

OMAE2007-29567

OFFSHORE WIND TURBINE FOUNDATIONS - THE COWI EXPERIENCE

Jørn H. Thomsen,
COWI A/S

Torben Forsberg
COWI A/S

Robert Bittner, P.E.
Ben C. Gerwick, Inc.

ABSTRACT

This paper presents the experience gained and the lessons learned over the last decade within the numerous offshore foundation projects undertaken by COWI in European waters. This experience derives from the close collaboration with, and interaction between the owners, contractors, and engineers in the various stages of project development. In turn, the experience draws on COWI's vast experience within foundation of large bridges world wide over half a century.

Focus is on two pioneering gravity base foundation projects:

- Nysted in Denmark, currently the largest offshore windfarm worldwide with 72 Nos Bonus 2.3 MW turbines in water depths up to 10 m in the relatively benign inner Danish waters
- Thornton Bank in Belgium, where the first phase - comprising 6 Nos REpower 5MW-turbines of a total of 60 - are planned to be built in the rough North Sea in water depths exceeding 25 m.

The two projects illustrate the speed at which the structural concept must keep pace with increases in turbine size. The projects exemplify how a tailor made design is made fit for purpose. The latter case uses state-of-the-art designs for thin-walled reinforced concrete shell structures.

INTRODUCTION

Offshore wind turbine foundation design requires development of highly cost effective concepts, because the share of the cost of the foundation relative to that of the complete wind turbine installation is considerably higher than that of an onshore foundation. Further, environmental and energy gain considerations require that windfarms be located farther from shore at consequently deeper waters. With this trend of ever larger turbines in deeper and rougher waters, the design and construction challenges and complexity increase

proportionally, and both become closer to or beyond normal experience.

Thus, value engineering becomes crucial for development of foundation concepts that are sufficiently robust to be carried through to site installation without impacting the economic viability of the projects.

This engineering approach is described in the following sections.

ENGINEERING CONSIDERATIONS

In all project phases from concept phase to detailed design, consideration of operational and environmental loads and hydrographic and geotechnical conditions needs to be given interactively with fabrication, installation and logistic demands.

While design develops, focus shifts towards the implementation aspects of the project.

Design, construction and installation of gravity base foundations for offshore wind turbines are similar to those of large bridge foundations, and experience from the latter is valuable for the former.

However, wind turbine foundation design imposes special challenges, in that

- the combined soil-foundation-wind turbine structure is a dynamic system
- hence, loads depend on the response of the system, i.e. are dictated by the overall stiffness of the system
- soil stiffness is load dependent in a nonlinear manner
- therefore, several load iterations are required between wind turbine and foundation designers to arrive at the design loads

- industry practise has it that turbine supply and design of turbines and foundations, respectively, are carried out under separate contracts with associated demands for strong interface management on the part of the owner
- the dominant loads are horizontal forces from wind, currents and waves
- hence, for gravity base foundations the challenge is to provide sufficient dead weight in the permanent stage through ballasting, while minimising structural dead weight within available equipment range in the installation phase during lifting and transportation
- therefore a close collaboration between the designer and the contractor is crucial in the design stage
- the cost share of the foundation relative to the complete turbine installation may be decisive for the viability of the offshore windfarm development

NYSTED WINDFARM

Background

The design and construction of the gravity foundations for the Nysted Offshore Windfarm, located some 10 km off the southern coast of Lolland, Denmark, (FIGURE 1) is an example of concept development and design as a result of close collaboration between the contractor and the designer. The foundation concept was developed jointly between the contractor P. Aarsleff A/S and the contractor's consultant COWI A/S in the tender stage and detailed after award of the contract to P. Aarsleff A/S.

The owner was a joint venture between energy companies which have today merged into DONG Energy of Denmark. In this case, the owner had selected to define a comprehensive design basis with all interfaces defined, including stiffness requirements of the foundation.

Project

The project comprises 72 windmill foundations for 2.3 MW Bonus wind turbines, arranged in 8 lines each with 9 turbines. Height of hub above the sea is 68.8 meters and rotor diameter is 82.4 meters, giving a total height of 110 m. The windmills with foundation level from -7.5 to -12.75 m MSL at natural water depths 6 - 9.5 m (MSL), and soil conditions are generally stiff moraine clay.

