A NOVEL OFFSHORE WINDMILL FOUNDATION FOR HEAVY ICE CONDITIONS

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ABSTRACT
A pilot offshore wind turbine with a new type of an ice-resistant foundation was installed in the Pori sea area of the Northern Baltic Sea during summer 2010. The water depth at the site is nine meters and the ice and wave conditions occasionally get quite heavy.

The gravity-type foundation consists of a light ice-strengthened steel shell with a ring footing, ice-breaking cone, and crushed rock fill. The fill provides mass for the foundation and supports the shell against local ice impacts and moments caused by uneven base pressures, as well as stability for the thin shell structure. The ring footing extends the stabilizing moment arm and provides anchorage against overturning.

This foundation concept is applicable to a variety of water depths with firm to hard bottom conditions. Foundation erection is fast and easy, making it well-suited for industrial wind farm roll-out.

INTRODUCTION
Europe is committed to increasing the share of renewable energy in total energy production. As a part of that effort, Finland has set itself a target of installing 2,000 MW of wind power capacity by 2020 (up from 147 MW at the end of 2009).

Offshore wind power has the advantages of good wind potential and greater social acceptability than onshore wind power. The northern Baltic Sea is particularly attractive among sub-arctic sea areas as it offers large shallow areas suitable for industrial-scale wind power development (Fig. 1).

Although windmills have been installed in areas with seasonal ice, no windmill to our knowledge has been erected in an area with heavy dynamic ice conditions. The main technical challenge was to develop a concept that could deal with ice and wave loads in a variety of water depths and bottom conditions, and allows for erecting dozens of turbines within a short seasonal window. Pile foundations are problematic in hard and rocky bottom conditions, and traditional caisson foundations tend to be expensive.

Suomen Hyötytuuli Oy, a Finnish wind power company, wishing to gain experience, adopted a gravity-based steel foundation concept described in Eranti et al. (2003) to construct a pilot windmill in the Pori Tahkoluoto offshore area (Fig. 2).
Manufacturing and installation of the foundation was performed by Technip Offshore Finland (TOF), a subsidiary of the Technip Group. Foundation engineering and design was shared between TOF and the concept developer Eranti Engineering Oy.

The site offered several advantages for the pilot project (Fig. 3). It is located in a zone of occasionally heavy and dynamic ice conditions. During major western storms, there are large breaking waves at the site. It is just two kilometers to the nearest access point to the national high-voltage grid. TOF’s Mäntyluoto manufacturing and harbor facilities lie about 10 kilometers from the site.

The Tahkoluoto area has several operational wind turbines. The expansion potential in its near-shore area is 50 MW with an additional 200 MW farther offshore.

THE PILOT FOUNDATION
A diagram of the pilot foundation appears in Figure 4. Unlike traditional, gravity-based offshore structures, the foundation is light and has an open bottom, making it easy to lift into place.

The purpose of the ring footing is twofold. It increases the stabilizing moment arm, and the tension side acts as an anchorage against slip under dynamic loads.

Figure 2. The pilot wind turbine in February 2011.

Figure 3. Map of the project area.
Granular fill provides the major portion of the gravity and stability for the foundation. The entire weight of the fill acts against sliding and roughly 90% against overturning due to the arching effect (as verified by model tests and FEM analysis). The fill also supports the shell against local ice loads, as well as stability loss under compressive and bending loads.

The conical shape helps reduce ice and wave loads, and effectively eliminates ice-induced vibration, as shown in Eranti et al. (2003). (For the dynamic ice structure interaction model and its verification, see Eranti, 1992.) The foundation does not respond much to the ice force and the tower with the turbine is too slow to react to the ice force fluctuations.

The foundation dimensions are a result of iteration-balancing of ice and wave forces.

Figure 4. Diagram of the pilot foundation.

SITE CONDITIONS AND LOADS

The turbine site is located between two shallows at a depth of 9 meters. The bottom consists of a layer of dense sandy and fairly stony gravel about 10 meters thick, overlaying bedrock.

Winter ice conditions in the area, although generally light with mainly thin, broken ice floes, can be severe. The once-in-50-years freezing index is based on past history close to 1,500 degree-days (Celsius). A century of ice mapping in the Finnish coastal areas in general and half a century of ice mapping in Pori’s offshore areas indicates that ice conditions at the site occasionally feature thick ice with heavily consolidated ice ridges and stamukhas. Year-round navigation in nearby shipping lanes increases the probability of ice dynamics during storms.

