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Experiences with simple and repetitive Offshore Foundations

Topic: *Offshore technology for wind energy application*
Subtopic: *Foundation concepts – Series production, installation concepts and risks*
Key words: *Lessons learned, installation methods, transition tower/foundation.*

ABSTRACT
The planning, the special development work, and the installation of the foundations for the offshore wind parks North Hoyle in the Irish Sea and Scroby Sands in the North Sea are described. The wind parks comprise each 30 2 MW Vestas V 80 turbines. In both wind parks monopile foundations were used. They were placed in open sea in tidal dominated areas. Water depths were varying from 6 – 20 m. It was decided from the beginning that the foundations should be as standardised as possible even though geotechnical and hydrographic variations were highly variable and that the installation should be quick and simple with few offshore operations.

This was done in spite of the fact that the offshore foundations in a wind park are the only items, which cannot be standardised. Turbines, towers, and cables can be standardised, but the foundation shall connect the highly variable underground and water depth with the standardised turbine component. The North Hoyle foundations were governed by large geological variations – a sand/clay overburden on top of a mudstone/sandstone formation. The Scroby Sands foundations, on the other hand, were governed by large fluctuations in seabed elevations, which annually were up to 3 m. In 25 yrs. they were up to 7 m. In spite of these variations the foundations and components could be standardised to a very high degree. Developments of special transitions, pile/foundation, telescopic j-tubes, and special scour protections were made.

Efforts were put into speedy installation. At Scroby Sands the transition pieces were omitted and the piles were driven directly with the flange on. At the top of the learning curve a complete foundation with platform, access arrangements, J-tubes etc. could be installed in 18 hours.

INTRODUCTION
The two first offshore wind farms offshore the British coastline have been erected and are operative. The locations are North Hoyle and Scroby Sands. They both comprise 30 turbines of the Vestas V80, 2 MW class and as foundations the monopile type was chosen. LICengineering A/S supplied the design of the monopile and the appurtenance structures.

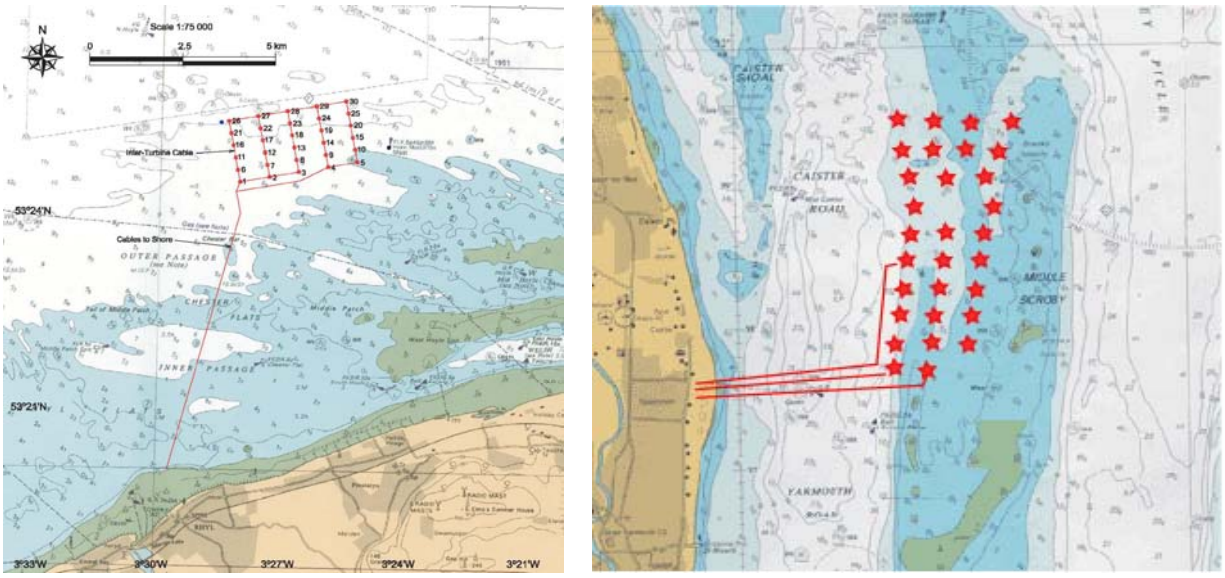
The North Hoyle location is situated in the Irish Sea North of Wales, Fig. 1a. It is sheltered from the east and south direction. However, between west and north there is a window to the open sea from where rather large waves can be expected. In addition there are very high tidal variations, Table 1. The upper soil is sand, clay and sediment layers, the underlying layers are mudstone and sandstone.

The Scroby Sands location is situated in the North Sea East of Great Yarmouth, Norfolk, Fig. 1b. It is a huge underwater sand bank created by the strong tidal flow. There are relatively large depth variations, strong currents, and sediment transport, Table 1. The sand is very dense sand with bands of silt and clay. The sand varies between 0.2 mm and 0.4 mm.

