mooring lines.
- Heeling and stability criteria under damaged conditions, with and without active ballast systems.
- Post-seismic settlement limits for anchors, moorings, and cables.
- Performance of the station-keeping system under disconnection scenarios, including towing or failure events.

3.4 External conditions

3.4.1 Characterisation of external conditions

The design of floating offshore wind turbines (FOWTs) shall account for external conditions that influence structural performance, serviceability, durability, and safety. These conditions are categorised as normal (frequent or operational) or extreme (rare but critical for design). The design load cases shall include combinations of environmental conditions and operational states, with joint return periods defined accordingly.

The characterisation of external site conditions shall follow the provisions of IEC 61400-3-1:2019, IEC 61400-3-2:2025, and DNV-ST-0437:2024. At a minimum, the following aspects shall be assessed:

- Meteorological conditions (wind):
  - Long-term sector-wise mean wind speeds, corrected for measurement bias, and the associated probability density functions.
  - Mean wind direction and frequency distributions (wind roses).
  - Extreme 10-minute mean wind speeds for 1-year and 50-year return periods.
  - Gust factors for converting 10-minute wind averages to 3-second averages and other critical intervals.
  - Wind shear profiles and assumptions used for their derivation.
  - Ambient wind turbulence intensity (mean and standard deviation).
  - Mean and extreme air density values, including seasonal and diurnal variations.
  - For typhoon or hurricane-prone regions, 10-minute mean wind speeds for a 500-year return period.
- Oceanographic conditions:
  - Significant wave heights and peak wave periods for 1-year and 50-year return periods.
  - Joint probability distributions for wind and wave events, including directional misalignment.
  - Wave spectral data, including directional spreading and partitioning between swell and wind sea.
  - Current velocity profiles and directional data, considering tide- and wind-driven currents.
  - Extreme surface currents for 1-year and 50-year return periods.
  - Mean sea level, tidal range, and storm surge elevations.
  - For typhoon/hurricane-prone areas, 500-year wave conditions shall also be considered.
- Seabed and Subsurface Conditions:
  - High-resolution bathymetric mapping of the site area.
  - Identification of natural and anthropogenic seabed hazards (e.g., boulders, gas pockets, wrecks, cables).
  - Assessment of seabed mobility and local scour potential.
  - Soil stratigraphy and geotechnical properties of the seabed relevant to the design of foundation, anchor, moorings, and cable burial.
- Seismic Conditions:
  - Site-specific ground motion parameters and probabilistic seismic hazard analysis.

  - Soil-structure interaction under dynamic earthquake loading, particularly for taut-leg mooring systems.
  - Assessment of liquefaction potential and dynamic soil behaviour at anchor points.
- Ice and Marine Growth
  - Occurrence and characteristics of sea ice, including drift speed and direction.
  - Static and dynamic ice loading effects on floating substructures.
  - Marine growth characteristics (type, thickness, distribution), and impacts on hydrodynamics, corrosion, and maintenance.
- General Environmental Effects
  - Effects of temperature, humidity, salinity, UV radiation, and other climatic factors on structural integrity and materials performance shall also be considered as per IEC 61400-3-2:2025.

Wave loading on floating offshore wind turbines (FOWTs) shall be represented using stochastic spectral wave models. Where appropriate, deterministic regular wave models may also be used for specific design checks. According to IEC 61400-3-2:2025, both linear and non-linear wave models are permitted, provided they are adequately calibrated for the target site.

The directional spreading of wave energy shall not be neglected, as it has a significant influence on yaw response and overall load estimation. Unlike fixed-bottom turbines, floating platforms are more susceptible to yaw motions under misaligned or multidirectional sea states. Ignoring directional spreading may lead to non-conservative design results.

The combined extreme event of wind, waves, water level, and other relevant parameters shall ensure that global extreme environmental actions with return periods of 1 year and 50 years are considered. Depending on the dynamic characteristics and geometry of the floating substructure, multiple combinations of these environmental variables may need to be evaluated.

Wave load conditions shall be defined using sea state representations that include:

- Stochastic linear wave models, based on site-specific wave spectra.
- Regular non-linear design waves, for worst-case load checks, where appropriate.