The characteristic ice-loading condition is an ice ridge impact. The ridge has a consolidated ice thickness of 1.2 meters and a keel thickness of 8 meters. Results from the Kemi 1 Test Cone Project (Fig. 5), as well as experience gathered from 200 Finnish ice-resistant offshore structures (lighthouses and channel markers) were used in creating the ice design basis.

The ice-ridge load was calculated by combining the solid ice failure component with the keel failure component. Ralston (1977) was used to calculate the solid ice failure component, while basic soil mechanics were applied for the keel failure component.

Figure 5. The Kemi 1 lighthouse, equipped with a force-measuring test cone, was subjected to heavy ice conditions (photo: Enqvist and Eranti, 1990).
The 50-year significant wave height for the Bothnia Sea is around 7 meters with a period of 11 seconds. However, the effects of shoals and shallow water are felt at the pilot wind turbine site. The governing wave loading condition corresponds to an impact of 8 meter-high spilling breaker with a period of 10 seconds.

The Siemens 2.3 MW wind turbine had a hub height of 80 meters.

The following characteristic loads and moments at base level were used in the foundation design:

<table>
<thead>
<tr>
<th></th>
<th>Wind</th>
<th>Ice</th>
<th>Wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>0.85 MN</td>
<td>6.1 MN</td>
<td>3.9 MN</td>
</tr>
<tr>
<td>Moment</td>
<td>70 MNm</td>
<td>40 MNm</td>
<td>32 MNm</td>
</tr>
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Add-freeze bond failure of ice and drifting ship impact were considered as exceptional loading cases. Local ice pressure criteria corresponding to design ice ridge impact are shown in Fig. 6.

Local ice and wind records were studied 50 years back in order to determine characteristic load combinations. It was found that extreme wind force was unlikely to occur simultaneously with severe ice conditions. On the other hand, there has to be a storm to dislodge heavy ice in the area. Based on wind speed records from severe-ice winters, it was concluded that $F = F_{\text{ice}} + 0.6 F_{\text{wind}}$ would be a conservative estimate for the characteristic load combination.

While the once-in-50-year sea state may exist when the once-in-50-year wind gust occurs, it is highly unlikely that the 50-year wave load will also occur within seconds of this gust. However, due to limited water depth, there may be more spilling breakers at the site than extreme waves at the open sea if the 50-year storm wind has sufficient duration and comes directly from the west. Based on Monte Carlo simulations, $F = F_{\text{wave}} + 0.9 F_{\text{wind}}$ and $F = 0.9 F_{\text{wave}} + F_{\text{wind}}$ were used as conservative estimates for characteristic load combinations.

The geotechnical functioning of the foundation was studied extensively in the feasibility study phase with model tests and FEM-simulations (Eranti et al., 2003). In the final design phase, the service level performance and stability were calculated using hand calculations and PLAXIS–3D finite element software.

The structural analysis was performed with ASAS FE software. Soil support was included in the cylindrical section. Granular fill support and membrane forces were shown to reduce the shell moments caused by uneven pressures on the ring footing, especially under extreme global loads. Plastic FEM-analysis up to failure revealed that the structure possessed considerable capacity reserve under local loads thanks to membrane forces (Fig. 7).

**STRUCTURAL ANALYSIS AND DESIGN**

A hierarchic engineering approach was developed for the foundation following the Foundation Analysis Methodology document. The methodology is based on recognized offshore structural engineering standards and rules. The main engineering rule followed is DNV-OS-J101: Design of Offshore Wind Turbine Structures (2007). Some adjustments were done based on local site conditions and experience with ice loading. The analysis started from local scantling design, followed by a series of global and local FE-, fatigue, soil capacity, and natural frequency analyses.
The wind turbine manufacturer set strict limits on the natural frequency of the structural entity. Our dynamic analysis of the structure thus considered the stiffness and mass of the seabed soil, foundation steel structure, internal fill, windmill tower, and outside water. The analysis showed that the foundation was dynamically massive and rigid like an onshore foundation.

A fatigue issue was identified at the intersection of the cone and the shaft. Eventually, the issue was resolved with a special structural arrangement.

FOUNDATION CONSTRUCTION

Manufacturing of the foundation started in January 2010 (Fig. 8). It was delivered in two parts and joined on a heavy-duty barge under a gantry crane (Fig. 9).

