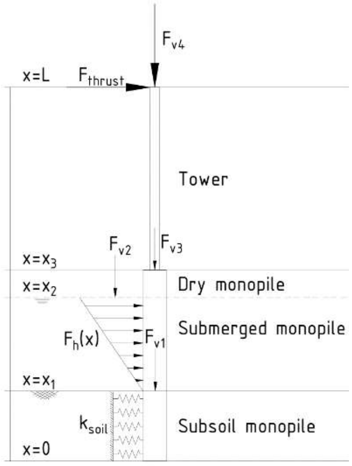
Technische Universiteit Delft

Offshore & Dredging Engineering

Buckling monopiles: stability of a monopile based offshore wind turbine

Offshore wind turbines are being placed all over the world. The increased popularity of these structures comes with a boost to the development of wind turbines in general, resulting in larger and higher constructions. To ensure the support structures of the turbines are able to withstand the extreme loads and environmental conditions, it is subjected to a series of tests and checks, prescribed by codes and standards. This thesis focuses on buckling checks, with global buckling in particular.

Several codes and standards define buckling checks, differing in approach. For example, the global buckling check is based on global buckling (compromised stability due to an axial force), but also takes eccentricities into account. How these parameters and safety factors are incorporated is analyzed for the Eurocode and the DNVGL, which are considered the most relevant design standards regarding offshore wind turbines around the Netherlands. Difference between both global buckling checks are analyzed using a monopile based reference wind turbine.



Looking to the more mechanical term of global buckling (also called Euler buckling), one finds an expression for the buckling load, based on the flexural stiffness and the buckling length of the structure. However, both parameters vary over the height of the support structure: the monopile has one relevant buckling value, where the flexural stiffness varies with its geometry. Therefore the buckling length cannot be constant for the structure. To tell something about this buckling length, the support structure is modeled with Euler beams as visualized in the figure. Subsequently the buckling force is analyzed, a constant value for the flexural stiffness is derived and the buckling length is calculated. Finally, the influence of the soil conditions on the buckling length of the structure is analyzed.

To determine whether a second order analysis is required to calculate the buckling force of the support structure, a comparison is made. Two Euler-Bernoulli beam models are introduced, one with a second order term, one without. The influence of the term on the bending, rotation, moment and shear force is analyzed, as well as the influence of the Euler buckling force. Subsequently an incremental load factor is introduced to incorporate the second order effect in the more simplified beam model.

Finally, the relevance of global buckling is considered. How relevant is the global buckling check for the currently installed wind turbines, and how relevant will it be for the larger support structures that are to be expected? To answer these questions, comparisons are made between the buckling checks and how far from failing the checks are. Subsequently, the local buckling is introduced to compare the global buckling check to the local buckling check regarding relevance.

The most important results and conclusions are summarized:
The buckling check of the DNVGL and the Eurocode differ for result. However, the unity check is a factor 20 lower than critical.
A buckling length of more than twice the length of the structure (from the seabed to the top) should be used for Euler buckling analysis.
The second order term affects the total displacement- and moment distribution minimally: approximately 5% of the total moment (and displacement) is contributed by the second order term.
Local buckling and global buckling are equally important, regarding the Eurocode. Both unity checks result in approximately the same values, which is a factor 20 away from being critical.

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Offshore & Dredging Engineering

Technische Universiteit Delft

Re-designing the GBM Vibro-drill for post-installation retrieval

With increasing diameters of offshore monopile foundations, impact hammers require more energy per blow in order to drive them into the seabed. This does not only increase the fatigue loading on the monopile, but it also increases underwater noise that affects marine life. The increase in installation costs due to additional material on the monopile, noise mitigation and longer installation times drives contractors to look for alternative installation methods.
GBM's Vibro-drill strives to install monopile foundations through a combination of jetting, liquefaction and fluidization to reduce the soil resistance to such low levels that the monopile will penetrate the soil under its own weight and thereby significantly reducing underwater noise. Although the working principles are still being tested, the Vibro-drill design needs to be improved for commercial application. The design must include the three operational functionalities stated above, but to make the Vibro-drill re-usable for consequential monopile installations, additionally retrieval and structural rigidity are required.
For this thesis, the Vibro-drill is re-designed to include these functionalities. Starting from a process description, all load cases and additional design requirements were found. Based on a first global load case, a first selection was made for the connection mechanism. Subsequently, a Multi-Criteria Analysis was performed yielding two suitable concepts: the Vibro-Boxer and the Vibro-Polyp.

The Vibro-Boxer relies on three extending arms that connect with a specially designed pile shoe using twelve hydraulic grippers. To feed the system with hydraulic fluid, water and air, an umbilical connects the installation vessel with the central hub of the Vibro-drill. At the end of each arm, eccentric weights are used to vibrate the pile tip.
The Vibro-Polyp has a similar lay-out except for the arms and connection mechanism. Nine hinged arms form three sets of folding parallelograms to expand or contract the Vibro-drill. The connection is made through a set of pins on each arm that slide into holes in the pile shoe.

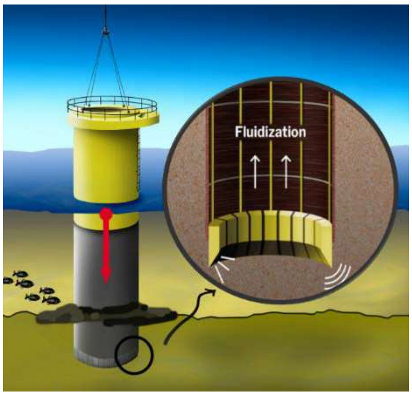

Figure 1. Working principle of the GBM Vibro-drill

Due to unknown soil properties and effectiveness of jetting, liquefaction and fluidization, the loads on the structure cannot be determined deterministically. Therefore, a Monte Carlo simulation is used to perform the structural analysis based on a best guesstimate for the distribution of these unknown parameters. Based on this approach, a tool is created that aims at performing the structural analysis while iteratively improving the design. As test results will become available after finalizing this thesis, input for the unknown parameters can be updated to improve the results of the structural analysis. Subsequently, based on this progressive insight, the design of the Vibro-drill can be optimized further. Note here that for the structural analysis, the system is assumed to be quasi-static which is a gross simplification of reality. Although this imposes limitations to the reliability of the results, this assumption is allowable for the preliminary re-design phase considered in this thesis. The structural analysis described here has been applied to both suitable concepts. For each concept, the external loads were identified and the internal loads were calculated. A series of structural checks in the Monte Carlo simulation provided a probability of failure. For both concepts the probability of failure was initially too high and therefore improvements to the structural components were made.

Based on the design criteria, the two optimized design concepts were compared. Due to the smaller frontal area of the Vibro-Polyp its soil resistance on the tip of the monopile and the Vibro-drill is the smallest and therefore requires the least eccentric force. Nevertheless, the structural analysis shows that its hinged arms are fatigue sensitive yielding a higher probability of failure. Therefore, despite its larger frontal area, the Vibro-Boxer has a higher reliability and is the most suitable concept for the Vibro-drill.
Finally, a more detailed design of the Vibro-Boxer concept is delivered that complies with all design requirements. For this design, recommendations are given on how to update the design based on the dynamic analysis and future test results.

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Offshore & Dredging Engineering

Technische Universiteit Delft

A parameter sensitivity study for a Soft Yoke Mooring System (SYMS)
Developing a design tool

Floating production units require to be permanently moored offshore. For shallow water field developments, typical designs include soft yoke mooring systems which is a single point mooring technology. Produced fluid is transported via a geostatic tower along the transfer hoses to the production unit. Single point mooring systems will weathervane into the offshore environment (wind, waves and current) and can often be considered as surge dominant induced by low frequency wave drift forces. Due to low damping at these low frequencies, an oscillation close to the natural surge frequency appears causing dominant mooring loads. By connecting the floating structure to the tower with various rigid steel frame components, including multiple hinges, unconstrained motions are preserved. This results in dynamically complex systems requiring advanced numerical methods for time domain simulations, in order to deliver the mooring design loads. By selecting mass and dimensions of the soft yoke mooring system, the stiffness of the mooring system can be adapted to influence the response of the floater.

