KENNETH PEIRE, HENDRIK NONNEMAN AND ERIC BOSSCHEM

Above: The first phase of the Thornton Bank Offshore Wind Farm project, where six Wind Turbine Generators (WTGs) were built on row D of sub-area A. The selected WTG is one of the largest and most powerful wind turbines in the world, specifically designed for offshore installation.

GRAVITY BASE FOUNDATIONS FOR THE THORNTON BANK OFFSHORE WIND FARM

ABSTRACT

A new design approach and offshore marine operations have been developed for the construction of the foundations for the first phase of the Thornton Bank Offshore Wind Farm, located some 30 km off the Belgian Coast. In contrast to the monopile foundations commonly applied to offshore wind farms, a novel Gravity Base Foundation (GBF) concept has been selected as the result of an extensive risk assessment and technical evaluation.

Innovative dredging technologies play a key role in the realisation of these foundations. Concrete caisson foundations for offshore wind turbines have traditionally been applied in near-shore wind farm projects, in relatively shallow and sheltered waters as they were believed to become uneconomical and technically too difficult with increasing water depths.

The Thornton Bank project owner has opted for the latest generation 5MW wind turbine generators (WTGs). This first offshore application at this exceptional scale represented a significant leap for the offshore wind industry and also required a different approach for the foundation structures. The large water depths up to 28 m, the harsh North Sea environment and complex soil conditions led to a monopile basic design with excessive diameters and wall thicknesses. The general increase in steel prices on world markets and the concerns raised with regard to the feasibility of pile driving gave advantage to the choice of the GBF.

The versatility of a GBF versus a monopole also resulted in less sensitivity of the design with regard to a particular type of WTG. The detailed design resulted in a slim concrete structure with a shape that can best be compared to an "Erlenmeyer" or a champagne bottle.

The construction works offshore started with the dredging of foundation pits to create a foundation level that safely caters for the movements of the surrounding sand dunes. Afterwards, the installation of a two-layer gravel bed within very narrow vertical tolerances created the sub-foundation on which the GBF is installed. The latter installation and positioning works were performed by a twin shear leg crane heavy lift vessel, which loaded the GBF from the onshore construction yard for subsequent transport to the offshore site.

Following installation of the GBFs, the foundation pits were backfilled by means of a purpose-built backfill spreader barge fed by a trailing suction hopper dredger.
The same multi-purpose barge is also fitted with dedicated installations for the ballast infill of the GBF and the installation of a two-layer scour protection system around the GBF.

The development of the offshore wind turbine support structure for the Thornton Bank Offshore Wind Farm demonstrates that the economic operating range of offshore wind farms can be significantly extended by innovative design and state of the art marine construction technologies, which build upon extensive experience gained in the dredging and marine construction industries.

This article was first presented at the CEDA Dredging Days 2008 and is published here in a slightly revised form with permission.

INTRODUCTION

Concrete caisson foundations for offshore wind turbines have traditionally been applied for wind farms close to shore, in relatively shallow and sheltered waters. Steel monopiles on the other hand have become the semi-standard solution for turbine support structures for North Sea offshore wind farm developments to date.

The present article deals with the design and construction of the Gravity Base Foundations (GBFs) for the Thornton Bank Offshore Wind Farm, located some 30 km off the Belgian Coast. The project owner has opted for the latest generation 5MW turbines. This first commercial application at this exceptional scale represents a significant leap for the offshore wind industry and also requires a different approach for the foundation structures.

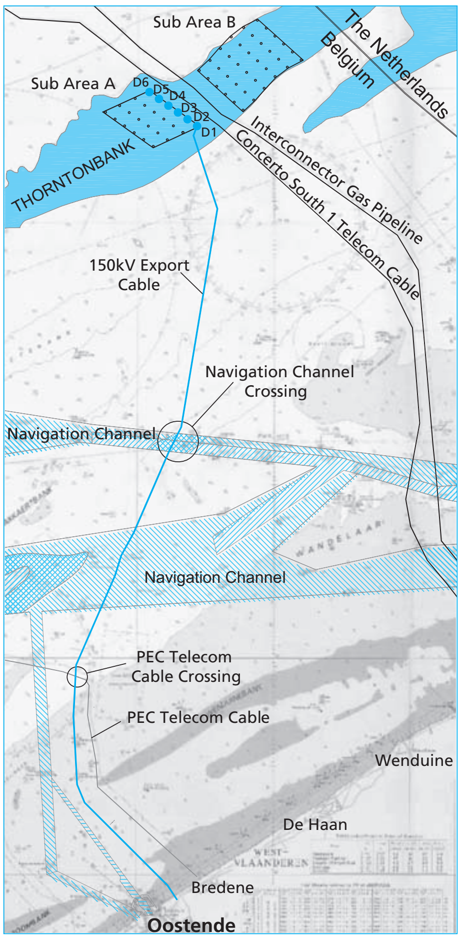

Figure 1. Location map of the Thornton Bank Project.

The article starts with the development of the project together with the contract strategy that has been adopted. Subsequently, the geotechnical and geophysical site investigations are discussed and the design of the foundations is briefly summarised. The various construction phases are dealt with in the following sections, starting with the onshore construction of the concrete structures, followed by the offshore preparatory foundation works consisting of the dredging of foundation pits and the installation of foundation beds made up of crushed rock.

Onshore transport, offshore transport and installation on site of the GBFs are discussed next, followed by the backfilling of the dredged foundation pits, the ballast infill of the structures and the installation of scour protection to ensure that adequate backfill remains in place. The article concludes with a description of the offshore levelling works of the transition flange on top of which the turbine towers are to be mounted, followed by conclusions from the experience gained during the construction of the first six foundations.