Concept Development

It was immediately evident that a monopile solution was not feasible due to a high content of boulders. At the same time, these soil conditions were favourable for a gravity foundation, as generally high bearing capacity was met near the natural sea bed.

In the course of tender design, the contractor found that the most cost-effective solution overall would be concrete foundations fabricated in Swinoujscie, Poland, where cheap and skilled labour was available. In turn, this required transport by barges to the site. On site, a floating crane would pick the units up and place them on pre-prepared stone beddings, thus maximising the effective time of the crane.

The transport and installation procedures required that the weight of the concrete foundation units be minimised. This was achieved by the concept of a hexagonal base structure with six open cells, and a shaft and an ice cone at top.

The necessary weight was achieved by filling on site with heavy duty ballast in the shaft and the chambers.

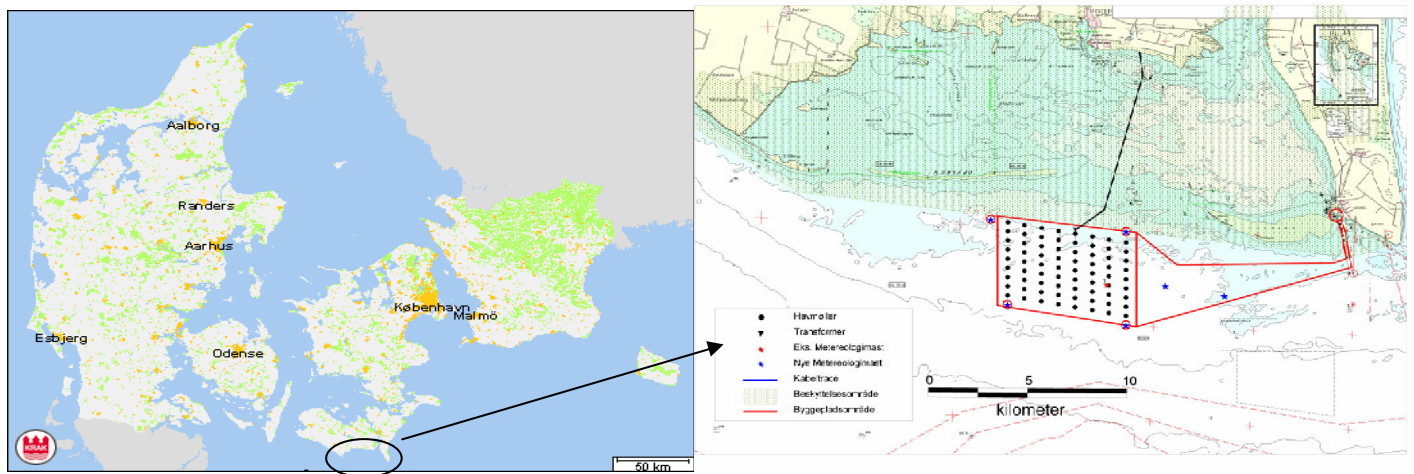


FIGURE 1 NYSTED OFFSHORE WINDFARM, LOCATION PLAN

Foundation Design

The design appears from FIGURE 2. The base dimension is 15 m and the maximum height 16.25 m. A concrete weight (in air) under 1300 t was achieved, corresponding to the operational limits set by the floating equipment. The additional weight necessary to provide stability against sliding and overturning was provided by heavy duty olivine material filled in the cells and the shaft, adding another 500 t to the weight.

Note the conical shape at top, which in accordance with Danish practise was required by the owner's specifications to minimise ice loads.

The contractor and the crane subcontractor Eide Marine designed a purpose built lifting device, shaped as a cone to fit the ice cone. The lifting forces were thus distributed over a large area of the solid concrete ice cone, reducing the local installation stresses to a minimum.

