EXLUSIVE SUMMARY
CONCEPTUAL FOUNDATION STUDY FOR KRIEGERS FLAK OFFSHORE WIND FARM, SWEDEN

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VATTENFALL

Conceptual Foundation Study for Kriegers Flak Offshore Wind Farm

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Abstract – This paper describes a conceptual foundation study carried out by Vattenfall with support from the Swedish Energy Agency. Five different foundation concepts have been evaluated and further developed using a site assessment from Vattenfall's planned wind farm at Kriegers Flak. The foundations are steel monopile, steel jacket, concrete gravity, concrete (gravity) tripod and (drilled) concrete monopile. The steel monopile was used as a reference in the study, as it is a well-developed concept. Although the concrete gravity and steel jacket concepts have been used in several projects, these concepts were developed further. For example, floating and semi-floating concepts for the concrete gravity foundation were developed. The concrete tripod and concrete monopile are promising new concepts that could be developed further.

INTRODUCTION

Vattenfall plans to develop an offshore wind farm in the Swedish part of Kriegers Flak. This is a shallow area in the southern Baltic Sea, 30 km from the Swedish coast and with a depth of 17–42 m. The wind farm is planned to have 128 turbines each rated at 5 MW, a total of 640 MW with an estimated annual production of 2.6 TWh.

At present, work is focused on compiling the site assessment. According to the project's timetable, procurement for the wind farm could start by 2011. To date, Vattenfall has made no investment decision for the wind farm. This could be done when all relevant permissions have been obtained, and when the site assessment is complete. The project must also subsequently fulfil Vattenfall's financial criteria. At present, the cost of building and operating the offshore wind farm is too high, taking into account the price of electricity and other economic support available in Sweden.

Vattenfall is one of the largest wind power producers in northern Europe, and the world's second largest company in offshore wind power. Today Vattenfall has wind turbines in Denmark, Finland, Germany, Great Britain, the Netherlands, Poland and Sweden. The target is to increase annual production from today's 2 TWh to 49 TWh by 2030.

Figure 1 Location of Kriegers Flak in the Baltic Sea (Swedish part coloured red).

Vattenfall, supported by Energimyndigheten (the Swedish Energy Agency), has carried out a conceptual study to evaluate different kinds of offshore foundations suitable for 3–5 MW turbines and a water depth of 20–40 m deep. The study has also investigated possible improvements regarding cost, manufacturing, installation, maintenance and environmental impact, to both existing and possible new foundation concepts.

The study focused on four different kinds of foundations: steel jacket, concrete monopile, gravity base structure and gravity concrete tripod. As a reference, a steel monopile was also evaluated. A seabed preparation robot was also subsequently developed. Helge Gravesen, of Grontmij | Carl Bro, was the executive project manager for the whole study.

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The study started in early 2008 with an open seminar at Vattenfall in Stockholm, where the project plan was presented to interested consultants, contractors, developers and others. Some ten consultants and contractors were engaged to develop the different foundations. Each group of consultant and contractor had main responsibility for a particular foundation, but there was very extensive cooperation between the groups in which the results were discussed and the designs further developed.

KRIEGERS FLAK WIND FARM

The wind farm

The Kriegers Flak project aims to use wind turbines rated at 5 MW. At present, there is no preferred turbine, and the foundation study was based on preliminary data for two sizes of wind turbines of 3.6 MW and 5.0 MW respectively [Ref 1]. The 3.6 MW turbine has a hub height of 72.5 m and the 5 MW has a hub height of 82.5 m. The nacelle masses for the two turbines are 220 tons and 410 tons respectively, and the tower masses are 220 tons and 300 tons.

Of the 128 turbines, 58 are located in water less than 26 m deep, 41 in depths of 26–34 m and 29 in water more than 34 m deep.

Site assessment

Grontmij **|** Carl Bro has compiled the site assessment for the foundation study [Ref 2].

Metocean conditions

The foundations were developed assuming a mean wind speed of 8.80 m/s at an altitude of 80 m above the sea surface (later analyses have indicated a somewhat higher wind speed). The 50-year 10-min. extreme wind speed was estimated to be 37.5 m/s, and the 3-s extreme gust was 49.6 m/s.

