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TECHNICAL REALIZATION OF EXTENSIVE AQUACULTURE CONSTRUCTIONS IN OFFSHORE WIND FARMS: CONSIDERATION OF THE MECHANICAL LOADS

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ABSTRACT

The presented study focuses on the development of offshore wind farms in conjunction with open ocean aquaculture within the German Bight. For aquaculture enterprises in the open ocean an extensive cultivation of various species, blue mussels (*Mytilus edulis*), oysters (*Ostrea edulis*, *Crassostrea gigas*) and seaweed (*Laminaria saccharina*), is considered. However, without the solid foundations for wind turbines, such as monopiles and tripods as anchor or connection points, economic installations of equipment for mariculture would not be possible in view of the high-energy environment in this part of the North Sea. Thus, one of the most important questions pertains whether it is technically possible and economic feasible to use the offshore foundation structures as fixation device for aquaculture operations, such as a longline as one possible culture design. A longline culture is an open-water suspended technology in which cultured species are on-grown on ropes or diverse substrates, such as rope collectors for the catch of mussel spat, suspended from anchored and buoyed surface or subsurface horizontal ropes (longline).

For the calculation of additional foundation costs generated through the attached longline system knowledge on the supplement loads and stresses as well as on the required constructive modifications of the foundation must be obtained. The development and the conceptual design of offshore foundation structures are complex and require an interdisciplinary approach. In the presented project we aim to evaluate the induced loads between a foundation structure for offshore wind energy turbines and a longline system and to develop appropriate connection points. As monopile and tripod foundations are the most common foundation structures to date, these both will be considered within the modeling approach which calculates the respective loads from wind and waves. Both foundation structures are in the dimension of 4-5 MW wind turbines, while the monopile design will be calculated for a water depth of 10 m whereas the tripod for a water depth of 30 m.

To validate the model outcomes, an entire monopile-longline-monopile construction is set up in the offshore waters 10 nautical miles off the Island of Sylt at a water depth of about 17 m. At this site, the deformation behavior of the entire system will be determined on the basis of analytically calculated loads supported by the measurement of local stresses at the junction of the longline with the foundation. An additional measurement of forces will be performed on selected mussel collectors. To evaluate the observed loads with respect to environmental conditions, namely currents and waves, accompanying sensors will be installed on site. These achieved datasets will be used for the verification of the computer model for mechanical loads at the longline. Finally it is intended to scale up the model to the proportions of a wind farm while considering the interactions in the wavefield in which the longline system will be located.

Keywords: mussel cultivation, offshore aquaculture, wind turbines, offshore foundation, environmental loads

INTRODUCTION

Nearly all European coastal countries are somehow engaged in mussel culture. Culture techniques vary depending on water depth, access to the culture site and some environmental parameters, such as currents and wave height (Hickman 1992). Mussel farming along the coastal sea of Lower Saxony and Schleswig-Holstein (German North Sea) has a long tradition (Kleinsteuber and Will 1988). In former times the exploitation of natural blue mussel beds (*Mytilus edulis*) in the German Wadden Sea has taken place for centuries. Nowadays, an extensive cultivation technique - a combined fishery-on-bottom culture system - has developed since the 1950's (Korringa 1976). This technique, described by Seaman and Ruth (1993), is based on the dredging of seed mussels from wild mussel beds in the subtital and intertidal area of the Wadden Sea. After collection of the spat the mussels are re-laid at densities of 30-40 t ha^{-1} on a culture plot area. These areas are known to guarantee optimum growth rates and doubling the mussel's size within a year (Hickman 1992). On these license areas the culturist has been assigned exclusive rights to the harvest.

A big drawback of the on-bottom culture is that the mussels are subject to a high predation pressure from birds, starfish and crabs. Further, this technique depends on the availability of seed mussels from the wild. However, due to strong natural fluctuation the latter disadvantage has an impact on the productivity of these extensive blue mussel cultures (Ewaldsen 2003). The natural spatfall with the following settlement of juveniles in subtital and intertidal parts of the Wadden Sea shows strong annual variations. This results in an increase in potential fluctuation of yield and subsequent economic returns to the fishermen. For instance, in 2003 an enormous quantity of mussel larvae occurred in the Wadden Sea of Germany. Due to successful settlement of the larvae, catches of spat resulted in high quantities of juveniles in the fishermen dredges that were used for reseeding. In the previous four years, however, only little yields of juvenile mussels were obtained, affecting production seriously. This is in contrast to the research findings of Walter and Liebezeit (2001), which revealed, that despite the annual low seed production seed mussels could be extracted with collectors in vast quantities directly out of the water column. It therefore can be concluded that a low spatfall ratio does not necessarily lead to a complete absence of mussel larvae, but is dependent on several other environmental factors, e.g. extraordinary seaward currents, seasonal high predation or starvation, which lead to a decrease of a successful settlement ratio. Thus, a proofed off-bottom culture with suspended ropes, which collect larvae directly out of the water column, could overcome the shortcomings of mussel larvae settlement at on-bottom culture operations. One technique used to catch mussel larvae from the water column consists of a longline. A longline culture is an open-water suspended technology in which cultured species are on-grown on ropes or diverse substrates, such as rope collectors for the catch of mussel spat, suspended from anchored and buoyed surface or subsurface horizontal ropes.

