SUPPORT STRUCTURES AND FOUNDATION CONCEPTS FOR OWECS

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ABSTRACT: A new order boom is predicted with wind energy conversion systems (OWECS) in the North and Baltic Sea. In this regard a group of four institutes at the faculty for civil engineering at the University of Hannover is working on a research program supported by the German Ministry of Economics and Technology since 2001. Within this research program structural design methods and solutions for support structures of OWECS in respect to safety and economy will be improved. In this paper influences on the dynamic properties of monopile and tripod foundations are presented.
Keywords: Foundations, Dynamic Models, Fatigue, Environmental Aspects

1 INTRODUCTION

The development of the wind energy production to offshore windfarms is the consistent advancement of the wind energy technology with its rapid increase in the past 20 years. The velocities of the wind are more uniform and higher over the sea, so that higher resource yields can be expected. But the effort for construction, maintenance, and grid connection will be significantly higher. On the one hand there are many technical questions for the planning of offshore windfarms to be answered, on the other hand environmental impacts have to be considered. The research program GIGAWIND (www.gigawind.de) at the faculty for civil engineering at the University of Hannover attends to these questions from the technical point of view. The Institute for Fluid Mechanics, the Institute for Steel Construction and the Curt-Risch-Institute for Dynamics, Acoustics, and Measurements, University of Hannover, and the Institute for Soil Mechanics and Foundation Engineering, University of Essen, are the partners in this project which is funded by the Federal Ministry of Economics and Technology of Germany.

The work at the Institute for Steel Construction is embedded in the activities performed by the Institute for Fluid Mechanics on environmental effects (wind and wave loading) and the activities of the Institute for Soil Mechanics on geotechnical problems.

2 CONCEPTS FOR FOUNDATION

In principle, OWECS can be designed with different types of foundations. Currently discussed are monopile foundations, gravity foundations, and braced towers which can be realised as space trusses, tripods, or lattice towers. A possibility to valuate these different types is to compare the concepts used at already realised projects. At the current offshore wind energy projects both, monopiles and gravity foundations have been used. The turbines have a nominal power between 1,5 MW and 2 MW. They have been constructed off shore of Denmark (Middelgrunden and Horns Rev), Sweden (Utgrunden) and the UK (Blyth), see Table I. The distance to shore is relatively small compared to sites which are projected in the North and Baltic Sea. The Horns Rev project takes with up to 20 km the next step to greater distances. It has to be stated that the water depth at these site does not exceed 15 m.

Even if there are no projects realised yet off shore of Germany, there are many windparks planned. The realisation of the first parks can be expected in the next few years. The planning in the German area of the North Sea refers to water depths of about 30 m and distances to shore up to 50 km. From the realised projects it can be supposed that in greater water depth gravity based foundations will not be used. The investigations are focused on the topic, whether monopiles or better different concepts like tripods have to be used in water

Table I: Recent offshore wind energy projects, technical data and type of foundations

Project		Middelgrunden	Utgrunden	Blyth	Horns Rev
Country		Denmark	Sweden	UK	Denmark
Manufacturer		Bonus Energy	ENRON	Vestas	Vestas
Nominal power per OWEC	[MW]	2	1,5	2	2
Diameter of rotor	[m]	76	70,5	66	80
Hub height	[m]	64	65	58	70
Number of OWECS		20	7	2	80
Water depth	[m]	4,0-5	7,0-10	around 6	5-15
Distance to shore	[km]	2	8	1	14-20
Type of foundation		Gravity foundation	Monopile	Monopile	Monopile

depth of 30 m. This decision is definitely influenced by technical possibilities for manufacturing and erection. For example, today piles for a monopile foundation can be driven into the seabed with maximum diameters about 4 m.

3 WAVE LOADS

For determination of wave loading to offshore structures the Morison equation is commonly used. For the application of Morison equation it is necessary to adopt the correct wave theory. The effect of misuse of the wave theories is outlined in [6] and can be significantly for certain parameters.