Windfarm	Depths LAT m	Tidal range m	Depth variation Short term m	Depth variation long term m	Scour Depth m	Max tidal currents m/s	Storm surge m/s	Waves m	Comments
North Hoyle	6-2-10	9.1	0	0	6.0	0.8	0.2	11.25	Waves are depth limited
Scroby Sands	1.3-11.3	2.8	±3.0	±7.0	7.0	1.6	1.2	10.6	

Table 1 Design parameters for the wind farms.

The most spectacular parameters in Table 1 are the large depth variations on the Scroby Sands. Up to 7.0 m general lowering of the sea bottom should be envisaged for the design.



a) North Hoyle. b) Scroby Sands.

Figure 1 Location and lay-out of windparks. a) North Hoyle. b) Scroby Sands.

The geotechnical conditions were different so different design and installation methods were necessary. A combined drill and drive installation was used for the North Hoyle site whereas a normal driving was used for the Scroby Sands. The soils were quite dense for both locations, so from a driving point of view the penetration of the piles should preferably be as small as possible. This should be held against the required penetration for the in-place stability.

In spite of the differences there are many similar items between the two developments.

THE GEOTECHNICAL CONDITIONS

For both wind parks the geotechnical conditions were described by a number of boreholes and a seismic investigation of the formations. The investigations are summarised in Table 2.

	Seismic study	Side Scan	Bore hole No.	SPT	Coring	In situ Characteristic	Lab Test	Met Mast Driving Results
North Hoyle	X	X	6	X	X	X	X	÷
Scroby Sands	X	X	4	X	X	X	X	X

Table 2 Geotechnical investigations. Borehole number = Number of geotechnical borings.

The lab test comprised the usual package, i.e. shear box testing, drained and undrained triaxial testing, grain distribution, curves, grain density, permeability coefficient and unconfined compression tests (for rock).

The in situ characteristics comprised pocket penetrometer testing and field evaluation. For the Scroby Sands the vibro driving and hammer driving records for the Met mast were available. This was an extremely valuable piece of information to verify the findings from the borehole and from the seismic study.

The seismic studies provided the overall view of the geological formation. The boreholes were used to calibrate the seismic findings. For instance, to locate the sediment/rock interface in the North Hoyle area and for the Scroby Sands area to locate sand/clay or sand/sand interfaces over possibly some gravel and stone nests. There were not a borehole or a CPT per foundation location. So decisions should be taken whether additional investigations should be carried out or whether the design for all thirty foundations should be made on available data. To determine that cost/benefit analyses were made.

The offshore geotechnical investigations were expensive and time consuming and the sites were difficult to operate due to strong currents and waves. In addition at North Hoyle the recovery rate from the coring of the mudstone (not so much the sandstone) was low, so what was the real in-situ strength of the rock when a great part disintegrated at the borings. These difficulties should be weighted against the knowledge on the sites. Both sites were banks where the upper sediments would be compacted by the wave action. They should therefore be expected to be dense. All tests showed that. Further, the history of the sites indicated that the sediment strengths were rather uniform.

The outstanding feature for North Hoyle was the rock strength (the rock surface was known from the seismic study). For Scroby Sands it was the possibility of encountering gravel or stone layers. But the seismic information did not indicate that.

The monopile dimensions were determined for the measured soil parameters in each borehole and the variation in monopile dimensions was determined. It turned out that the variations in wall thicknesses and driving lengths were small compared with the effects of other variations such as rock/sediment interface (North Hoyle) and long term water depth (Scroby Sands).

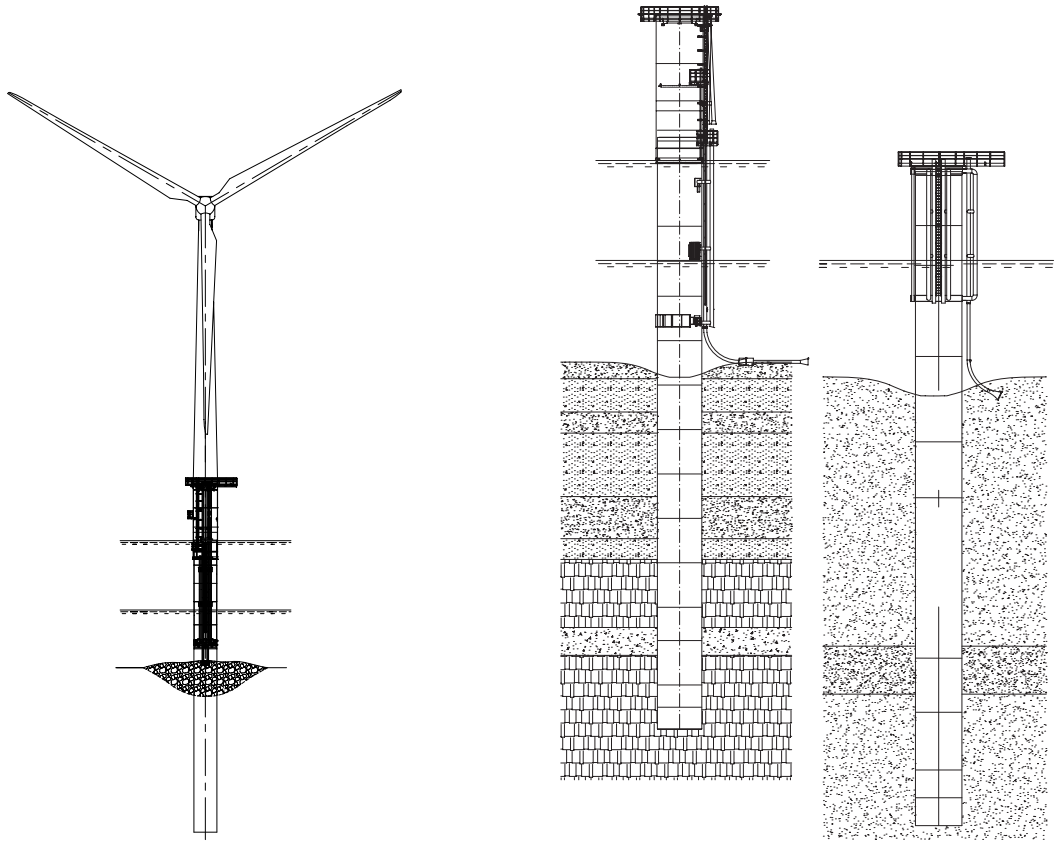
From a cost/benefit point of view the conclusions were clear. It was decided only to use the available data, but with additional confirmatory seismic study for each of the sites. In addition very robust installation methods were defined in order to secure that the installation could be done irrespective of the strength of the soils.