Wave spreading should always be incorporated when calculating loads on floating structures. Omitting spreading may underestimate yaw-induced motions and loads, leading to underprediction of fatigue or ultimate responses.

Although sea currents may vary spatially and temporally, they are typically modelled as horizontally uniform fields, varying with depth. The following components of current speed shall be accounted for:

- Sub-surface currents caused by tides, storm surges and atmospheric pressure changes.
- Near-surface wind-induced currents.

The resultant current speed shall be taken as the vector sum of these components.

The Normal Water Level Range (NWLR) shall be defined as the long-term difference between the Highest Astronomical Tide (HAT) and the Lowest Astronomical Tide (LAT). This range shall be used in both fatigue and ultimate limit state analyses involving normal and severe sea state conditions. For severe sea states (SSS) with a return period of 1 year, NWLR is to be used in combination with wave and current conditions.

The influence of sea currents on the dispersion relationship (i.e., wavelength versus wave period) is generally minor and may be neglected in most cases.

At high-latitude sites, ice loading on floating substructures may become critical. This includes:

- Static loads from land-fast ice.
- Dynamic loads from drifting ice floes caused by wind or current action.

Repeated or prolonged impacts from drifting ice can result in significant cumulative loading. A detailed site-specific assessment of ice occurrence, properties (e.g. thickness, strength), drift directions and velocities shall be conducted if ice presence is anticipated.

In the scope of this report, marine growth can significantly alter the physical and hydrodynamic characteristics of the FOWT system by:

- Increasing structural mass and surface roughness.
- Changing load coefficients and natural frequencies.
- Affecting access for inspection and maintenance.

Earthquake loading is not typically the governing design condition for floating platforms. Nevertheless, seismic effects shall be considered in the design of FOWTs located in seismically active areas. In catenary mooring systems, the low horizontal stiffness of the mooring lines generally decouples the substructure from direct seismic ground motion. Nonetheless, earthquakes may induce dynamic tension variations in the mooring lines. In taut-line or tendon-based systems, higher stiffness values cause seismic inertial forces to be transmitted directly to the substructure. This may lead to significant heave motion and dynamic tension in the mooring elements.

Where multiple mooring lines or tendons are used, the seismic movement phase difference between anchor points must be evaluated, as asynchronous loading can result in roll and pitch motions that exceed design hypothesis.

In all cases, the geotechnical properties of the seabed shall be assessed to evaluate:

- Dynamic behaviour of soil or rock masses under seismic excitation.
- Potential for liquefaction at anchor locations.

Anchor design must ensure stability and performance during and after seismic events.

3.4.2 Assessment of external conditions

A site-specific metocean database shall be developed to support the structural and mooring design of FOWTs. In accordance with IEC 61400-3-2:2025, this database shall include the following parameters:

- Wind speed and direction (mean and extreme values).
- Significant wave height, period, and direction.
- Wind–wave correlation and joint probability statistics.
- Current speeds and directions at various depths.
- Water levels, including tides and surge events.
- Ice occurrence, drift direction, and speed (for cold climates).
- Icing risk on turbines and support structures.
- Other site-specific parameters (e.g., temperatures, salinity, bathymetry, marine growth).

The database shall be based primarily on site-specific measurements, supported by validated numerical simulations where appropriate. The monitoring time interval must be sufficient to ensure statistical robustness for both individual and joint parameters.

When correlation analysis is used instead of full on-site monitoring, the reference station should be located within 50 km of the wind farm, with comparable water depth, bathymetry, and fetch conditions.

Long-term site-specific measurements may be waived if validated regional data and modelling tools are available for reliable transposition to the site. However, where uncertainty is significant, conservative assumptions and safety margins shall be adopted.

3.5 Definition of loads

DNV-ST-0119:2021 (clause 4.3.1.2) classifies design loads into the following categories:

- Permanent loads (G)
- Variable functional loads (Q)
- Environmental loads (E)
- Accidental loads (A)
- Deformation loads (D)

There is a notable difference in terminology between the Structural Eurocodes and the standards used in offshore wind engineering. In the Structural Eurocodes (EN 1990:2023), the term "action" refers to both direct actions - which are the forces (loads) applied to a structure - and indirect actions, which include imposed deformations or accelerations caused by factors such as uneven settlement or earthquakes. In contrast, the term "load" in offshore wind engineering encompasses all actions that need to be considered.