Figure 1. Soft Yoke Mooring System

Currently, mass and dimensions of new soft yoke mooring designs are established using proven mooring solutions by conducting small adjustments of mooring components in time consuming dynamic simulation software. Improvement in efficiency of the design process is accomplished by developing a computational efficient design tool, to be used before dynamic modelling, to provide the designer with an optimized set of mooring design parameters in a given environment. The developed design tool contains an integrated single degree of freedom model including given vessel properties and extreme collinear offshore environment, in order to produce estimates of the maximum surge response based on the given mooring characteristics. Eventually, by adapting the mooring stiffness accordingly, the design tool is able to provide an optimum set of mooring design parameters which minimizes the maximum mooring load.

The mooring characteristics are implemented using a linear and non-linear approach. A validation of surge response results has been performed for three collinear extreme offshore environments including wind, waves and current using state-of-the art dynamic modelling software OrcaFlex. Results showed that the linear model can capture the sensitivity of the surge response related to mooring design parameter variation. It was demonstrated with the Runge-Kutta method that the achieved accuracy with the proposed non-linear model will be similar or even worse than using the linear model without the relevant computational costs. Therefore, the linear model was implemented in the design tool and accomplishes surge response calculations of 10,000 sets of mooring design parameters within a few minutes.

Results showed that the consequence of the linear mooring force and single degree of freedom assumptions in the design tool leads to an underestimation of the surge response in an extreme collinear environment. Despite the surge dominance, especially heave and pitch motions induce high mooring loads at maximum surge offset. Analyses of two moderate collinear environments in OrcaFlex revealed less underestimation and even overestimation of the surge response by the design tool, which indicates the high dynamic complexity of soft yoke mooring systems. However, the surge response validation procedure using OrcaFlex affirmed that the design tool provides the correct set of mooring design parameters resulting in a minimum mooring load within 2~10% accuracy for all three environments. By implementing the proposed set in OrcaFlex and obtaining the design loads, a 25% decrease in absolute maximum mooring load is demonstrated when compared to the benchmark mooring design parameters. This indicates the increased efficiency of the design process by using the developed design tool.
An additional graphical user interface is programmed where the designer can import their own vessel properties, environmental conditions and can vary desired mooring design parameters. Conclusively, a design tool has been developed for preliminary estimations of the set of mooring design parameters that have been shown to minimize the mooring loads and to limit the number of time domain analyses in future projects.

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Offshore & Dredging Engineering

Vibrations in an active controlled hexapod

Safe offshore access for people and cargo is a major challenge in the offshore industry. The Ampelmann system is an active motion compensated system for six degrees of freedom. Creating a platform isolated from the motions of the vessel makes offshore access as easy as crossing the street. All the Ampelmann system can be used for is personnel transfer, while some of the systems can also be used as a cargo crane. The basic system can be divided in two main systems: the hexapod and the transfer deck and gangway. Usually the system is installed on a ship deck. However, in various cases the height of the Ampelmann system is not sufficient to reach the landing point. An often-used solution is to place the system on a pedestal which can be over 15 meters high. The Ampelmann system occasionally starts vibrating unexpectedly, especially while the system is placed on a pedestal. These vibrations are believed to be caused by the eigenfrequencies of the system and/or amplification caused by the motion control algorithm. In this research an investigation in this phenomenon was done.

This investigation was done via an analysis of the eigenfrequencies of the active-controlled hexapod. A finite element method model was created to determine the eigenfrequencies of the system. This model was made using MATLAB and the toolbox StaBIL 2.0, created by the university of Leuven. All the elements of the system are modeled as beams except the hydraulic actuators. The properties of the elements which represent the hydraulic actuators are calculated separately using a modelling study on stiffness characteristics of hydraulic cylinder under multi-factors.

Possible causes for the unexpected vibrations have been investigated via measurements performed on Ampelmann systems. Data which was readily available is analyzed. Based on this data three possible causes have been determined. These are: the influence of the pedestal, residual motions due to limitations of the Ampelmann system and vibrations in the bottom frame due to compensating for gangway motions.

To investigate the influence of the pedestal and the vibrations in the bottom frame two experiments have been performed. The residual motions have been investigated via calculations based on data already available. The amplitude of the response in the results from the experiment performed to investigate the vibrations in the bottom frame due to gangway motions is negligible over the entire test period. The data from the calculations done to investigate the effect of the residual motions show no amplification. The results of the experiment and the calculations lead to the conclusion that these do not cause unwanted behavior.

The experiment to determine the influence of the pedestal shows four peaks in the frequency domain of both the signals. The first is directly caused by vessel motions. The other three have a cause which is not directly related to vessel motions. The data from the sensor on the Ampelmann system, at the top of the pedestal, does not contain a peak which is not also present at the ship deck. From this it can be concluded that the eigenfrequencies of the pedestal do not have a relevant influence. For one of these peaks the amplitude of the graph related to the top of the pedestal is higher than the one corresponding to the ship deck. A possible explanation for this phenomenon could be the eigenfrequencies and corresponding eigenmodes of the ship deck. The pedestal functions as a lever arm amplifying the rotations related to eigenmodes of the ship deck (Figure 1). This may cause the unexpected vibrations.

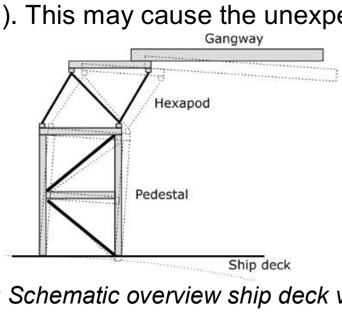

Figure 1: Schematic overview ship deck vibrations

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Offshore & Dredging Engineering

Technische Universiteit Delft

Rescue craft davit performance on an FPSO in heavy sea states and a davit design proposal

The purpose of this research is to increase the workability of a rescue craft launch and retrieval system on FPSOs in heavy sea states. Although a rescue craft's purpose is to improve safety, multiple incidents recorded in the GISIS database have proven that the launch and recovery operation can be dangerous or even deadly. The problem research shows that the davit system is the main cause for incidents, which are related to design flaws, lack of maintenance and human errors.

The opinion of the author is that a different type of launch and recovery system can lead to improvement on all three parameters and to an increased workability of the system. To compare a new design with the conventional design, a computational model of both designs is built to simulate the launch of a rescue craft from an FPSO in various sea states.
The conventional model shows dangerous accelerations in high sea states and the risk to collide with the hull of the FPSO. The concept design aims to reduce these motions and, in addition, provide a more redundant design with easy maintenance and focused on reducing human errors.

After comparison, the concept design proves to reduce dangerous motions during launch and increases the workability in high sea states, while being very simplistic robust and easy to operate. However, in the splash zone the concept model does not mitigate dangerous motions sufficiently. To further substantiate this conclusion, it is advised to further investigate the splash zone model and to develop a more detailed model of the concept design.

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Offshore & Dredging Engineering

Technische Universiteit Delft

Feasibility of a marginal offshore development in the Guyana-Suriname Basin

The Guyana-Suriname Basin off the coast of Suriname possesses large amounts of hydrocarbons. Suriname therefore wants to engage in developments in the shallow areas (0 - 30 m) offshore through their local oil company Staatsolie Maatschappij Suriname N.V. The expected discoveries are marginal and the soil consists of extremely low strength clays. This and the local lack of experience regarding the offshore industry represent the main challenges for offshore developments in Suriname. The objective of this thesis is to assess whether offshore developments in this basin are technically and economically feasible, assuming that the discoveries are marginal. Because a reservoir is yet to be discovered, the reservoir characteristics (location, size, etc.) are unclear. Hence, the important figures are currently only best estimates. The reservoir is estimated to possess 30 million barrels (30 mmbbl) recoverable reserves.

