Foundation of Offshore Wind Turbines

Kerstin Lesny, Jens Wiemann, Werner Richwien

Institut für Grundbau, Bodenmechanik, Felsmechanik und Tunnelbau,
Universität Essen, 45117 Essen
Tel. 0201 /183-2857, Fax 0201 / 183-2870,
werner.richwien@uni-essen.de, http://www.uni-essen.de/grundbau/

Abstract

The paper discusses the design considerations for foundations of offshore wind turbines with special respect to the foundation conditions in the German North-Sea. Several technical solutions are presented and compared to experience with conventional offshore structures. Generally gravity foundations are restricted to water depth of less than 10 m, provided the soil at the seabed has sufficient bearing capacity. For larger water depth piled foundations by the use of tripods or jackets may be performed within the todays state of the art, but they are believed to be too costly. Monopiles are up to now restricted to pile diameters below 4 m, more insight in the lateral load transfer of piles with larger diameter and equipment to install the piles is missed.

1 Introduction

At the end of 2001 in Germany 11400 wind turbines with an installed power of 8000 MW have been in operation. The electrical output covers about 3,5 % of the electrical energy in 1998, offshore turbines are not yet included. Offshore wind turbines simply do not exist in Germany up to now. This will change in the next future since due to the energy policy of the German government up to 2005 the installed power and the electrical output of wind turbines shall be increased at least by the factor two. And since the space for onshore turbines becomes short even in the not so dense populated coastal zones, offshore wind parks 30 to 50 km in front of the coastline are planned in the North-Sea, in water depth between 20 to 30 m, with an installed power of 5 MW and a nacelle height of 90 m.

Similar plans exist for the Baltic-Sea. Depending to the predictions (optimistic or very optimistic) in 2030 the installed power thus shall be increased to 20 000 to 25 000 MW with an electrical output of 15 to 18 % of the energy production of 1998.

The plans in the German parts of the North-Sea and the Baltic-Sea are illustrated in Fig. 1.

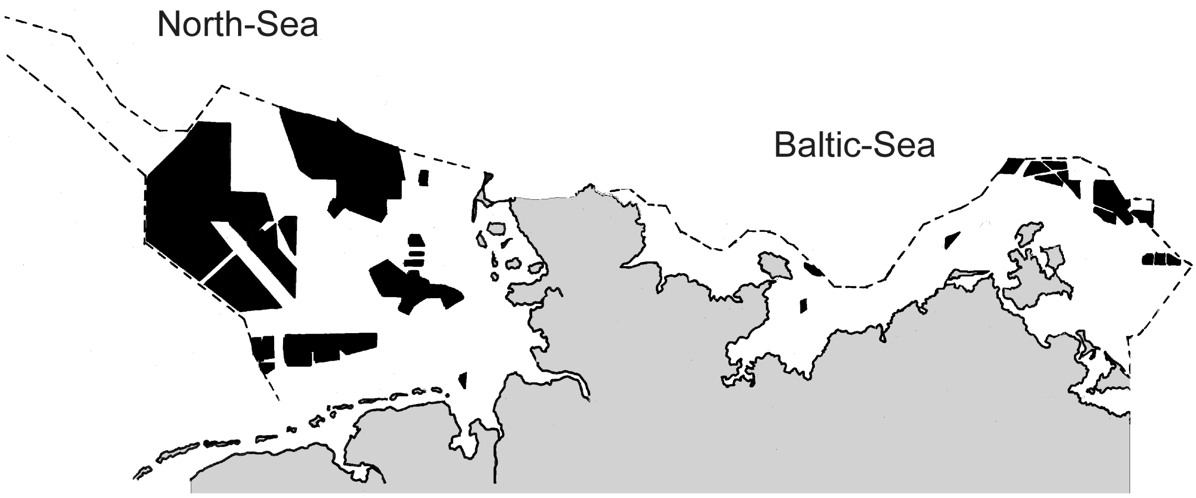

Fig. 1: Map of the North-Sea and the Baltic-Sea with requested wind park areas

2 Design Considerations

Design and construction of any building needs clear definition of loads and detailed investigations of the foundation subsoil. Both of these elements make sure, that the structure is optimal designed and risks in constructions are minimized. Wind turbines in wind parks are not prototypes, with respect to economical reasons they have to be erected in hundreds of specimen of the same type. Standard designs are preferred with respect to costs and installation time. The foundation is then the connecting structural member between the tower and the subsoil. Carefully performed and professionally analysed field and laboratory tests are necessary design elements to minimize construction risks.