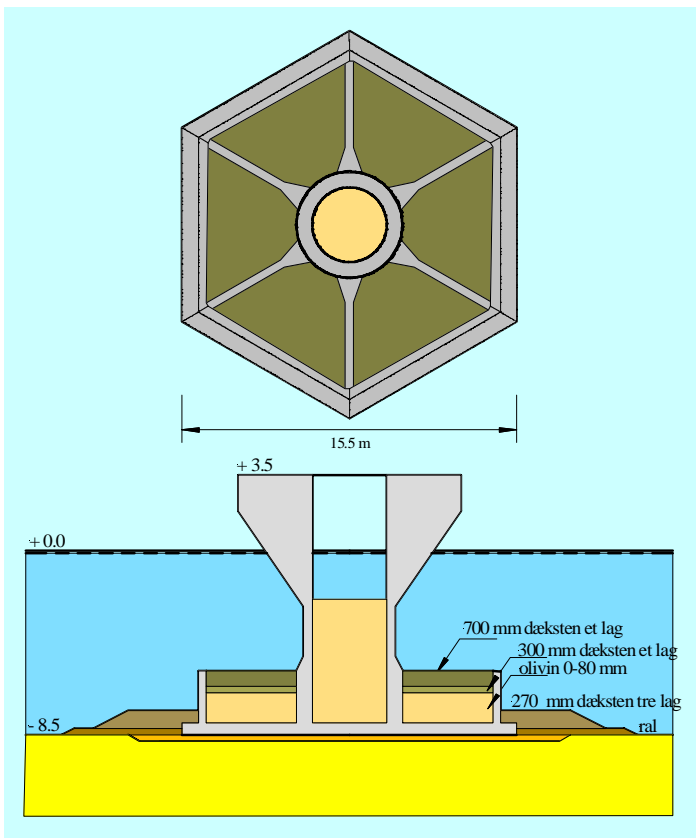


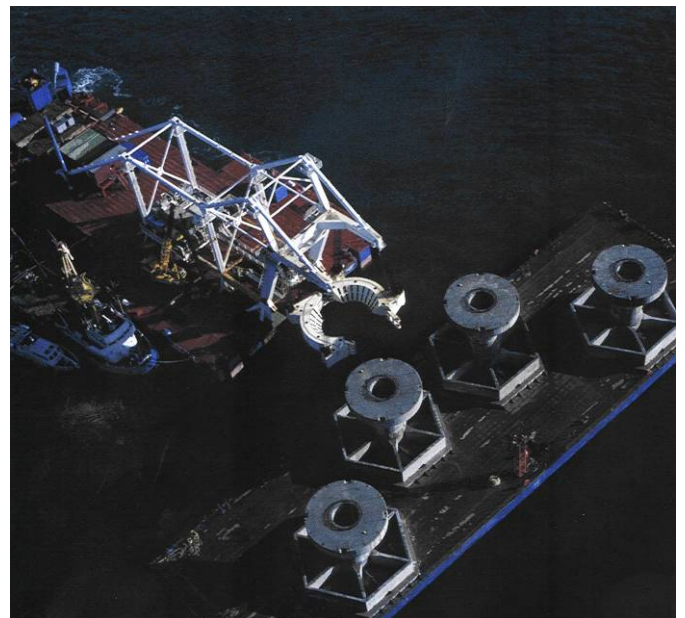
FIGURE 2 NYSTED OFFSHORE WINDFARM, GRAVITY FOUNDATION CONCEPT

Foundation Installation

The actual performance proved the adequacy of the concept, as a production cycle for 4 foundations on one 10,000 t barge was carried through in 30 days or less, once teething troubles were overcome. With 3 barges in the line, 4 foundations were placed every 10 days, weather permitting. The project was carried out according to schedule, from contract award in March 2002 to all foundations in place in the summer of 2003, ready for reception of the wind turbines, FIGURE 8



FIGURE 3 NYSTED OFFSHORE WINDFARM, INSTALLATION OF FOUNDATIONS (ABOVE AND BELOW)



