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Geotechnical Aspects of Offshore Wind Turbine Foundations: A Review with Implications for Brazilian Offshore Conditions

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ABSTRACT: Offshore wind energy offers a strategic opportunity for Brazil, given its extensive continental shelf and favorable wind regime. The structural integrity of offshore wind turbines is governed primarily by foundation response under combined gravitational, aerodynamic, and hydrodynamic loading, with cyclic lateral actions controlling stiffness, rotation, and long-term performance. This study provides a structured synthesis of bottom-fixed and floating foundation systems, including gravity-based, monopile, tripod, jacket, and suction caisson solutions, within a limit state design framework. Emphasis is placed on mechanical behavior, soil-structure interaction, preliminary design methodologies, and installation constraints derived from established international practice. The applicability of these approaches to Brazilian offshore conditions - characterized by stratified deposits, soft clays, and carbonate sediments - is critically examined. Key uncertainties related to cyclic degradation, stiffness evolution, and installation-performance interaction are identified. This study consolidates design principles for foundation selection and provides a technical basis for reliable and safe offshore wind deployment in Brazil.

KEYWORDS: Offshore Wind Foundations, Foundation Design, Geotechnical Engineering, Literature Review.

1 INTRODUCTION

The expansion of offshore wind energy is driven by the need to increase renewable generation capacity under more stable and higher wind regimes. Brazil reached 33.7 GW of installed wind capacity in 2024 (GWEC, 2025), and the establishment of a legal framework for offshore development has initiated a new stage of expansion.

From a geotechnical perspective, offshore wind turbine foundations differ substantially from conventional offshore oil and gas structures. Wind turbines are slender, dynamically sensitive systems subjected to large overturning moments generated by wind thrust and amplified by wave loading. As highlighted by Wang et al. (2018) and Wu et al. (2019), cyclic lateral loading governs design in most bottom-fixed configurations.

The implementation of offshore wind farms involves multiple stages (Jiang, 2021), yet foundation design and installation remain the most geotechnically demanding phases. The foundation must satisfy ultimate limit states while simultaneously controlling rotations and displacements within strict serviceability tolerances to ensure turbine operability. Bhattacharya and Adhikari (2011) demonstrated experimentally that soil-structure interaction significantly influences dynamic characteristics, reinforcing the importance of accurate stiffness estimation.

Brazil's continental shelf presents extensive shallow areas (Azevedo et al., 2020), suggesting technical feasibility for bottom-fixed systems. However, Brazilian offshore sediments may include soft clays, calcareous sands, and stratified deposits. Many international simplified procedures were developed assuming homogeneous profiles. Their direct application without calibration may therefore compromise reliability.

Unlike purely descriptive reviews, this study emphasizes geotechnical behavior and limit state implications to provide a structured synthesis applicable to emerging offshore markets.

2 IMPLEMENTATION REQUIREMENTS WITH EMPHASIS ON FOUNDATION DESIGN

The implementation of offshore wind farms involves sequential stages that include planning, installation, operation, and decommissioning (Jiang, 2021). Among these phases, foundation installation represents one of the most technically demanding and environmentally sensitive activities (Hernández et al., 2021). Consequently, foundation design plays a central role in the overall feasibility of offshore projects.

Offshore wind turbine foundations must be designed considering combined gravitational, aerodynamic, and hydrodynamic actions, with particular attention to cyclic lateral effects at the seabed (Wang et al., 2018; Wu et al., 2019). These loading conditions directly influence installation feasibility, construction logistics, and serviceability performance. Experimental investigations have shown that soil-structure interaction affects the dynamic characteristics of offshore wind turbines, emphasizing the importance of reliable stiffness estimation (Bhattacharya and Adhikari, 2011).

Foundation selection depends primarily on water depth and geotechnical conditions (Arshad and O'Kelly, 2013; Wang et al., 2018). Fixed foundations are generally adopted in depths below approximately 50 m, whereas floating systems become necessary in deeper waters (Wu et al., 2019). However, soil stratigraphy and strength parameters also influence feasibility, particularly under cyclic loading.