Due to the nature reserve status along the German North Sea and its harsh and highly dynamic environmental conditions, the issue of potential direct expansion of the industry in the marine environment is limited (NPLSH 1999; NPLLS 2001). Further, protected bays for a save mussel longline cultivation are inexistent in the German Wadden Sea and tidal backwaters and estuaries become developed by mussel on-bottom culture and other competing activities (Krause et al. 2003), more focus will be placed on exposed locations (Buck 2002). With this in mind, a multiple use concept for the areas where offshore wind farms are planned has been developed (Buck et al. 2004). For the aquaculture in this offshore region an extensive cultivation of blue mussels (*Mytilus edulis*), oysters (*Ostrea edulis*, *Crassostrea gigas*) and seaweed (*Laminaria saccharina*) is considered. However, despite the potential of a multifunctional use of the same offshore area by wind farm companies and mariculture enterprises without the solid foundations of the wind turbines as anchor or connection points, economic installations of equipment for an extensive mariculture would not be possible in view of the high-energy environment in this part of the North Sea.

OFFSHORE FOUNDATIONS

The development and the conceptual design of offshore foundation structures are complex and require an interdisciplinary approach. One of the most important questions pertains whether it is technically possible and economic feasible to use offshore foundation structures as fixation device for aquaculture operations, such as a longline construction as one possible culture design.

For the calculation of additional foundation costs generated by such longline systems knowledge on the supplement loads and stresses as well as on the required constructive modifications of the foundation must be obtained. In this project we aim to evaluate the induced loads between a foundation structure for offshore wind energy turbines and a longline system. Several alternative connection points are tested. As monopile and tripod foundations are the most common foundation structures to date, these both will be considered within the modeling approach calculating the respective loads from wind and waves. Both foundation structures are in the dimension of 4-5 MW wind turbines. While the monopile design will be calculated for a water depth of 10 m the tripod design will be computed for a water depth of 30 m.

MONOPILE

The monopile will be calculated and designed with the representative environmental loads from the area of the planed wind farm "Nordergründe". For the static calculation of the monopile we use the structural analysis program RSTAB in the version 5.14.191 and the add-on module STEEL from Ingenieur-Software Dlubal GmbH. The 2nd order theory is used to get the results. In Figure 1 the static system, the bending moments and the transverse loads based on the maximum loads from the wind energy converter are plotted.

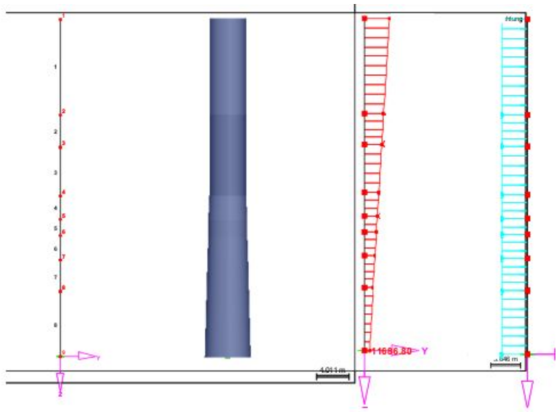

Figure 1: Static system of a monopile, moments and transverse loads.

The next step is to determine the connection point of the longline system considering biological and technical safety aspects. From a biological point of view the longline should be fixed in short distance below the water line. However considering the static analysis the connection point should be located as deep as possible. Thus it is necessary to find a compromise between theses both aspects. Furthermore, the interest of the wind farm operator to reach the windmill with a service vessel without barriers and dangers must be taken into account. At the same time, the potential of damage to the aquaculture system by vessels must be considered. For the prototype an installation in 5 m below the water line is assumed.