MONOPILE LAYOUT

The monopile foundations comprised the following main parts:

- The pile
- The transition piece (to fit the tower)
- The sea access and platform
- J-tubes for tie-in of electrical cables
- Scour protection

The transition piece, the sea access, and platform, and the scour protection could be standardised and made repetitive. The pile length and wall thickness, on the other hand, had to vary with water depth and soil conditions. The J-tubes would have to vary with water depth and scour depths.



a) b) c)

Figure 2a Monopile designs for North Hoyle and Scroby Sands. 2 MW offshore turbine 2b) and 2c Soil conditions, tidal and seabed variations as well as the environmental loads determine the pile layout and seabed penetration. The figures b) and c) are to the same scale.

The monopiles were fabricated in rolled and welded steel tubulars with an outer diameter of around 4.0 m in sections with different

wall thickness in the range 40-70 mm. On the North Hoyle foundations, transition sections were used stabbed over the top of the monopile after the pile had been installed, and grouted in place, Fig. 2b. The reason for choosing this design was the hard driving, which was expected for the drill and drive installation. The target depth could not necessarily be reached, so the transition piece could compensate for these tolerances. Further, it was expected that the hard driving might result in deformations on the top of the pile. This made the grouted solution attractive.

On Scroby Sands the piles were designed as single items without transition sections, Fig. 2c. Therefore the pile should be driven or vibro-driven with the flange for the tower installed. This implied that the pile should be driven to target ±0.5 m, which was the tolerance for the flange elevation. The pile should also be driven sufficiently vertical to meet the tolerance criterion for verticality - 0^0.5. This solution had the advantage that it would reduce time on site to a minimum. To secure driving to final depth a spread for plug lifting was envisaged. The flange was specially designed to sustain the driving loads.

THE PILES

The water depths and the soil conditions in combination with the external loads determine the required dimensions of the piles. The Ultimate Limit State (ULS) forces govern the pile penetration. The fatigue loads (Fatigue Limit State FLS) govern the wall thickness in the upper part of the pile. The driving fatigue damage and driving stresses can decide the wall thickness in the bottom of the pile.

For the North Hoyle wind park it turned out that three types of piles were practical to cover the variations of water depth and rock strength. For Scroby Sands the variations in water depth and general subsidence of the sea bottom could also be covered by three different pile lengths, Table 3.

Area	OD	Total foundations No.	Pile type 1			Pile type 2			Pile type 3		
	m		Length m	Mass Tonnes	No.	Length m	Mass Tonnes	No.	Length m	Mass Tonnes	No.
North Hoyle	4.0	30	48.4	252	5	53.3	275	17	51.8	269	8
Scroby Sands	4.2	30	45.48	199	10	41.98	152	14	40.98	143	14

Table 3 The 3 different types of piles used for North Hoyle and Scroby Sands.

The piles were slimmed down as much as load requirements, transport and driving would allow. From Table 3 it is seen that it was not so much the pile length, which differ. It was the pile masses. So, from a repetitive point of view the length of piles may have been the same. Driving resistance, however, dictated that piles were not made longer than necessary. The weight saving was also worth more than a standardsation.

PILE TO TOWER TRANSITION

The V80, 2MW windturbine tower normally had a bolted flange connection at the base. The foundation should fit this interface.

For the North Hoyle wind farm a transition piece was used. It had a length of 13.285 m and was used in top of the monopile. The reason for this solution was that the top of the pile necessarily had to be rather high and above high water in order to operate the drilling equipment during the drill/drive operation. It would therefore be waste of steel to make it longer.

The transition piece was installed by landing it with an overlap over the driven monopile after pile installation. It was then grouted in place using high strength fibre re-inforced concrete based grout. The transition section was fitted with a 3-point hydraulic levelling system, enabling out of vertical tolerances for the main pile to be corrected.