3.5.1 Permanent loads

DNV-ST-0019:2021 defines permanent loads as those that will not vary in magnitude, position or direction during the period, including:

- Mass of structure.
- Mass of permanent ballast and equipment.
- External and internal hydrostatic pressure of a permanent nature, including permanent differential pressure differences.

In EN 1990:2023, a permanent load is defined as an action that is expected to act throughout a given reference period with negligible variation in magnitude or a variation always in the same direction (monotonic) until a limit value is reached.

3.5.2 Variable loads

Variable functional loads are loads with non-negligible variation in magnitude, position and direction during the period under consideration, and which are related to the operation and normal use of the structure in question (DNV-ST-0119:2019), mainly consist of:

- Loads on platforms, ladders, and access structures.
- Boat landing impacts.
- Variable ballast weights and pressures.
- Crane operational loads.

3.5.3 Environmental loads

Environmental loads are caused by environmental phenomena. These are loads whose magnitude and direction may vary with time (IEC 61400-3-2:2025 and DNV-ST-0119:2019), such as:

- Wind forces.
- Hydrodynamic forces from waves and currents.
- Earthquakes.
- Tides, marine growth.
- Snow and ice accumulation

When long-term environmental data time series, such as measurement or hindcast data, are available, they can be used to evaluate the DLC factors associated with fatigue strength. This data can also help establish long-term joint probability distributions of metocean parameters, enabling their use for other DLC factors. If such data is not available, conservative combinations should be applied instead

3.5.4 Accident loads

According to LR-RP-003 (2024), accidental load cases should be selected such that they have annual probabilities of exceedance in the range 10^{-2} to 10^{-4} and shall be taken as loads with a 500-year return period (i.e. loads with an annual probability of exceedance of $2x10^{-3}$), unless otherwise specified by IEC 61400-3-2:2025 or other adopted standards. Amongst others, those relevant for geotechnical design should include:

- Vessel collisions.
- Ballast system failures.
- Mooring line failure.
- Unintended change of pressure loads on the floating substructure.
- Fire, explosion.
- Flooding.
- Cyclones.

3.5.5 Deformation loads

Deformation loads are loads caused by inflicted deformations (DNV-ST-0119:2019), such as :

- Temperature effects,
- Built-in deformations.
- Creep and settlement.

3.6 Design situations and load cases

The structural integrity of a Floating Offshore Wind Turbine (FOWT) must be verified against the Ultimate Limit State (ULS), Fatigue Limit State (FLS), Accidental Limit State (ALS), and Serviceability Limit State (SLS), to ensure both global stability and local component strength throughout its design life. Due to the dynamic nature of floating systems, detailed coupled analyses are required to capture the complex interactions between hydrodynamic, aerodynamic, structural, and mooring responses.

Material selection shall comply with durability and corrosion resistance requirements appropriate to the marine environment, and fatigue life shall be verified using site-specific load spectra. Structural design guidelines are detailed in Section 7 of DNV-ST-0119:2019.

The design of a FOWT must consider the various design situations that reflect the most relevant conditions the structure is expected to face during its service life. These include normal operational conditions, as well as specific scenarios related to transport, installation, maintenance, and fault occurrences.

Design load cases (DLCs) shall be established by combining:

- normal design situations with corresponding normal or extreme external conditions.
- fault design situations with relevant external conditions.
- transport, installation, and maintenance scenarios with appropriate environmental conditions.

All relevant load cases with a reasonable likelihood of occurrence shall be considered, including the influence of the wind turbine control system on structural response. Where correlation exists between a fault condition and an extreme environmental event, a realistic combined scenario shall be explicitly evaluated as a design load case. According to IEC 61400-3-2:2025 (section 7.4), as a minimum, the following groups of design issues, each of which with several associated design load cases (DLC) should be considered:

- Power production (6 DLC).
- Power production plus the occurrence of fault (6 DLC).
- Start-up (3 DLC).
- Normal shut down (3 DLC).
- Emergency stop (1 DLC).
- Parked (standing still or idling) (5 DLC).
- Parked and fault conditions (2 DLC).
- Transport, assembly, maintenance and repair (4 DLC).
- Redundancy check and damage stability (power production) (3 DLC).
- Redundancy check and damage stability (parked, standing still or idling) (3 DLC).