PROJECT DEVELOPMENT

The Thornton Bank Wind Farm is the first offshore wind farm in Belgian waters (Figure 1). The project has been developed by C-Power, a project development company owned by a variety of shareholders with different backgrounds. These shareholders are DEME, a Contractor Group specialising in the fields of dredging and marine construction, SRIW Ecotech Finance, the Environmental Holding Company of Walloon Investment Company, SOCOFE, the Investment Company of the public administrations of the Walloon Region, NUHMA, an Investment vehicle for the participation in electricity and utility ventures and EDF Energies Nouvelles, a private company in which EDF holds 50% of the shares.

Owing to the relatively small area of Belgian territorial waters and the large number of limiting factors, the range of possible locations for offshore wind farm development is limited. Following an evaluation of near-shore projects, public decision-making resulted in the designation in 2004 of a zone for the production of electricity from wind, water or currents. Within this zone, C-Power's preference was for a location outside the 12-mile zone. The Thornton Bank, one of the many sandbanks characterising the Belgian section of the North Sea, turned out to be the most appropriate location for the development of a distant offshore wind farm.

An Environmental Impact Study was submitted and an application for a Domain Concession was submitted. In 2003, both the necessary environmental permit and the domain concession for the project on the Thornton Bank were granted. The required building permits for the cabling works onshore and offshore were subsequently obtained between 2003 and 2006.

The Thornton Bank is located approximately 30 km from Zeebruges. The distance to Ostend along the 150kV export cables trajectories is 38 km.

C-Power has opted for a split location which does not conflict with the Navy's anti-mine and target practice areas and which maintains a minimum distance of 500 metres from the nearby telecom cables and gas pipelines and from individual sand concession areas.

This results in 2 sub-areas, A and B, across which a total of 60 Wind Turbine Generators (WTGs) are planned. Sub-area A is intended to accommodate 24 WTGs (4 rows of 6 WTGs each), whilst sub-area B caters for 36 WTGs (6 rows of 6 WTGs each). Sub-area A is located to the West of the Concerto South 1 telecommunications cable and sub-area B to the East of the Interconnector Gas Pipeline.

During the first phase of the project, 6 WTGs were built on row D of sub-area A. The distance between these WTGs is 500 metres. The selected WTG is the Repower 5M model with a rotor diameter of 126 m, one of the largest and most powerful wind turbines in the world,

KENNETH PEIRE
graduated in 1995 as an MSc in Civil Engineering and worked as a Project Engineer on the master plan for safeguarding Venice before joining DEME in 1997 as a Superintendent. He then became Project Manager for offshore oil & gas projects and coordinated tenders in a variety of disciplines and business areas. For the realisation of the first phase of the Thornton Bank Offshore Wind Farm he was Project Manager Marine Operations. At present he is Engineering Manager for the second phase of the project.

HENDRIK NONNNEMAN
graduated in 1992 as an MSc in Tropical Agriculture working on African development and irrigation projects before joining Dredging International in 1998 as a Project Engineer. His assignments were in dredging, remediation, wreck removal and revetment works in Europe. He then joined the Research Method and Estimating Department, Benelux Division. He was Tender Coordinator and Design Coordination Manager for the first phase of the Thornton Bank Offshore Wind Farm and is presently Project Coordinator for Design and Build Projects in general and for Offshore Wind Farm Projects in particular.

ERIC BOSSCHEM
graduated as an MSc in Electro-mechanical Engineering and joined DEME's Technical Department in 1976 to manage maintenance and repair for several dredgers. Since 1980 he has managed diverse projects. As General Project Manager for the Thornton Bank Offshore Wind Farm he is responsible for the construction of the Gravity Base Foundations and associated Electrical Infrastructure. He previously held similar positions for the New Doha International Airport platform project and marine infrastructure works at Le Havre's Port 2000 container terminal development.

specifically designed for offshore installation. The rated power of the WTG is 5MW, which is achieved at a rated wind speed of 13.0 m/s. Cut-in wind speed (at which the WTG starts power production) is 3.5 m/s (Beaufort scale 3), whilst cut-out speed is 30.0 m/s (Beaufort scale 11).

Power production is controlled by electrical blade angle adjustment, resulting in pitch and speed control. The rotor consists of 3 blades, each of 61.5 m vane length and rotates at 6.9 – 12.1 rotations per minute. 33kV in-field cables ensure the connection between the turbines; a 150kV cable ensures the connection to shore.

The total investment for the first phase of the project amounts to approximately € 150 million, whilst the overall project is anticipated to require an investment of € 850 million. Part of the investment of the first phase is to be depreciated over the entire project. The expected annual generation capacity of the wind farm matches 6% of the total Belgian household consumption.

CONTRACT STRATEGY

A multi-contract strategy has been adopted for the realisation of the first phase of the project. This approach was the result of a number of tendering exercises, cumulating into the award, in spring 2007, of three main contracts with following scope:
- The first contract has been awarded to Seawind, a consortium between Dredging Marine and Electrical Infrastructure Works (MEC)
- Design, Supply, Transport and Installation of the WTGs (WTC)
- Supply and connection of the marine export (150kV) and in-field (33kV) power cables (ABB)

International and Fabricom GTI, whilst the second and third contracts have been awarded to REpower and ABB respectively. The Marine and Electrical Contract (MEC) between the Seawind consortium and C-Power is of an Engineering, Procurement and Construction (EPC) nature and includes, among others, the detailed design and construction of the Gravity Base Foundations (GBFs). Within the consortium, Dredging International is in charge of all marine infrastructure works, whilst the transformer station and cable works onshore are for account of Fabricom GTI.