The transition pieces for North Hoyle were all alike. So with this item repetivity in fabrication and installation were reached.

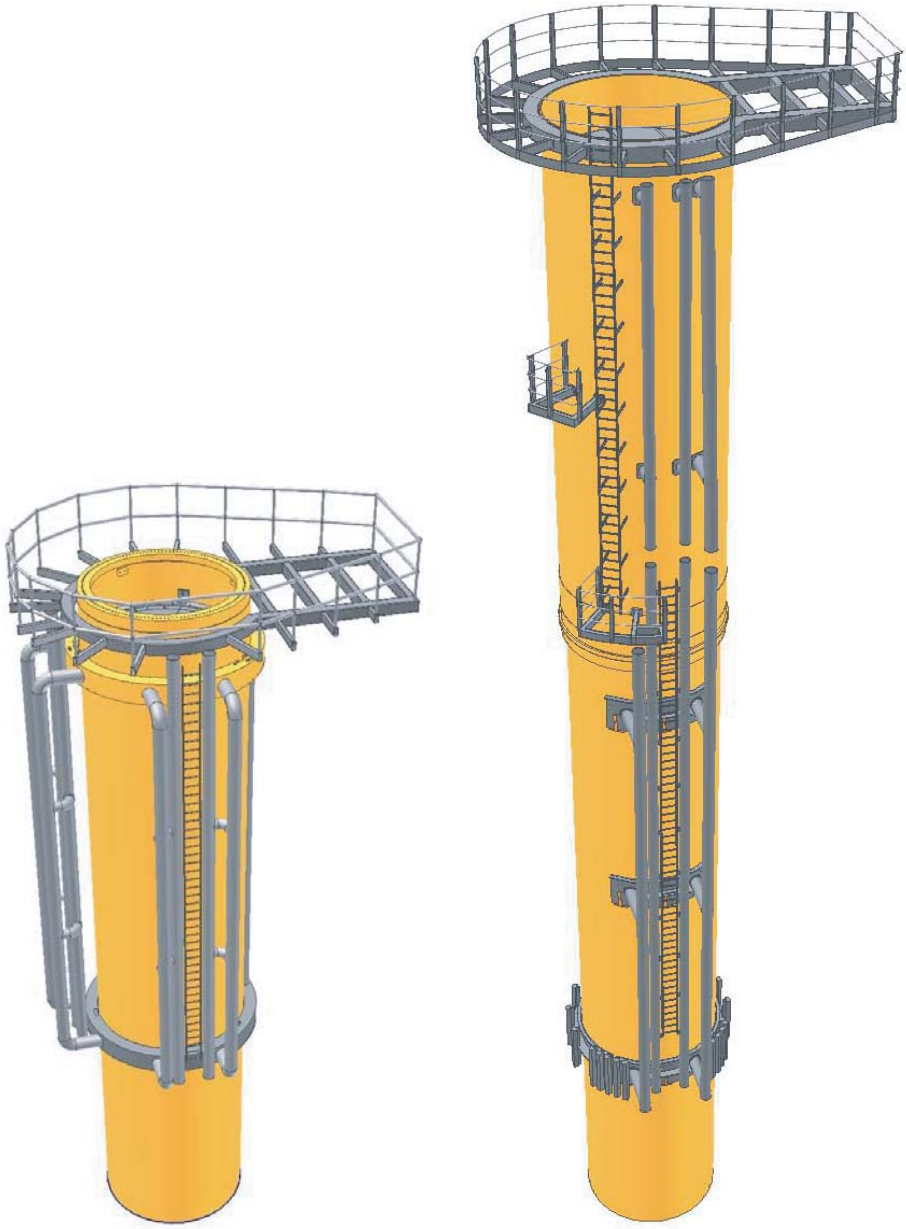
SEA ACCESS AND PLATFORM

The offshore windturbines required access platforms for maintenance purpose. The platforms were placed near the top of the monopile foundation at the elevation of the tower flange out of the wave zone. They were shaped in order to allow lowering of larger parts of the turbine components from the nacelle and laydown temporarily on the access platform. The platforms also had navigational aids installed. The platforms were alike within the projects.

The layouts of the sea access to the platforms are depicted in Fig. 3.

The access should preferably be possible from many directions depending on wind and wave. Typically this will result in design with two separate boat landings perpendicular to each other or at opposite sides of the monopile. This was made for the Scroby Sands foundations because of the strong tidal currents in combination with the waves. There was a course of cost for both in steel but also in addition hydrodynamic forces on the structures in strong wave situations. In the present case, however, the force level was governed by the wind forces. The North Hoyle solution was different. The reason was that the strong sea states propagating in from the Outer Irish Sea were mainly parallel with the tidal currents (there was only a difference on 15). This made it possible to place the sea access

in the lee side such that it would not contribute to the hydrodynamic drag on the foundation.



a) b)

Figure 3 Monopiles shown from seabed and up including access arrangements and platforms. Cables are running inside the vertical fenders. Lower parts of J-tubes and cable exits not shown. a) Scroby Sands. b) North Hoyle.