In order to investigate possible development approaches, marginal field developments across the world were looked into. Based on this, it appears that mostly low cost, minimum facilities platforms are used for development of marginal fields across the world. By using similar approaches and taking into account the local (social and economic) aspects which are significant to this project, possible development scenarios for a field offshore Suriname are formed. The proposed scenarios are the all-land (treatment on land, 9 mbbl/day), the sea-land (treatment at sea, 9 mbbl/day) and the minimal production and logistics scenario (treatment on land, minimal CAPEX, 3 mbbl/day). These scenarios consist of on- and offshore facilities of which the offshore platform is further assessed to investigate its technical feasibility. In order to determine the most suitable platform for each scenario a multicriteria analysis is performed. The technical feasibility of the selected platforms is analysed by performing a structural analysis. For the all-land scenario the proposed platform is a wellhead platform (WHP), consisting of 4 conductors which also function as the support structure (4-conductors support structure (4-CSS)). For the sea-land scenario a jacket with an adjacent WHP is proposed. For the minimal scenario the proposed platform is a freestanding conductor.

Because of the shallow water depth the wave loads are calculated using the 5th order Stokes waves. The environmental loads and the permanent & variable loads on the platforms are calculated and the structural integrity is assessed by performing ultimate limit state (ULS) strength checks, which are specified in ISO 19902. The foundation of the platforms is assessed by looking into the axial and lateral soil resistance. The checks are only performed for a static load case. By using WHPs the overall weight of the platform is limited (50 tons for 4-CSS and 15 tons for freestanding conductor). The weight of the jacket is kept relatively low by situating the well bay on an adjacent WHP. When only considering a static load, the jacket, 4-CSS and freestanding conductor are technically feasible in all water depths (0 – 30 m).

The economic feasibility is assessed by evaluating the total costs of each of the proposed scenarios. The main cost components are the drilling & exploration, the offshore and onshore facilities, storage, transport and OPEX. Based on analysis it appears that the minimal development scenario is ultimately the most attractive scenario for development of a 30 mmbbl reservoir. This scenario includes a freestanding conductor as offshore platform with 1 well in production. The raw crude is transported to the TLF refinery via tanker, where facilities are built for primary treatment. The initial investments for this scenario are about 120 MM€ lower than for the all-land and sea-land scenario while the net profit (NPV) over the field life span is about 65 MM€ less. The OPEX and price per barrel can vary significantly. The net profit is estimated with a market sales price of 35 €/bbl and an OPEX of 7.20 €/bbl. The low production rate indicates a longer field life span for the minimal development scenario, 30 years compared to 12 for the other scenarios. By combining the current onshore production with the offshore production, the feed to the refinery can be kept steady and no expansion of the refinery will be required. Because of the low initial costs and the guaranteed longer steady feed to the refinery, the minimal development scenario is proposed as the best development scenario for a marginal field offshore Suriname.

Figure 1 – Freestanding Conductor

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Offshore & Dredging Engineering

Modelling of wall-bounded flows near a cylinder-bed junction in turbulent flow conditions using an IDDES turbulence model to asses initial particle entrainment

Due to the presence of a monopile in a turbulent flow swirling vortices, known as horseshoe vortices, can form upstream of the structure near the cylinder-bed junction. Those vortices then travel downstream of the cylinder as they are being dragged along with the current. The horseshoe vortices can scoop up bed material surrounding the cylinder, weakening the foundation of the structure. This phenomenon is known as scour. A common protection method to reduce the effects of scour is the dumping of stones in the vicinity of the cylinder-bed junction. The aim is to alter the flow dynamics near the bed in such a way that the underlying sediment is mostly unaffected. However, the protection material itself is also subject to hydrodynamic forcing and can therefore be entrained as well. This would be described as damage to the protection layer as its effectiveness reduces due to re-exposure of the underlying sediment. It is for this reason that protection layers must be carefully designed depending on their use. The mechanism of the horseshoe vortex system and its damaging aspects are not completely understood yet, making engineering of specific protection layers challenging.

To better understand the flow behaviour upstream of a cylinder-bed junction, where the formation of the horseshoe vortices takes place, several tests have been performed at the Eastern Scheldt Flume in the Hydro Hall of Deltares. Here different cylinder and bed protection configurations were subjected to turbulent current and wave conditions where the upstream flow fields were measured with a PIV measurement system. Since the obtained information of the tests is limited to a specific area, there was an interest in modelling the test cases by means CFD, while using the test results as validation.
In this thesis several of the test cases have been modelled with the Improved Delayed Detached Eddy Simulation (IDDES) hybrid turbulence model, based on the Spalart-Allmaras formulation, which include the following:

a) Open channel with a smooth bed and no monopile
b) Open channel with a rough bed and no monopile
c) Open channel with a smooth bed and a smooth monopile
d) Open channel with a rough bed and a smooth monopile

The modelling strategy used starts off with a basic simulation case (a) which is compared to the test results for validation of the simulated flow characteristics. This model is then elaborated on by inclusion of either a rough protection model (b) or a smooth cylinder (c). Both models are again validated with the test results so that the ability of the IDDES model to model the fluid-structure interaction is investigated. Finally, a simulation that includes both a rough bed and a smooth cylinder (d) is performed as shown in Figure 1. For simulation models b, c and d an assessment is made for potential initial particle entrainment by means of hydrodynamic forcing indicators. Additionally, the effects of bed model surface roughness on the entrainment of bed material are briefly considered.

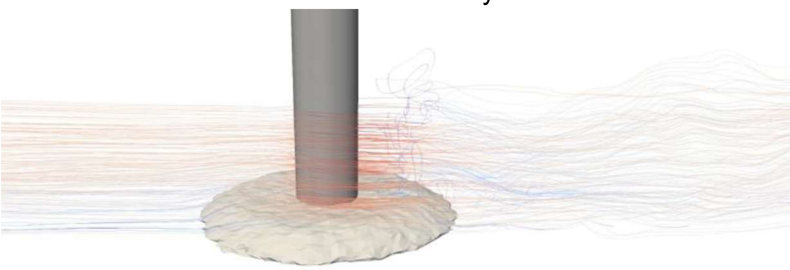

Figure 1: Incoming turbulent flow interacting with a model that includes both a rough bed and a smooth cylinder

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Offshore & Dredging Engineering

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Design of a Motion Compensation System for Offshore Wind Turbine Installation

To reach the Paris Agreement goals, switching from fossil fuels to renewable energy is inevitable. Wind power has proved to play a critical role in this transition. To speed up this transition, the wind industry must keep innovating. The major part of Wind Turbine Generators (WTGs) is installed by a jack-up which not only has its limitations from an engineering point of view, such as water depth, soil characteristics and lifting capacity but also from a financial point of view. To surpass these limitations, this research aimed at developing an innovative concept design for the installation of offshore WTGs.

A vessel dynamic analysis showed that the Mighty Servant 1 is the most suitable Boskalis vessel to install WTGs from. The same dynamic analysis also highlighted that a motion compensation system is required to mitigate wave-induced dynamics and enabling WTG installation in floating conditions. After developing multiple concepts of motion compensation systems, a multi-criteria analysis in the form of an analytic hierarchy process is performed. It is found that the most promising concept should rely on hydraulic actuators. To find the optimal values of the design parameters of the chosen concept, a kinematic multi-objective optimization is carried out by means of a genetic algorithm. The optimal set of design parameters is selected by taking advantage of the Pareto front, which is computed by using three chosen performance indexes.