The detailed design of the GBFs has been performed on behalf of Dredging International by the Danish engineering consultancy COWI. It includes, among other things, the design of the concrete structures and appurtenances, the design of the gravel beds on which the GBFs are placed and the design of the ballast infill of the GBFs.

The detailed design has been developed on the basis of the Final Design Basis (FDB) and of the Basic Design (BD) prepared by the Owner's Engineer (OE), in which the overall layout and dimensions of the support structures were defined. The Owner's Engineer (OE) is a joint venture between Technum and IMDC from Belgium and DONG Energy from Denmark.

Other parties involved in the project are DNV Danmark A/S. as the Project Certification body and SECO (Technical Control Bureau for construction) with regard to the ten-year liability insurance policy.

The project was financed through a non-recourse project-financing scheme with DEXIA as Mandated Lead Arranger and Rabobank as Mezzanine Lender. This approach resulted in the involvement of Mott MacDonald as Lenders' Engineer, to which C-Power reports on a monthly basis.

The weather risk included in the contract price is based on average weather statistics and workability criteria for the vessels envisaged for the execution of the works. Actual reimbursement of weather downtime is based on equipment day rates and effectively incurred weather delays. For each major vessel, criteria have been established beyond which reimbursement of vessel downtime is granted, provided that the vessel was operational and ready to work and did indeed incur downtime as a result of inclement weather conditions.

SITE INVESTIGATIONS

A thorough site investigation programme was performed in 2004, consisting of a geotechnical and a geophysical part. The six turbine locations of phase 1 were covered, including the offshore transformer station and the meteo-mast locations and the cable trajectories offshore and onshore.

The geotechnical investigation comprised borings with undisturbed sampling, borings for pressure meter testing and cone penetration tests with the measurement of pore water pressures (CPTU), all performed from a jack-up platform. In addition, vibrocore borings and seabed CPTUs were performed from a work vessel. An extensive laboratory testing programme was performed by the Geotechnical Division of the Ministry of Mobility and Public Works of the Flemish Government.

The geophysical investigation consisted of bathymetric surveys of the seabed using Multi Beam Echosounder (MBE), Side Scan Sonar Surveys (SSS) to obtain a morphological image of the seabed and to detect any obstacles present, Seismic Surveys to assess the subsoil's Quaternary and Tertiary layers and Magnetometric Surveys to detect any metallic objects (wrecks, anchors, UXO,…) at or below the seabed.

A 3D geological model was established on the basis of the seismic results, calibrated using the data from the geotechnical campaign. In general the following soil layers can be distinguished (from top to bottom):
- Coarse to medium dense sand with a gravelly horizon at the bottom, thickness 10 metres
- Stiff clay (tertiary layer), at the bottom a transition to more silty or sandy material, thickness 10 metres
- Dense sand, slightly silty to clayey, thickness 3 metres
- Very to extremely dense (aged) slightly silty to clayey fine sand with seams or pockets of clay, thickness 8 metres
- Stiff tertiary clay down to the end of the boreholes.

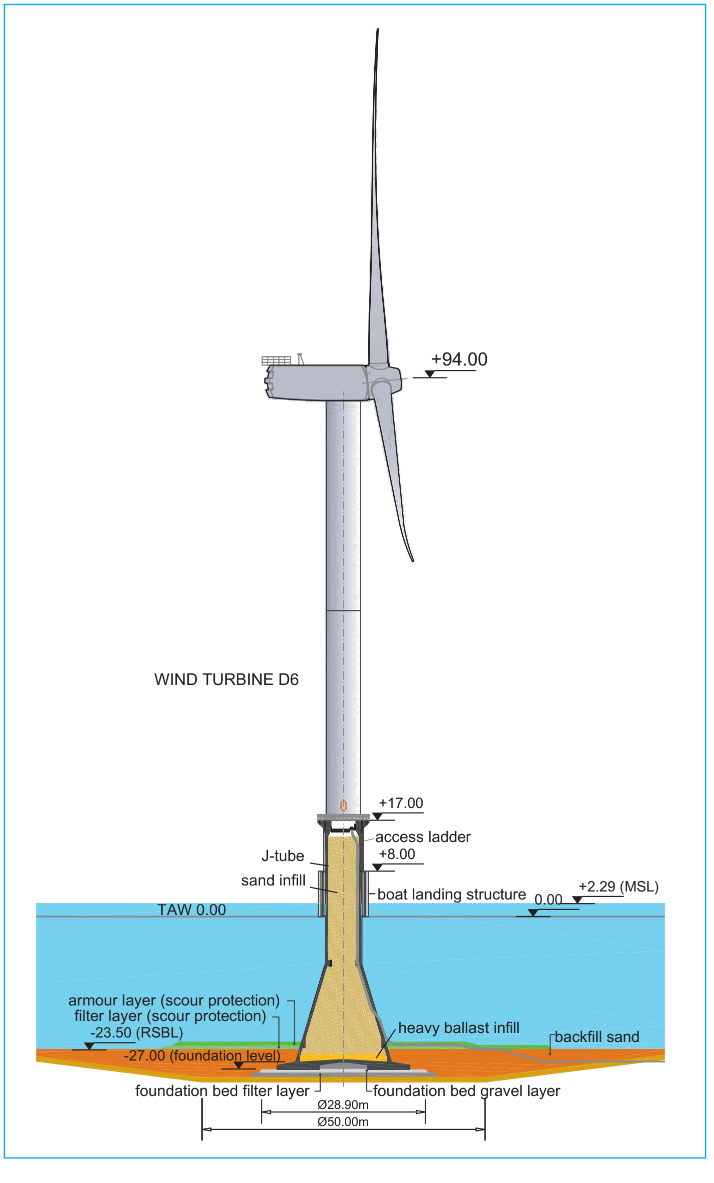

Figure 2. Design lay-out of the integrated structure.