The boat landings were designed to allow the boats to slide up and down along vertical bars without any obstructions during all normal water levels, wind directions and sea states up to a pre defined level. The access ladders were designed to enable personnel to make a safe transition from/to the boats, were moving up and down along the ladder.

For the North Hoyle site the upper access was welded to the transition piece, Fig. 4. The lower access was hung on the pile and fastened in special fixtures, Fig. 4. For the Scroby Sands piles the access was attached to a cage, which could be sled down the pile, Fig. 5.

Since the sea access and the platforms were in the water line and above the water they could be made completely identical within each wind farm. So in this case repetitiveness was achieved for both windfarms.

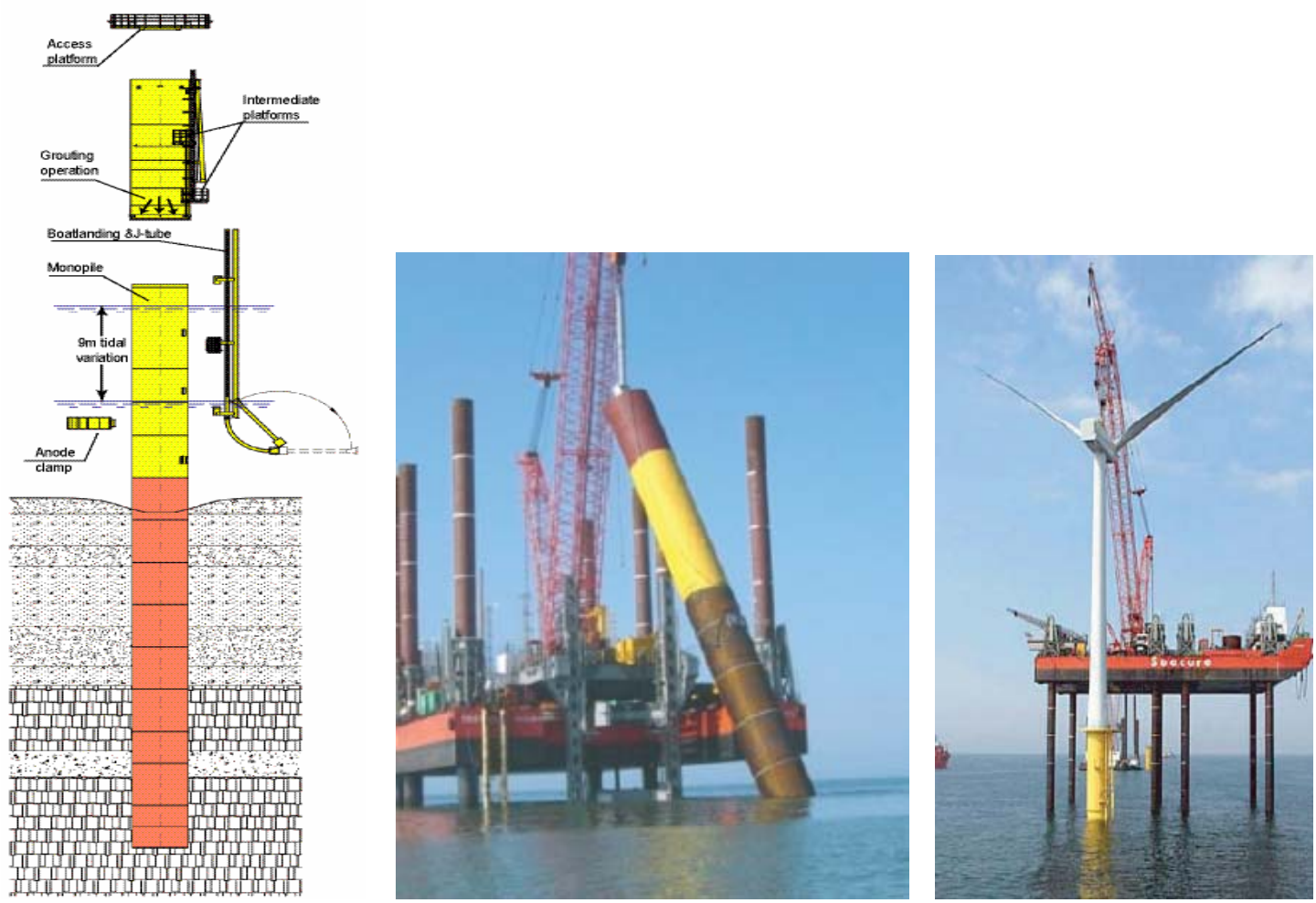
J-TUBES AND CABLE EXITS

It was decided to use outer J-tubes because they could be used integrally with the sea access. The basic design was made for the two-J-

tube system where the cross section could be standardised. For the few wind turbines with three cables tied in a third J-tube was just added to the side. The tubes were fabricated in steel because they were part of the boat fendering system. The J-tube was the item, which could only be standardised in diameter and wall thickness, but not in length. The water depth and the expected scour decided the length.