At the Institute for Fluid Mechanics within this project a computer program has been developed to calculate the wave loading for support structure of OWECS. The water particle kinematics of the flow i.e. surface elevation, water particle velocities and accelerations are evaluated using following wave theories:

- Stokes First Order Theory (Airy)
- Stokes Second Order Theory
- Stokes Third Order Theory
- Stokes Fifth Order Theory
- Lagrangian formulation by Woltering
- Stream -Function Theory in Formulation by Dalrymple
- Stream -Function Theory in Formulation by Fenton (in preperation)

At the Institute for Steel Construction an interface has been developed to use the wave loads computed with the described program in commercial FE-packages to evaluate arbitrary structures.

4 DESIGN AND SAFETY CONCEPTS

For the discussion of different types of foundations it is important to know the loads which are significant for the design of the structure. The loads for OWECS are mainly caused by wind and waves. Additionally significant loads can be expected from ice, especially in the Baltic Sea. Like for onshore wind turbines the design refers not only to the ultimate limit state with long return periods (e.g. 50-year wave) but also to fatigue. Alternating stressing due to both, operation of the turbine and wave excitation has to be taken into account [5].

If the design values of the stresses due to different effects of loading have been determined, the well established assessment methods for ultimate limit state and fatigue design may be applied. The question to answer is, whether the probabilistic safety concept, that has been developed for onshore building construction, should be applied to OWECS.

The safety concept for building construction is based on the agreement, that the safety index β has to be at least 3,8 for a return period of 50 years. From this basis the partial safety factors are fixed subject to the distribution of the different effects (e.g. [2]). With this method the probability of failure per structure and year has a value of 10^{-6} to 10^{-7}. The accepted probability of failure is affected if human life is at risk by failure of the structure, as it is the case for onshore building construction.

When the safety concept is applied to OWECS, it has to be considered, that on the one hand the relevant impacts can have different distributions, for example the waves in comparison with the traffic loads for building construction, on the other hand the potential risk for persons is significantly smaller. Schueller [7] points out, that in this case probabilities of failure per structure and year are accepted with values of 10^{-3} to 10^{-4}. From these few points it can be seen, that for an economic design of OWECS the safety concept that is proven for onshore building construction has to be modified to fit the special conditions.

5 INFLUENCES ON THE DYNAMIC BEHAVIOUR OF OWECS

As described above, monopile and tripod foundations are possible solutions for OWECS in water depth of more than 10 m. The dynamic behaviour of a construction is significantly identified by the eigenfrequencies. The eigenfrequencies have an influence on the loads coming from wind and waves because dynamic amplifications can occur, if the eigenfrequencies are in the range of high wave energies or in the range of the excitation frequencies of the operating turbine. Therefore the different types of foundation are investigated with regard to their dynamic behaviour.

5.1 Monopile Foundation

The static system of the monopile is idealised by a spatial beam model. The interaction of soil and structure is realised by linear springs, which are taken into account in the directions of the global axes. In the upper part of the soil (mud area) the stiffness of the springs is reduced. The masses of the nacelle and the rotor are represented by a point mass. (see Figure 1). The influence of the water masses moved with the monopile is considered in the numerical model.

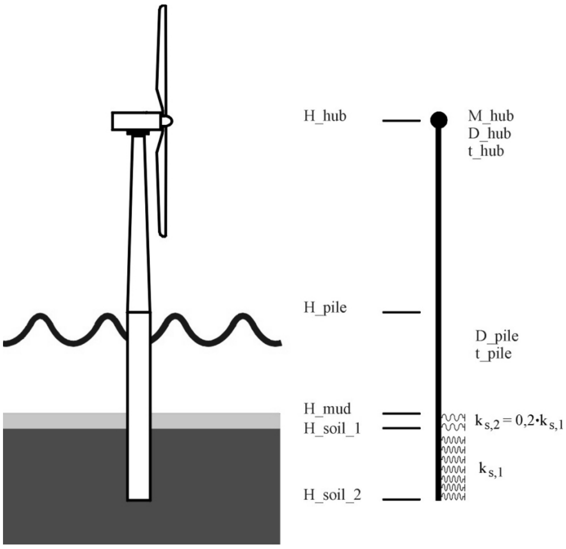

Figure 1: Monopile model and parameter

As boundary conditions for the investigated parameters the environmental conditions are matched to the conditions which can be expected for the planned sites for OWECS off shore of Germany. Calculations have been done both for wind turbines according to the actual size of OWECS with a nominal power of about 2 MW and for the planned size of 4,5 MW.