3.7 Geotechnical safety analysis and modelling

In accordance with Section 5.2 of IEC 61400-3-1:2019, the use of a validated structural dynamics model is recommended for the prediction of design load effects on offshore wind turbines and, consequently, their anchoring systems.

The calculation of loads and structural deflections shall account for:

- The influence of site-specific seabed soil and rock masses' properties on the dynamic response characteristics of the offshore wind turbine support structure.
- The potential long-term variation in dynamic properties arising from seabed changes, including scour and seabed movement.
- The effects of cyclic loading on the seabed soil and rock masses' properties shall be considered in the geotechnical design of anchors for the station-keeping systems of floating wind turbines (DNV-ST-0119:2021).

Such considerations shall be integrated into the design load analysis to ensure accurate assessment of fatigue and ultimate limit states throughout the turbine's operational life.

The risk of scouring around an anchor foundation shall be considered unless it can be demonstrated that the surrounding soils will not experience scouring for the expected range of water particle velocities. This is relevant for anchors with exposed parts above the seabed, such as pile anchors, suction anchors and, in some instances, fluke anchors.

Load transfer mechanisms and anchor performance shall be demonstrated through calculation and appropriate testing.

3.7.1 Station keeping system

The design of station-keeping systems, including mooring lines and tendons constructed from steel or fibre materials, shall comply with the requirements specified in Section 8 of DNV-ST-0119:2019.

The applicable design load cases for station-keeping systems shall be defined following DNV-ST-0437:2024. The establishment of characteristic line tensions shall be carried out as follows: characteristic values of mean tension and of dynamic tension shall be determined based on time-domain simulations or measured time series of mooring line tension response, following the methodology detailed in DNV-OS-E301:2021.

All mooring line components shall be manufactured to a high standard of quality control and shall comply with recognised manufacturing standards, including but not limited to:

- DNV-OS-E302:2021 (Offshore Mooring Chain).
- DNV-OS-E303:2021 (Offshore Fibre Ropes).
- DNV-OS-E304:2021 (Offshore Mooring Steel Wire Ropes).

For the design of fibre rope tendons against fatigue failure, design methodologies and testing requirements are specified in DNV-OS-E301:2021 and DNV-OS-E303:2021, which guide evaluating fatigue resistance and qualifying fibre rope systems for offshore applications.

3.7.2 Anchor foundations

The geotechnical design of anchoring systems, which transfer loads from mooring lines or tendons to the seabed, shall be performed per ISO 19901-4:2025, ISO 19901-7:2013, and DNV-ST-0119:2019.

The design requirements for each anchor type shall be as follows:

- Drag Embedment Anchors:
  - Design shall be carried out following ISO 19901-4:2025.
  - All drag embedment anchors are required to be test loaded at installation.
- Suction Anchor Piles:

    - Design shall comply with ISO 19901-4:2025 and DNV-RP-E303:2021.

- Driven Anchor Piles:
    - Design shall be performed under ISO 19901-4:2025, DNV-ST-0126:2021, and DNV-RP-C212:2021.
    - Where appropriate, the applied design methodology should account for the installation process.
- Plate Anchors:
    - Design shall follow ISO 19901-4:2025 and DNV-RP-E302:2021.
- Gravity Anchors:
    - Design shall conform to DNV-ST-0126:2021, ISO 19901-4:2025, and ISO 19903:2019.
    - In addition to general anchoring requirements, gravity anchor design shall demonstrate compliance with the following criteria:
        - Sufficient combined capacity to resist vertical, horizontal, moment, and torsional loads.
        - Acceptable vertical settlements under short-term and long-term loading, including immediate, secondary (creep), and long-term components.
        - Limitation of horizontal displacements and tilts within permissible limits, accounting for both recoverable and non-recoverable movements.
        - Control of accumulated or differential movements resulting from cyclic loading or variability in soil properties across the foundation area.

Prestressed rock anchors shall be designed and verified for anchoring solutions on rock substrate following EN 1997-1:2024 and EN 1537:2013.