For the North Hoyle project the bathymetry conditions were such that it was possible to limit the design to 3 different lengths. The system was originally designed diverless with an automatic clamp system. It was later changed to a diver installed system with a bottom clamp and a hinge system to accomodate for the varying lengths due to water depths and scour holes, Fig. 4.

For the Scroby Sands turbines the J-tubes were also limited to 3 different designs. The design was dictated by the very large changes in water depths and scour depth. Therefore, the J-tubes were made telescopic such that they could be extended into the scour hole, which would develop around the base. In this way the cable could be pulled in well below the mudline and there would remain an ample overburden above the cable even in the case of subsidence of the sea bottom.



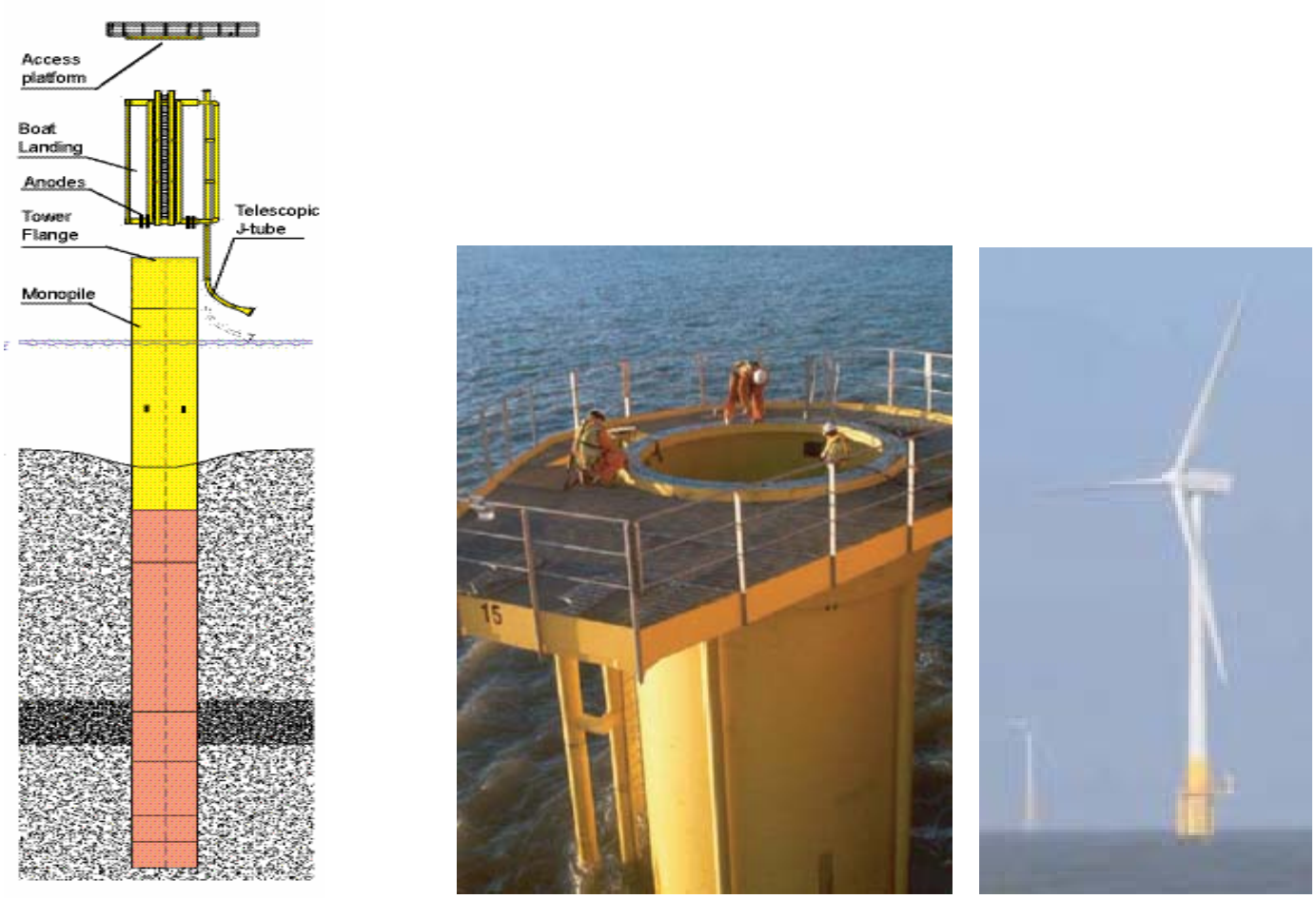
a) b) c)

Figure 4 North Hoyle. a) Design, b) Installation c) Completion

SCOUR PROTECTION

The sandy seabed at the two locations gave rise to serious deliberations of what kind of scour protection should be used or if there should be used scour protection at all. At both locations the spring tide currents could develop a complete scour hole of 1.5 pile diameter over the tidal cycles in a 14 days spring tide cycle. This meant that scour holes of 6 m depth should be considered, if no scour protection was applied.

It was deliberated whether a scour protection actually was needed, because the monopile could just as well be driven so much further into the ground. One important issue here were the cables tied-in to the windturbine. The prospect of having cables spanning a scour hole was grim even if they were encased in a J-tube.



a) b) c)

Figure 5 Scroby Sands. a) Design, b) Installation c) Completed.