A second design consideration is related to the prediction of the structure behaviour under operation. Oscillations of the structure might be critical for the turbines, it is however sure that they are important for the lifetime of the structure and the load transfer into the subsoil. Mainly the accumulation of plastic soil deformations might result in permanent heave and settlement and reduce the bearing capacity of structural members like foundations and piles.

Last but not least: the wind turbines and their foundations have to be removed at the end of their lifetime. Two generations of turbines are believed to be installed within 50 years on one foundation. The investors have to present the concept of removal in advance and they have to set up financial reserves for the removal of their turbines. Up to now there is no specific experience available how and to which costs large numbers of offshore turbines can be removed in 50 years and no one knows which equipment might be available in 50 years.

3 Experiences from conventional offshore structures

We have more than two decades experience in design and construction of offshore structures in the North-Sea. It is clear that the state of the art in foundation of offshore wind turbines therefore is based on these experiences. It is however necessary and worthwhile to recognize the differences between conventional offshore structures and the foundation of wind turbines (Table 1).

	Conventional Offshore Structures	Offshore Wind Energy Turbines
water depth	20 – 120 m	10 – 30 m
vertical structure load	5000 – 30000 t	100 – 500 t
horizontal structure load	10 % - 20% of vertical load	70 % - 150 % of vertical load
overtopping moment	water depth x horizontal load	(water depth + 50 m) x horizontal load

Table 1: Foundation conditions of offshore wind turbines and conventional offshore structures

Conventional offshore structures in the North-Sea have been founded in water depth between 20 and 120 m, the water depth in the foreseen wind parks is only 20 to 30 m, which is surely less difficult.
The total vertical loads to be transferred into the subsoil range between 5 000 and 30 000 tons in case of conventional offshore structures and they are only 100 to 500 tons for the wind turbines. This seems to be less difficult, too.
In relation to the lateral load however the conditions for wind turbines are more critical than in conventional offshore structures. The lateral loads to be transferred by the foundations of wind turbines are in the same order of magnitude as the vertical loads, with alternating directions since the lateral loads orginate from wind, current, and waves. We will see that this fact needs foundations different from conventional offshore structures. Related to the large lateral loads and the geometry of the tower the overtopping moment in the mudline becomes relatively larger in case of wind turbines too. Thus the foundations of wind turbines are different from those of conventional offshore structures mainly with respect to the large lateral loads and overtopping moments.

4 Foundation Concept

Actually two different structures of the tower are discussed, monotowers and lattice towers. Monotowers may be made of steel or concrete, lattice towers are steel constructions. These tower structures are very similar to those onshore. Generally for both of them we have the piled and the gravity foundation type (Fig. 2).

In case of gravity foundations the towers are directly connected to the foundation, in large water depth the foundation might be completely under the water level. Skirts prevent scours under the foundation and erosion and they increase their bearing capacity. An other option is a rubble layer beneath of the foundation.