DESIGN

The design life requirements are 30 years for the foundations and 20 years for the WTG components (tower, rotor, turbine generator system).

The versatility of a GBF versus a monopole foundation structure results in a design that is less sensitive to a particular type of WTG. Furthermore, the presence of a homogeneous very dense fine sand layer at approximately 28 metres below the seabed, resulted in significant basic dimensions for the monopiles and associated concerns with regard to driveability and cost, also as a result of the increase in steel prices on world markets. Following an extensive risk assessment and technical evaluation, the monopile foundation concept, which was considered in parallel with the gravity base structures in the basic design stages, was ruled out.

The GBFs are designed as concrete caisson structures ballasted with infill material (Figure 2). The foundation level (i.e. the level of the bottom slab of the GBF) differs from location to location as indicated in Table I. All levels are referenced to the Belgian reference system TAW. In sub-area A, TAW is located 0.18 m below MLLWS, and 2.29 m below MSL. The tidal range is approximately 4 metres at spring tide.

Table I. Gravity Base Foundations by location.

GBF #	Foundation level (m TAW)	Reference Seabed Level (m TAW)	GBF Height (m)
D1	-21.50	-18.00	38.50
D2	-23.50	-20.00	40.50
D3	-26.00	-22.50	43.00
D4	-26.00	-22.50	43.00
D5	-27.00	-23.50	44.00
D6	-27.00	-23.50	44.00

The platform (or transition) level of each GBF is at TAW + 17.00 m. The WTG hub height is established at TAW + 94.00 m.

The reference seabed level (RSBL) at a given foundation location is defined as the minimum level or design seabed level (SBL) that can be guaranteed during the lifetime (30 years) of the foundation, considering the mobility of sand waves and natural erosion and accretion. The RSBL is determined as the minimum SBL in a circular area of diameter 75 m, reduced with 0.75 m. At each location, foundation level is taken 3.50 m below RSBL, whilst backfill of the foundation pits is defined up to RSBL.

Each GBF consists of a base plate, a conical section, a cylindrical section, and a top platform. The ring-shaped base plate has an outer diameter of 23.50 m, an inner diameter of 8.50 m and a height of 1.265 m average. The conical GBF section extends 17.00 m (measured vertically) from the base plate, where it starts with a diameter of 17.00 m. The cylindrical section has an outer diameter of 6.50 m. The overall wall thickness is 0.50 m. The transition between the cylindrical and the conical section is at all times well below water, thus catering for safe mooring conditions for the maintenance vessels during the operational phase of the wind farm.

For accumulated effects of creep and settlement for the GBF, an off-vertical tilt of 0.25° is considered as design criterion. This corresponds to the difference between total design tolerance (1.00°) and installation tolerance (0.75°) of the GBF, whilst for the turbine towers, these values become 0.50° and 0.25° respectively.

The design of the scour protection system around the GBF structures has been performed by C-Power as Project Owner, taking into account the anticipated maintenance of these protective rock berms. This was an iterative process as the Owner's Engineer's assessment of the scour protection system had to incorporate feedback from COWI's geotechnical design. A similar iterative process resulted in the detailed design of the sand-backfill of the dredged foundation pits, an activity to be performed directly after the installation of each GBF and prior to the installation of the scour protection system.

CONSTRUCTION OF THE GRAVITY BASE FOUNDATIONS

Construction of the GBFs was performed at a dedicated yard located at the "Halve Maan" site on the eastern side of the access channel to the port of Ostend. The Port of Ostend has provided the site in concession to C-Power, whilst the Maritime Access Division, a division of the Ministry of Mobility and Public Works of the Flemish Government, provided the quay facilities (Figure 3).

The site has been upgraded to accommodate the GBFs and now allows for design loads of 10 tonne/m². To achieve this, over 800 concrete piles were driven into the soil, which is further covered with a 0.75 m thick layer of reinforced concrete. The quay wall has been upgraded and now safely allows for the mooring of the Heavy Lift Vessel (HLV) *Rambiz*, which performed the lift off, transport to site and installation of the GBFs.

On the "Halve Maan" site, construction of the GBFs was performed at 6 pre-defined positions. At each of these locations, concrete beams supported the base plate of the GBF. These beams allowed the passage underneath the base plate of Self Propelled Modular Trailers (SPMTs), which transported the GBFs from their construction position towards the quay platform for lift-off by the HLV *Rambiz*.

Figure 3. The Halve Maan construction yard adjacent to the access channel to the port of Ostend.

Figure 4. TSHD Brabo lowering her draghead.

The weight of each individual GBF varies between 2,800 and 3,000 tonnes. Per GBF, an average of 1,085 m³ of concrete was used and some 215 tonnes of reinforcement steel. The concrete complies with compression strength class C45/55, environment class ES4 and consistency class S3. Gravel used in the concrete has a 0-22 mm grading, whilst the cement type is Cem III HSR 42.5 LA. Cement was used at a ratio of 450 kg/m³, with a water/cement factor of 0.36. Post-tensioning tendons, 32 pieces, each of 1770 MPa tensile strength, are applied between platform level and anchorage blockouts on the lower part of the inner side of the conical section.

The construction of the GBFs was performed by MBG as a sub-contractor to Dredging International. An average of 135 working days was required for completion of each GBF.

DREDGING OF FOUNDATION PITS

At each offshore turbine location, a foundation pit was dredged to a depth of some 7 metres below the surrounding seabed. The target level for these dredging works was 1.30 metres below the target foundation level, which in turn was subsequently obtained through the construction of gravel foundation beds.