In the end it turned out that the sea bottom conditions were more stony and clayey at North Hoyle resulting in little scour. It was therefore decided only to protect the cable tie-in and the low end of the J-tubes by placing scour protection over these items. This was done to avoid hooking or impact from falling objects. Scour was permitted to develop on the remaining part of the seabed so long as it was not deeper than 2 m.

On Scroby Sands, however, there were no stones on the seabed. The complete scour developed in a spring tidal cycle, Fig. 6. The development of scour during neap tide conditions, on the other hand, was slow.

The maximum sour depth varied from 4.2m to 6.3m (corresponding to 1 to 1.4 pile diameters) and it extended 3 to 4 pile diameters from the center, Fig. 6.

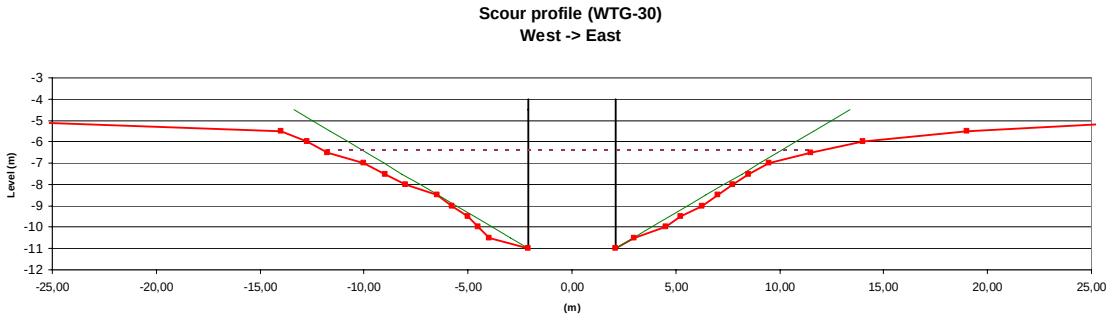


Fig. 6 Scroby Sands measured natural scour hole.

In the selection of stone sizes for the scour protection material the following design criteria were applied.

- The scour protection should be placed in a fully developed scour hole as deep as possible in order to account for future subsidence.
- The scour protection material should sustain the amplified bed shear stress caused by the foundation. However, the stone material was selected as small as possible in order to allow minor movements and even out at hot-spots and in order to obtain as gradual transition as possible to the surrounding seabed.
- The upper 85% fractile of the scour protection material should be unconditionally stable for frequent currents (tidal current, storm surge).
- The scour protection material was allowed to move under strong and extreme wave motions so long as it is verified that the storm or a sequence of storms will not completely disperse the materials and create a scour hole, which would influence the buried power cables.
- The scour protection should be able to follow the lowering of the seabed on its way down.
- Maximum global seabed lowering of 7 m.
- Maximum local scour in the scour protection itself was 2 m.

The selected scour protection material comprises stones with sizes from 10 mm < d < 300 mm. It was used both for North Hoyle and Scroby Sands. At North Hoyle only the cables and the ends of the J-tubes were covered. At Scroby Sands the scour holes were filled up to an elevation of 1 m below the existing sea bottom. This could be done by a volume of 900 m^3 stone material per foundation. Omitting the filling of the last 1 m saved a large stone volume (actually it was cheaper to extend and drive the OD 4.2 m pile an additional metre and omit this upper metre of stone protection).

INSTALLATION

On North Hoyle, a drive/drill solution was used. The pile was floated to the location with temporary bulkheads hydraulically locked to the pile ends. One of these bulkheads included an upending and lift arrangement. The pile was upended at location and placed at the seabed. The pile was driven through the upper sand and sediment layers until contact was obtained with the underlying bedrock. The internal core was then removed by use of drill and jetting equipment and an undersize hole was drilled into the stone layers. The pile was driven to the required penetration. After that, the transition piece was grouted to the top of the pile. The lower sea access and the J-tubes and lower anodes were fitted to the pile.

On Scroby Sands the monopile was installed using a pure pile driving operation. The monopile was driven with a pre-fitted flange for the tower connection, therefore no transition section was required. A platform was pre-installed in the foundation. The platform was secured in a temporary strap and compression block arrangement enabling pile driving with the platform in position. After pile driving the temporary hang-off arrangement was replaced by a bolted arrangement. The boat landing, access ladder and J-tubes sections were installed in one operation afterwards by sliding them over the piles and down. Finally the access platform was landed on top of the foundation. The platform and the sea access arrangement were locked to the foundation using bolt arrangements. The foundation was then ready for tower installation. The installation jack-up could comprise 5 piles with platforms, sea access units and J-tube unit in one load, Fig. 7. This resulted in a very quick installation of each foundation. Completion time was down to 18 hours.

The installation of the scour protection was made by dumping from a side dumping barge. To distribute the material around the pile, side dumping took place from 6 directions. At a distance of 2 m from the pile the unloading started and the barge was then moved away from the pile while unloading. An example is shown in Fig. 8.