TRIPOD

A tripod is an offshore foundation construction for water depths of more then 25 m. The weight of a tripod for a 4-5 MW turbine is up to 1000 tons of offshore steel S355 NL/ML. The tripod considered within this project is constructed and calculated for the area “Borkum Riffgrund”, where the German research platform FINO1 (N 54° 0.86’ E 6° 35.26’) is located. We will employ the common wind loads and the waves for this position to create a tripod model which is the basis for the following investigations (GL-WIND 2002). Figure 2 shows the construction and the static model for the calculated tripod.

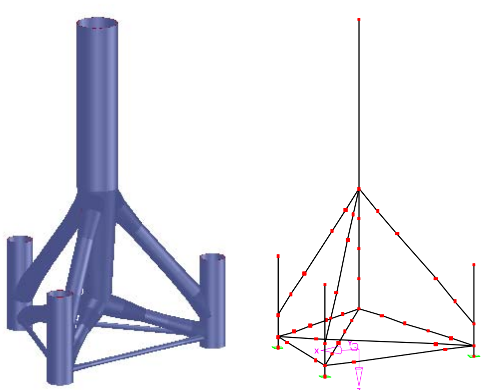

Figure 2: Construction and static model of a tripod.

The model in Figure 3 shows a possible connection point. A tripod has a main joint which is the technical limit for the depth of the connection point. This is located about 5 m below the water line.

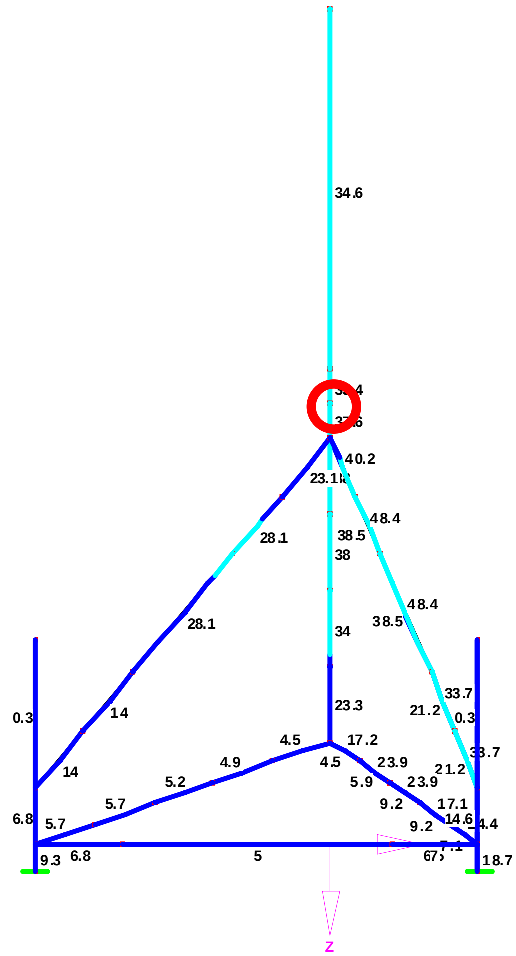

Figure 3: Possible connection point at a tripod for the attachment of a longline system.

As shown above both foundation structures were modeled and analyzed for possible connection points. Since it is the aim of the project to calculate the loads and the stress in the monopile and tripod foundations to attach a longline it is necessary to know the loads induced from the longline system itself. These will be derived from experimental studies and data measured at a real longline demonstrator, describe in the following.

LONGLINE DEMONSTRATOR AND STUDY SITE

The longline technique for mussel cultivation was chosen because this design is known to withstand in a submerged mode high energy environments. The whole construction consists of a buoyed, horizontal running backline, which is commonly described to be the backbone of the entire system. The line is typically anchored at either end and is the carrying line of the mussel collectors. The backbone, the buoys and the anchors are the three basic components. The collectors are fixed to the longline and are vertically suspended in the water column. Collectors are commonly made of polypropylene or sisal and act as hard substrate for the settlement of mussel larvae. After a grow-out time of 1-2 years mussels are ready for harvest. For this purpose the entire collector harness will retrieved and the mussels mechanically stripped from the collector. In this project the determination of the settlement of mussel larvae on collector ropes is not the main objective. Moreover, the concentration of mussel larvae in the water column at the study site was already determined to be very low. Therefore, test bodies were built, which have the same diameter and weight to simulate a fully colonized mussel collector (Figure 4).