A model is developed in MATLAB and Simulink to simulate the dynamics of the motions compensation system. The simulated results showed that a controller which uses velocity feed-forward and position feedback is the preferred way to go. The results also highlighted that the required amount of hydraulic power has a great impact on the economic feasibility of the system. Therefore, to reduce the hydraulic power and guarantee the feasibility, a passive system based on a hydraulic accumulator is added.

Based on the results of this research, it can be concluded that the next generation offshore wind turbine generator can be motion-compensated with hydraulic actuators including hydraulic accumulators. Further research could be carried out by assessing more installation phases in combination with a wider range of load cases.

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Offshore & Dredging Engineering

Technische Universiteit Delft

An analysis of a deep-sea nodule mining system: Vertical transportation by means of mechanical lifting

Deep sea minerals can offer an additional resource to meet the increasing mineral demands, instigated by population growth and technological advancements. Deep sea minerals exist in different forms at the bottom of the ocean. In this research, polymetallic or manganese nodules are the kind that are of interest. The nodules are 1 to 12 cm large and contain a variety of minerals like copper, nickel and cobalt, but owe their name to its main component manganese. The region with the highest approximated resource of polymetallic nodules is the Clarion-Clipperton Zone (CCZ), situated in the Pacific Ocean between Hawaii and Mexico. The CCZ has water depth reaching 6000 meters, which is a significantly larger working depth than state-of-the-art deep sea projects within the offshore industry. These depths are accompanied by challenging environmental conditions exerted on the deep sea mining system.

A deep sea mining system typically consists out of three components: 1) Production Support Vessel (PSV), 2) Vertical Transport System (VTS) and 3) Seafloor Production Tool (SPT). The SPT harvests the nodules from the seabed, the VTS transports the mined nodules through the water column to the surface where they are transferred to the PSV. The focus in this thesis will be on the Vertical Transport System. Where most deep-sea mining developments are considering hydraulic vertical transport with a riser, Boskalis introduces a concept that utilizes mechanical lifting for the vertical transport. This allows for energy efficient transport, relative simplicity of concept and a maximization of the amount of power units above water.

The objective of this thesis is captured in the following research question: *What is the behaviour of the combined mining system (ropes, skip and SPT) during vertical transportation by means of mechanical lifting?* To answer this question, a wide overview is given of the deep-sea minerals that exist on the seafloor and the existing technologies to harvest them. Whilst the system is in principle relatively simple (just two containers (skips) that are alternatingly filled, hoisted to the surface, emptied and lowered again) many challenges arise. To identify these challenges, the system and the production cycle are discussed in detail. Literature research has been done to ensure realistic modelling of characteristics like structural damping of the rope, drag forces and added mass. The safe working load of steel wires is mostly consumed by its self-weight at a length of 4000 meters, making them unsuitable for deep-sea mining. Instead, the less common but naturally buoyant synthetic fibre rope is envisioned.

Many of the challenges in this deep-sea mining system originate from the environment as the system is subject to wave action and currents. Therefore, the current profile and wave spectrum typical for the Clarion-Clipperton Zone are obtained to serve as input for further investigation in the hydrodynamic analysis software Orcaflex. The system will be deployed over the entire 6000 m water column, causing the current but also the forward velocity of the system to possibly lead to high drag forces. A reduction of the forward velocity by introducing a new harvesting method is implemented, resulting in a large reduction of the drag forces and offset.

The system consists of at least eight ropes, with two moving skips. Combined with the current and vessel motion, rope entanglement is a risk. A solution to prevent the rope entanglement is presented in this thesis. Possible occurrence of vortex-induced-vibrations (VIV) is identified and future research is recommended. The offset analysis shows that a large offset (500m) between the PSV and SPT results in relatively low horizontal forces on the harvester. The system is connected to the PSV, which is subjected to the Pierson-Moskowitz wave spectrum environment it is situated in, resulting in vessel motions. These motions will govern the dynamic behaviour of the system. The skips with attached fibre ropes have different eigenfrequencies on different water depths, as a longer rope will make for a softer system. This causes both skips, full and empty, to resonate in some regions. Consequently, the dynamic tension in the ropes is higher than the static tension, although it does not come forward as problematic. However, undesired slack rope conditions can occur when lowering the empty skip.

To conclude, an analysis of the deep-sea mining system has been done in which the eventual design has been modelled to the best extent currently possible. This research underlines the technical feasibility of this deep-sea mining concept. This research also evaluates the questions that have not been answered yet and recommends a variety of interesting topics for future research.

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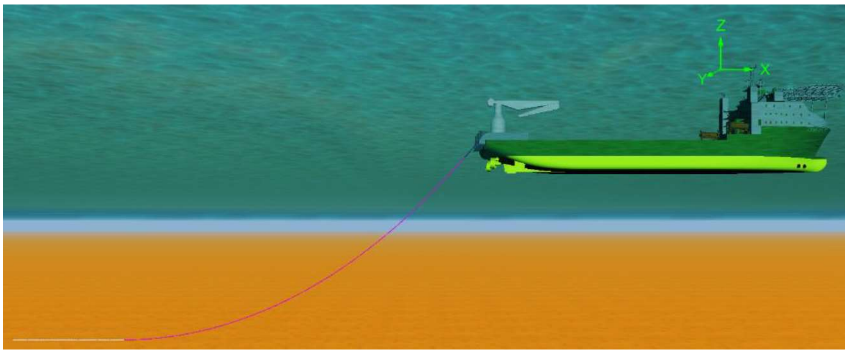
Offshore & Dredging Engineering

Fatigue analysis for Offshore power cable installation

Over the last decade, the demand for offshore power cables has increased significantly due to, in particularly, the emergence of offshore wind. Despite, this growth, industry-wide rules and guidelines to analyse fatigue during cable installation operations are yet to be developed, even though fatigue can become an important parameter in the installation design. Gaining knowledge of fatigue in offshore power cable installation will ultimately improve efficiency and safety of operations.

In similar offshore operations, for example installation of pipelines or umbilicals, fatigue is assessed based on fundamental fatigue theory like rainflow counting, S-N curves and Miner's rule and therefore these principles form the basis of analysis in this research. However, as opposed to pipelines, submarine power cables consist of numerous layers of different materials that result in complex cable cross-sections. The fatigue behaviour of the cross-sectional elements due to external loads has been investigated to determine a maximum stand-by time during installation operations. In this regard, a cross-sectional analysis was performed to establish the stress-strain response of the individual cable components to the global cable deformations. For bending behaviour, the analysis was shown to be consistent with existing test data. However, this type of data is scarce and the analysis was based on a limited sample size. Moreover, geometrical cross-sectional data of submarine cables is rarely provided by suppliers and hence several assumptions were made in the analysis. For future work, it is recommended to develop in-house test data of cables such that the cross-sectional model can be accurately verified and improved.



Thereafter, the cross-sectional stresses were implemented in a fatigue assessment model, in which the local stresses were calculated based on the output of global modelling software OrcaFlex and subsequently analysed with rainflow counting and Miner's rule.
The model was applied to three cable types and it was found that lead, used for cable sheaths, is the critical cable component in terms of fatigue. When no lead is used in the power cable, the conductors are the critical component. Furthermore, for mild loading scenarios, i.e. waves with significant wave heights $H_s \leq 1.5$ m, the model yields components infinite life for all cable components. For higher load cases, i.e. $H_s \geq 2.5$m, the model showed that fatigue mitigation measures are required to stay within the fatigue budget.