The significant wave height was estimated to be 5.2 m with a maximum wave height of 9.6 m. Icy conditions must be taken into consideration, with an ice thickness of 0.38 m, and crushing and bending strengths of 1.9 MPa and 0.5 MPa respectively.

Geology

The pre-Quaternary surface layer contains Upper Cretaceous chalk. The uppermost 350 m of the sedimentary bedrock is found to consist of white, soft chalk with abundant chert in the upper part. In the central parts of Kriegers Flak, the basement is covered by less than 20 m of Quaternary sediments. In general, the Quaternary sediments are composed of glacial diamict and glaciofluvial deposits, overlain by glaciolacustrine and marine sediments. The glacial landscape is dominated by northwest-southeast elongated moraine ridges a few metres high in the northeastern and southwestern parts of Kriegers Flak. Two till units can be identified in the area in question: an older unit of lodgement till, which can be related to the glaciotectonic deformation, and a younger unit as a cover layer of flow till.

Most of the sand and gravel deposits are littorina deposits formed as spit deposits on the lee side of the moraine ridges. Sub-recent and recent processes can be observed, giving evidence of erosion and redeposition in connection with storm conditions. A depositional analysis indicates that sediments with high contents of gravel, stones and boulders could be found in extensive amounts in the proximal beach areas. The till deposits are found at different depths cut off by layers of coarser materials, e.g. stones and boulders.

Late glacial clay covering till deposits is observed at water depths of about 26 m. A thin sand layer generally covers the clay deposits. Fine to coarse sand deposits including pebbles and stones are characteristic of the central shallow area of Kriegers Flak.

THE FOUNDATIONS

To date, offshore wind farms have been constructed in relatively shallow waters with up to 20–25 m water depth. Concrete gravity-based structures and monopiles have been the preferred foundation concepts for these water depths. At Kriegers Flak the water is just below 40 m deep, and the next generation of wind farms could be constructed in water up to 50–60 m deep. To meet the site specifications at these water depths, further development and improved design are clearly needed. As mentioned above, the study included steel monopile, steel jacket, concrete gravity, concrete (gravity) tripod and (drilled) concrete monopile. The steel monopile was used as a reference in the study, as it is a well-developed concept.

Steel monopile

Introduction

The steel monopile foundation concept for offshore wind turbines is well proven, and is used in several operating offshore wind farms such as the Horns Rev site off the west coast of Denmark.

The conceptual study for the steel monopile was performed in collaboration between Rambøll Wind and MT Højgaard [Ref 3].

Design

The monopile foundation consists of two main parts: the monopile itself, which is driven to the target penetration by a large hydraulic hammer, and a transition piece installed on the top of the pile. The annulus between the pile and the transmission piece is grouted with high-performance grout. For the 5.0 MW turbine, the pile diameter varies between 5.75 m and 6.75 m and the pile penetration between 25 m and 29 m. The transition pieces are designed with conical sections to fit both the tower and the pile. This section is located beneath an ice cone, which makes it possible to mount the ice cone on a straight part. For the 5.0 MW turbine, the total steel weight for the monopile is 525–1050 tons (depending on water depth and pile penetration).

Cost

The cost (including design, fabrication and installation) of 40 steel monopile foundations for 5.0 MW turbines, at a reference water depth of 35 m, is estimated to be €620 000/MW.

Other

The soil on the Kriegers Flak site has been found suitable for monopile foundations. Although boulders occurred in 18% of the site investigations, they did not cause significant obstruction.

Dampers on the structure can be used to provide additional damping, although their incorporation will demand an extensive design process with the turbine manufacturer if tower design changes are necessitated. It is therefore concluded that on the Kriegers Flak site the monopile foundation can be further optimized. Furthermore, it appears that a detailed analysis, applying load iterations between the turbine manufacturer and the foundation designer, may reduce the amount of material even further.

Steel jacket

Introduction

The jacket foundation concept is widely used in the oil and gas industry, and has also found use in the offshore wind industry, e.g. in the Beatrice Offshore Wind Farm, Scotland.

The conceptual study for the steel jacket was performed in collaboration between Rambøll Wind and MT Højgaard [Ref 4].