Installation constraints must be evaluated during the design stage. Pile driving resistance, suction-assisted penetration, and seabed preparation are key factors for gravity-based, monopile, and suction caisson foundations (Malhotra, 2007; Houlsby and Byrne, 2005a, 2005b; Sturm, 2017; van Dijk, 2018). Moreover, foundation installation is associated with seabed disturbance and environmental impact (Hernández et al., 2021), reinforcing the need for integrated technical and environmental assessment.

Offshore wind farm implementation therefore requires foundation design to simultaneously address cyclic loading, soil-structure interaction, installation feasibility, and environmental constraints. Within this framework, foundation engineering constitutes the primary geotechnical component governing structural reliability and project viability.

3 FOUNDATION SYSTEMS AND DESIGN APPROACH

Offshore wind turbine foundations are conceived to ensure structural stability and service performance under combined static and dynamic loading (Roga et al., 2022). Their configuration is governed primarily by anchoring mechanism, bathymetry, and geotechnical conditions (Arshad and O'Kelly, 2013; Wang et al., 2018). Accordingly, foundation systems are broadly classified as bottom-fixed or floating, depending on site depth and seabed characteristics.

Design is performed within a limit state framework that integrates structural resistance and geotechnical reliability, as established in the IEC 61400 series, DNV standards, and ISO offshore codes (IEC, 2019; DNV, 2023; ISO 19901-4, 2016). Ultimate limit states (ULS) verify capacity under extreme environmental actions, including wind, wave, and current loading. Serviceability limit states (SLS) control rotations, displacements, and stiffness to ensure turbine operability. Fatigue limit states (FLS) address cumulative damage induced by cyclic loading, and accidental limit states (ALS) consider rare extreme events. These verification categories constitute the basis of contemporary offshore wind foundation design (IEC, 2019; DNV, 2023).

In the absence of national standards specific to offshore wind foundations in Brazil, engineering practice relies on internationally established codes. The IEC 61400 series define turbine design requirements; DNV standards (DNV-OS-J101, DNV-ST-0126, DNV-ST-0119) provide guidance for fixed and floating support structures; API recommended practices (API RP 2A-WSD, API RP 2T) address offshore structural systems; and ISO standards (ISO 19901-4, ISO 19902, ISO 19903, ISO 19904) establish geotechnical and structural design principles. ABS (2020a, 2020b) classification guides complement these frameworks for bottom-founded and floating installations. These documents prescribe load combinations, safety formats, and verification procedures, including soil-structure interaction considerations.

During preliminary design stages, simplified analytical formulations are commonly employed for initial sizing, stiffness estimation, and capacity assessment (Arany et al., 2017; Hu, 2022; Jalbi and Bhattacharya, 2020; Lefebvre and Collu, 2012). These approaches frequently rely on idealized soil models, such as p-y formulations, and simplified stiffness representations (Gupta and Basu, 2020; Wu et al., 2019). However, Brazilian offshore sediments may present stratified and heterogeneous profiles (Azevedo et al., 2020), and geotechnical design standards emphasize the need for site-specific investigation and parameter selection (ISO 19901-4, 2016). Despite the maturity of these frameworks, their reliability depends fundamentally on the

quality of site-specific geotechnical data and the representativeness of soil models adopted in preliminary analyses.

3.1 Bottom-fixed offshore wind turbines

Bottom-fixed foundations transfer loads to the seabed through combinations of bearing resistance, shaft friction, and lateral soil reaction. Their behavior is strongly governed by cyclic soil-structure interaction. Typical bottom-fixed foundations are illustrated in Figure 1.

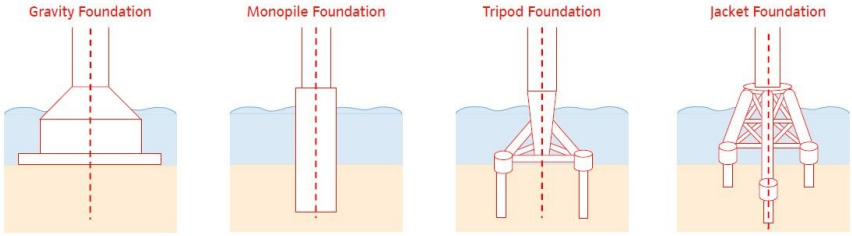


Figure 1. Schematic diagram of fixed foundation types for offshore wind turbines (Miceli, 2012).