Several mitigation methods were implemented, from which it was found that increasing the layback length of the cable combined with adjusting the vessel heading to favourable conditions most effectively reduces fatigue damage as all load cases with $H_s = 2.5$ m resulted in maximum stand-by times of $t_{sb} \geq 125$ days. However, for higher loading senarios, i.e. $H_s = 4$ m, all researched mitigation measures were insufficient to stay within fatigue budget. For future work, it is therefore recommended to improve the mitigation measures such that severe load cases can be survived.\\\\

Lastly, the wave conditions in this study were simulated as JONSWAP waves. These simulations are time-consuming and therefore not many loading scenarios were modelled. It is recommended to research methods to approximate wave conditions with regular waves, as the duration of OrcaFlex simulations will decrease exponentially. An increase in number of load cases will result in more accurate limit states for the cable components.

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Prognosis and fault detection of drivetrains in medium-speed 10-MW Floating Wind Turbines

Premature failures in large offshore Wind Turbines are often attributed to bearing failure despite gearboxes being designed and developed using the best bearing design practices. Furthermore, as turbine size and rated power increase, bearings display an enhanced tendency to fail. Unscheduled bearing replacement at sea is a complex, costly, weather-dependent and time-consuming operation that results in high turbine downtimes. Market trends show an increase in turbine rated capacity and a noticeable shift towards deeper waters and far-off remote sites which further delays and complicates unscheduled maintenance activities and aggravates the cost penalties of idle turbines. Detecting an incipient bearing fault (diagnosis task) is therefore a major aspect to evaluate drivetrain and overall wind turbine reliability. Moreover, estimating the remaining useful life of bearings and predicting their operational state in the future (prognosis task) can achieve a breakthrough in optimising maintenance programs, improve wind farm operation and decrease wind turbine downtime which can bring about a significant cost reduction.

The purpose of this work is to investigate the health monitoring and prognostics possibilities of drivetrain bearings in a floating spar-buoy offshore wind turbine. The drivetrain concept considered in this work is based on DTU's 10-MW reference wind turbine. Specifically, this study targets the prognosis of four critical drivetrain bearings located in the main shaft and the high-speed shaft.

The absence of run-to-failure data of real wind farms, although inconvenient, is overcome by using model-generated degradation data. A high-fidelity numerical twin of a state-of-the-art drivetrain concept is used in this work and is established using a multi-body system (MBS) approach. The numerical twin models a medium-speed 10-MW gearbox that consists of 3 stages, 2 planetary stages and 1 parallel stage, supported in a 4-point configuration layout with two main bearings and two torque arms. The drivetrain concept studied in this work uses a novel selection of bearings which is currently gaining traction in large offshore wind turbines. The two main bearings that support the main shaft are tapered roller bearings (TRB) that carry both axial and radial loads as opposed to the main bearings used in traditional high-speed gearbox designs which typically use a cylindrical roller bearing to carry radial loads and a spherical roller bearing to carry axial loads.

Faults are applied on the main bearing and on the high-speed shaft bearings of the numerical model. The model-generated degradation data, namely forces and acceleration measurements at several shafts and bearings, is used as input data for two independent prognosis models: a physics-based prognosis model and a data-driven prognosis model. The physics-based approach will culminate in a prediction of the remaining useful life (RUL) of several bearings under a range of faults. The fault detection and fault prognosis capabilities of the proposed prognosis methods is evaluated and compared. This work will also assess the merits and limitations of using model-generated degradation data for the development of prognosis models. Lastly, based on this study, the requirements to enable bearing prognosis from a purely data-driven approach, as opposed to a physics-based approach, is put forth.

Keywords: wind turbines; offshore; floating; spar-buoy; gearbox; bearings; diagnosis; prognosis; vibrations; condition monitoring

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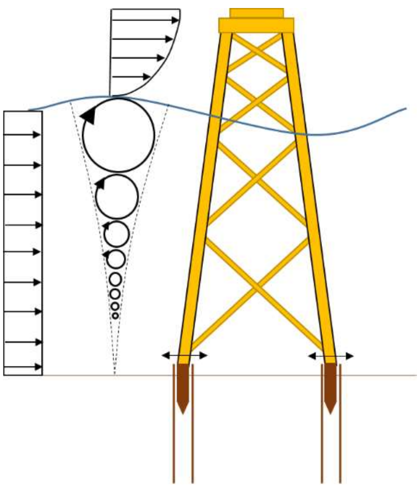
Early age cycling in the grout connection of an offshore wind jacket structure

The yearly installed percentage of offshore wind jacket substructures is rising. The default installation method for a jacket structure nowadays makes use of a pre-piling template in order to install all foundation piles within project tolerances. The jacket is then lowered to the sea bed until the legs are resting on the foundation piles through friction based stopper connections.

In order to rigidly fix the connection, grout is pumped into the annulus between the pile and leg. During the curing period of grout, generally taken as 24 hours, environmental loads cause the jacket to oscillate in various directions. As a result, the jacket leg will move relative to the foundation pile. This movement, which is called Early Age Cycling (EAC), can cause crack formation in the cured grout therefore decreasing the shear capacity of the connection. The DNVGL has restricted this relative movement to a conservative 1 mm within the first 24 hours due to limited knowledge on the subject. The strict regulation forces companies to use expensive EAC mitigation concepts of which the real effects are a debated issue.

This research investigates the behavior of EAC by simulating a number of pile-leg connections for a range of load cases in the Finite Element (FE) program Femap. A reference model is used to assess the actual magnitude of motions for an optimal friction connection. Based on these reference values, the behavior of modified stoppers will be investigated. These stopper comprise a variable number of brackets and a variable contact area in order to find an optimal configuration to minimize EAC. Furthermore, the effect of friction and wave directionality is examined.

Simulations showed that EAC and relative sliding of the jacket-pile interface are two different phenomena which need to be limited in order to meet the EAC design criterion. EAC tends to be most efficiently solved by increasing the number of brackets in order to evenly distribute the stress around the circumference of the pile while limiting moment induced rotations in line with the wave direction. The effect of moment induced rotations on the magnitude of EAC is significant and therefore needs to be limited by all means. Sliding can most efficiently be solved by increasing the friction coefficient. This is highly recommended since it greatly improves the performance of the stopper connection for larger waves.
This research could be further extended by performing a large sensitivity study to normalize the current results. This could result in an optimal stopper configuration dependent on specific key project parameters.



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Swaying piles during installation with seabed templates: modelling dynamic behavior and finding a solution

Pre-piling templates are often used in the offshore industry to ensure the vertical installation of foundation piles for jacket structures. Boskalis is preparing such project to be executed in the Taiwan Strait. This region has relatively soft soils and seismic activity. Consequently, the piles are very long in order to enable sufficient bearing capacity. In earlier work, an Orcaflex model was developed to predict the dynamic behavior of 90 m long piles stabbed in the template with 5 m penetration into the seabed. The model resembles the situation prior to pile driving. Results indicated excessive loads on the template due large swaying motions of the piles. This problem is caused by resonance: the natural swaying frequency of the long piles interferes with significant wave energy. In this thesis, this model is further developed. Three shortcomings of the model are identified and addressed.

First, the model does not account for wave diffraction effects at the piles. A simplified model is developed to study the impact of wave diffraction on the pile swaying amplitude in the frequency domain using a theory by MacCamy and Fuchs. Next, in the Orcaflex model, diffraction-corrected added mass coefficients were assigned to each pile node based on spectral density analyses of the acceleration of the waves relative to the pile, using the same theory. Second, in the adapted model, the effect of flow oscillation is not taken into account in the drag coefficient definition, which leads to inaccurate modelling of the drag loads. This is corrected by modelling the influence of the Keulegan-Carpenter number on the drag coefficient. To do so, the period parameter of the Keulegan-Carpenter number at each pile node is assumed based on spectral density analyses of the velocity of the waves relative to the pile.