The foundation pits measured 50 m x 80 m at the bottom and had slopes of 1:8 along the main axis and of 1:5 across the width. These dimensions, combined with the orientation of the pits (heading +/- NE-SW along the main axis), were inspired by the prevailing current directions.

Dredging of the foundation pits was executed in two stages, using the recently commissioned, state of the art trailing suction hopper dredger (TSHD) *Brabo* with an 11,650 m³ hopper capacity (Figure 4):
1st stage: *Bulk dredging:* removal of the sand dunes and the top layer of the foundation pit.
2nd stage: *Precision dredging:* removal of the bottom layer of the foundation pit (a layer thickness of approximately 1 metre) to realise a surface within specified vertical tolerances.

Precision dredging was only executed in favourable sea conditions in which the vertical movement of the drag head of the TSHD was limited. Multi-beam echosounder (MBE) surveys, performed from a dedicated survey launch, were scheduled at least once a day per foundation pit in order to closely monitor progress and accuracy.

All dredged materials consisted of medium loose to very dense sands, which were disposed of within the concession area at 3 disposal locations, each at some 300 metres from the foundation pits. In order to limit dispersal of materials, these disposal locations were defined between the crests of the sand dunes that are present in the area. The identification of these locations was subject to approval of the authorities (MUMM) and duly considered the recommendations of the EIA. Disposal of the materials was performed through the bottom doors of the TSHD.

Part of these dredged materials, placed within the disposal areas, subsequently served a dual purpose:
1. As backfill materials for the backfilling of the foundation pits following the installation of the GBFs.
2. As ballast infill materials within the GBFs.

On average, some 90,000 m³ were dredged per foundation pit.

INSTALLATION OF FOUNDATION BEDS

As one of the most important interfaces in the project, the foundation bed ensures that the stresses induced in the base plate of the GBF remain within acceptable limits. The foundation bed also creates a first, crucial level for achieving the specified verticality of the turbine towers and further ensures that the weight of each GBF is properly transferred to the subsoil.

The foundation beds consist of two layers: a circular filter layer from the dredged level up to 0.55 m below foundation level, followed by a circular gravel layer up to target foundation level. Specifications were as in Table II.

The installation of the foundation beds was performed using the Dynamically Positioned Fallpipe Vessel (DPFV) *Seahorse*. The vessel is a DP Class 2 vessel with a rock loading capacity of 18,000 tonnes.

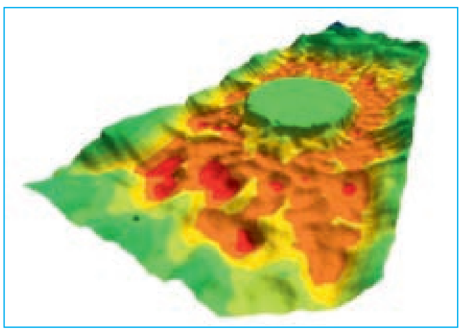

Figure 5. Visualisation of D1 foundation bed level, 1.30 m above the surrounding bottom of the dredged pit (4x enhanced vertical scale)

Table II. Two layers of the foundation beds.

Filter layer	
Material	Crushed gravel 0/63 mm
Layer thickness	Min. 0.40 m
Diameter of layer	Min. 32.10 m
Gravel layer	
Material	Crushed gravel 10/80 mm
Layer thickness	Min. 0.40 m
Diameter of layer	Min. 28.90 m
Max. inclination of gravel bed layer surface	<0.75°

Gravel complying with specific grading envelopes was loaded at Norstone's Dirdal quarry near Stavanger in Norway. An average of 2,500 tonnes of filter layer material and 1,200 tonnes of gravel layer material was placed per location.

Gravel placement with a DPFV is achieved by transferring gravel from the vessel's holds into a fallpipe system that can be accurately steered by means of a Remotely Operated Vehicle (ROV) equipped with thrusters. The fallpipe ROV (FPROV) is also equipped with state of the art survey equipment (including Multi Beam Echosounders) and cameras, which allow to verify and monitor progress of the works and to document the as-built status. All survey operations were performed and processed on board of the vessel.

Gravel was placed following pre-defined tracks. Once the required volume of material was placed, precision levelling was achieved with a purpose-designed levelling tool. This ensured the levelling of local overfills on the surfaces of both layers. The tool was attached to the lower end of the fallpipe and was carefully dragged across the area until the installation tolerances were achieved.

An almost perfectly horizontal surface of the gravel layer was achieved on all foundation beds, whereas an allowance for tilt of 0.75° was included in the design. At 30 km from the shore, and in water depths of almost 30 metres, this is a unique achievement, especially considering the dimensions of the surfaces (approximately 700 m², equivalent to two adjacent basketball fields) (Figure 5).

HEAVY LIFT, TRANSPORT AND OFFSHORE INSTALLATION OF THE GBFs

The GBFs have been designed bearing in mind a lift-off from the quay by means of the Heavy Lift Vessel (HLV) *Rambiz*.

Prior to lift-off, an onshore transport from construction position towards the quay platform needed to be performed. This was achieved by means of Self Propelled Modular Trailers (SPMTs). The SPMTs were driven underneath the GBFs, in between the concrete supporting beams designed to accommodate these vehicles. They then used their hydraulic suspensions to lift the GBFs from these supporting beams.

SPMTs constitute a grid of several dozen computer-controlled wheels, in order to evenly distribute weight and to steer accurately. Each individual wheel can swivel independently from the other wheels, to allow the SPMT combination with the GBF to turn, move sideways, or even spin in place. A combination counting 112 axle lines, each capable of carrying 30 tonnes, was deployed to perform the onshore transport. This combination consisted of 3 trains of 24 axle lines and 2 trains of 20 axle lines. The GBFs were carried towards the quay wall at a very low speed, controlled by a centralised computer system.