3.8 Characterisation of seabed and anchoring system

The characterisation of the seabed and the associated foundation or anchoring systems is a critical component in all phases of a floating offshore wind farm project, from early feasibility study to detailed design. The type, quantity, and spatial density of the geotechnical and geological data collected must be progressively refined as the project evolves, ensuring that the information is fit for purpose at the preliminary design and final design.

Comprehensive seabed characterisation must enable the detailed design of the anchoring or foundation systems, accounting for both short-term construction requirements and long-term performance under environmental and operational loads. In line with the recommendations of DNV-RP-C212:2021, seabed investigations are typically divided into three interdependent components: geological studies, geophysical surveys, and geotechnical investigations.

Geological studies provide the foundational framework for understanding the evolution and composition of the seabed. They are based on regional and site-specific geological history and serve to identify major stratigraphic units, sedimentary environments, faulting, and other geological hazards. This information is important in defining the scope, objectives, and techniques to be used in subsequent geotechnical investigations.

Geophysical surveys play a crucial role in defining seabed morphology, bathymetry, sediment layering, and subsurface structures over wide spatial extents. Typical techniques include multibeam echosounder, side-scan sonar, sub-bottom profiling, and seismic reflection. These non-intrusive methods support the optimal placement of boreholes and in-situ testing locations and enable the correlation of discrete geotechnical data points into continuous stratigraphic models. They are also instrumental in detecting seabed anomalies such as boulders, wrecks, pipelines, or voids, which may affect foundation or anchor performance.

Geotechnical investigations encompass both in-situ testing and laboratory analysis of soil and rock samples. In-situ techniques include, but are not limited to, cone penetration tests (CPT/CPTU), pressuremeter tests (PMT), dilatometer tests (DMT), field vane shear tests (FVT), T-bar and ball penetration tests. These are typically supplemented by borehole sampling and laboratory testing to determine key soil parameters such as shear strength, stiffness, permeability, compressibility, and cyclic resistance. The interpretation of this data should provide a robust and representative set of geotechnical parameters that reflect the variability of the site, both laterally and with depth.

The effects of cyclic loading due to wave action and wind-induced motions must be explicitly considered during parameter interpretation. Changes in shear strength and shear modulus due to strain accumulation, strain rate dependency, and dynamic loading conditions can significantly influence foundation response, including stiffness evolution, settlement, and fatigue life. Specialised laboratory and in-situ tests are required to quantify these effects, such as resonant column, cyclic triaxial, and direct simple shear tests.

The seabed and anchoring system characterisation must be both systematic and iterative. It should integrate geological, geophysical, and geotechnical data to provide a comprehensive basis for design, reducing uncertainties, and improving reliability in both the short-term installation phase and the long-term operational phase of floating wind systems.

3.8.1 Site geological and geotechnical models

The development of coherent geological and geotechnical models is essential to underpin the design of anchoring and foundation systems for floating offshore wind turbines. These models serve as the primary reference for interpreting site conditions and for informing all subsequent design phases.

The geological model should integrate regional and local geological data to define the stratigraphic sequence, identify lithological units, and map geological structures and potential hazards (e.g., faults, gas pockets, boulders, soft layers). This model is typically derived from the synthesis of geophysical survey data, borehole logs, and regional geological mapping, and should be refined iteratively as site investigations progress.

The geotechnical model builds upon the geological model and provides a detailed interpretation of soil and rock properties relevant to foundation and anchoring performance. The objective is to define a set of geotechnical zones (of similar geomechanical behaviour) within which one or more geotechnical design profiles can be established. Each profile should represent a specific soil layering sequence and be associated with a set of well-defined geotechnical parameters.

Each geotechnical design profile shall include, at a minimum:

- A comprehensive description and classification of soils and rocks in accordance with recognised standards.
- The in-situ stress conditions, including effective stress state and pore water pressure distribution.
- The shear strength parameters for both drained and undrained conditions.
- The stiffness parameters, such as small-strain shear modulus (G_0), accounting for stress level and strain rate effects.
- The cyclic and post-cyclic behaviour, including cyclic shear strength, modulus degradation, and liquefaction susceptibility.
- Time-dependent parameters, such as creep rate and secondary compression index, particularly relevant for long-term settlements.
- Parameters governing the soil-structure interface behaviour.

