v. 4, n. 26, 2024

Journal of
Engineering
Research

STRUCTURAL ANALYSIS INTEGRATION METHODOLOGY FOR GRAVITY-BASED FOUNDATION DESIGN OF OFFSHORE WIND TURBINES IN BRAZIL

Acceptance date: 01/11/2024
Submission date: 18/10/2024

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Abstract: Renewable energy sources have become an increasingly attractive alternative to fossil fuels thanks to technological advances and environmental care. The Brazilian Northeast Region has experienced significant development of wind farms, with notable rates of growth and energy generation. The positive results of these parks demonstrate the enormous potential for generating energy from offshore wind turbines, leading to less visual and acoustic impacts. Most offshore wind turbines use monopile foundations and gravity-based foundations; however, due to the calcareous and sandy soil characteristics in the Northeast of Brazil, the use of fixed monopile foundations becomes more challenging, making gravity-based foundations more attractive solutions. The authors apply a methodology to tackle the various aspects related to the engineering behind the technology, following a combination of numerical systems to account for aspects such as environmental loads and tower dynamics. The cyclic nature of the loading and the soil-structure interaction are accounted for, and design criteria such as long-term damage in the reinforced concrete, ultimate limit strength, soil bearing capacity, and displacements are evaluated against international standards for a case study. This paper aims to address the challenges related to the numerical representation of gravity-based foundations applicable for shallow water offshore wind turbines.
Keywords: dynamic simulations, offshore foundations, concrete structures, wind tower.

INTRODUCTION

The use of renewable energy sources has become an increasingly attractive alternative due to technological advances and social awareness of environmental care. In this industry segment, the Brazilian Northeast has shown a great development of onshore wind farms, with significant rates of growth and energy generation. The positive results of the implementation of these parks demonstrate the enormous potential of wind power generation by the installation of offshore turbines, leading to less visual and acoustic impact on the surrounding populations.

The foundation must provide adequate suпport and stability for the offshore wind turbines (OWT) under various loading conditions, such as wind, wave, current, ice, and seismic. Moreover, the foundation must be compatible with the site characteristics, such as soil resistance, bathymetry, water depth and the operational conditions. Therefore, the selection and design of the foundation, as well as the numerical simulation of its behavior, are crucial steps for the feasibility assessment, design, and optimization of offshore wind projects.

Most offshore wind turbines use monopile foundations and gravity-based foundations (GBF); however, due to the calcareous and sandy soil characteristics in the Northeast of Brazil, the use of fixed monopile foundations becomes more challenging, allowing gravity-based foundations as attractive solutions. Motivated by the positive perspectives associated with the development of offshore parks in the region, the authors propose a numerical integrated methodology to represent the actual conditions a GBF of an OWT will be submitted to during the design life, allowing that all the excitations that influence the design are considered and permitting the integrity verification of the structural system under extreme conditions and fatigue.

The premise of a sandy and homogeneous soil, due to the lack of actual site data characterization available in the current literature, allows the soil-structure interaction to be accounted for by a sequence of simulations applying specialized engineering software and, consequently, enables a methodology based on what is available in terms of representation of each component isolated and accounting for a level of interaction among the physical effects, taking into account their dynamics and geotechnical aspects, as well as the normative and safety requirements.

The research also aims to contribute to the development of guidelines and best practices for the analysis of GBF for OWT, aiming the application, improvement of the efficiency, and demonstration of the reliability of these systems in the context of sustainable energy generation in Brazil.

THE USE OF GBF FOR OWT

Offshore wind energy is one of the fastest-growing renewable energy sources in the world, with a global installed capacity of about 67.4 GW by the end of 2023, according to the World Forum Offshore Wind (WFO, 2024). The main advantages of offshore wind energy generation are the higher and more stable wind speeds, the lower noise and visual impacts, and the possibility of installing larger turbines when compared to onshore ones. However, offshore wind energy also faces some challenges, such as higher costs, logistics difficulties, harsh environmental conditions, and complex design and construction issues.