Design

The jacket foundation concept consists of three parts: piles, the jacket and a transition piece. The jacket is characterised by three or four legs stiffened with K-, N- or X-braces. It appears that the 4-legged jacket stiffened by X-braces and supported by main piles is particularly suitable for the offshore wind industry. The design therefore includes a 4-legged jacket and a concrete transition piece in the tower interface. The interface is located at level +10.5, a height at which the crest of the 50-year wave does not hit the concrete transition piece. Due to the much higher stiffness of a jacket structure compared with a monopile structure, it has not been possible to keep the first natural frequency within the specified range. If the frequency must be lowered, a more slender tower is needed. Alternatively, the hub height could be increased.

The steel jacket for the foundation for a 5 MW turbine weighs 261 tons, the four piles weigh 248 tons and the transition piece weighs 700 tons.

Fabrication and installation

There are several production facilities in northern Europe for steel jackets. After fabrication, the structures could be transported on barges/coasters directly to the installation vessel at the Kriegers Flak site.

To maintain continuous production at the site, the use of two jack-up vessels is suggested, with one doing the piling and one installing the jacket and the transition piece. After pre-driven the piles, the top level of each of the four piles is recorded for pre-adjustment of the jacket structure if necessary, and the template is recovered and adjusted for the next position. The installation vessel for the jacket and transition piece will jack up at the actual pile position, and the jacket structure will be positioned on the piles. Next, the transition piece will be placed on top of the jacket.

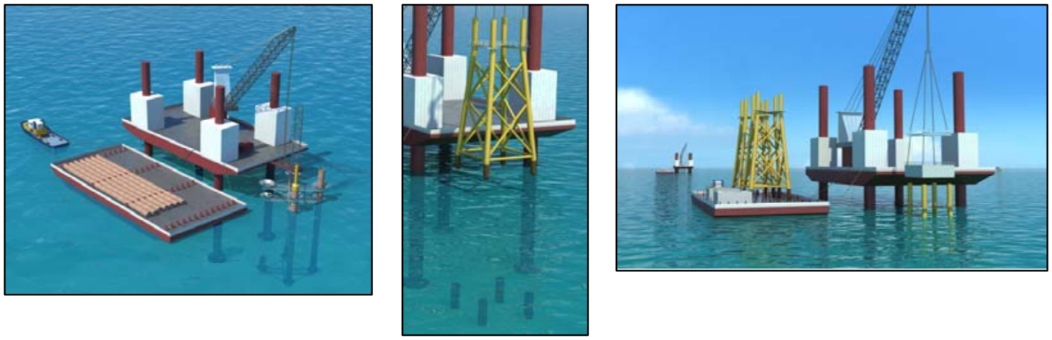

Figure 2 Installation of the steel jacket. First the pilings are installed, then the jacket is placed on the piles and finally the transition piece is located on the jacket. (Illustrations from Rambøll)

Cost

The cost of 40 jacket foundations for 5.0 MW turbines, at a reference water depth of 35 m, is estimated to be €608 000/MW.

Other

In general, the benefits of using the jacket foundation concept are found to be a lower wave load, a higher level of stiffness and lower soil dependency compared with monopile foundations. The design will therefore be suitable for installations in deeper water or in waters with high waves and at sites with bad soil.

It is concluded that the proposed design is not fully optimized for the site even though that two main improvements (pre-driven piles and concrete top) have been implemented. An optimized design will probably be competitive with the monopile foundation design in water depths of 30–35 m and above. This conclusion is based on the material reduction in an optimized design based on more realistic loads obtained from load iterations with the turbine manufacture, and possibly also some design changes.

Concrete gravity foundation

Introduction

The concrete gravity foundation concept (also called a gravity-based structure, GBS) is used in several offshore wind farms such as Vattenfall's Lillgrund wind farm in the Swedish part of the Öresund, between Copenhagen and Malmö.

The conceptual study for the concrete gravity foundations was performed in collaboration between COWI A/S and Per Aarsleff A/S [Ref 5].