Special attention should be given to the effects of cyclic loading, particularly from wind and wave action, and with the appropriate consideration of seismic actions. These can cause degradation of soil stiffness, and progressive accumulation of permanent strains. Therefore, the geotechnical model should explicitly incorporate the expected impact of cyclic loading on both strength and stiffness parameters. Laboratory and field tests aimed at evaluating cyclic response (e.g., cyclic triaxial, or simple shear test) should be considered essential, especially in soft clays, loose sands, or carbonate sediments.

The vertical and lateral variability of geotechnical parameters must be characterised and quantified. This includes defining representative values (e.g., mean, characteristic lower-bound) and variability measures (e.g., standard deviation, coefficient of variation) to be used in deterministic or probabilistic design frameworks. Where appropriate, spatial correlation lengths should also be defined to inform geotechnical risk assessments and reliability-based design.

Ultimately, the integration of geological and geotechnical models enables the identification of technically and economically viable anchoring solutions, informs installation methodology, and supports the long-term performance assessment of the foundation system.

3.8.2 Parameters for geotechnical design of foundations

The geotechnical design of anchoring systems and foundation elements for floating offshore wind turbines requires a comprehensive set of soil and rock parameters. These parameters must capture the relevant mechanical, hydraulic, and dynamic behaviour of seabed materials under both monotonic and cyclic loading conditions. The design must account for the full life cycle of the structure, from installation to operation and decommissioning, and must be robust against environmental loads and long-term soil-structure interaction effects.

The key geotechnical phenomena that influence design include, but are not limited to:

- Static and cyclic bearing resistance.
- Cyclic degradation of strength and stiffness.
- Permanent and cyclic displacements.
- Scour susceptibility.
- Liquefaction potential and strain accumulation.
- Interface friction and adhesion.
- Resistance to penetration (for suction buckets or driven piles).
- Long-term creep and time-dependent settlements.
- Soil-pile interaction under dynamic loading.
- Soil reactions and stiffness for fatigue-sensitive components.

To address these challenges, geotechnical parameters should be grouped into three categories: basic identification parameters, advanced parameters for specific design issues, and parameters for non-standard soils and anchoring conditions. These are required for general characterisation and preliminary design, as outlined in standards such as ISSMGE (2005) (Table 3-4). The parameters summarised in Table 3-5 are required for addressing specific failure modes and performance criteria.

Table 3-4: Basic soil and rock parameters (Table 8.2-1 in ISSMGE, 2005)

Clay	Silt, sand or gravel	Rock
− General description − Layering − Grain size distribution − Water content − Total unit weight − Atterberg (plastic and liquid) limits − Indicative shear strength (miniature vane, torvane, pocket penetrometer, fall cone, UU, etc.) − Remoulded shear strength − Sensitivity − Soil stress history and overcon-solidation ratio − Organic material content	− General description − Layering − Grain size distribution − Water content (silt) − Maximum and minimum densities − Relative density − Drained angle of shearing resistance − Soil stress history and overcon-solidation ratio − Angularity − Carbonate content − Organic material content	− General description − RQD (Rock Quality Designation) − Water absorption − Total unit weight − Unit weight of solid blocks − Unconfined compression strength − Mineralogy − Carbonate content

Table 3-5: Additional parameters that might be required for specific issues (Table 8.2-2 in ISSMGE, 2005 & Table 5.2 in CFMS, 2020)

Application	Required Parameters
Scour / erosion	Grain size, relative density, critical shear stress, permeability
Bearing capacity	Monotonic and cyclic shear strength, interface friction angle, φ', φ'_{cv}
Liquefaction potential	Cyclic resistance ratio (CRR), CPTU parameters (qc, Bq, FR), shear wave velocity (Vs)
Earthquake loading	Strain-rate effects, dynamic shear modulus (Gmax), damping ratio
Cyclic and permanent displacements	Cyclic modulus degradation curves, permanent strain development
Installation behaviour (e.g., suction buckets)	Undrained strength, remoulded strength, strain softening
Long-term behaviour	Consolidation coefficient, creep index, ageing parameters
Soil-structure interaction	p-y curves, t-z curves, cyclic skin friction, mobilised interface stiffness
Corrosion and material compatibility	Soil pH, redox potential, sulphate content, microbiological activity

In carbonate sediments, soft organic clays, or weakly cemented formations, conventional parameters may be insufficient. Additional tests are often needed to assess:

- Crushability and compressibility of carbonate sands.
- Cementation strength and destructuration behaviour.
- Interface properties between fibre-reinforced anchors and granular soils.
- Anisotropy and rate-dependency in soft clays.