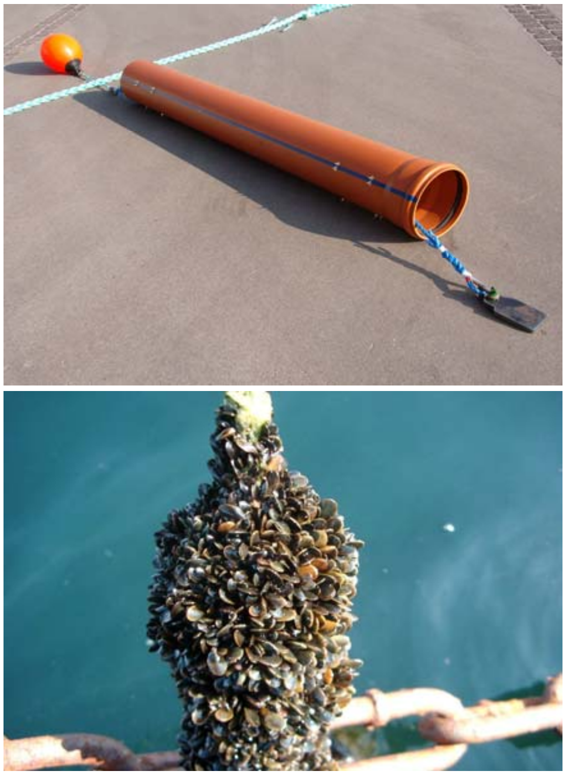

Figure 4: Test body (top) and a fully grown mussel collector (bottom).

The longline construction was established within the test area ODAS (N 55° 59´ 50´´ E 7° 54´ 30´´), which is accounted as a prohibited area and is located 16 nautical miles west of the Island of Sylt (Germany) (Figure 5).

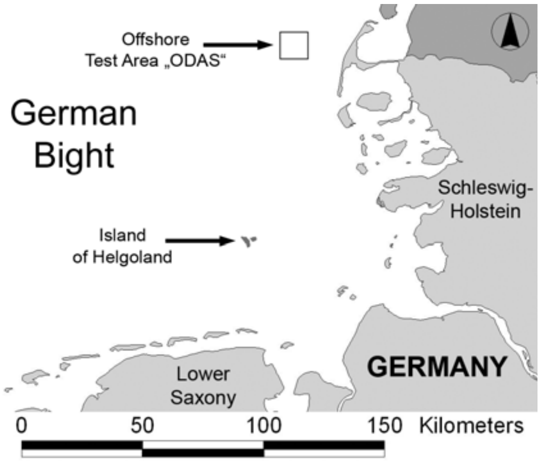

Figure 5: Map of the German North Sea region. The study site is located 16 nautical miles west of the Island of Sylt.

This marine area was chosen because of the adjacent wind farm, planned from the company “Butendieck”. Further, two 25 years old research platforms from the Federal Maritime and Hydrographic Agency (BSH), which have the shape of rounded metal piles, are located in this test area (Figure 6). Each pile has a height of approx. 18 m from the seabed to the water surface and in a depth of 5 m a diameter of nearly 1.36 m. The distance between the two piles is approx. 56 m. Over the past years both piles are no longer in use, thus, it was an adequate fixed position within an offshore region, which can be used for our purposes. A permit for the utilization of the study sites was obtained in January 2006.

Figure 6: Single pile of the research platform ODAS, which serves as one longline connection.

The piles are chosen to simulate a monopile structure of an offshore windmill. Instead of concrete blocks to anchor the longline the piles were chosen to hold the entire construction. The longline served to fasten 22 V-shaped test bodies perpendicular to the water surface. Six further single collectors were connected to the longline to measure settlement success. An additional horizontal line serves as marker line. In Figure 7 the preliminary design of the longline-monopile set-up is demonstrated.