Several types of foundations have been used or proposed for shallow water OWT, such as monopiles, steel piles in jackets and tripods, reinforced prestressed concrete or steel gravity-based, suction piles, and others. The choice of the foundation depends on several factors, such as the size and weight of the turbine, the water depth, the soil conditions, the installation method, and the cost-effectiveness of the overall solution. According to the European Patent Office and the International Renewable Energy Agency (IRENA, 2023), there is an increased invention in offshore wind with dominance in Europe, Asia and USA, with the former emerging as a future market and showcasing the urge for more research in this area.

Gravity-based foundations are one of the oldest and simplest types of foundations for offshore structures. They consist of a massive concrete or steel structure that rests on the seabed by its own weight without any imposed penetration or mooring. GBF usually have a hollow cylindrical or conical shape, with a flat or stepped base and a tapered or flared upper part. The hollow section can be filled with ballast material, such as sand, gravel, debris, or water, to increase the stability and reduce the scour effects. The GBF can also have skirts or piles attached to the base to improve the bearing capacity and lateral resistance (Mathern, et al., 2021).

GBF have some advantages over other foundation types, such as the simplicity of the design and construction, the ease of installation and decommissioning, the reduced environmental impact, and the possibility of prefabrication and escalated production. However, GBF also have some drawbacks, such as the high strength material needs and transportation costs, the large footprint and seabed preparation requirements, the sensitivity to uneven or sloping seabed, and the limited applicability for deep water and soft soil conditions. Therefore, GBF are more suitable for shallow waters, e.g., less than 30 m, and sandy soil sites, where the self-weight of the system associated with the soil bearing capacity can provide enough stability for the OWT.

In 2008, gravity-based substructures were installed in water depths of about 20 m at Thornton Bank, which constituted the deepest application of this type of substructure for almost a decade, up until the installation of the gravity-based substructures for the Blyth Offshore Demonstration Project in 2017 at water depths of almost 40 m. These new-generation gravity-based substructures off the coast of Northumberland, in the Northeast of England, constitute a milestone in the use of this type of substructures in deeper waters, from which five concrete gravity-based substructures were built and installed at water depths up to 42 m to support 8 MW turbines (Mathern, et al., 2021). In France, 71 concrete gravity-based foundations were inaugurated in 2024 at the Fécamp Offshore Wind Farm to support 7 MW turbines at depths between 25 m and 30 m and distances between 13 km and 22 km from shore, exceeding by this project the number of gravity-based foundations installed in Europe since 2010. The construction started in June 2020, with the production of its first megawatt-hour in July 2023 and full connection to the grid in May 2024.

METHODOLOGY

The assessment of the integrity of such an offshore system consists of four main steps: (1) definition of the design parameters and the environmental loads; (2) geotechnical analysis and definition of the soil-foundation interaction; (3) structural analysis and design of the GBF; and (4) verification of the stability and performance of the GBF under loads. The workflow of the numerical methodology proposed by the authors is illustrated in Figure 1 and detailed in the following subsections.

The analysis and design of foundations for offshore wind structures must comply with specific standards and regulations. An overview of the relevant international and national standards for the design of wind turbine foundations in Brazil is presented in the study developed by Moraes (Moraes, 2024), with a special focus on NBR 6118 (Brazilian Standard for Concrete Structures Design) and other pertinent normative.

Assuming the use of an integrated tool is not a reality, accounting for the several sources of complexities that are sought in this development, the methodology proposed involves the use of specialized engineering software, including, but not limited to, the use of the software PLAXIS 2D for geotechnical analysis, SACS for offshore structural analysis, and STAAD for structural analysis and design of the reinforced concrete gravity-based foundation.

The methodology of integrated analysis is divided into several interconnected steps, which range from the characterization of the soil to the final verification of the foundation. The steps include the soil characterization through internal friction angle, cohesion, and specific weight. The geotechnical simulation is performed in PLAXIS 2D, as the software is used to create a representative mesh of the soil applying an axisymmetric formulation for gravitational associated loads, and plain state for the horizontal loads and the moments accounting for equivalent geometrical properties. Through the simulation tool, unit loads on a rigid element with the dimensions of the foundation are transferred to the soil model. This simulation allows the determination of the equivalent spring stiffnesses representative of the soil-structure response to be accounted for in the subsequent simulation steps.