Whenever possible, cyclic-specific laboratory tests should be used to determine degradation of behaviour, accumulation of strain, and stiffness reduction. For parameters related to soil damping and dynamic response, resonant column or bender element tests are also recommended.

3.8.3 Design values of parameters

The derivation of design values for geotechnical parameters is a critical step in the foundation and anchoring system design process for floating offshore wind turbines (FOWTs). These values are essential for ensuring structural safety, serviceability, and long-term performance under static, cyclic, and dynamic loading conditions. Design values must reflect both the inherent variability of seabed materials and the uncertainties associated with data acquisition, interpretation, and modelling.

In accordance with Eurocode 7 (EN 1997-1), three types of parameter values are typically distinguished:

- Measured values: values obtained directly from laboratory or in-situ tests.
- Characteristic values (X_k): conservative estimates representing the value of a parameter with a low but acceptable probability of being unfavourably exceeded. These are derived based on statistical analysis and/or engineering judgement, considering data quality and spatial variability.
- Design values (X_d): values used in calculations, obtained by applying partial safety factors (γ_M) to characteristic values: $X_d = X_k / \gamma_M$.

For design purposes, characteristic values must be selected based on statistical analysis of site data and engineering judgement. For this goal, the following must be considered:

- Spatial variability (vertical and lateral);
- Sample disturbance effects.
- Differences between laboratory and in-situ measurements.
- Soil behaviour under expected loading regimes (static, cyclic, dynamic).
- Safety factors appropriate to the project's safety class and consequence category.

Design values of stiffness parameters (e.g., E′, G′, p–y curves) must reflect strain levels compatible with the expected load regime. For example:

- Initial (small strain) stiffness for dynamic analyses and fatigue assessments.
- Secant stiffness for monotonic loading in static equilibrium analyses.
- Degradation-modified stiffness for cyclic loading cases.

Damping ratios used in dynamic analyses should also reflect the soil type, strain amplitude, and loading frequency. Where appropriate, empirical correlations (e.g., between shear wave velocity and small strain shear modulus) may be used to supplement limited test data.

The partial factors (γ_M) applied to the characteristic geotechnical parameters depend on the safety class and the selected design code.

It should be noted that, under Eurocode 7, geotechnical design can be carried out using one of three distinct design approaches (DA), designated by DA1, DA2 and DA3. They correspond to alternative, yet valid, ways of designing civil engineering structures The approach adopted in each country is specified in its respective National Annex of Eurocode 7, which defines the methodology to be applied following the European standard. In Portugal the Design Approach 1 has been defined as mandatory.

4 | General Guidance for the geotechnical characterisation

The geotechnical site survey reports must include the field data from site investigation works, following as guidance the standards and technical specification included in EN ISO 14688-1, EN ISO 14689-1, and EN ISO 22475-1, and for geodetic surveys, IHO (2024) guidelines for Order 1 surveys and EN ISO 10012.

4.1 In situ investigations

Intact samples (Sampling, handling, transport, storage and recording)

Soil identification, based on the examination of samples obtained with grabbers, and the operations of handling, transport, and storage of samples are outlined in ISO 14688-1 and ISO 22475-1, respectively.

For fine soils, sediment samples must be collected with a quality grade of 4 or better to ensure that their composition remains unchanged. For coarse soils, the goal is to obtain sediment samples with a minimum quality grade of 3 (BSH; 2014). Guidance for the characteristics of the grabbers used for sampling are provided in ISO 22475-1(Table 1). The requirements for the enterprise and personnel (qualified operators and responsible expert) must comply with ISO/TS 22475-2.