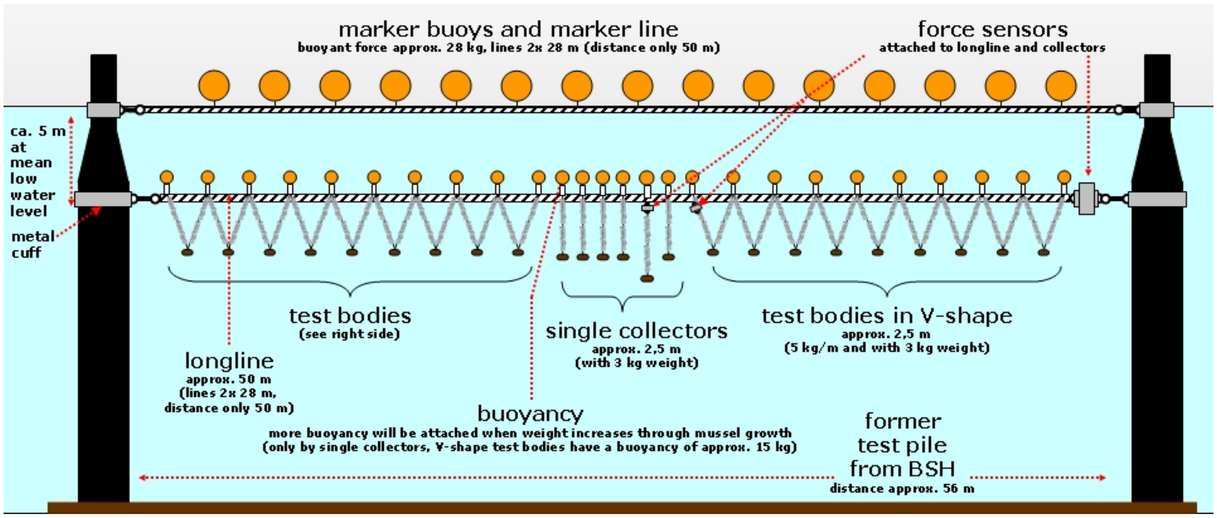

Figure 7: Possible longline design at the study site

To quantify the loads induced by environmental actions like wind, waves and currents it is necessary to measure real loads on the test structure. Measurements of currents in the plane of the collectors, approx. 7 m below water surface is achieved by applying an Aanderaa (Norway) RCM-9LW current meter at a mooring site in approximately 30 m distance from the longline demonstrator. The current meter is additionally equipped with a pressure, a temperature and a conductivity sensor to address the oceanographic conditions as well as a turbidity probe and a shallow water oxygen sensor, both to account growth parameters of the biological setup. Tidal and wave conditions are sampled by a tide and wave recorder TWR-2050 manufactured by RBR, Canada. Wave directions and general meteorological conditions will be derived from satellite observation based datasets. The forces inside the longline demonstrator will be measured at three locations by means of load sensors and data will be sampled by a submersible data logger from iSiTEC, Germany. However, as a first step it will be necessary to roughly estimate the maximal forces to qualify the load sensor class. Figure 8 shows a schematic depiction of a single collector load system.

The estimate of current forces is executed according to the equation

$$F_c = \frac{1}{2} \cdot \rho \cdot c_D \cdot A_c \cdot v^2 \qquad (1)$$

with

$$v = v_c + v_{ow} \qquad (2).$$

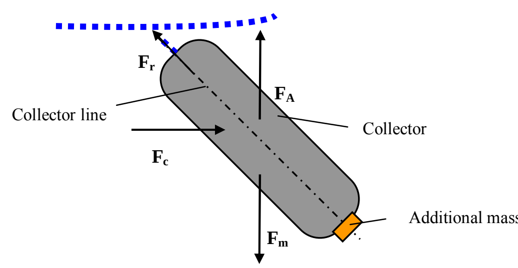

Figure 8: Model of collector loads for a single collector attached to a longline system.

ρ is the sea water density in the test field (approx. 1026 kg/m³) and A_c the vertical projected area of the collector.

The drag coefficient c_D is taken from literature being 1.4 (Lien and Fredheim, 2003). This data seems to be plausible since a vertical approach panel with a proportion width to height (b/h) of 10 leads to a $c_D = 1.29$ and with b/h of 18 to a $c_D = 1.4$. Another validation results from CERC (1984) where for a Reynolds' number of Re smaller than $2 \cdot 10^5$ a value of $c_D = 1.2$ is been given for a circular cylinder. Therefore we can argue that with $c_D = 1.4$ a good agreement of different approaches is achieved.

The velocity v consists of the current velocity v_c and the orbital wave velocity v_{ow}. The equation is a modified Morision-formula (Morision et al., 1950). The maximum of current velocity in the test field is specified as $v_c = 0.8$ m/s (Mittelstaedt et al., 1983). To calculate the horizontal orbital velocity we applied the method of the linear wave theory (Wiegel, 1964) and to check these results the cnoidal wave theory was used. To be on the safe side we decided to use the linear wave theory, due to the fact that the results are 6 % higher. The required significant wave height in the test area was measured during the PISA study of the Federal Maritime and Hydrographic Agency (BSH), Hamburg, from 1993 to 2004. For 1994 a maximum significant wave height of 7.08 m (Figure 9) was selected. Applying with the criteria for breaking waves and the Goda-diagrams (Goda, 2000) calculated the maximal wave height by 1.48 times the significant wave height, resulting in a maximum wave height of 10.48 m.

