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GRAVITY-BASED FOUNDATIONS FOR OFFSHORE WIND TURBINES IN ICE-INFESTED WATERS

In regions like the Bothnian Sea and the Bay of Bothnia, significant ice cover is common. In these regions, level ice as well as pressure ridges and ice keels, thick ice formations extending below the water surface, can exert extreme loads on foundations of OWT.

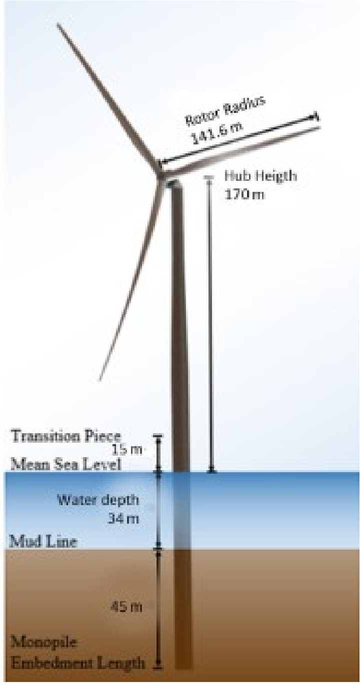
It has proven to be difficult to obtain reliable data for water depth and material properties for the seabed in the area defined for the Korsnäs Offshore Wind Farm area. While no detailed geotechnical tests have been conducted in the Korsnäs Offshore Wind Farm area, the limited available data suggest that the seabed consists of medium-dense to dense sandy moraine, which presents challenges for monopile foundations due to its high penetration resistance. Additionally, large ice-related forces further reduce the feasibility of monopiles in the Korsnäs area. However, the high load-bearing capacity of moraine makes it well-suited for offshore wind turbines with gravity-based foundations.

This study presents conceptual design of a gravity-based, reinforced concrete, foundation for offshore wind turbines in ice-infested waters.

Korsnäs Offshore Wind Farm area

The Korsnäs project will become the first offshore wind farm located in the open sea area in Finland. Vattenfall has entered a joint venture with Metsähallitus (owner) to build and operate Finland's first major offshore wind farm. Korsnäs area is located off the Finnish west coast and will have a capacity of 1.3 GW and a potential annual production of 5 TWh. During the first phase of the project, 70 to 100 turbines with a nominal power of 12 to 22 megawatts would be built in the area. Distance from Shore is about 14 km outside Vaasa in the Gulf of Bothnia. The wind conditions in the sea area off the Korsnäs shore are ideal. The average wind speed on the site may exceed 9 m/s. The water depth and seabed geology are also well suited for wind power construction. The water depth at the project site is mainly 10 to 30 m and is well suited for wind turbines with gravity-based, reinforced concrete foundations.

This study presents a conceptual design of a gravity-based, reinforced concrete, foundation for offshore wind turbines. The conceptual design is based on the IEA 22 MW Reference wind turbine (RWT), as illustrated in *Picture 1*.



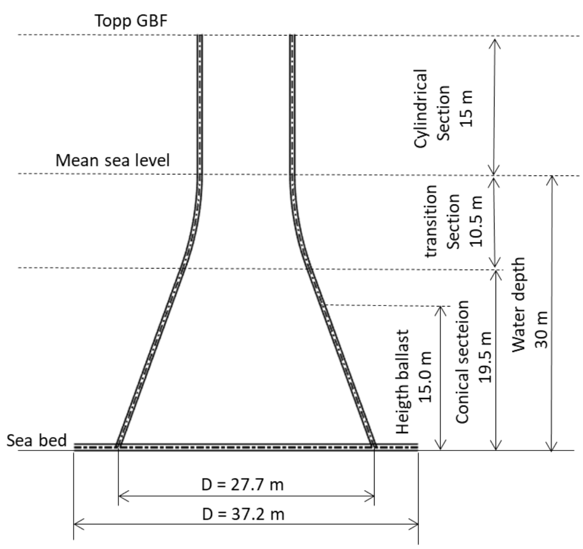
Picture 1. Illustration of IEA 22 MW Reference wind turbine.
Open source https://github.com/IEAWindTask37/IEA-22-280-RWT

The IEA 22 MW RWT has a hub-height of 170 m, with a 5.614 m vertical distance between the rotor apex and tower top. The tower is assumed to start 15 m above mean sea level and its length is therefore 149.3 m. The monopile is designed for a water depth of 34 m and its length in the seabed is 45 m, giving a total length of 94 m to reach the tower base. The assembly also includes a transition piece, of a total mass of 100 t, which is located between the tower and monopile 15 m above mean sea level. The hub height of 170 m leaves a clearance of 30 m between mean sea level and blade tip.