3.1.1 Gravity-Based Foundations

Gravity-based foundations (GBFs) transfer loads to the seabed primarily through self-weight and ballast, mobilizing base contact stresses to resist sliding, overturning, and bearing failure (Malhotra, 2007; Oh et al., 2018; Wu et al., 2019). They are typically adopted in shallow waters, generally below 10 m (Oh et al., 2018; Wu et al., 2019), and may be extended to depths approaching 30 m depending on site and loading conditions (Wang et al., 2018). Their suitability is associated with cases where dead load provides the principal stabilizing mechanism and environmental loading remains moderate (Malhotra, 2007).

These systems commonly consist of a reinforced concrete caisson connected to a cylindrical shaft supporting the tower and resting directly on the seabed (Malhotra, 2007; Oh et al., 2018; Wu et al., 2019). Preliminary design follows global equilibrium verification in accordance with limit state principles, including sliding, overturning, and bearing capacity checks (Hu, 2022). Based on procedures derived from DNV-RP C212, Hu (2022) specifies that the horizontal resultant must not exceed the frictional resistance at the soil-foundation interface, overturning is verified through moment equilibrium, and load eccentricity must remain within limits that preserve effective compressive contact and bearing capacity. The framework incorporates foundation geometry, load combinations, cyclic effects, and instability drivers.

For initial design, Hu (2022) proposes practical geometric assumptions, including tower-matching top diameter, base dimensions related to water depth constraints, defined wall thicknesses, ballast positioning below interface elevation, and scour protection extending at least three times the base diameter.

GBFs are advantageous where pile driving is impractical, such as on competent soils or rock ledges (Malhotra, 2007; Wang et al., 2018). However, they require seabed preparation and scour protection (Wang et al., 2018; Oh et al., 2018). Installation typically involves seabed leveling, heavy-lift placement, and ballasting, with alternatives such as the “float and submerge” method proposed to reduce lifting demands (Jiang, 2021). Their feasibility decreases with increasing water depth and environmental loading intensity (Wang et al., 2018; Wu et al., 2019).

3.1.2 Monopile Foundations

Monopiles are the most widely adopted foundation type for offshore wind turbines. They consist of large-diameter steel tubular piles, typically 4-12 m in diameter, installed in water depths of approximately 20-40 m (Wu et al., 2019; Wang et al., 2018). They are particularly suitable for hard to semi-hard seabed conditions (Jiang, 2021) and are generally considered cost-effective for installations below 40 m (Chen and Kim, 2021). Installation is generally performed using impact or vibratory driving, with drilling or boring required in rocky seabeds (Jiang, 2021; Wu et al., 2019).

Their response is governed by lateral cyclic loading, which generates significant bending moments at mudline and progressive rotation (Wu et al., 2019). Design must therefore satisfy ultimate, serviceability, and

fatigue limit states (Arshad and O'Kelly, 2016). Arany et al. (2017) proposed a structured 10-step preliminary design methodology integrating structural resistance, geotechnical capacity, stiffness evaluation, natural frequency verification, long-term deformation assessment, and fatigue checks. The procedure is iterative, requiring dimension updates whenever safety or performance criteria are not satisfied.

Initial diameter selection is typically governed by structural yielding considerations (Arany et al., 2017), and wall thickness may be estimated according to API RP 2A-WSD (2014):

$$t_p \geq 6.35 + \frac{D_p}{100} \quad (1)$$

Embedment length may be estimated following DNV-OS-J101 (2014). For normally consolidated clay or cohesionless soils:

$$L_p > 4.0 \left(\frac{E_p I_p}{n_h}\right)^{\frac{1}{5}} \quad (2)$$

where n_h is the lateral soil resistance parameter. For overconsolidated clays:

$$L_p > 2.5 \left(\frac{E_p I_p}{k_h D_p}\right)^{\frac{1}{4}} \quad (3)$$

where k_h is the modulus of subgrade reaction. The required platform elevation above mudline may be estimated as (DNV-OS-J101, 2014):