Design

The study has focused on a cone foundation type. The cone concept offers advantages of being effective in terms of quantities and hence in installation weight. However, it requires special formwork due to the curved design, as well as heavy lift equipment with a lifting capacity of 3000 tons or more. A floating concept was therefore also developed. In an attempt to additionally simplify the formwork, the so-called KIS (Keep It Simple) concept was developed, composed mainly of straight elements. As well as sufficient buoyancy, the floating concept also requires sufficient floating stability at all times during transport and lowering. To achieve this, structural dimensions must be increased. A third concept, the semi-floating structure, was developed to achieve a partial reduction in the quantities needed.

The weight of the cone foundation is 3300 tons (the base diameter is 25 m). The weight of the KIS foundation is 5900 tons (diameter 31 m). Finally, the weight of the semi-floating foundation is 4200 tons (diameter 25 m).

Figure 3 The three concrete gravity foundations: cone, KIS and semi-floating. (Illustrations from COWI)

Fabrication and installation

A fabrication yard could be arranged in an existing port, the total area needed being around 40 000 m^2. Construction can be organised as two production lines each with four or more construction pads and a central storage line. The foundations are moved from the construction pads to the storage line and the load out position at the quay by skidding.

For the cone concept, the basin should have a minimum water depth of 6 m, allowing access for heavy lift installation vessels such as the Rambiz or Svanen. The KIS concept needs a launching system, either a ramp or a syncrolift, to move the foundations to the water. The water depth must be at least 14 m. For the semi-floating foundation, the water depth must be at least 12 m.

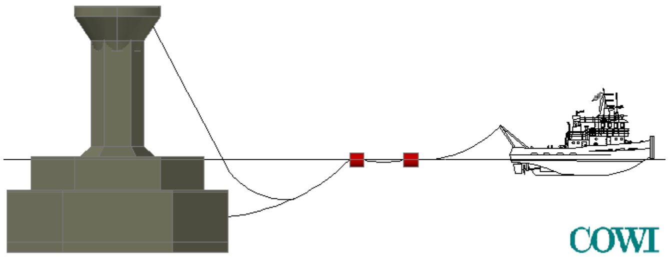

Figure 4 Towering operation for the KIS caisson. (Illustration from COWI)

Prior to installation, the seabed must be dredged to a level that achieves competent soil layers. A gravel bed is then placed on the dredged surface.

The cone foundation is transported partly submerged to the installation site and lowered to the gravel bed. The KIS foundation is towed to the installation site, and lowered by ballasting the cells with water. The semi-floating foundation achieves the required buoyancy via the foundation itself and a 750 m^3 pontoon. On site, the foundation is lowered to the gravel bed by ballasting with water and progressively releasing the cables that attach the foundation to the floating support.

Cost

The cost of 40 foundations for 5.0 MW turbines, at a reference water depth of 35 m, is estimated to be €475 000/MW for the conventional cone foundation (Thornton-type), €800 000/MW for the KIS foundation and €600 000/MW for the semi-floating foundation.

Other

There are various options for reducing concrete quantities if the lifting capacity should become critical, but at the expense of increased reinforcement and compensating ballast. However, further development of the structure could reduce the cost.

Concrete gravity tripod

Introduction

The proposed concrete gravity tripod is an untraditional design that is more suitable for the deeper water at Kriegers Flak.

The conceptual study for the concrete gravity tripod was performed in collaboration between ISC A/S and Skanska AB [Ref 6].

Design

The foundations studied used polygonal elements for the structure, which leads to simpler construction for the reinforcement and formwork. However, the hydrodynamic forces will increase compared with circular shapes. The main structural elements are thus hexagonal prestressed concrete elements with horizontal steel tubes in the bottom. Traditionally, steel or concrete tripods are arranged with a centre column. In this study the three legs were directly connected to the ice cone structure. This results in a rational structure with greatly improved lateral strength and stiffness, which is beneficial with respect to wave load and ice load, especially dynamic ice load.

The vertical forces from the dead load of the rotor, nacelle and turbine tower pass into the foundation through the ice cone, through the three supporting legs and the footing and into the seabed. The lateral forces from the wind acting on the wind turbine and on the turbine tower give a moment and shear force acting on the assembling plate on the top of the ice cone. From the ice cone, the loads pass into the legs via bending moments and normal forces and on to the footings and down to the seabed. The vertical and lateral forces from the waves and currents acting on the ice cone and legs also go into the seabed through the footings.