LESSONS LEARNED

Verticality of the installed monopiles was obtained within small tolerances below 0.5 degree. Therefore, adjustments using the transition section were not implemented. Penetration depth was achieved with good accuracy around ± 0.5 m even for the hard driving in rock. In fact most of the piles were placed very accurately in spite that many of the operations were executed in the winter.

The driving with the flanges mounted on the piles at Scroby Sands went well so long as the specified procedure and the specially selected anvil were used. The flanges were not deformed nor indented (except the first two flanges, because a non-authorized anvil was used).

The operation is not standard and strong site supervision shall be deployed.

The installation tolerances on the Scroby Sands sea access arrangement turned out to be slightly strict in view of the fabrication methods used. Nominal radial clearances of typically 1 inch are not much when considering ovality of a 4 m diameter monopile constructed from rolled plate material, excessive weld heights, and elastic deformations in the system. For the monopiles it was found that quite significant radial deflection (elastic) occurred due to gravity alone for a pile lying in horizontal position. The access platform landing interfaces were quite simple and did not result in any tolerance difficulties.

Fig. 7 Jack-up loaded for installation of Scroby Sands.

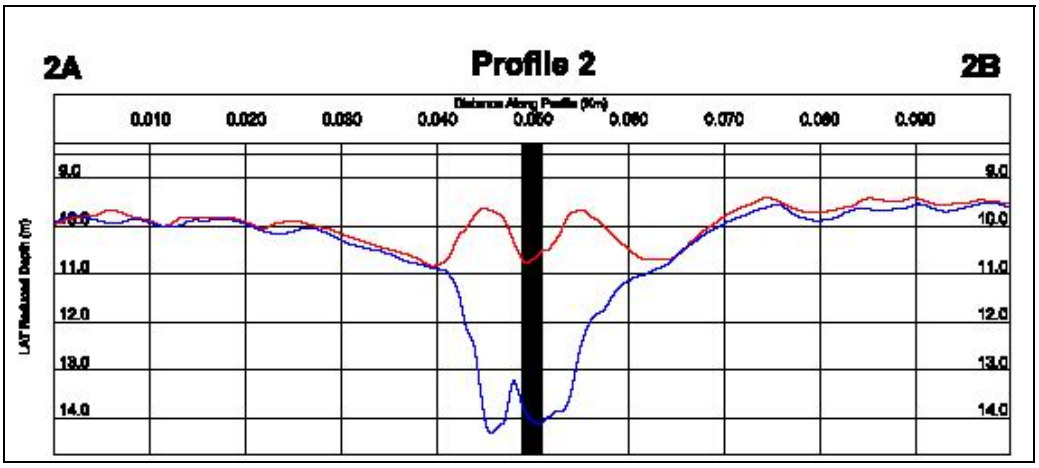


Fig. 8 Scour protection out-survey. Blue is scour hole. Red line is the surface of the protective stone layer.

The tolerances for all offshore-mated items should be relaxed as far as possible in order to ease installation under the difficult working conditions at sea and high cost for the installation spreads.

J-tubes can with advantage be made so that they are part of the sea access. Repetitiveness can be obtained by making the J-tubes telescopic.

The following observations concerning the installation of scour protection were made. The side dumping technique proved not particularly accurate in spite of generous tolerances so some of the fillings had to be replenished. In the NE corner the sea bottom changed very rapidly and in the centre of the wind park there was actually one foundation, where the scour hole did not develop immediately (because it was under neap tide conditions). After the first spring tidal cycle, however, the scour hole developed.

CONCLUSIONS

Many components for monopile foundations for offshore wind turbines can be made repetitive. They are the transition piece (if such one is used), the sea access and platform, and the scour protection. The J-tube system for cables can be made over the same template with the same cross sections but the length will necessarily have to suit the water depth and possible scour. Telescopic J-tubes may be used to account for varying water depths.

The pile itself can only be made repetitive to a certain degree depending on the bathymetry and the geotechnical conditions on site. For two wind parks completed in UK each of 30 turbines it turned out to be beneficial to operate with 3 types mainly derived by weight.

A monopile foundation can be established without a transition piece to the tower by driving the pile with this flange on. This solution provides the possibility for the quickest completion, but it also requires good site supervision.

ACKNOWLEDGEMENTS

The North Hoyle windfarm is operated by National Wind Power Offshore. Vestas Celtic was the main partner in the supply and construction contract and Seacore installed the 30 monopile foundations, using an 8-legged jack-up drill rig. The turbines, towers and foundations were supplied by Vestas, who generated the wind- and wave load time series for the foundation design and LICengineering A/S carried out the detailed design for the foundations and provided engineering support throughout the project. Smulders B.V. supplied the main steel and provided the fabrication layout for various parts of the steel details.

The Scroby Sands windfarm was developed by Powergen Renewables Offshore. Vestas Celtic supplied turbines, towers and foundations for the Scroby Sands Wind Farm. Vestas generated the wind- and wave load time series for the foundation design and LICengineering A/S carried out detailed design of the foundations and associated structures. The structures were fabricated by Isleburn. The installation of the turbine foundations including installation of scour protection was undertaken by Mammoet Van Oord.

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