$$L_s = HWL + H_{m,50} + 0.2H_{s,50} \quad (4)$$

Lateral stiffness and deformation are commonly evaluated using the nonlinear p-y method, in which soil resistance is represented by uncoupled nonlinear springs along an Euler–Bernoulli beam (Gupta and Basu, 2020). Although incorporated in API and DNV frameworks, this approach may not fully capture long-term cyclic degradation under wind turbine loading spectra (Wu et al., 2019). Fatigue assessment typically follows DNV-RP-C203 (Arany et al., 2017).

3.1.3 Tripod Foundations

Tripod foundations consist of a central steel column connected to three piles arranged in an equilateral triangular configuration (Wang et al., 2018; Wu et al., 2019). Derived from monopile concepts, they redistribute tower loads to three discrete supports, increasing global stiffness and moment resistance relative to single-pile systems (Wang et al., 2018; Wu et al., 2019). This configuration improves rotational control at mudline and limits tower deflections (Malhotra, 2007). Tripods are typically applied in water depths of 10-35 m (Wu et al., 2019).

Geotechnical behavior has been investigated under ultimate and cyclic loading. Zhao et al. (2017) developed analytical formulations for ultimate lateral capacity in undrained clay. Jeong et al. (2021) proposed a simplified method for long-term rotational stiffness estimation based on vertical pile stiffness interaction. Cyclic deformation mechanisms have been examined experimentally and numerically (Ochmański et al., 2021), while centrifuge studies addressed bearing and installation mechanisms (Senders, 2008). Conceptual structural design considerations are discussed by Wijngaarden (2013).

Tripods are suitable for stiff clay and medium-to-dense sand deposits and may also be adopted in softer soils depending on design requirements (Chen and Kim, 2021). However, fabrication and simultaneous installation increase structural weight and construction complexity compared to monopiles, resulting in higher deployment costs (Wang et al., 2018; Chen and Kim, 2021). Scour effects under wave and current action may influence performance and require consideration in design (Ma et al., 2018; Chen and Kim, 2021).

3.1.4 Jacket Foundations

Jacket foundations are space-frame steel structures composed of three or four tubular legs interconnected by bracing members and supported by multiple piles (Malhotra, 2007; Wu et al., 2019; Jiang, 2021). Adapted from offshore oil and gas platforms, they are typically applied in intermediate water depths of approximately 5-50 m (Wu et al., 2019).

Their trussed, open-frame configuration provides high global stiffness and structural redundancy while reducing hydrodynamic loading relative to solid-section foundations (Malhotra, 2007; Wu et al., 2019). This makes jackets suitable for severe offshore environments with significant wave and current actions.

Conceptual design follows structured procedures integrating geometric definition and dynamic verification (Jalbi and Bhattacharya, 2020). After establishing the design basis, preliminary external dimensions are defined, including platform elevation, leg spacing, batter angle, bracing configuration, and bay geometry. The platform height may be determined using the same environmental clearance criteria adopted for monopiles, from which the number of bracing levels is defined. Typical batter angles are approximately 1:6, with diagonal brace intersections near 45°. Initial leg diameters and thicknesses are selected based on fixed-base natural frequency requirements of the coupled tower–jacket system, and brace dimensions are subsequently defined to satisfy stiffness and strength criteria (Jalbi and Bhattacharya, 2020).

Despite their structural efficiency, jackets involve greater fabrication, transportation, and installation complexity than monopiles, leading to higher deployment costs (Wang et al., 2018; Chen and Kim, 2021). Their heavier and more intricate substructure increases construction demands relative to simpler bottom-fixed alternatives (Chen and Kim, 2021).

3.2 Suction caissons

Suction caissons, or bucket foundations, are cylindrical steel skirts closed at the top and connected to a central column, transferring loads through skirt-soil interaction and base resistance (Malhotra, 2007; Sturm, 2017; van Dijk, 2018). Installation begins with self-weight penetration, followed by suction-assisted embedment achieved by pumping water from inside the caisson to create a pressure differential that drives the skirt to the required depth (Malhotra, 2007; van Dijk, 2018).