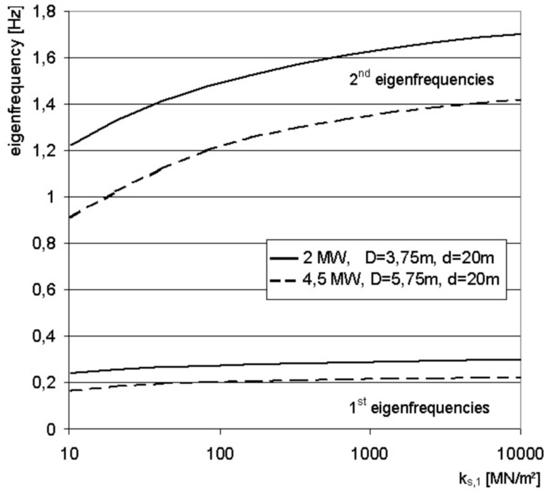

Figure 2: Eigenfrequencies of 2 MW and 4,5 MW OWECS, water depth d=30m

The properties of the soil have an significant influence on the eigenfrequencies of monopile structures. For individual projects the characteristic values of the soil have to be determined by soil explorations. To illustrate the dependency, eigenfrequencies calculated for different soil properties are illustrated in Figure 2.

For the examples that have been calculated the 1st eigenfrequency of the 4,5 MW turbines is in most cases smaller than the 1st eigenfrequency of the 2 MW turbines. The effect of the higher stiffness of the tower for the big turbines does not exceed the effect of the significant higher masses of the of nacelle and rotor and the greater hub height. The difference between the eigenfrequencies of the 4,5 MW and the 2 MW turbine is in the example displayed in Figure 2 about 20 to 40 percent.

5.2 Tripod Foundation

Additionally to the investigation on monopiles calculations have been done concerning a tripod structure for the foundation. Based on a first study of a tripod for a 4,5 MW turbine the influences on the eigenfrequencies have been reviewed both in respect on the dimensions of the tripod construction and the soil properties. The model used for the described calculations is shown in Figure 3.

Contrary to the monopile, the horizontal soil properties have a smaller influence on the first eigenfrequencies of the tower than the vertical properties as it can be seen in Figure 4 and Figure 5. Further calculation showed that the dimensions of the tripod members have only little effect on the first eigenfrequency of the tower when they are varied near to the worked example. The influence on the second eigenfrequency is higher because the upper tripod point takes a greater part in the deformations of the second eigenmode.

If it is supposed that the installation of the piles results in a defined high longitudinal stiffness the dynamic properties of the tripod are slightly influenced by the soil properties. This means that the prediction of the dynamic behaviour of a tripod could be more accurate in comparison to a monopile foundation.