The presence of dense moraine makes piling difficult, rendering monopile foundations an impractical choice. In addition, the findings reported in the literature indicated that, from both a technical and economic perspective, the design of monopiles for the Bothnian Sea North and the Bay of Bothnia without ice-load-mitigating measures resulted in excessive weight and inefficient designs.

Conceptual design of the gravity-based reinforced concrete foundation

The conceptual design of the gravity-based reinforced concrete foundation is shown in *Picture 2* and key parameters provided in *Table 1*.



Picture 2. conceptual design of gravity-based reinforced concrete foundation.

The GBF is designed as reinforced concrete structure with a total height of 45 m. The conceptual design consists of a cylindrical upper section, which provides the main structural support for the wind turbine tower and NRA. The height of the cylindrical upper section is 15 m and diameter is 10 m. A transition section is placed between the cylindrical shaft and the conical lower part. It helps in load distribution by gradually transferring forces from the tower and cylindrical upper section to the broader base. The height of this transition section is 10.5 m, and the radius is equal to 30 m. A cone-shaped section extends downward from the transition piece, expanding the load-bearing area and improving overall stability. The height of the conical section is 19.5 m, and diameter is 27.2 m at the bottom, respectively. The conical shape aids in distributing forces efficiently into the seabed, reducing local stress concentrations. The conical section contributes to maximizing stability in ice-infested waters. The cone is supported by a large, circular base plate, with diameter equal to is 37.2 m, which increases the overall footprint of the foundation. This design provides additional resistance against sliding and overturning forces by spreading the load over a wider area. To further enhance stability, the conical section is filled with sand as ballast to a height of 15 m. This preliminary design represents a stable and efficient foundation solution for offshore wind turbines, particularly in regions with challenging seabed conditions, such as dense moraine and heavy sea ice environments.

Table 1. Key parameters for proposed design of 22 MW OWT with gravity-based reinforced concrete foundation.

Parameter	Value
Power rating [MW]	22
Rotor diameter [m]	283
Number of blades	3
Cut-in wind speed [m/s]	3
Rated wind speed [m/s]	11
Cut-out wind speed [m/s]	25
Hub height [m]	170
RNA mass [t]	1208
Tower top diameter [m]	6
Tower base diameter [m]	10
Steel Tower mass [t]	1574
Water depth [m]	30.0
Volume of ballast [m^3]	16242
Mass of ballast [t]	32483
Volume concrete [m^3]	2531
Mass of concrete [t]	6327

Investigated Design load cases

Gravity-Based Foundations (GBFs) for Offshore Wind Turbines (OWTs) must withstand multiple loading conditions, including dead loads (eigen loads), environmental loads (wind, waves, currents, ice), and operational loads (thrust forces). DNV-ST-0437 (*Loads* *and Site Conditions for Wind Turbines*) provides comprehensive guidance on Design Load Cases (DLCs), external loads, including wind, waves, currents, and ice.

In the conceptual design phase of the GBF, only the DLC 9.1 given in DNV-ST-0437 is considered, i.e.: 50-year sea ice conditions are investigated during power production. The environmental loads are wind loads acting along the steel tower, and ice forces acting at the waterline of the GBF. The gravitational forces due to the self-weight of the Rotor-Nacelle Assembly (RNA), steel tower, and Gravity-Based Foundation (GBF), including ballast, are critical considerations in the design and analysis of offshore wind turbine support structures.

Aerodynamic loading during power production

Thrust force is a key aerodynamic load acting on an OWT during power production. Thrust force is generated by wind pressure on the rotor blades and transferred through the nacelle to the tower. It acts horizontally at the center of the hub, causing bending moments and structural loads on the tower and GBF. The thrust force is influenced by wind speed, rotor diameter, and operational conditions, which are derived from wind turbine power curves, rotor thrust coefficients, and wind speed distributions. Data for the thrust force acting on hub is taken as for the IEA 22 MW Reference wind turbine, and the trust force is almost constant between wind speed of 9.0 m/s and 11.8 m/s, i.e., maximum thrust force is 2.66 MN. In addition to thrust force, wind pressure acts on the tower. An idealized model for the wind speed profile is used and the wind pressure is calculated as described in DNV-RP-C205 (2007).

Ice forces acting on the GBF for 50-year sea ice conditions

The ice forces acting on the GBF are calculated in accordance with ISO 19906 (Petroleum and Natural Gas Industries – Arctic Offshore Structures). It is assumed that the ice forces act horizontally at the waterline of the GBF. In this study, it is assumed that the level ice or FY force interacts with a vertical structure with a circular cross section, with structural diameter equal to the outer diameter 10.5 m. For a 50-year return period the ice thickness is 0.77 m, resulting in a global level ice force of 10.08 MN. In comparison, for the same 50-year return period for first-year ridges, the consolidated layer thickness is 1.16 m, and the keel depth is 9.6 m. The corresponding global first-year ice ridge force is 19.55 MN, which is nearly twice the magnitude of the global level ice force. The level ice force and FY ridge force cannot act simultaneously.