Fabrication and installation

The tripods are prefabricated at a construction site near the turbine park. This could be a port in Germany, Poland, Sweden or elsewhere in the Baltic Sea area, depending on the most advantageous balance between local costs for materials, wages, etc., and the towing distance. The load out quay required is approximately 150 m long with a depth of 8 m and located in a sheltered area. The site is assumed to be tailor-made and constructed to meet the special requirements for prefabricating the foundations. Once manufactured and erected, the tripods are towed on a barge to the turbine park for placement on the seabed by a floating crane. Finally, the soil under the footings is grouted and the legs are filled with ballast material. Two different types of leg batter have been designed for tripod manufacturing.

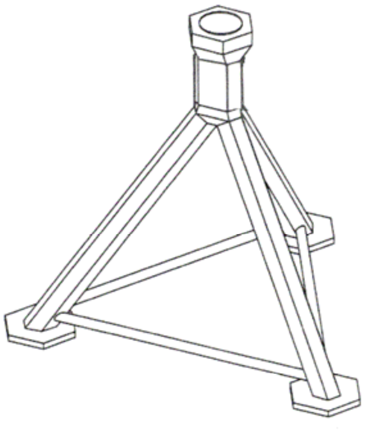

Figure 5 Illustration of the foundation structure. (Illustration from ISC)

A barge is used for transportation to the installation area. The barge is reinforced and widened with skidding and support beams across the deck. A floating crane with a capacity of 3200 tons will be based in the installation area.

Cost

The cost of 40 concrete tripod foundations for 5.0 MW turbines, at a reference water depth of 35 m, is estimated to be €770 000/MW.

Other

The concept is in initial development phase and needs further development which could reduce the cost.

Concrete monopile

Introduction

The concept of a drilled concrete monopile has not yet been tested in an offshore wind farm. However, the suggested technique is similar to that used in horizontal tunnel drilling. The concrete monopile is placed vertically on the seabed and a drilling machine is lowered within the monopile. This cutter head will drill the whole construction into the ground.

The conceptual study for the concrete monopile was performed in collaboration between Ballast Nedam and MT Piling [Ref 7].

Design

The monopiles consist of pre-cast reinforced concrete ring elements. These ring elements will be assembled and post-tensioned to form a complete monopile. A steel pile toe is mounted at the bottom of the monopile to enable it to ‘cut’ through the soil and create an overcut. Injection lines are cast in the concrete lining to fill the overcut with a self-hardening drill fluid.

The top of the monopile is fitted with a concrete ice cone. For the 5.0 MW turbine, the outer diameter of the monopile is 6.9 m and the wall thickness is 0.7 m. The pile toe is located 61 m below MSL and the total weight is 2200 tons.

The cutter head of the drilling machine is designed to make it possible to drill through the various soil layers present on the Kriegers Flak site without changing the head. The variable diameter of the cutter head enables the machine to drill inside the monopile as well as under the monopile lining.

Fabrication and installation

The fabrication of the ring elements and ice cones, and the assembly of the monopiles, will take place in a nearby port. Fabrication and assembly require a yard of approximately 48 000 m^2. The ice cone platforms and ring elements could also be fabricated in a more distant location. The monopiles are transported self-floating from the fabrication yard to the installation location. The ice cone platforms are delivered on barges.