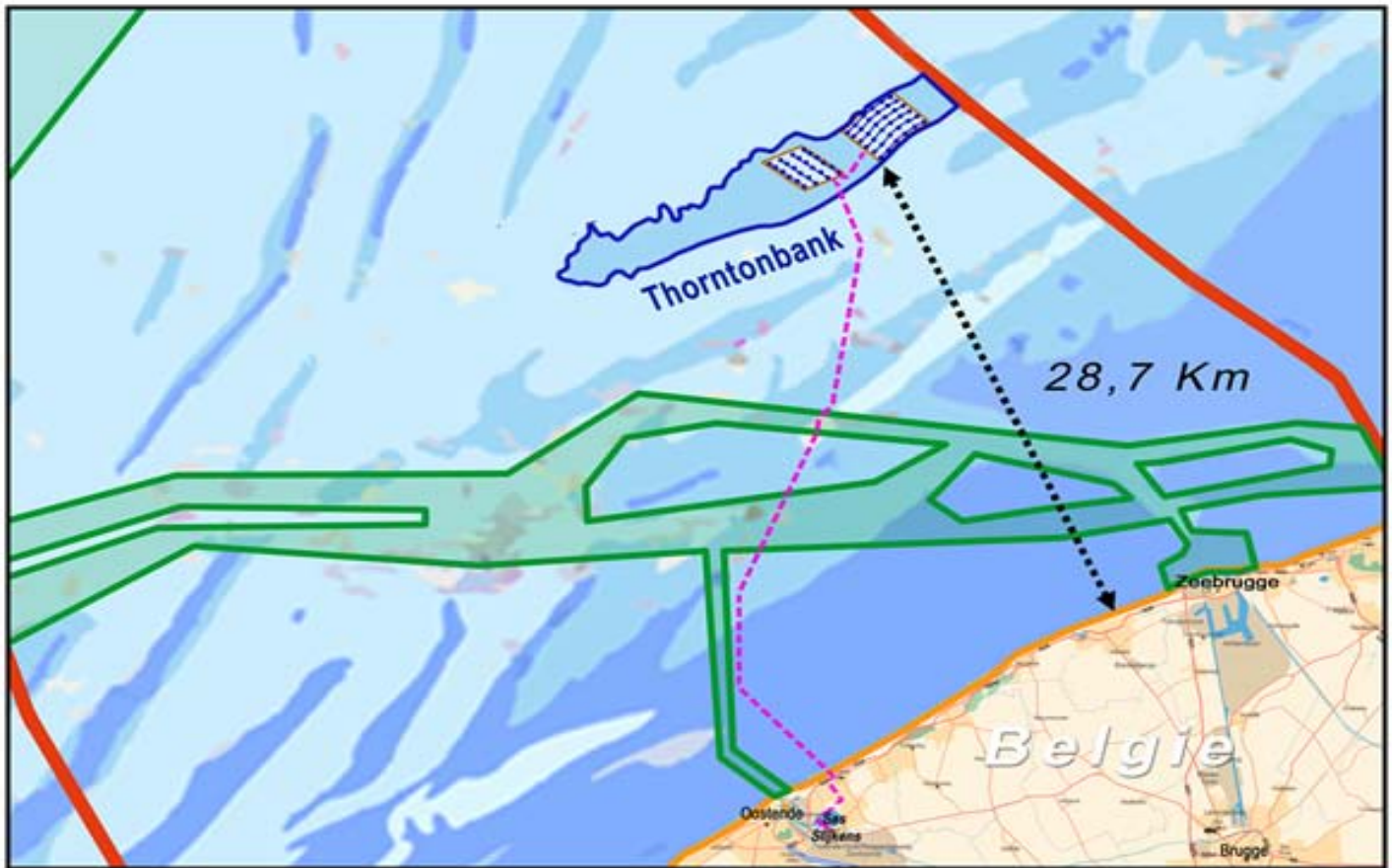


FIGURE 4 THORNTON BANK WINDFARM, LOCATION PLAN

THORNTON BANK OFFSHORE WINDFARM

Background

One of the most challenging offshore wind turbine projects is currently being developed for the Thornton Bank in Belgium, planned for installation in year 2008.

The owner is C-Power n.v. of Belgium, who is undertaking this development of the first offshore windfarm in Belgium. Due to the level of development at the time of writing, only general information is provided.