The software SACS is used to perform a modal analysis of the structure, determining its natural frequencies and vibration modes. The wave and wind spectra, obtained from real or modeled data (here modeled) are inversely Fourier transformed on the

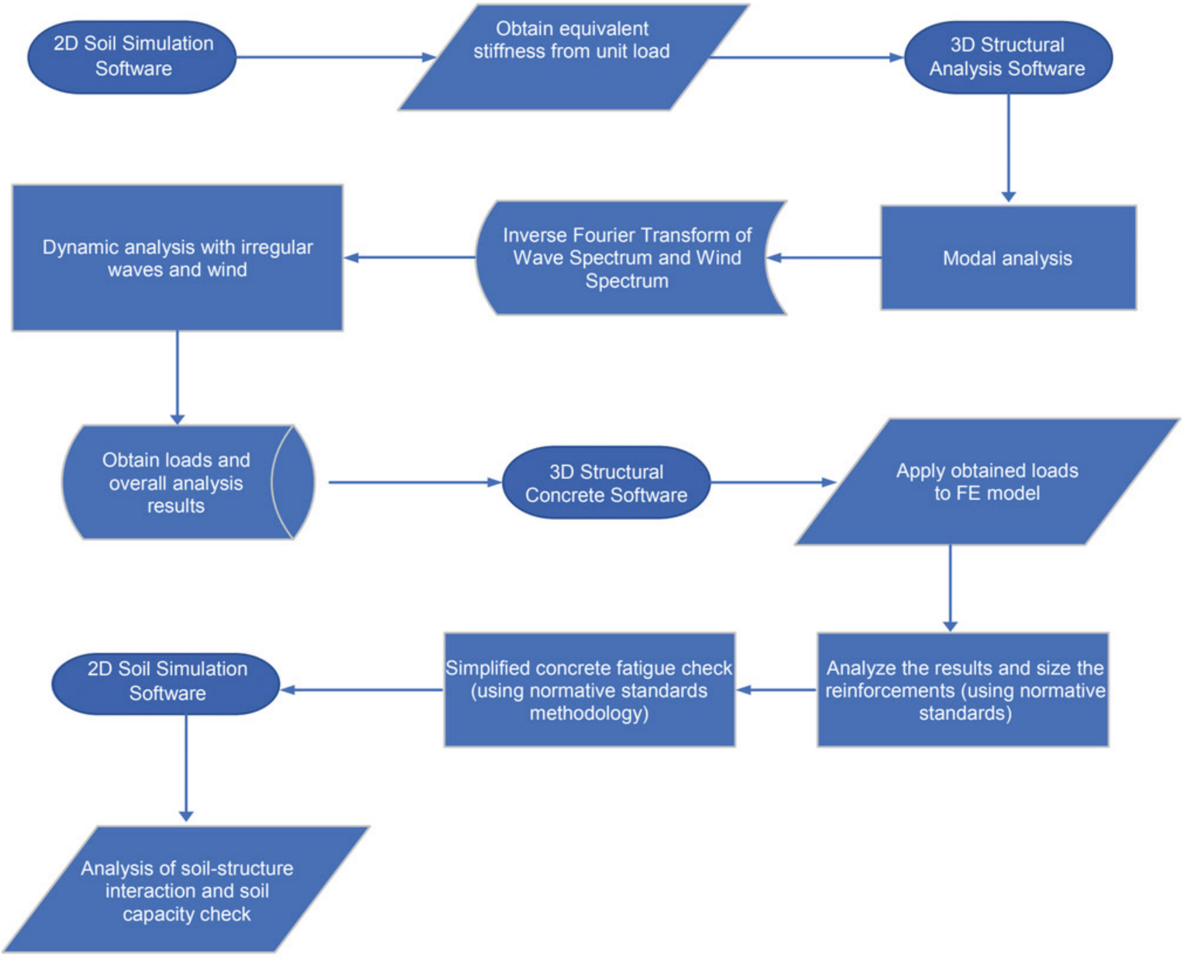

Figure 1. Numerical Methodology Flowchart

development of irregular time series for the time domain dynamic simulations. The wind loads are applied directly to each of the wind turbine blades, considering the shape factors associated with each element; wave loads follow the same approach for submerged elements. The aforementioned stochastic loads are incorporated in addition to the environmental water current loads.