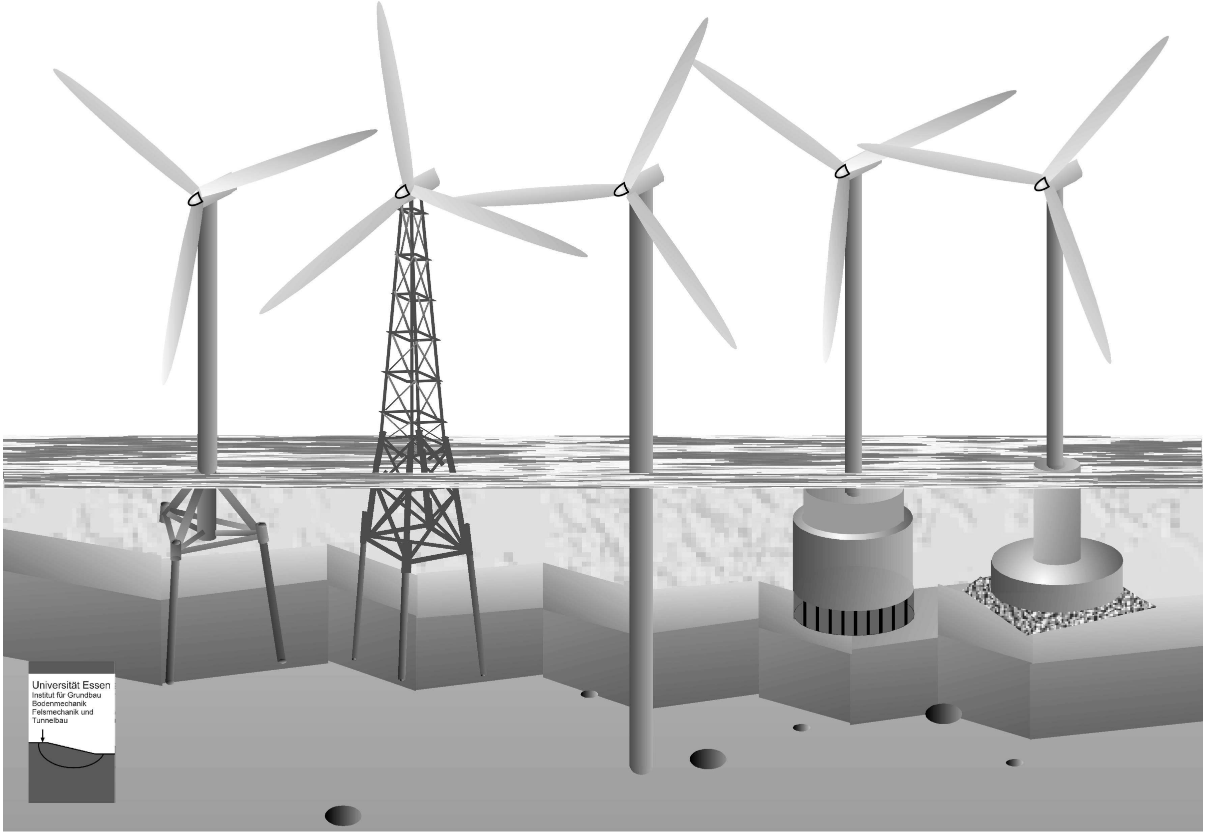

Fig. 2: Foundation concepts of offshore wind turbines

In case of piled foundations the tower rests on a tripod or a jacket and the legs of tripod or jacket are supported by one or more piles, driven into the subsoil to such a depth that the loads are transferred into layers of sufficient bearing capacity.

Gravity foundations distribute the loads over a large area, where the soil pressures under the foundation edges are relevant. They can be controlled by the dimensions of the foundation. The load transfer into the subsoil is well known, there are improved techniques for the installation of such foundations available. Gravity foundations thus are state of the art in each water depth. The foundation masses however become very large with large water depth and prefabrication needs harbors with sufficient shipping depth nearby. Furthermore gravity foundations are restricted to soils which have sufficient bearing capacity directly at the sea floor or in low depth beneath. Scour and erosion must be prevented by skirts or by gravel layers. The removal of gravity structures is difficult and costly.

An example for a gravity foundation of wind turbines is Middelgrunden in the Danish Baltic-Sea. The water depth is 6 to 8 m, and the foundations have been prefabricated in a dry dock, floated to the site and sunk to a prepared bed.

Tripods and jackets spread the loads geometrically, and the piles beneath the legs are grouted in sleeves. Pile loads and pile diameters can be controlled by the geometry of the tripod or the jacket, the pile length depends on the depth of the soil strata with sufficient bearing capacity. The lateral loads are easily absorbed by inclined piles. Pile dimensions thus are in the conventional range and driving techniques are available. Driving might become difficult however in case of large boulders or very stiff soils, but this is typical for piling in general and can be recognized in advance by field tests.
Problems of tripods and jackets may arise during maintenance, since the approach by ship is difficult. Up to now wind turbines have not been founded on jackets or tripods, but this solution is favoured in the actual discussions, mainly with respect to the available site technique.