In this case the owner has decided that the foundation design be carried out as a process between the Owner's Engineer - Technum n.v. of Belgium in cooperation with DONG Energy of Denmark; the turbine supplier - REpower Systems AG of Germany, and the Marine Contractor - Dredging International with its consultant COWI A/S of Denmark as designer.

Project

The final project will comprise 60 wind turbines, arranged in 2 arrays each with 4x6 and 6x6 turbines, respectively, see FIGURE 4. The development is planned in three design/construction phases, of which the current first phase comprises 6 turbines.

The turbines, located some 30 km off the Belgian coast, are planned to be REpower 5 MW turbines, with hub above the sea is 95 m TAW (chart datum corresponding to LAT). The windmills are founded at -21.5 to -27 m TAW and soil conditions are generally sand of medium grain size.

Concept Development

This concept was initially developed as a result of collaboration between the marine contractor and his designer.

Given the rough environment of the North Sea, it was evident that construction procedures at sea should be kept at a minimum. Therefore, the Nysted solution with external chambers was not relevant as infill works would be vulnerable to adverse sea conditions.

For the large water depths and the increasing size of wind turbines, structural stiffness and fatigue issues become decisive. A post-tensioned concrete structure offered solutions to these issues.

Further, structural weight minimisation consideration led to the conclusion that a conical shell structure would be most efficient in terms of:

- providing sufficient volume for ballast material
- direct load transfer from turbine base to foundation level
- slender structure, yet with high stiffness
- one set-up for in-fill operations
- no need for diver assistance

An important feature at the location is that sediment transport takes place, causing sand dunes to move along the area. Foundation level should therefore be selected to ensure that troughs of the sand dunes would not jeopardise the integrity of the foundation layers. This aspect has been dealt with by the owner's engineer in subsequent design phases.

For the sake of comparison to the Nysted project it should be mentioned that no ice cone is needed at this location.

Foundation Design

At the time of writing the design process is ongoing, with design loops between the foundation and turbine designers. The design is presented at this preliminary stage of the project.

The structure is composed of a cylindrical shaft on top of a conical base transferring the loads from the turbine directly to the base slab. The base slab is designed with a central void filled with soft material in order to ensure that the dynamic loads do not create a hump with risk of rocking.

The structure is post tensioned in order to provide sufficient strength and linear stiffness properties as well as fatigue and crack resistance.

The design features appear in FIGURE 5. At the deepest location the foundation extends from foundation level -27m TAW to top level +17 m TAW. The foundation base diameter is 21.5 m and the shaft diameter is 6.5 m, matching the diameter of the turbine tower.

The structural concrete weight is about 2700 tonnes. The ballast will be a combination of sand and heavy fill, sufficient to ensure the stability against the overturning moments. The

total dry weight may be up to 7000 tonnes, depending on quantity and type of heavy fill.

The scour protection, designed by the owner's engineer, is arranged at a level below the trough of moving sand dunes.