They are particularly suitable for soft clay seabeds (Wu et al., 2019) and are considered cost-effective solutions for shallow and transitional waters (Oh et al., 2018; Wu et al., 2019). Compared with driven piles, installation generates reduced vibration, noise, and sediment disturbance (Oh et al., 2018). However, suction foundations remain relatively recent in offshore wind applications, and their design and installation procedures continue to evolve with field experience (Sturm, 2017; van Dijk, 2018).

Design methodologies for clay and sand were established by Houlsby and Byrne (2005a, 2005b), addressing installation resistance, bearing capacity, and uplift capacity. The applied suction pressure must remain below critical limits to prevent soil plug instability or hydraulic failure (Houlsby and Byrne, 2005a; van Dijk, 2018). Design typically involves definition of soil stratigraphy and loading conditions, preliminary geometric selection, verification of installation feasibility, and assessment of serviceability performance and stiffness interaction (Sturm, 2017; van Dijk, 2018). Performance prediction becomes more complex in layered soils or in the presence of gravel and coarse inclusions, which may restrict penetration and influence long-term response (Sturm, 2017; van Dijk, 2018).

3.3 Floating foundations

Floating foundations (Figure 2) are adopted when increasing water depth renders bottom-fixed systems technically or economically impractical (Wu et al., 2019). In deeper waters and soft seabed conditions, they become comparatively more viable, although overall cost is strongly influenced by mooring configuration and line length (Chen and Kim, 2021). Adapted from offshore oil and gas practice, floating wind systems require adjustments to account for the lower mass and distinct dynamic response of wind turbines (Lefebvre and Collu, 2012).

Floating platforms are generally classified into three main concepts: spar-buoys, which achieve stability through deep ballast; semi-submersibles, which rely on distributed buoyancy and wide waterplane area; and tension leg platforms, which are vertically moored by taut tendons. Each configuration exhibits distinct hydrodynamic behavior and mooring requirements. Barge types are less common as semi-submersibles are preferred - with similar stabilization mechanisms - due to their superior hydrodynamic performance.

Stability is achieved through buoyancy combined with mooring and anchoring systems designed to satisfy hydrostatic equilibrium (Jiang, 2021). Preliminary sizing focuses on floatability, restoring moment capacity, and hydrostatic stiffness to control pitch and roll motions (Lefebvre and Collu, 2012; Collu and Borg, 2016). Ballast systems ensure adequate draft and counterbalance gravitational loads, while inclination limits are typically defined during conceptual design to maintain operational stability (Collu and Borg, 2016). Dimensioning is therefore governed by buoyancy and restoring moment relationships, followed by simplified hydrostatic and stability analyses (Lefebvre and Collu, 2012; Collu and Borg, 2016).

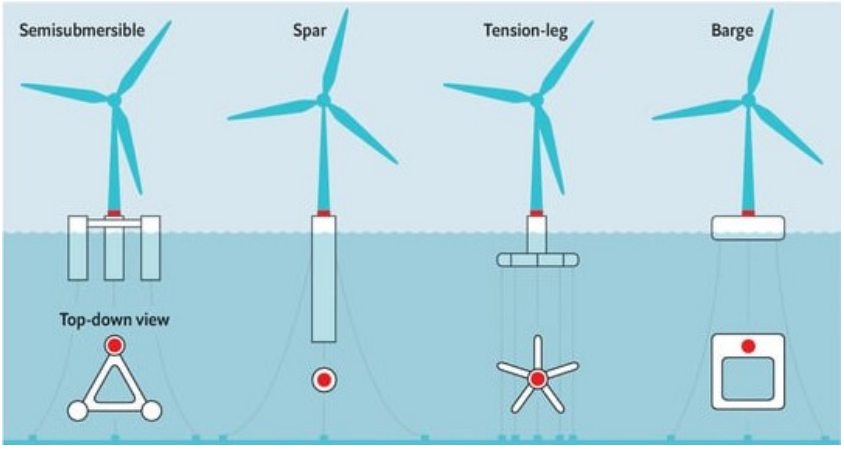


Figure 2. Schematic diagram of floating foundation types for offshore wind turbines (Mei and Xiong, 2021).