Once the SPMTs had reached the quay wall, the GBF was released for lift off by the HLV Rambiz. Lifting of the GBFs was achieved using a purpose-built lifting frame catering for the safe transfer of loads between the suspended GBF and the *Rambiz* (Figure 6).

Purpose-designed lifting lugs were integrated in the GBF structure. The connection with the crane hoisting wires was via custom-made hydraulic pin release mechanisms, which were released once the structure was placed onto the seabed. This mechanism allows for safe installation procedures without the need for diver interventions.

Figure 6. The lifting of the GBF from the SPMT combination.

Figure 7. Two views of the lowering of the GBF, in front of quay wall and on its way out to sea.

The weights of the GBFs just fit within the lifting capacity of the *Rambiz*. Once loaded, and when the GBF was clear from the quay wall, the GBF was lowered below the water table prior to leaving the entrance channel to the port of Ostend (Figure 7). As soon as the vessel reached deeper waters, the GBF was further lowered down to 10 metres below the water table.

On location, the *Rambiz* was brought and maintained into position by means of 4 flipper delta anchors of 7 tonnes each. To allow for sufficient and equal suspension of the crane hooks and as such increasing stability during the lowering of the GBF, the GBF was ballasted with water.

Highly accurate LRK positioning systems were installed in both crane booms of the *Rambiz*, whilst an electronic inclination measurement device was mounted at the top of the GBF. Four echo sounders near the base plate of the GBF allowed the assessment of the position of the GBF with respect to the gravel bed during the lowering operations. The achieved installation offsets from target centres were on average about 0.5 metres, whilst the inclination of the installed structures averaged 0.10° (Figure 8).

During the entire construction period, a detailed weight management system was implemented, respecting both DNV and ISO standards, in order to control weight progress of the GBFs. Part of this operation included 3D volume scans, material weighing and listing, and so on.

Prior to lift off, the GBFs were physically weighed with an accuracy of less than 0.5% in order to be sure that the weight requirements for the *Rambiz* were met and to determine the structures' Centre of Gravity (CoG). This allowed for a site decision whether the GBFs would be installed heading NW or SE. It was preferred to have the CoG nearer to the *Rambiz* as this allowed for verticality correction by means of the tugger lines.

During the engineering phase, extensive physical model tests were carried out by the Danish Hydraulic Institute (DHI), whilst numerical modelling was performed by MARIN. Dedicated current measurement campaigns were performed prior to and during the installation works in order to compare the actual conditions on site against the models. The entire operation has been scrutinised by DNV as Marine Warranty Surveyor for the project.

BACKFILL OF FOUNDATION PITS

Backfill denotes the filling of the dredged foundation pits following the installation of the GBFs. The requirement for backfilling is dictated by the geotechnical stability of the structures. As a result, erosion protection is equally important to ensure that the required amount of backfill material can be guaranteed throughout the design life of the structures.

Figure 8. The GBF D1 in the water after installation.

Backfill operations around the GBF structures were performed with sands dredged from the nearby disposal areas, which originated from the dredging of the foundation pits. Specifications for the backfill were as in Table III.

The requirement for a very low fines content was achieved by using sand that has been dredged twice (once during the dredging of the foundation pits, and once when dredging the same materials from the disposal areas for backfilling purposes) by means of TSHDs. Each time the material

is dredged and deposited in the hopper well, the fines are being washed out by the vessel's overflow system. Samples taken from inside the hopper well prior to the backfilling, confirmed compliance with these specifications.

The TSHD *Jade River* was deployed for dredging the backfill materials. The dredged materials were spread hydraulically in the foundation pits by means of a purpose-built spreader barge, the *Thornton 1*, which was also equipped for carrying out the ballast infill and the scour protection works (Figure 9). The connection between spreader barge and TSHD was done via a self-floating pipeline of approximately 300 metres length, coupled to the TSHD via a common bow connection system.

The *Thornton 1* is provided with a 12-metre wide diffuser spray pipe for spreading of the sand across the foundation pits according to a controlled layer pattern. The outlet of this spray pipe was kept at a fixed height of approximately 1 to 2 metres above the intended spraying level of the backfill layer, and was continuously and automatically corrected for tidal changes.

The tracks of the *Thornton 1* are pre-defined, whilst hauling speeds are based on multi-beam survey data collected immediately prior to sailing the relevant tracks and on on-line velocity and concentration measurements of the mixture pumped by the TSHD.

Determination of these tracking speeds occurs in a dynamic and fully automated fashion by a dedicated computer system that controls the barge's winches. The *Thornton 1* is kept in position using six (6) hydraulic winches in combination with anchor wires connected to 7 and 12 tonnes flipper delta anchors previously installed at strict pre-defined locations. The system is capable of holding the barge in a very stable position regardless of the swell and current conditions.

The quantity of backfill material required per foundation pit was on average 60,000 m³, or the equivalent of 24 loads of the TSHD *Jade River*

BALLAST INFILL

The requirement for ballast infill of the GBF also originates from the geotechnical design. The required amount of infill is closely linked with the design of the backfill and, as a result, with the design of the erosion protection that covers the backfill. Design assumptions for the infill sands were unit weights of 15.80 and 19.24 kN/m³ for sand above, respectively below water level. Laboratory tests on dredged sand samples confirmed these assumptions to be conservative.