Offshore dredging and leveling works started in July. The barge was then towed and anchored at the site. The foundation was lifted from the floating barge with a standard Demag CC2800 crane (Fig. 10). The foundation shell was filled with crushed rock from the top via a chute pipe using a grab dredge.

The tower and the wind turbine were erected from the barge with the same crane. The barge was equipped with a special-purpose fork attachment, i.e. the barge was partly hinged to the foundation to enable lifting in floating mode.

Determining sea state probabilities and computing barge and crane response under wave action was a non-trivial task. Movements of the moored barge were quite limited in ordinary Pori offshore summer sea conditions. The foundation installation, inside fill, and wind turbine erection took one week. The windmill component lifts were done during a single working day. The installation works were completed on July 17, 2010.

Figure 8. Manufacturing the foundation at Technip Offshore Finland.

Figure 9. Foundation sections assembled under the gantry crane.
FURTHER DEVELOPMENT

Offshore wind power, which has high up-front costs, has to compete not only with onshore wind power but also other forms of electricity production. Wind availability is greater offshore, of course, but cost-competitiveness dictates that prices still need to fall for the wind turbine and its foundation.

The Pori pilot wind turbine project has provided valuable hands-on experience on offshore wind power development in northern Baltic Sea conditions. It is an important iterative step towards large-scale wind power development in ice-infested waters.

Four areas (design, manufacturing, installation and cost structure of the pilot wind turbine) were examined after the project. Design solutions for a variety of ice conditions, water depths and bottom conditions were developed further, and methods and costs of serial manufacturing and installation were studied. Some findings are described below.

The pilot wind turbine was designed to take the impact of an extreme Baltic Sea ice ridge, but ice conditions are typically lighter. In many areas, foundations are subject only to minor ship-track side ridges. In other areas, only broken level ice moves and static ice pressures dominate. The offshore wind farm may break a moving ice field or stabilize an ice field that might otherwise move. Considerable steel weight and cost savings can be achieved by using proper local ice pressure criteria.

The rigid joint between the cone and shaft proved to be problematic. One option would be a simple offshore bolt connection. This would reduce manufacturing costs and enable filling the foundation directly from a deck barge (eliminating the need of a grab dredge).

The foundation concept can easily be adapted to a variety of bottom conditions in water depths ranging from 3 to 25 meters by changing dimensions and burial depth. However, deeper water requires larger foundations. When methods of serial production were studied, large one-piece foundations were found increasingly difficult and expensive to manufacture and handle.

One option to extend the foundation into deeper water is to use a separate cylindrical steel shell filled with granular material in a manner similar to what is routinely done in oil tank foundations (Fig. 11). The feasibility of this approach has been verified by small scale model tests (Fig. 12).

Figure 10. Lifting the foundation in to position from the heavy-duty barge.

Figure 11. For deeper water, the foundation can be set on granular material contained by a simple cylindrical steel shell.
For economic reasons large blocks of new development, say, 50–200 MW, should be brought on stream in a single construction season. Leaving the construction unfinished over winter can have severe economic consequences (e.g. re-mobilization of equipment that may already be reserved elsewhere, loss of energy production, and heavy capital costs). Delays also add to greenhouse gas emissions (1,000 to 2,000 metric tons of CO$_2$/MW per year). This calls for an industrial approach to wind farm construction. Construction should proceed like clockwork even as depths and bottom conditions vary.

The suggested construction approach is illustrated in Figure 13. While the foundations are rolled out from the manufacturing yard, one working group prepares bases for wind turbines, another group installs foundations, a third group fills foundations, a fourth group does trenching and cabling, a fifth group erects wind turbines, and a sixth group does the hook-up and commissioning works while the first group returns to complete erosion protection works.

A serial approach to manufacturing and erection alone was roughly estimated to cut the foundation cost by a third. As mentioned, further cost savings are available by design development.

![Figure 12. Feasibility testing of two-piece foundation.](image)

![Figure 13. Work phases in wind farm construction.](image)
CONCLUSIONS
The Pori pilot offshore wind turbine project is an important step towards large-scale wind power development in the northern Baltic Sea. The concept is also applicable to other shallow sea areas with firm-to-hard bottom conditions with or without ice.

Industrial-scale manufacturing and installation will reduce costs of foundations and offshore wind power. Improvements in design and construction will also cut costs, making offshore wind a viable energy production option in sub-arctic conditions.

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