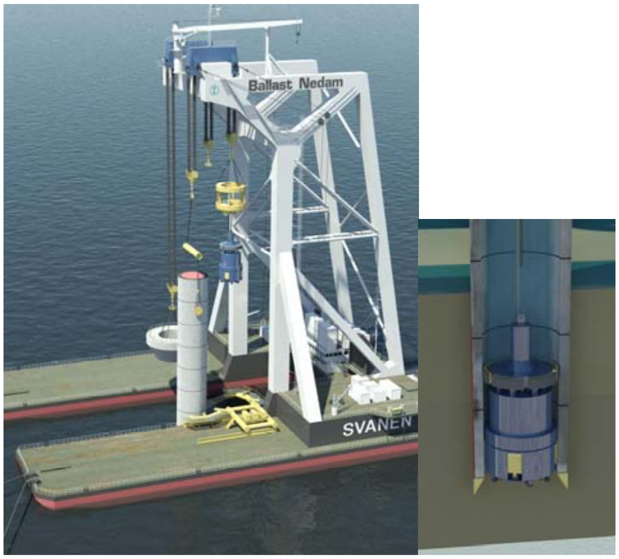

Figure 6 Installation of the concrete monopile. Left: The Svanen lowers the monopile to the seabed. The drilling equipment hangs from the crane. Right: The drilling head. (Illustrations from Ballast Nedam)

The foundations could be installed by the Svanen Heavy Lifting Vessel. The work method consists of the following steps:

- The ice cone platform is delivered on a barge to the Svanen.
- The self-floating monopile is transported to the Svanen, which then upends it.
- The monopile is positioned in a guiding frame. The monopile is lowered onto the seabed. The monopile will settle several metres into the seabed.
- The drilling machine is lowered into the monopile and hydraulically clamped.
- Drilling starts inside the monopile and, after settling stops, drilling continues underneath the monopile until the final depth is reached.
- After completion of the drilling process, the drilling machine is lifted out of the monopile.
- After positioning the ice cone platform, the Svanen moves to the next foundation location.
- The cable installation and finishing works are performed by a separate installation spread.

Cost

The cost of 40 concrete monopile foundations for 5.0 MW turbines, at a reference water depth of 35 m, is estimated to be €625 000/MW. As the drilling equipment is quite expensive, a significant cost reduction is possible if more turbines are installed.

Other

Using a drilled concrete monopile has several environmental advantages over the traditional steel hammered monopile:

- No underwater noise or vibrations that might harm marine life.
- CO_2 emissions during fabrication are much lower for a concrete monopile than for a steel monopile.
- Concrete is much more durable than steel in an offshore environment. There is no need for cathodic protection or coatings causing emissions of metals such as aluminium or zinc.

However, large boulders are a risk. Boulders up to 50 cm in diameter are crushed or broken by the cutter head. Larger boulders should also be mainly crushed. Another option is to pull up the drilling machine and remove the boulders from the excavation front under the monopile.

SEA BED PREPARATION

Construction of gravity basis structures in water up to 40 m deep is a new challenge. Until now, seabed preparation in Scandinavian waters has employed conventional plant with diver assistance to maximum 12 m water depth. In deeper water, the effective diving work time is significantly reduced, which in turn increases costs.

Within the foundation study Pihl, LicEngineering, GEO and Eiva have cooperated on the development of a new concept for seabed preparation. This is based on the use of a remotely controlled multipurpose preparation robot [Ref 8]. The initial requirements and function description have resulted in the design of a robot covering all activities without diver assistance.

Stone bed preparation robot

Design

The methods used for the construction of the stone beds for the Great Belt Bridge foundations and the Öresund immersed tunnel have formed the basis for the development of a new method for stone bed preparation in deep water. The new method is based on the use of a special machine/robot consisting of a circular frame supported by six adjustable supporting spokes, installed and powered from a pontoon and equipped with all the required gear and measuring devices. Bathymetry sensors, slurry suction device, CPT equipment, vibrocore, stone bed placement cradle with a fall pipe and other devices are installed on the frame.

Operation

The initial part of the seabed preparation is dredging. The overall dredging works are not covered by the function of the robot. However, the robot handles the completion of the dredging, including the final treatment of the remoulded surface soil layer.

Seabed preparation with the robot includes the following activities:

- Location of the robot on the seabed.
- Detailed area surface bathymetric survey and spot locations by polar coordinates.
- Subsoil investigation with CPT, vibrocore and/or SPT.
- Soil surface sweeping/cleaning.
- Stone bed placing and levelling for a thickness of 0.3-1.0 m and an accuracy of ±2 cm.
- Final survey with echo array equipment.
- Contingency works with possible reestablishment and rectification works.