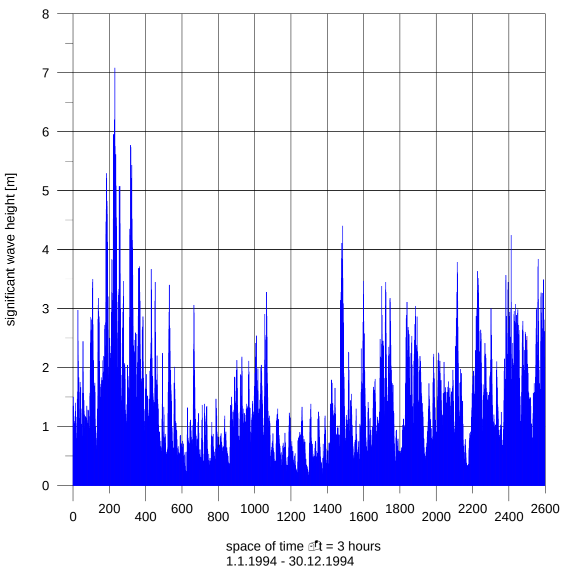

Figure 9: Significant wave height at the test area "ODAS" in 1994, derived from data measured by the Federal Maritime and Hydrographic Agency (BSH), Hamburg.

Utilizing the values of the maximum wave it is possible to calculate the maximum horizontal orbital velocity in the test area to v_{OW} = 3,77 m/s, and with equation (1) we obtain the current force F_c as one of the load vectors of the resulting forces on the connection between the collector and the longline.

The buoy (Figure 10) is calculated similar to the collector. The vertical forces are caused by the mass of the collector and the buoyancy. The mass force is defined as

$$F_m = m \cdot g \qquad (3)$$

with

$$m = m_c + m_l + m_a \qquad (4),$$

where m_c is the collector mass, m_l the line mass and m_a the additional mass.

The buoyancy was calculated applying

$$F_b = V \cdot \rho \cdot g \qquad (5),$$

where V is the volume of the buoy, ρ is the density of seawater and g the gravity constant.

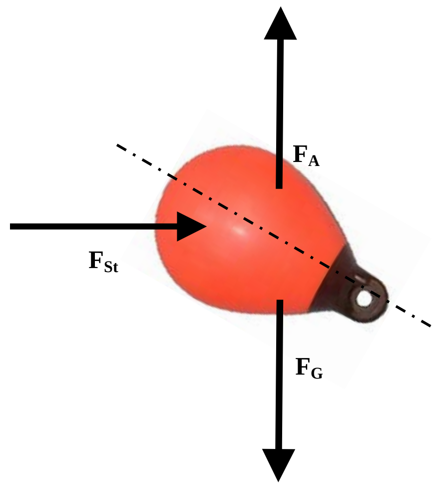

Figure 10: Schematic diagram of a buoy and its forces.

Given the resulting forces from the single collector and the buoy it was possible estimate the total load from the collectors and finally the longline system itself.

CONCLUSIONS AND FUTURE STEPS

It is the aim of the project to evaluate if it is technically possible and economic feasible to use offshore foundation structures as fixation device for aquaculture operations. The presented work addresses this question for the two major offshore foundations under use, namely the monopile and the tripod. Setting up static models of both foundation structures, and taking into account the needs of an aquaculture longline, realistic water depths for connection points were deduced. To feed these models with forces induced by real longline systems, a demonstrator setup was planned in a slightly downscaled environment, scheduled for deployment in March 2006. The experimental setup and the load sensors to be installed within this demonstrator, however, need information of the maximum forces to be expected on a single collector and on the longline in total. Therefore a rough estimation based on available hydrographic datasets was performed within this work.

The next steps of the project will be the deployment of the longline demonstrator and the evaluation of first results two month later. Yet, since mussel growth will accumulate along time, the forces measured are not expected to be at the limit expected within this short period. After one year of deployment, which is the time intended for the longline demonstrator experiment, substantial information on the correlation of environmental driving factors, such as currents, winds and waves, and the forces induced are expected. From there on, results will be scaled up to the dimensions of planned wind farms and feed into the static models described above to find and evaluate technical and economical aspects of aquaculture usage in combination with offshore wind farms structures.

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