The reinforced concrete structure of the foundation is modeled using STAAD through finite elements representing the actual geometry of the system. The forces and moments obtained in the SACS analysis are treated and applied as nodal loads at the top of the foundation. In this step, verifications are carried out in accordance with the applicable standards and regulations, such as NBR 6118 and DNV standards. The design of the foundation reinforcements is executed, ensuring overall safety and stability criteria. The concrete fatigue is evaluated according to the simplified method proposed by DNV (DNV, 2018), considering the cyclic dynamic loads imposed on the foundation by the thrust arising from the wind loads as well as water waves in the submerged elements. This analysis step aims to ensure the service limit state during the design life of the foundation.

Final verification is performed in PLAXIS 2D again for obtaining soil stresses and proceed to the check against soil failure modes. In addition, the maximum displacements of the foundation under extreme dynamic loads are verified.

CASE STUDY

The OWT considered is a generic 10 MW turbine with a hub height of 120 m, a rotor diameter of 178 m, and a nacelle weight of 400 t. The GBF is assumed to have a cylindrical shape with a height of 30 m, an outer diameter of 18 m, and a wall thickness of 60 cm. The GBF is made of reinforced concrete, with a unit weight of 25 kN/m^3, a compressive strength of 50 MPa, and a tensile strength of 3.5 MPa. The GBF is also assumed to have four steel skirts attached to the base, each with a length of 6 m, a width of 3 m, and a thickness of 50 mm. The skirts have a unit weight of 78.5 kN/m^3 and a yield strength of 355 MPa. The site is assumed to be in the Northeast of Brazil, at a water depth of 20 m, with a sandy and homogeneous soil with a unit weight of 18 kN/m^3, a friction angle of 35 degrees, and a cohesion of 5 kPa.

The environmental loads include the wind, wave, current, and operational loads acting on the OWT and the GBF. The wind load is calculated based on the wind speed, the air density, the drag coefficient, and the projected area of the OWT components. The wind speed is assumed to follow a Weibull distribution, with a mean value of 10 m/s and a shape parameter of 2.0. The air density is assumed to be 1.225 kg/m^3, and the drag coefficient is assumed to be 1.2 for the tower and the nacelle and 0.8 for the blades. The wave load is calculated based on the wave height, the wave period, the water density, and the Morison equation, which correlates loading in submerged elements with the wave data by the hydrodynamic coefficients and geometry. In order to account for extreme conditions, an irregular wave is obtained from the wave spectrum of the site, which is assumed to follow a JONSWAP spectrum, with a significant wave height of 8 m and a peak period of 12 s. The water density is assumed to be 1025 kg/m^3, and the hydrodynamic coefficients are assumed to be 2.0 for the inertia and 1.2 for the drag, for both the tower and the GBF. The current load is calculated based on the current speed, profile, water density, drag coefficient, and the submerged projected area of the OWT and the GBF components. The current speed is assumed to be 1.0 m/s, and the drag coefficient is assumed to be the same applied to the wave load calculations.

The structural analysis and design of the GBF consist of determining the internal forces and stresses in the GBF components, thus verifying if they satisfy the ultimate and serviceability criteria. The strength criterion is based on the ultimate limit state (ULS), which requires that the maximum stresses in the concrete and the reinforcement steel do not exceed their respective resistances. The serviceability criterion is based on the serviceability limit state (SLS), which requires that the maximum deflection and cracking in the concrete do not exceed certain limits. The limits for the deflection and the cracking are assumed to be 0.003 times the height of the GBF and 0.2 mm, respectively.