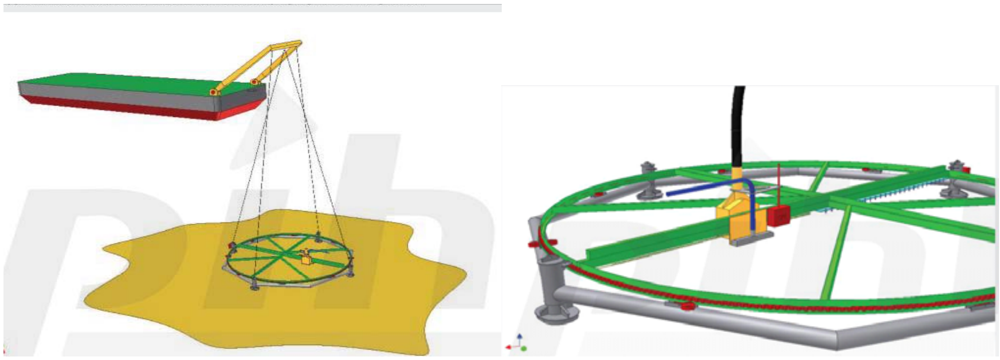

Figure 7 The seabed preparation robot. Left: How the robot is placed on the seabed. Right: Detail of the submerged part of the robot. (Illustrations from Pihl)

All moving parts are hydraulically driven by a submerged power pack units, which avoids long high-pressure hydraulic transmission hoses from the pontoon. The control and monitoring systems employ PLC communication between the control station on the pontoon and the robot. The subsoil investigation is conducted by integrated CPT equipment.

Cost

The cost of seabed preparation is estimated to be €230 000–350 000/unit (assuming 40 units). The cost includes fabrication of the robot and seabed preparation at 40 positions, but not the cost of dredging to sufficient soil bearing capacity.

CONCLUSIONS

The study brings together both proven technologies for offshore wind turbine foundations (steel monopile, steel jacket and gravity base) and new techniques (concrete tripod and concrete monopile). For the proven concepts, the further development carried out has shown that there are possibilities for cost reductions. For the new technologies studied, there is great potential for further cost reductions.

During the study it became clear that a detailed site assessment is an important tool for reducing risks, and thus also the costs. The development of the foundations for a particular site should also be carried out jointly with the turbine, and tower, suppliers.

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REFERENCES

[1] Gravesen, H, Jørgensen, LB. Kriegers Flak Offshore Wind Farm, Design Basis Foundations. Vattenfall Vindkraft AB. 2009.

[2] Gravesen, H, Jørgensen, LB. Kriegers Flak Offshore Wind Farm, Site Assessment. Vattenfall Vindkraft AB. 2009.

[3] Rambøll Wind and MT Højgaard. Kriegers Flak Offshore Wind Farm. Conceptual study of Monopile Foundation for Wind Turbines. 2009.

[4] Rambøll Wind and MT Højgaard. Kriegers Flak Offshore Wind Farm. Conceptual study of Jacket Foundation for Wind Turbines. 2009.

[5] COWI. Kriegers Flak Offshore Wind Farm. Gravity Based Foundations. Conceptual design report. 2009.

[6] ISC and Skanska. Kriegers Flak Foundation Concept. Gravity Tripod Report. 2009.

[7] Ballast Nedam and MT Piling. Kriegers Flak Foundation Concepts. Conceptual Design Study Drilled Concrete Monopile. 2009.

[8] Pihl. Kriegers Flak Offshore Wind Farm Wind Turbines. Sea Bed Preparation Machine/Robot. 2009.

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Celebrating Vattenfall's Centennial 2009, we turn our attention to the Energy and Climate issue and the future development of the energy sector. Our focus on the Energy and Climate issue expresses a promise to society and our customers. We are determined to make our activities climate neutral by 2050. That is our contribution to a sustainable society. To achieve that, we need growth. Vattenfall is Europe's fifth largest generator of electricity and the largest producer of heat. Our target is to more than double our annual electricity generation. "Making Electricity Clean" is the essence of our strategy. It is a contribution to a global re-structuring of the energy supply system towards sustainability. We have a concrete, realistic and ambitious plan, showing what has to be done. On the basis of a century's experience, we take on this important mission for the future.

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