Next, drag coefficients are calculated from the Keulegan-Carpenter numbers and related to Reynolds numbers. This relation is used in Orcaflex. Third, the modelling of the pile clamps is simplified in the adapted model. The working principle of the hydraulic pile clamps is studied, and a clamp design is assumed. The clamp is modelled accordingly. 3-hour time-domain simulations are performed and the maximum observed results in several parameters are obtained. These show a decrease in the loads on the template in short wave sea states when diffraction effects are taken into account. Further, while model results with the elaborated drag coefficient show an increase in pile swaying velocities, the observed loads on the template and pile inclination angles remain more or less unchanged. Yet, with the revised pile clamp, the model results are significantly worse. Overall, the results show a violation of the template design limits in several load cases. This implies the need for either redesigning the template, or finding a work method solution to mitigate the pile swaying. The latter goal is pursued by modelling vessel wave shielding.

By turning the vessel in a certain heading, one can shield incoming waves and reduce the loads on the piles. To model this, a hydrodynamic diffraction analysis is performed in Ansys Aqwa. Velocity potential data is obtained to describe the influence of the vessel on the waves near the piles. This influence is then implemented in the Orcaflex model. Now, the model results no longer exceed the design limits. This proves that shielding can be applied to ensure workability, provided that the vessel roll motion does not become excessive. Since roll can cause large crane tip motions that complicate the operation, it is recommended to further study the vessel motions during shielding.

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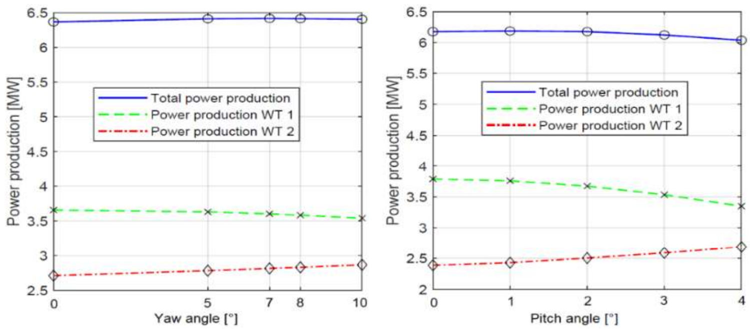
Effects of induction control and wake steering control on drivetrain fatigue and wind farm power production

Power optimization through wake steering and axial induction control is a well investigated topic in wind energy, which is generally proven to work. The influence of control manoeuvres on the fatigue of static components is generally discussed, but drivetrain fatigue due to wake steering and axial induction control is rarely discussed, while it is known that the drivetrain is a highly vulnerable part of the wind turbine and its downtime can result in a significant increase in cost.

Having a better understanding of turbine wake interaction and wind farm power optimization and its influence on drivetrain dynamic behaviour serves as a reference for future wind farm cost optimization and predictive maintenance. The main research question answered in the thesis is as follows:
To what extent does wind farm power optimization increase profit when wind farm power production and drivetrain bearing fatigue damage is considered?
With the following sub-questions being answered:
To what extent does power production change for different wind farm power optimization manoeuvres?
What is the influence of wind farm power optimization on local drivetrain damage of the considered wind turbines?

Multiple test cases for wake steering and axial induction control are considered, where different yaw angles, γ, and the blade pitch angles, β, are chosen for the upwind turbine. For each test case, power production and bearing damage is studied. A cost estimation is made and for a range of energy prices, the most profitable test case is found. For verification, a two and four wind turbine case in an uniform wind field is considered. Power production results for this low turbulent case are studied and compared to literature.

Turbulent wind field results show that both wake steering and induction control result in a limited power production increase of 0.78% for γ = 7° and 0.17% for β = 1°, shown in the Figure below. The power production increase for the two and four wind turbine case in the uniform wind field for wake steering and induction control are 4.78% for γ = 15°, 16.6% for γ = 20°, 0.19% for β = 1° and 5.04% for β = 3° respectively.
Overall absolute bearing damage of WT1 and WT2 increases with increased yaw angles for WT1 and the overall bearing damage of WT1 and WT2 decreases with increased blade pitch angles for WT1. INP-A and PLC-B bearing damage significantly increased for the downwind turbine.
In the high turbulent wind field (TI = 0.203), when considering two wind turbines, wake steering can result in an increase of profit ranging from -€3,70 to €4,-, while axial induction control can result in an increase in profit ranging from €3,- to €40,-. In the low turbulent wind field (TI = 0), when considering four wind turbines, the power production increase for wake steering can result in a profit increase ranging from €30,- to €130,-, while axial induction control can result in a profit increase ranging from €15,- to €60,-.
Both wake steering and induction control can result in increased profit. The desired control manoeuvre is highly dependent on the ambient wind, wake overlap of the downwind turbine and the wind farm arrangement.



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Validation of aero-servo-hydro-elastic load an motion simulations for the Hywind Scotland floating offshore wind farm

Climate change, as a result from global warming, requires an energy transition: the annihilation of greenhouse gas emissions from fossil fuels and a radical innovation of the global energy system to proceed apace. Offshore wind is an important source of clean, renewable energy, and it plays a key role in the transition. 80% of the worldwide offshore wind is to be produced on locations in deep waters; here floating foundations are required, that to date are far more expensive than their bottom-fixed counterparts. To reduce costs of floating wind energy, reliable, detailed predictions of the system's loads and motion response are crucial. Floating foundations are designed using 'aero-hydro-servo-elastic' software codes that simulate the dynamic response of a floating offshore wind turbine system to the offshore environment. Predictive accuracy can be improved by comparing simulation results from a model of a known system against measurements taken from the real-world system, a so-called model validation. One promising state-of-the-art aero-hydro-servo-elastic software code is BHawC/OrcaFlex, developed by Siemens Gamesa Renewable Energy (SGRE). Due to its novelty, however, validation of the code has only been carried out to a limited extend, giving rise to uncertainty about the interpretation of simulation results.
The purpose of this MSc. thesis project is to validate the performance of BHawC/OrcaFlex by comparing its simulated load and motion results to measurements on a real-world floating turbine from the Hywind Scotland floating offshore wind farm (Hywind). Measurement data and a description of the 'as-built' system were made available by the wind farm owner Equinor ASA. In order to establish an achievable level of modelling accuracy and predictive value of BHawC/OrcaFlex, the code was verified against another aero-hydro-servo-elatic software code: OrcaFlex, by setting up a similar model of the Hywind system in both codes. Both models were then subjected to multiple load cases that step-by-step increased in complexity, to further isolate causes of discrepancies between the models. Simulation results from running both models appeared to be nearly identical, though some errors in both model set-ups made it difficult to draw a pure comparison. Discrepancies identified proved to originate mainly from avoidable errors in the model set-up in both models. Limited information is available on the performance of OrcaFlex in floating wind load and motion predictions. Therefore, it was in turn verified against a wide range of industry-standard aero-servo-hydro-elastic software codes, using a modeled system that closely resembled the Hywind turbine and load cases of increasing complexity. OrcaFlex predictions matched well across all load cases. The main differences were attributed to too low modeled additional linear hydrodynamic damping. The final validation of BHawC/OrcaFlex to full-scale Hywind measurements is performed at below-rated, rated and above cut-out wind speeds with a wind-wave and swell components and currents each with different directions. In general, BHawC/OrcaFlex motion predictions appeared to correspond well to the actual Hywind measurements. Most phenomena in the low-frequency, wave-frequency and high-frequency region were captured by the simulations. Discrepancies were found originating from errors in the model set-up, e.g. lack of hydrodynamic damping, structural tower damping or simplifications in the wave model. In the predictions of mooring line tensions, most phenomena in frequency-domain analysis were captured well by the model, but mean tensions and their variations were off. Tuning of the mooring system showed improvement of the results, but further improvements could be made. Several sensitivity studies were added on parameters, such as hydrodynamic drag, tower damping and mooring drag. The main recommendations for further research are to further remove errors identified in the model set-up. In addition, some yet unexplained phenomena that are not captured by BHawC/OrcaFlex in the current model, are to be addressed. Finally, a the development of a standardized approach to relate model validation studies in the field of floating wind to cost improvements could further quantify the value of future comparison studies.