The geotechnical analysis and design of the soil-foundation interaction consist of determining the bearing capacity and the displacements of the soil underneath the GBF, and verifying if they satisfy the stability and performance criteria. The bearing capacity and the displacements are obtained by applying the operational loads and the self-weight of the GBF to a numerical model of the soil. The stability criterion is based on the ULS, which requires that the factor of safety (FOS) of the soil under the GBF be greater than or equal to 1.5. The FOS is defined as the ratio between the ultimate capacity and the applied load. The performance criterion is based on the SLS, which requires that the maximum settlement and rotation of the GBF do not exceed certain limits. The limits for the settlement and the rotation are assumed to be 0.01 OD and 0.02 rad (~1°), respectively. A summary of GBF and OWT parameters is presented in Table 1, performance criteria are presented in Table 2.

Item	Value	Unit
Turbine	10	MW
Hub Height	120	m
Rotor Diameter	178	m
Nacelle Weight	400	t
GBF Shape	Cylindrical	-
GBF Height	30	m
GBF Outer Diameter	18	m
GBF Wall Thickness	60	cm
GBF Material	Reinforced Concrete	-
GBF Unit Weight	25	kN/m³
GBF Compressive Strength	50	MPa
GBF Tensile Strength	3.5	MPa
GBF Skirts	4	-
Skirt Length	6	m
Skirt Width	3	m
Skirt Thickness	50	mm
Skirt Unit Weight	78.5	kN/m³
Skirt Yield Strength	355	MPa
Site Location	Northeast of Brazil	-
Water Depth	20	m
Soil Type	Sandy and Homogeneous	-
Soil Unit Weight	18	kN/m³
Soil Friction Angle	35	degrees
Soil Cohesion	5	kPa
Wind Speed Distribution	Weibull	-
Mean Wind Speed	10	m/s
Shape Parameter	2.0	-
Air Density	1.225	kg/m³
Drag Coefficient	1.2 (tower & nacelle), 0.8 (blades)	-
Wave Significant Height	8	m
Wave Peak Period	12	s
Water Density	1025	kg/m³
Hydrodynamic Coefficients	2.0 (inertia), 1.2 (drag)	-
Current Profile	Constant	-
Current Speed	1.0	m/s

Table 1. Summary of the GBF and OWT parameters

The verification of the stability and performance of the GBF under extreme load conditions consists of checking if the GBF can withstand the most severe combination of environmental loads without failure or excessive deformation. The extreme load condition is defined as the collinear combination of the maximum wind load, the maximum wave load, the maximum current load, and the maximum operational load, which occur with a very low probability during the design life of the OWT. The verification is done by applying the extreme load condition to the finite element model of the GBF and the numerical model of the soil, then comparing the results with the ultimate, serviceability, stability, and performance criteria. Analyses models are presented in Figure 2.

Strength Criterion	Ultimate Limit State	Unit
Serviceability	Serviceability Limit State	-
Deflection Limit	0.003 x GBF height	m
Cracking Limit	0.2	mm
Stability	Ultimate Limit State	-
Factor of Safety	1.5	-
Performance	Serviceability Limit State	-
Settlement Limit	0.01 x GBF OD	m
Rotation Limit	0.02	rad

Table 2. Summary of the GBF and OWT criteria

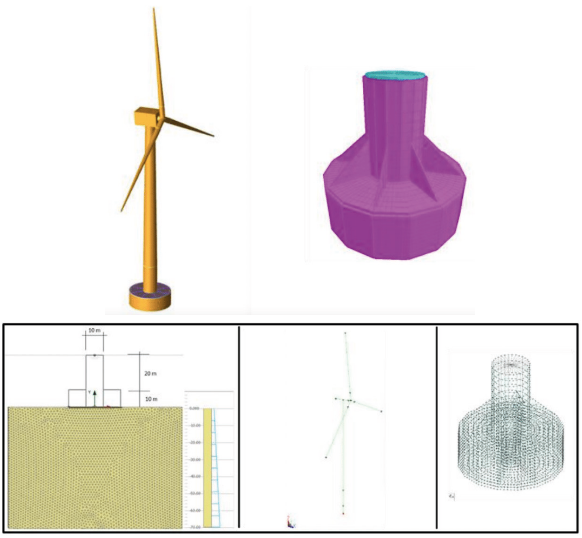

Figure 2. Analyses models for the OWT and GBF Solid Shapes Upper and Meshes Lower