Vibrocores (Sampling, handling, transport, storage and recording)

Guidance for sampling obtained using vibrocores are provided in ISO 19901-8 highlighting in particular sections 9.6.1 and 9.6.2.

For laboratory geotechnical testing the inner diameter of the vibrocores sampler shall be at least 100 mm

CPTu tests

The EN ISO 22476-1 outline the procedures for Piezocone penetration tests (CPTu), to measure the parameters stated in section 6.1 of that standard, i.e. sleeve friction, penetration length, cone resistance, pore pressure in the face of the cone, pore pressure at the cylindrical extension of the cone, u3 pore pressure measured above the friction sleeve and total angle between the vertical axis and the axis of the cone penetrometer. CPTu testing are usually carried out continuously from the seabed (seabed CPTu)

4.2 Laboratory testing

To handle, store, and process soil samples in the laboratory, the requirements of EN 1997-2 (section 5.3.2.2) must be followed. The primary requirements are outlined in items (3) and (4), which state that soil samples must be protected from damage, deterioration, and significant temperature changes. Special care should be taken with undisturbed samples to avoid distortion and moisture change during the preparation of test specimens. The water content of the soil samples should be kept constant before testing, as this may impact the test results due to moisture modification, especially in the case of moisture loss.

Tests for classification, identification and description of soil

Soil classification, identification, and description shall be conducted following ISO 14688-1:2017 and EN ISO 14688-2:2017, ensuring compliance with the requirements outlined in Table M.1 of Annex M of EN 1997-2.

Tests for determining soil index properties

The particle size distribution and the liquid and plastic limits shall be determined according to ISO 17892-4:2016 and ISO 17892-12:2018, respectively.

The determination of water content, bulk density and particle density shall be performed following ISO 17892-1:2014, ISO 17892-2:2014 and ISO 17892-3:2015, respectively.

Compressibility testing of soil

For the determination of the compressibility of a stratum of clay, silt or organic soil, undisturbed samples (Quality Class 1) shall be used, as stated by EN 1997-2. Incremental oedometer test or constant rate of strain oedometer tests may be considered, following, respectively, ISO 17892-5:2017 or ASTM D4186/D4186M-20e2.

Triaxial shear tests

Consolidated triaxial compression tests on seabed soils shall be conducted to characterise shear resistance, shear moduli and compressibility on saturated samples. These shall comply with ISO 17892-9:2018. The tests shall be performed in undrained condition with a convenient low shear rate so as to allow time for the equalization of pore pressure buildup during the test. Prior to the test, the state index properties shall be obtained following the relevant standards as above.

Direct simple shear tests

Direct simple shear tests are a convenient alternative to the shear testing in triaxial chamber. Monotonic and cyclic tests shall be performed in constant volume conditions. The former should be conducted according to ASTM D6528-17. The frequency used to cyclically test the soil samples shall be representative of the relevant frequency content of the relevant cyclic actions.

5 | Concluding remarks

This report is of the geotechnical consultancy services requested by the Instituto Português do Mar e da Atmosfera, I.P. (IPMA), within the scope of studies for the development of offshore energy potential in the Leixões and Figueira da Foz areas, as part of the Recovery and Resilience Plan (process PRR RP-C21-i07.01).

The document identifies the main national and international standards applicable to the design of foundations for floating offshore wind structures, taking into account the geotechnical characteristics and significant water depths of the study areas. It also defines the technical and methodological criteria for conducting geophysical and geological survey campaigns, as well as for the geotechnical characterisation of the seabed soils, which are essential for obtaining the parameters required for subsequent project phases.

Considering the prevalence of Eurocodes (EN 1990 to EN 1998) in Portugal, and the absence of applicable legal standards for offshore wind structures, LNEC recommends prioritising the use of standards defined by Bureau Veritas (BV) since they impose the use of Eurocodes in the topics where these are applicable. Furthermore, BV standards incorporate various other entities' standards to ensure completeness. In cases where BV standards are silent, referring to the remaining standards mentioned is recommended.

This report therefore provides a fundamental technical basis for the planning and development of foundation solutions, ensuring compliance with the safety and performance requirements established in current regulations. The guidelines presented herein can also serve as technical support for future phases of planning, design, or contracting procedures related to the deployment of offshore wind farms in Portuguese offshore areas.

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