Wave-induced motions constitute a primary design challenge due to their influence on turbine performance (Collu and Borg, 2016; Jiang, 2021). Mooring systems may adopt catenary configurations, which rely on line self-weight and are suited to deep waters, or taut systems, which mobilize axial stiffness and are more appropriate for shallower sites (Lefebvre and Collu, 2012). Installation typically involves platform positioning, ballasting (for spar-type concepts), and mooring hook-up operations (Jiang, 2021).

Early-stage design generally follows guidelines and recommended practices issued by certification authorities, with detailed verification requiring advanced numerical modeling and dynamic analysis beyond preliminary assessment (Collu and Borg, 2016).

From a comparative perspective, bottom-fixed systems are governed by cyclic soil-structure interaction and stiffness control, whereas floating systems are primarily controlled by hydrostatic equilibrium and mooring system dynamics. Monopiles remain the dominant solution in shallow to intermediate depths due to simplicity and cost-effectiveness, while jackets and tripods provide enhanced stiffness in larger turbines and harsher environments. Gravity-based foundations may be limited by seabed preparation requirements, and suction caissons present advantages in soft clays but require careful evaluation in layered or carbonate soils. For Brazilian offshore conditions, where extensive shallow continental shelf areas coexist with stratified deposits, foundation selection must balance cyclic performance, installation feasibility, and soil variability.

4 CONCLUSIONS AND FUTURE PERSPECTIVES

This study presented a critical and structured review of offshore wind turbine foundation systems, focusing on mechanical behavior, soil-structure interaction, and preliminary design methodologies relevant to Brazilian offshore conditions. Bottom-fixed solutions - gravity-based, monopile, tripod, jacket, and suction caisson foundations - remain technically viable for extensive shallow regions of the Brazilian continental shelf, whereas floating systems extend feasibility to deeper waters. The review consolidated the analytical basis of the formulations and limit state procedures currently adopted in international practice and examined their implications for preliminary design and foundation selection.

The synthesis confirms that cyclic lateral loading governs the response of most bottom-fixed foundations. Accurate prediction of stiffness and rotation is therefore central to dynamic performance and long-term operability (Bhattacharya and Adhikari, 2011; Wang et al., 2018; Wu et al., 2019). Although IEC, DNV, ISO, and API frameworks provide consistent safety formats and verification procedures (Arany et al., 2017; Hu, 2022; Jalbi and Bhattacharya, 2020), many simplified approaches rely on idealized soil models and homogeneous profiles. Brazilian offshore sediments may include stratified deposits, soft clays, and carbonate sands (Azevedo et al., 2020), introducing uncertainty in stiffness degradation, accumulated rotation, and capacity prediction under long-term cyclic loading.

Installation constraints further influence foundation reliability. Driveability of large-diameter monopiles (Jiang, 2021), suction caisson penetration in layered soils (Sturm, 2017; van Dijk, 2018), and scour effects in pile-supported systems demonstrate that constructability and in-service performance are intrinsically coupled. For floating foundations, while hydrostatic equilibrium and restoring analyses are well established (Lefebvre

and Collu, 2012; Collu and Borg, 2016), refinement of coupled aero–hydro–soil dynamic modeling remains necessary to capture turbine-specific sensitivity.

Brazil currently lacks dedicated technical standards for offshore wind foundations and relies on international guidance developed for distinct sedimentological and metocean conditions. Calibration of design parameters to Brazilian soils, improved cyclic characterization, integrated installation-performance assessment, and implementation of monitoring programs are strategic priorities for reducing epistemic uncertainty and ensuring consistent reliability.

By consolidating existing methodologies, highlighting governing mechanical mechanisms, and identifying critical domains requiring calibration under Brazilian offshore conditions, this study contributes to a technically consistent basis for foundation selection. The findings support safe, economical, and sustainable offshore wind deployment in Brazil while reinforcing the need for integrated geotechnical characterization, cyclic assessment, and installation-performance validation.

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