RESULTS AND DISCUSSION

The GBF submitted to the methodology satisfies the strength criterion for all components, with utilization factors ranging from 0.06 to 0.94. The higher utilization factor is observed for the concrete compression stress in the GBF wall, which reaches 94% of its capacity under the extreme load condition. The lowest utilization factor is observed for the reinforcement steel tension stresses in the base, which reaches only 5% of its capacity under the normal load condition. The GBF also satisfies the serviceability criterion for the overall deflection, with a utilization factor of 0.81. The maximum crack width in the GBF wall is 0.13 mm below the limit of 0.20 mm, which may not compromise the durability and watertightness of the structure, however, the prestressed reinforced concrete solutions are options to be accounted for in offshore structures.

The results of the geotechnical analysis and the soil-foundation interaction show the soil satisfies the bearing capacity criteria for all load conditions, with utilization factors ranging from 0.17 to 0.28. Regarding GBF stability, the lowest safety margin is observed for the extreme load condition, which induces a Factor of Safety of 3.56 for the overturning and 3.25 for the sliding stability in the soil underneath the GBF. The soil also satisfies the performance criterion for the settlement, with a short-term displacement of 15 cm. However, the soil violates the performance criterion assumed for the rotation - rotors and rotating equipment suppliers are to be consulted in actual projects - with maximum rotation of the GBF of 0.03 rad (1.8°) larger than the limit of 0.02 rad, which may cause excessive misalignment and vibration of the OWT. Table 3 summarizes the safety criteria for the main elements investigated in this paper.

Component	Criterion	Utilization Factor	Observation
GBF	Strength	0.06 to 0.94	The lowest concrete compression stress in the GBF wall, highest for steel tension in the base
GBF	Serviceability (Overall Deflection)	0.81	Satisfies the serviceability criterion for deflection
GBF	Serviceability (Cracking)	N/A	Satisfies the serviceability criterion for cracking, 0.13 mm against 0.20 mm
Soil	Bearing Capacity	0.17 to 0.28	-
Soil	Stability	0.42 and 0.46	Overturning and sliding
Soil	Performance (Settlement)	N/A	Satisfies the performance criterion for settlement, 15 cm against 0.01 OD
Soil	Performance (Rotation)	N/A	Violates the performance criterion for rotation, 0.03 rad larger than 0.02 rad

Table 3. Summary of the results for the OWT using GBF

CONCLUSIONS

The authors propose a numerical methodology using systems separately, allowing the application of what is available in terms of numerical analysis and design approach for gravity-based offshore wind turbines, considering structural dynamics and geotechnical aspects as well as engineering best practices. The methodology described in the paper is developed for a case study of a 10 MW turbine with a hub height of 120 m, a rotor diameter of 178 m, and a nacelle weight of 400 t.

The GBF satisfies the strength criteria for all components, including the serviceability criterion for cracking, however, some aspects may compromise the durability and watertightness of the structure, and prestressed reinforcement concrete may be a solution to overcome these challenges. The soil satisfies the stability criterion and the performance criterion for the settlement but violates the performance criterion for the rotation in the case study proposed in this paper, which may cause excessive misalignment and vibration of the OWT; the blades and rotatory equipment suppliers should be consulted in a real project. The GBF and the soil present the most critical results under extreme load conditions, with the highest internal forces and stresses for the structure, leading to higher utilization factors and displacements in the soil underneath the foundation.

It is noted throughout the execution of the study that the GBF and the soil have a significant interaction, which affects the load transfer and the deformation of the system, therefore, the integration of the structural and geotechnical models is essential for the accurate and reliable design of the foundation.

The main limitation of this work is the use of a simplified and idealized geometry and material properties for the GBF, the OWT, and the soil characterization, which may not reflect the actual conditions of a real site and a real structure. Also, it may also be a limitation the use of a linear and elastic analysis for the GBF and the soil, which may not capture the nonlinear and inelastic behavior of the structure and the soil under large deformations and stresses.

This is a research paper, and hence, it represents research in progress. This paper represents the opinions of the authors, which are the product of in-progress research. It is not meant to represent the position or opinions of the institutions or companies they represent, their members, or the official position of any staff members. Any errors are the fault of the authors.

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