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Ice Loads: The effect of climate change on Arctic offshore structure design

For the development of Arctic offshore structures, design ice loads are required. These design loads represent the ice loads a structure may be exposed to for specified requirements. The design ice loads depend on magnitude of the ice loads and on the probability of exposure to the ice loads. Both are impacted by local sea ice conditions.

Climate change affects the sea ice conditions causing change in the ice loads Arctic offshore structures are expected to experience. To obtain accurate design loads, the effect of climate change should be considered in defining those.

Conventional methods to determine design ice loads are based on historical data and assume this data can be used to represent the loads during the lifetime of the structure. However, historical data cannot represent future ice conditions if climate change is considered as sea ice conditions will change. This means that the effect of climate change is not incorporated in the design ice loads when these are based on conventional methods. To include the effect of climate change a new method needs to be developed. In this thesis, such a new method is proposed that enables to include the effect of climate change into the design ice loads. Instead of historical data, the new method considers the future ice conditions. The method allows to base the design ice loads on sea ice conditions that change over time.
To determine design ice loads, extremal distributions are used. Extremal distributions describe the probability of seasonal maximum ice loads. Commonly, the extremal distribution is based on data covering multiple seasons and cannot properly include inter-seasonal change in sea ice conditions. The new method allows to determine the design ice loads based upon changing extremal distributions. The extremal distributions are determined for seasons separately based on sea ice conditions of one season only.

For the proposed method, a concept referred to as an 'ice state' is introduced. Ice states describe a period of time in which the sea ice conditions are assumed to be constant. When sea ice conditions are constant, the corresponding short-term ice load distributions and the ice load frequency can be determined. Both are required to be able to determine the extremal distribution for one season. According to the new method, the increase of drift speeds causes increase of design ice loads whereas the decrease of ice concentration, thickness and compressive strength causes decrease of the design ice loads. Based upon expected future climate change scenarios, the new method indicates that design ice loads are lower when compared to the design ice loads according to the conventional method.

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Dynamic response of a deep-water SRI concept based on experimental data

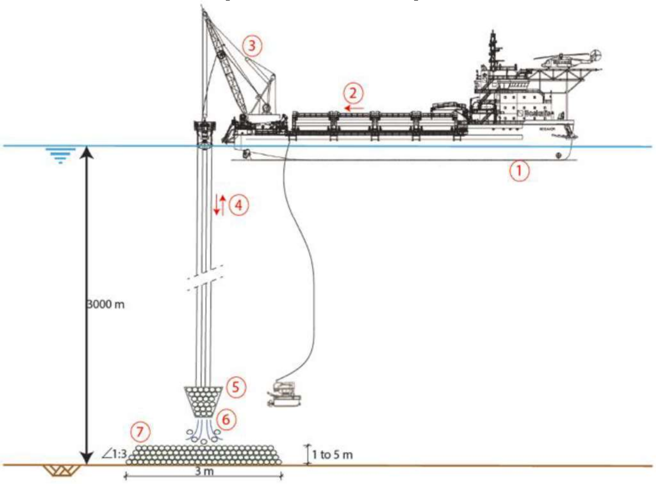
As the exploration for oil and gas is shifting towards greater water depths, there is a market for subsea rock installation (SRI) at these large water depths as well. Boskalis is a key player in the rock installation market and installing rock material at water depths of approximately 3000 meters is still far from routine work. Therefore, Boskalis is researching accurate and cost-efficient systems for installing rocks in these ultra-deep waters.

Boskalis has the envisaged deep-water SRI concept to lower a basket filled with rock material using a winch and carefully install the material at the desired location on the seabed (+/- 3000 meters). After releasing the rocks, the basket will return to the surface. If needed, it will be refilled and the process described above will be repeated till the desired amount of rock material is installed.

Since this is a concept with operations that are not applied before by Boskalis, there are no structural test data available that could be used for research purposes. Therefore, it is decided to perform scaled model tests to obtain reliable production rates of the rock installation process. The basket and its corresponding release mechanisms is built on scale and forces are measured during the release process for different configurations. The production rates that followed from these force measurements are used as input parameter in the model that simulates the dynamic response of the envisaged concept.

In order to better understand the force and motion behaviour of this envisaged concept, a simplified one-dimensional cable model has been constructed in Matlab to simulate the dynamic response of the lifting wire and basket, and the force distribution in the lifting wire.

Based on the limitations of the model experiments and dynamic model, further research is recommended on obtaining scaled production rates in dynamic conditions. Also, it is recommended to further research the horizontal contributions in this concept design due to horizontal forces that occur at specific release mechanisms and hydrostatic and dynamic horizontal forces.



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Fault Detection of Drive Trains in 10 MW Offshore Wind Turbines using Non-Traditional Methods

One of the world's biggest concerns is global warming, a solution to this can be wind energy. Offshore wind energy has advantages over onshore wind energy, however, the levelized cost of energy is higher. The maintenance costs are a major cost contributor. To lower these costs, research is performed on faults and its detection. Currently, little is known about fault detectability and vibration propagation in a drive train of an offshore wind turbine. Fault detection and vibration propagation in a drive train of a 10 MW floating offshore wind turbine is therefore investigated to get an insight about the effect of faults on the vibration monitoring data of a drive train. Three different faults with five different degradation levels are applied one by one on the bearings of a 10 MW drive train model. These faults are radial and axial damage in the main shaft front bearing and radial damage in the high speed shaft rear bearing. One traditional, two non-traditional and two novel fault detection methods are used to detect faults and their vibration propagation.

One common and one novel fault detection method are deployed in the time domain: the Velocity Root-Mean-Square (RMS) Threshold Method and the Peeters' Anomaly Detection Method. The Velocity RMS Threshold Method compares the RMS of the vibration velocity of non-rotating parts with a threshold proposed by ISO 10816-21. The latter method makes use of statistical indicators and is tailored for this study. Although changes after fault introduction were observable, the methods can not be used and need to be altered for usage in the wind industry.

The non-traditional Angular Velocity Error Energy Method is deployed in the frequency domain. It makes use of the angular velocity measurements from the drive train's shafts and compares the normalized energy of its spectra with a threshold. This method inspired the development of novel fault detection methods introduced in this study, being the Bearing Velocity Energy Method (making use of bearing velocity measurements and also based on the Velocity Root-Mean-Square Threshold Method) and the Shaft Vibration Energy Method (making use of the velocity and acceleration of shafts). Both methods compare the normalized energy of the spectra with a threshold. Radial damage in the main shaft front bearing could be detected using the Angular Velocity Error Energy Method, the Bearing Velocity Energy Method and the Shaft Vibration Energy Method. Damage was detectable from 15% degradation onwards. Next to a change in vibration in the main shaft and its bearings, a different vibration behaviour was observed at the planet carrier front and rear bearing, intermediate speed shaft front bearing and on the low speed shaft. Axial damage in the main shaft front bearing could only be detected using the Shaft Vibration Energy Method. It was shown that this kind of damage was detectable by monitoring the main shaft's vibration from 50% degradation and higher. Radial damage in the high speed shaft rear bearing could be detected using the Bearing Velocity Error Method and the Shaft Vibration Energy Method. Damage could only be detected for degradation higher than 70%, by monitoring the high speed shaft and its bearings. Next to the typical measurement locations, it is recommended to place extra sensors measuring velocity on the first stage planet carrier front and rear bearing housings, intermediate speed shaft front bearing housings and on the low speed shaft.