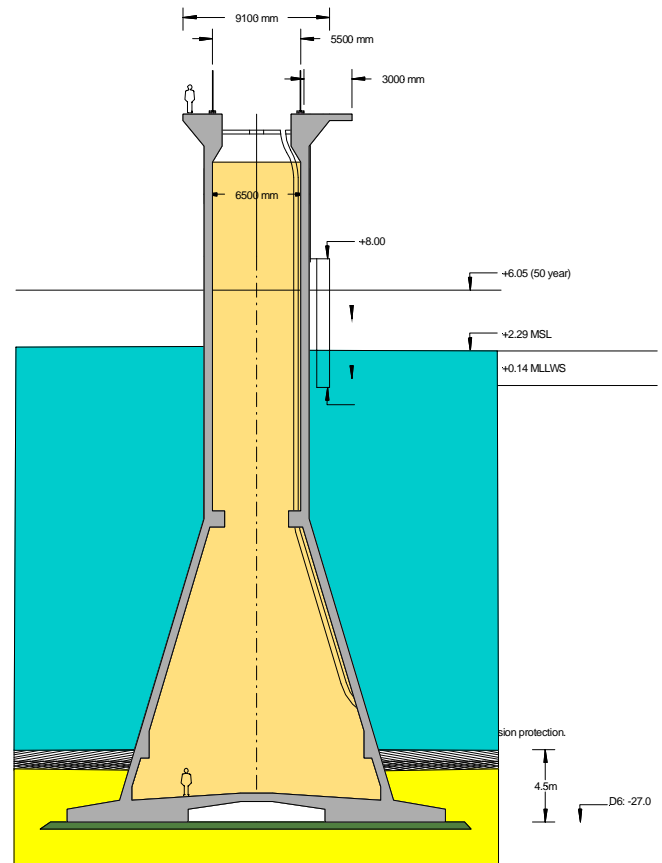


FIGURE 5 THORNTON BANK WINDFARM, GRAVITY FOUNDATION CONCEPT

Installation Considerations

The design assumes that the foundations will be constructed onshore at a yard with necessary quay facilities. The lifting and transport consideration are based on use of a floating crane.

Installation procedures are being developed at the time of writing and further detailing is referred to the future. However, given the size and the environment it is a prerequisite that marine equipment and operators be of capacity and experience capable of meeting the challenges met.

FIGURE 6 shows the installation of a REpower 5MW turbine for the Beatrice Windfarm Demonstrator project August 2006.



FIGURE 6 INSTALLATION OF REPOWER 5MW TURBINE FOR THE BEATRICE WINDFARM DEMONSTRATOR PROJECT, SCOTLAND

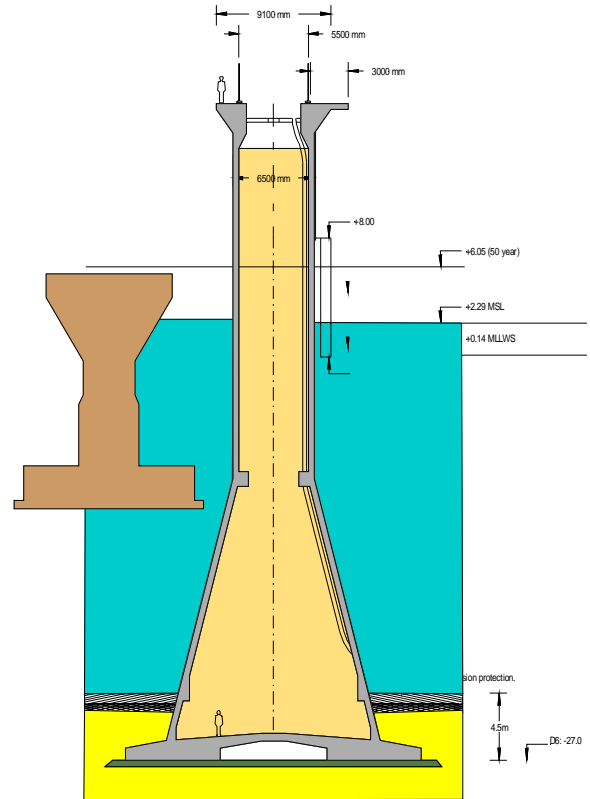


FIGURE 7 COMPARISON OF NYSTED AND THORNTON WINDFARM FOUNDATIONS

LESSONS LEARNED

Development Trends

The presented projects demonstrate the speed at which wind turbine industry is developing in general, and offshore windfarms in particular.

Obviously, the economic viability of offshore windfarms is depending on the competitiveness relative to other energy sources. The introduction of the Clean Development Mechanism (CDM), see e.g. [1], of the Kyoto Protocol in 2008 is believed to further favour the competitiveness of renewable energy projects. This is argued for in a recent publication issued by Vestas [2].

It has been said that the current development stage of the wind industry is comparable to that of the aeroplane industry in the fifties and sixties: any prediction of the limits to turbine and windfarm sizes are quickly surpassed by the actual developments.

FIGURE 7 visualizes the case, showing the two foundation concepts of Nysted and Thornton, respectively, to same scale. Over a short span of years, the limits for offshore gravity foundations have been pushed to meet the increased demands from the increased turbine size and the rough environmental conditions associated with the interesting wind fields for this category of wind turbines.