The infill of the GBFs was executed in 2 stages:

1. Hydraulic infill: Materials dredged at the disposal locations by means of the TSHD *Vlaanderen XXI* were pumped into the GBF via a dedicated infill tower on board of the *Thornton 1*.
2. Dry infill: Upon completion of the hydraulic infill and settlement of the materials, dry infill was executed with sands.

The hydraulic infill activities were separated into two distinct phases:

1. Dredging of the infill materials by means of the TSHD *Vlaanderen XXI*, and
2. Subsequently the hydraulic pumping of the materials into the GBF using the multi-purpose barge *Thornton 1*, previously deployed for the backfilling works.

The *Vlaanderen XXI* is a 1,750 m³ TSHD that was recently converted for supplying marine sand and aggregates for the building materials market. As a result, it is provided with on board drainage pumps to drain the dredged mixture and with a materials handling crane for offloading the materials to shore or onto other vessels or barges. For the purposes of the hydraulic infill works, the *Vlaanderen XXI* moored alongside the *Thornton 1*, each time positioned adjacent to one of the GBF structures, for transfer of the materials into the hold of the barge.

Pumping of sand from the *Thornton 1* into the GBF was performed in a controlled way, limiting the pump flow. For structural design reasons, the mixture density was to be kept below 13 kN/m³. In order to bridge the difference in level between the deck of the *Thornton 1* (level fluctuating with the tidal range) and the top of the GBF (level +17 m TAW), an infill tower was conceived, reaching several meters above the top of the GBF.

A total volume of approximately 2,000 m³ was required for the infill of each GBF. Two hopper loads of the *Vlaanderen XXI* were required to achieve this.
The GBFs were filled hydraulically up to the target level of +14.50 m TAW, following which the infill mass was drained down to MSL. When the water level inside the GBF

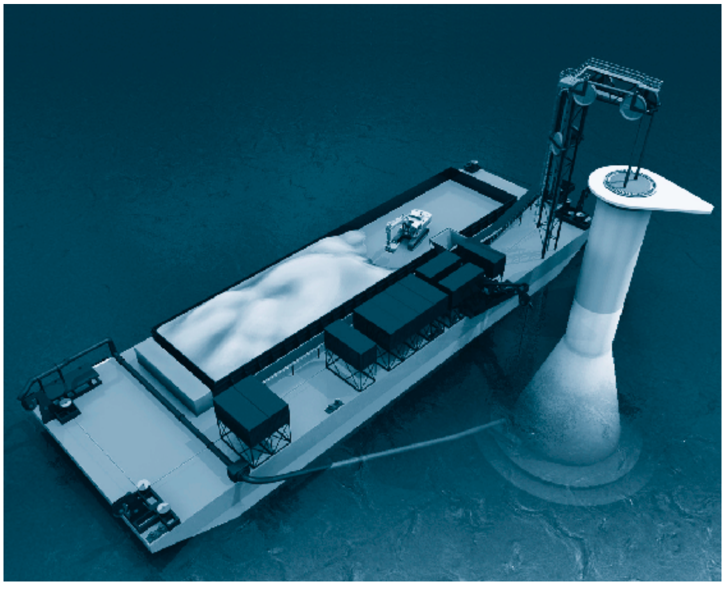

Figure 9. Multi-purpose barge Thornton 1 depicted in backfill and infill mode.

Table III. Specifications for the backfill.

Material characteristics	Sand from the Thornton Bank, D50 > 200µm, silt content <2%
Top level of the backfill	Up to Reference Seabed Level (RSBL)
Extent of the backfill	Covering the full surface of the dredged foundation pits.

Table IV. Required filter and armour layer for scour protection.

GBF #	RSBL (top of backfill) (m TAW)	Crest diameter for the armour layer	Crest diameter for the filter layer
D1	-18.00	44.0 m	48.5m
D2	-20.00	44.0 m	48.5 m
D3	-22.50	44.0 m	48.5 m
D4	-22.50	50.0 m	54.5 m
D5	-23.50	51.0 m	55.5 m
D6	-23.50	58.0 m	62.5 m

Table V. Specifications of the scour protection system.

Filter layer (installed on top of the sand backfill)	
Material	Crushed gravel 10/80 mm D50 = 50 mm; wide gradation $D_{85}/D_{15} > 5$
Layer thickness	min. 0.60 m
Armour layer (installed on top of the filter layer)	
Material	Quarried rock 10/200 kg D50 = 350 mm; wide gradation $D_{85}/D_{15} > 5$
Layer thickness	min. 0.70 m
Top level	Reference Seabed Level + 1.30 m / + 1.45 m

had decreased and the sand had further settled, dry infill (using dredged sand) was used to make up for the loss of volume and to complete the infill up to the design level of +14.50 m TAW. These dry infill works were performed as a separate activity using the jack-up platform that was deployed at a later stage for the levelling and grouting of the transition piece on each GBF.

For GBF D6, the entire infill operation was performed using “dry materials”. This approach was adopted since, as a result of slightly less favourable underlying soil conditions, the geotechnical design called for part of the infill to be performed with heavy minerals. Infill with these heavy ballast materials was performed first as bottom fill, whilst the remaining infill was executed with dredged sands up to final level. All operations at GBF D6 were performed from a jack-up platform. The same infill approach was to a certain extent adopted at some of the other locations in these instances, however, dictated by operational priorities.

SCOUR PROTECTION

Around each GBF, a scour protection system has been conceived, providing protection for the backfill materials against the impact of currents and waves. The design consists of a filter and armour layer of quarried rock materials (Figure 10).

The required extent of this protection is closely linked with the geotechnical design and is summarised in Table IV.