Gravitational forces

In accordance with DNV standards, the design of Gravity-Based Foundations (GBFs) for offshore wind turbines must account for both gravitational forces from structural components and buoyancy effects, i.e., Rotor-Nacelle Assembly (1,208 metric tons), Steel Towe (1,574 metric tons), concrete GBF (6,327 metric tons). To enhance stability, the GBF is filled with sand (32,483 metric tons) as ballast. To account for buoyancy effects, the density of materials below the waterline is reduced by subtracting the density of water. This approach aligns with standard engineering principles and is consistent with DNV recommendations for offshore foundation design.

Stability of GBF

DNV-RP-C212 (Offshore Soil Mechanics and Geotechnical Engineering) outlines a systematic approach for verifying the stability of GBFs. In this conceptual design phase, stability is assessed through bearing capacity, sliding resistance, and overturning resistance. In the ultimate limit state, stability is verified by applying partial material factors to the characteristic soil properties and partial load factors to the external forces.

Control of Bearing Capacity

The bearing capacity of the Gravity-Based Foundation (GBF) is evaluated in the ultimate limit state and checked against two different failure mechanisms—Rupture Type 1 and Rupture Type 2—according to DNV-RP-C212. Rupture Type 1 corresponds to general shear failure, which occurs when the foundation soil undergoes a global bearing capacity failure, leading to large plastic deformations and potential foundation collapse. The failure surface extends outward from the base of the foundation in a well-defined shear zone. This type of failure is more common in dense or stiff soils, where significant resistance is mobilized before failure occurs. Rupture Type 2 corresponds to punching shear failure, which occurs when the foundation penetrates the soil without fully mobilizing a large failure surface. The soil beneath the foundation experiences local shear failure, potentially causing the foundation to progressively sink into the seabed. This failure mode is more common in soft or loose soils, where there is insufficient lateral support to develop a full shear mechanism. The bearing capacity utilization factor is defined as the ratio of effective soil pressure divided by design bearing capacity. In this case, with a base plate diameter of 37.2 m, the bearing capacity utilization factors are: 0.12 for Rupture Type 1 and 0.29 for Rupture Type 2. To ensure foundation stability, the bearing capacity utilization factor must remain below 1.0, preventing bearing failure.

Control of sliding resistance

Sliding resistance is the ability of a foundation to resist horizontal movement caused by external lateral forces. In this case, the lateral forces consist of the thrust force acting at the hub, wind pressure on the tower, and ice forces acting on the GBF under 50-year sea ice conditions, as described above. In principle, sliding resistance is primarily determined by friction between the foundation base and the seabed soil and vertical loads acting on the foundation, which press it against the seabed. The sliding resistance utilization ratio is defined as the total horizontal force acting on the foundation divided by the available sliding resistance. In this case, the sliding resistance utilization ratio is 0.15 < 1.0, indicating that there is no risk of sliding.

Control of Stability against Overturning

The stability of a Gravity-Based Foundation (GBF) must be verified against overturning failure, ensuring that the structure remains securely positioned on the seabed under extreme environmental loads. Overturning occurs when the sum of horizontal forces and moments acting on the foundation generates an excessive tilting effect, potentially causing rotation or uplift of the structure. Overturning forces and moments occur due to the thrust force at the hub, wind pressure acting along the height of the steel tower, and ice forces from drifting level ice or FY ice ridges, particularly in 50-year return period conditions. The foundation must develop sufficient restoring moments to counteract the overturning effects. The resisting forces and moments include the gravitational forces from the RNA, tower, concrete GBF and ballast material. In this case the ratio of the total overturning moment from external forces divided by total restoring moment from gravity and soil reaction is 0.8<1.0 and indicates that there is no risk of overturning.

Summary

Gravity-Based Foundations (GBFs) are a favored choice for offshore wind turbines in ice-infested waters due to their inherent stability and ability to withstand heavy ice-induced forces. These structures rely on their substantial weight and broad base area to remain securely anchored on the seabed, effectively resisting the horizontal pressures exerted by moving ice. This design significantly reduces the risk of displacement or structural failure, ensuring the reliable operation of wind turbines in harsh icy conditions.

GBFs are most suitable for shallow to medium water depths (10–50 meters), where ice loads are particularly severe. In deeper waters exceeding 50 meters, the size and cost of GBFs increase substantially, making them less viable

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