Project organisation

Also offshore windfarm project organisation practises are in a development stage, and it can hardly be claimed that a general industry practise has been established.

Split design and build contracts

The first Danish offshore windfarms were contracted on separate design-and-build contracts for turbine, cables, and foundations, respectively. The client tendered out the project based on front end engineering designs (FEED) and actively took on the responsibility for design and construction management.

This contracting model implies that the foundation designer works directly for the contractor. Therefore, the design is tailor made to suit the contractor's construction, installation and construction procedures and equipment.

Consequently, the foundation design can be optimised with regard to the actual construction methods.

Tenders are based on tender designs from the three main contractors.

The tender designs will then have to be merged in the detailed design phase following award of contracts.

As mentioned above, interface management on the part on the Client is crucial under this model. The interface to the cable contractor is fairly straightforward. In contrast, the design loops between the turbine and the foundation designers are time consuming and may reveal requirements that could not be taken into account in the tender design.

Turn key contracts (EPC)

In recent years, windfarm developers have tendered offshore windfarms on a turn key basis. Under this model, the turbine contractor is typically the main contractor with the cable and the foundation contractors being subcontractors. Interface management is thus largely taken on by the main contractor, shortening the communication and responsibility lines.

The benefits of this model are similar to the split contract model. In addition, the tender design benefits from the joint design between the turbine and the foundation at tender design stage.

Also this contracting model require a substantial design work to be carried out after award of contract, although the key issues are solved in the early design loops between the turbine and foundation contractor.

It appears that in spite of the apparent advantages of this contracting model, the industry does not seem to be ready to adopt it in practise. Recent tenders have returned to the split contract model.

Split contracts based on detailed design

Most recently some developers are turning towards a contracting model based on detailed design carried out by the client. In turn, it requires that the client has in-house design and construction management resources.

The advantage of this model for the client is control of the project both in terms of designs and cost at an early date. Risks are often identified in the detailed design phase and can be mitigated before tender.

The number of potential tenderers is increased, as they do not have to possess or acquire specialist engineering resources. Hence, competition is expected to be increased.

Tender costs, and therefore also overall construction costs, will decrease, as the tenderers will not have to make parallel, expensive tender designs.

Overall time is expected to decrease, as all major constraints should be identified and dealt with at an early date.

However, for the foundation designer new challenges emerge. Designs will have to be generic, and rather than designing for specific construction/installation methods and equipment the objective will be shifted to designing for a wider range of methods and equipment.

Conclusion

It follows from the above considerations that offshore wind turbine foundation design is subject to a developing project environment.

Every project has unique features, which have to be taken into consideration. The combination of

- integral wind turbine - foundation structure
- soil conditions
- hydraulic conditions
- construction methods
- transport/installation equipment and methods
- project organisation

sets the frame for the individual project, and the solution has to be optimised with respect to all elements.

For large water depths and turbines no standard solution exists. This is true for both concrete gravity base foundations and steel foundations, as the simple monopile concept would exceed the limits for fatigue and stiffness.

The elements of particular concern are:

- the turbine loads and the design loop process between the foundation and the turbine designer
- variations in water depths over project area
- the soil conditions, which are the most varying element and therefore need to be designed for each individual turbine location;
- weight limits for lift/installation and consideration of the working procedures related hereto
- the interface issues set by the project organisation

ACKNOWLEDGMENTS

The authors wish to thank the companies mentioned below for permission to reference the projects described in this paper and to use maps and pictures in their custody.

C-Power n.v. of Belgium for permission to reference the Thornton project and to use site map.

To the construction companies P. Aarsleff A/S of Denmark, and Dredging International b.v. for the joint project

development discussion and for sharing their knowledge on construction procedures with the designers in the concept development phases and for valuable comments during the detailed design phase.

REpower Systems AG of Germany is thanked for their permission to include the photo from the Beatrice Windfarm Demonstrator project.

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FIGURE 8 NYSTED WINDFARM, TURBINE INSTALLATION