At the 33 and 150kV cable bellmouth locations, where these cables enter the GBF structures, the design caters for the armour layer to be placed after the installation of the cables. The armour layer at these locations was further extended (10 m wide stretches extending 15 m from the edge of the scour protection system) to provide additional cover of the cable in the transition area between the edge of the scour protection system and the trenched cable (Figure 11). Specifications of the scour protection system are shown in Table V.

With the aim of processing standard quarry products, quarry run 0/120 mm was agreed to be used for the filter materials, whilst the armour grading was achieved using a 20%-80% mixture of 5-40 kg and 40-200 kg products respectively. Both products consisted of hard, compact limestone rock produced at Carrières Lemay. The materials were transported by trucks to a temporary storage and rehandling yard in the port of Zeebruges.

The *Vlaanderen XXI* was again used for supplying the rock materials from the stockpile area in the port of Zeebruges towards the *Thornton 1*, which in turn was equipped as a fallpipe barge for these works.

The barge’s position-tracking features and automotive movements along pre-defined tracks are also available in “fallpipe mode”. A belt weighing device is included in the system, allowing the continuous monitoring of the rock quantities transferred and installed. This data serves as input for the computer-controlled movements of the barge along pre-defined rock placement tracks.

GBF COMPLETION WORKS

The transition level for installation of the wind turbine towers was to be provided within a tolerance of 0.25° from horizontal level which is the specified vertical

installation tolerance for the turbine towers. The transition piece of each GBF consists of a levelling flange made out of 6 segments, each supported by plastic levelling nuts. The flange is the upper part of a cylindrical "anchor cage", consisting also of a lower flange, cast in the upper cylindrical part of the concrete structure and connected to 180pcs. 2.6 m long tensioning bolts, which are protected from the surrounding concrete by a plastic casing. The bolts pass through the transition flange, which is conceived to correct any inclination of the GBF (Figure 12).

Since the installation of all GBFs was performed well within the specifications for final inclination of the transition level, no further adjustment of the levelness of the flange was required offshore. Fine-tuning of the flange sections was performed by the WTG supplier, following which the volume between the flange and the concrete top level of the GBF was filled with a self-levelling high strength, non-shrink grout.

A jack-up platform was deployed for these operations and also catered for the execution of the remaining dry infill, the lowering of the water table inside the GBF down to MSL and the installation of the remaining appurtenances (access ladders and so on).

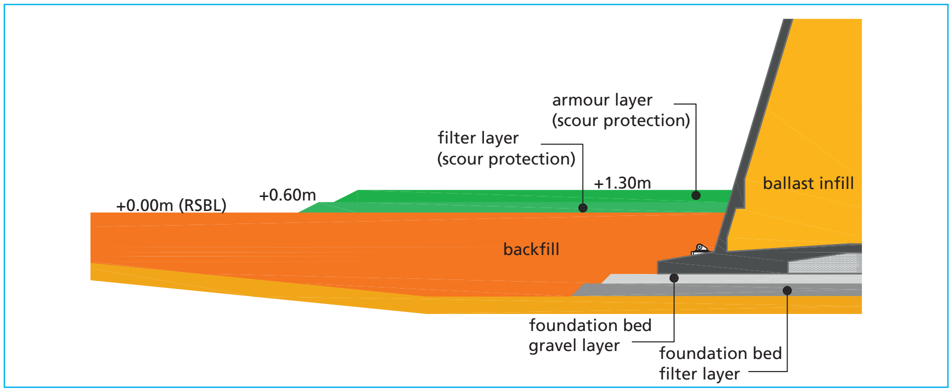

Figure 10. General scour protection lay-out.

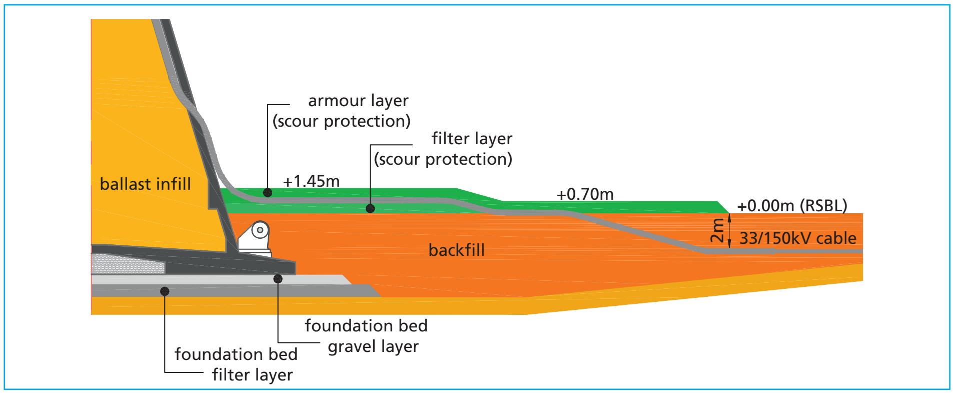

Figure 11. Scour protection lay-out at bell mouth locations.

CONCLUSIONS

The novel Gravity Base Foundation concept developed for the Thornton Bank Offshore Wind Farm has proven to be a viable and competitive wind turbine support structure for deployment in deeper North Sea waters. Innovative design resulted in a complex matrix of interfaces from design into construction, involving not only the detailed design engineer and the Contractor, but also the Project Owner, its Engineer and certification bodies. Many aspects of the offshore execution relied upon extensive experience gained in the dredging and marine construction industries. The design has meanwhile been patented and is being considered for marketing towards other offshore wind project developers.

REFERENCES

MUMM and C-Power (2004). Thornton Bank Wind Farm Environmental Impact Assessment and related documents. See http://www.mumm.ac.be/EN/Management/Sea-based/windmills_docs.php?proj=cpower2mod

Figure 12. Onshore assembly of anchor cage