Last but not least the monopiles are believed the most advantageous foundation types for offshore wind turbines. A single pile of large diameter is embedded in the soil and transfers the vertical loads by shaft friction and point resistance, the lateral loads by the earth pressure along the pile shaft. This type of foundation reduces the foundation mass to a minimum, at water depth of 20 to 30 m the pile diameter needed is suggested to be in the range of 8 m and more however. There is no experience available up to now how piles of these dimensions can be designed for the lateral loads and furthermore no technique is available to install piles of 8 m diameter and more with length of 50 m and more.
An example of a monopile foundation is Blyth (GB), where the water depth is 6 m and piles of 3.5 m diameter, 33 m length and a mass of 120 tons have been driven conventionally. Recently pipe piles with a diameter of 4 m have been driven to a depth of 25 m in Horns Rev (DK). These pile dimensions mark the ability of the actually available offshore driving technique.

5 Subsoil Conditions

The foundation subsoil in the North-Sea has been formed by glacial processes over the last 2.5 million years. In the Pleistocene (2.5 million years BC to 8000 years BC) several glacial periods lowered the water level of the North-Sea by about 120 m so that the coastline had been shifted north by about 200 km. Instead of water the todays seafloor was covered by ice up to 200 m height.

Under the ice load the Pleistocene soils have been heavily over-consolidated. Since 8000 BC the ice melted and the melting water formed large streams in northern direction which eroded the Pleistocene soils in deep grooves, and with the increasing water level the coastline moved back towards the inland. The todays coastline had been reached around 1000 AC. Holocene sediments covered the Pleistocene and filled the grooves. Thus the subsoil in the North-Sea generally consists of Holocene sediments over Pleistocene over-consolidated soils. The thickness of the Holocene ranges from 10 to 20 m, in the refilled erosion grooves the Holocene may exceed 40 m. Fresh sediments (mud) covers the seafloor from a few decimeters up to in average 2 m, in the estuaries of the rivers Elbe and Weser the thickness of the fresh sediments might increase locally up to 15 m. In the transition zone of Pleistocene and Holocene stone layers and boulders up to 30 m³ might be found.

The soil types of the Holocene are weak organic sediments, mud, peat and loose to medium dense tidal sand. The latter has only limited bearing capacity since its mineral skeleton is spread by clay and silt minerals trapped in the structure. Gravity foundations may be placed on the Holocene sands, provided that no weak organic layers are below of the foundation level. Piles can not be placed in the Holocene sands.

The soil types of the Pleistocene are dense to very dense sand and highly over-consolidated basin sediments and till. Even very large pile loads can easily transferred into these soils and especially in the sand, but driving of piles might be difficult and time demanding. Stone layers and boulders will make pile driving difficult too, one of the most important tasks of field investigations therefore surely is to improve the optimal driving equipment.

In case that the construction site meets one of the refilled erosion grooves pile length increases dramatically. Thus the localization of these grooves is another task of the field tests, which preferably might be solved by the performance and interpretation of seismic and geophysical measurements. Additionally for each single foundation the representative soil parameters of the Pleistocene and the Holocene have to be identified by field and laboratory tests.

6 Conclusions

Under the soil conditions given in the North-Sea the foundation of wind turbines in 30 m water depth is a demanding task and there is no specific experience available. Nevertheless on the basis of conventional offshore solutions piled foundations using tripods or jackets can be performed. They are believed however to be too expensive, compared to the calculations of the energy-suppliers. This is why monopiles are preferred in the discussions. Experience with this type of foundation is restricted however to pile diameters up to 4 m and pile masses up to 120 tons. In 30 m water depth the expected pile diameter is 8 to 10 m and the length reaches 50 m and more. We do not have any model for the relation of horizontal deflections of the pile and the activated lateral earth pressure, scaling up of the experience with piles of smaller diameter is surely not allowed. From the same reason we are today not able to predict the oscillations of the foundation under operational loads. Last but not least, up to today we have no technique to install piles of the above given dimensions, not onshore and not offshore.

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