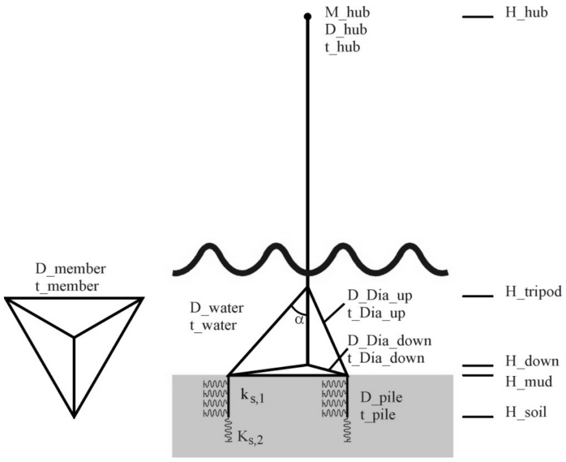

Figure 3: Tripod model and parameter

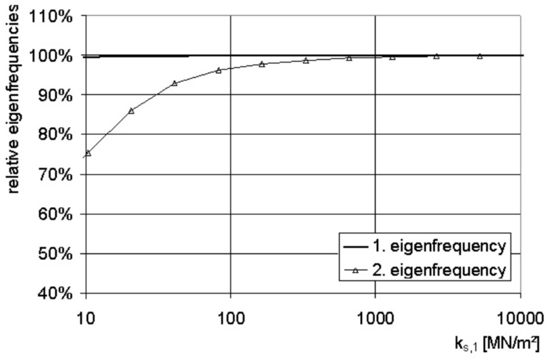

Figure 4: Influences of horizontal soil conditions on the eigenfrequencies of a tripod

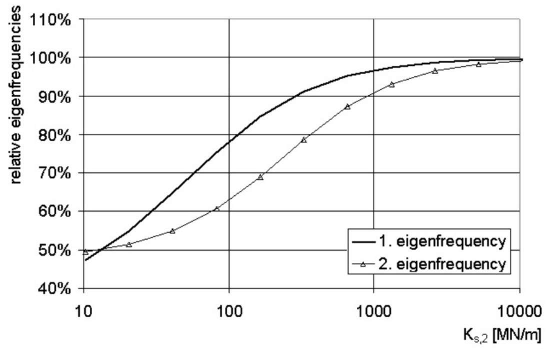

Figure 5: Influences of vertical soil conditions on the eigenfrequencies of a tripod

6 FATIGUE AND CONSTRUCTIONAL DETAILS

As OWECS are highly dynamic loaded structures the fatigue analysis is an important part of the design and has an influence on the concept of the support structures. Fatigue problems arise where stresses are concentrated. This is typically the case where the dimensions of the structure are changing or at nodes of complex structures like for example tripod foundations or at connections between different parts of the structure like ring flange joints.

For the installation of platforms for the oil and gas industry often grouted pile-sleeve connections are used to fix the steel structure to the foundation piles (see e.g. [4]). This kind of connections is also used for an existing OWECS (e.g. Utgrunden and Horns Rev). The ring flange joint, the typical connection for the sections of onshore wind energy towers, is regularly used in the realised offshore projects.

A critical point for a tripod structure is the upper point of the tripod (at H_tripod in Figure 3) where the members get together and the bending moment of the tower is transferred to normal forces into the members. A numerical analysis of this problem showed that for certain parameters empirical design methods used in [3] and [1] would not lead to a safe design. Within this research program further investigations will be done to clarify the structural behaviour of such joints. This calculations are done and will be proceed using FE-method and models as shown in Figure 6.

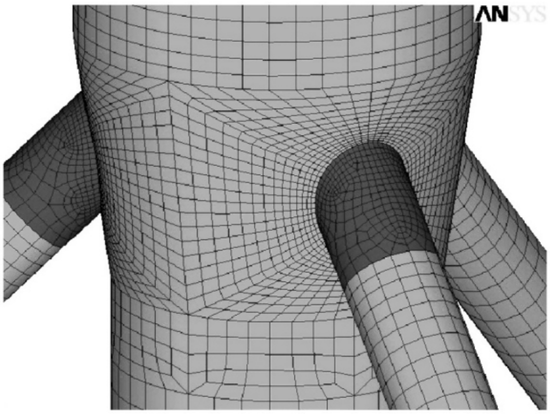

Figure 6: FE-Model of tripod joint

7 SUMMARY

For the development of OWECS experiences of the oil and gas industry in offshore structures as well as experiences in onshore wind energy have to be taken as a basis. The safety concepts which have been developed for onshore building construction have to be reviewed to match the intended level of both, safety and economics.

Influences on the dynamic behaviour of possible concepts for support structures monopile and tripod foundation are discussed. The results of the presented studies permit the conclusion, that different soil conditions have less effects on the tower eigenfrequencies of tripod foundations. These comparisons will be amplified in the further work on the GIGAWIND research project in Hannover. Beside this the structural behaviour of constructional details like e.g. tripod joints is investigated.

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For additional information see: www.gigawind.de