The outcome of this study contributes to the understanding of vibration propagation and fault detection in a drive train. The fault detection methods can be implemented in maintenance and monitoring methods for offshore wind turbines. Maintenance engineers can use the detected vibration propagation to check the affected gearbox components and replace them before they fail.

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Assessment on the potential use of vessel motion limit criteria for subsea cable installation

Van Oord is active in the subsea cable installation industry and executes most of their cable lay projects with their cable laying vessel: The Nexus. In this thesis the focus is on the normal lay phase of the cable installation, which comprises the phase when the vessel is pulling out cable and putting it down on the seabed following the desired cable routing. In order to ensure cable integrity during cable installation, a normal cable lay analysis is executed in the dynamic analysis software Orcaflex. The aim of the cable installation analysis is to ensure cable integrity during the installation process, by defining the installation limits in terms of the sea state. However, the vessel motions of the Nexus can be measured instantaneously and accurately on board of the vessel. Therefore, an assessment into the use of vessel motions for expression of the handling limits during cable installation is performed. The assessment is executed for a normal lay configuration with an export cable and a 50 meter water depth. The static configuration of the model in Orcaflex is depicted in Figure 1.
The focus is on the maximum curvature and maximum tension response of the cable.

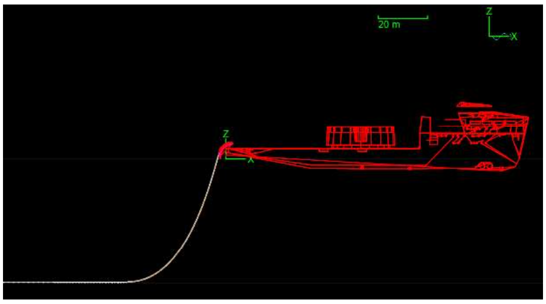

Figure 1: Static configuration of the base case model in Orcaflex.

The cable dynamics result from both the vessel motions and the direct cable loads. First, the effect of these phenomena independently is assessed with the use of Orcaflex simulations. The influence of the vessel motions on the cable dynamics is found to be low for small wave periods, as the vessel hardly reacts to this kind of waves. As a result, vessel motion limit criteria are less suitable for expressing cable installation limits at less severe sea conditions. Next, the most suitable vessel motion for application of vessel motion limit criteria is determined based on the time lagged cross correlations between the cable response and the vessel motions. By using this method, the vessel motion which is most linearly related to the cable response is selected. Finally, the performance of the selected vessel motion as limit parameter is compared to the use of the wave elevation, equivalent to sea state limit criteria. The performance of both is assessed by linear regression analysis of the peaks in the limit parameter time history and the associated peaks in the cable response. This analysis led to the conclusion that higher certainty can be given to vessel motion limit criteria compared to sea state limit criteria, which eventually can lead to an increase of the workability.

Furthermore, a sensitivity analysis is performed to identify if the selected vessel motion for the application of vessel motion limit criteria is sensitive to changes in the normal lay configuration. The selected vessel motion and accompanied magnitude of the correlation was prone to changes in the normal lay configuration. Therefore, the applicability of vessel motion limit criteria for the base case in this thesis cannot straightforward be generalised for other normal lay configurations.

Due to the nonlinear nature of the cable lay system all analysis are executed using time domain simulations in Orcaflex, which are associated with large computational time. In light of reducing the computational time for normal lay analysis, the potential use of a transfer function for estimation of the maximum cable response is evaluated. The transfer function is set up based on the first order frequency response of the cable system to regular waves. Before application of the transfer function approach, the nonlinear behaviour of the system is studied on the basis of the spectral response of the cable towards regular wave simulations in Orcaflex. Especially the contribution of the higher order frequency components and the effect of the nonlinear drag term in the Morison equation are addressed.

The maximum cable response estimation of the transfer function for a three hour time duration is compared to the statistical three hour maximum resulting from nonlinear Orcaflex simulations. The transfer function is found to underestimate both the curvature and tension response of the cable, leading to the conclusion that this transfer function approach is not suitable for the prediction of the maximum cable response. The underprediction is caused by the high dynamic complexity of the normal lay system.

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Offshore & Dredging Engineering

Upscaling the TetraSpar – design methodologie and modelling of large scale floating wind turbines

During the past decade, the offshore wind energy industry evolved to bigger turbines, going into deeper waters and farther offshore. As bottom-fixed wind turbines are limited to shallow water depths, floating wind structures are the next frontier to unlock the vast potential of wind energy. Despite many techno-economic challenges, several full-scale floating wind structures have been successfully deployed and have shown the potential for floating offshore wind.

One project near completion is the 3.6 MW TetraSpar demonstrator developed by Shell. With its tetrahedral shaped base and suspended counterweight keel, developed with the focus on ease of fabrication and installation, this spar concept is expected to offer a competitive package for floating wind using future, larger (10 MW+) wind turbines. The goal of this research is to investigate the capability of the TetraSpar platform to accommodate significantly larger wind turbines and to identify challenges in an early stage of development. Since technology upscaling of floating wind substructures has not been done before, this thesis first develops a novel design methodology for upscaling and then is applies it to the TetraSpar as case study.
This work builds on academic efforts thus far but focusses on the key design drivers in for upscaling of floating wind, namely the fundamental equilibria in vertical and rotational direction: the structure's weight is equal to its buoyancy, and the restoring moment equals the maximum overturning moment by wind. Specific emphasis is put on correctly capturing these equilibria, as they generally apply for floating wind substructure technologies, including the TetraSpar.

First a design basis is created with functional requirements and design criteria for floating wind structures in general, and specifics to the TetraSpar. Also, key specifications of future 10 MW, 15 MW and 20 MW wind turbine types are explored. Secondly, a model is developed for upscaling based on physical modelling of hydrodynamic stability (water and waves) and aerodynamic thrust (wind). Based on these inputs, the substructure is upscaled using the future turbine type wind thrusts.

The model employs an algorithm to find a new equilibrium design point and computes key properties for upscaled substructures. The resulting design concepts are then evaluated for first order wave-structure interactions using a diffraction/radiation solver (WAMIT). Key evaluation aspects are free-floating hydrodynamics, including hydrodynamic coefficients, wave forces and response amplitude operators. Fourth, selected structural elements of the upscaled design concepts are evaluated for structural strength. The fifth and final step assesses the extent to which the now evaluated upscaled design concepts still meet on the functional requirements and design criteria.

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Concept design of a foldable Cold Water Pipe for a 10 MW OTEC installation

Ocean Thermal Energy Conversion (OTEC) has been heavily researched and developed over the last decade. However, no commercial scale for OTEC has been reached yet. OTEC is a clean and renewable source of energy which utilizes the seawater temperature difference between the upper and deep ocean layers to generate electricity. The heat exchangers and the cold water pipe design are considered to be the most challenging part. The cold water pipe is often stated to be the largest risk. The installation of the cold water pipe, the high investment costs of the cold water pipe and the large forces acting upon the cold water pipe are crucial factors for the future success of OTEC. In this thesis, a new kind of cold water pipe concept is introduced.

The FLEX-hose concept consists of a thin sheet of nylon, supported by concrete rings and polyester cables. The total length of the foldable concept design is 1000 m. The nylon sheet is attached to the concrete rings and the cables are attached to the concrete rings. The cables run through the concrete rings and can be used during installation to lower the pipe. Deployment of the foldable pipe is expected to be relatively easy thereby lowering the installation costs. The Multi Criteria Analysis performed in this thesis show the FLEX-hose foldable concept to be attractive compared to a foldable spiral concept, a flexible composite concept, a rigid composite pipe and a HDPE pipe. However, the inclination angle occurring while pumping may not become significant, meaning above 7.5 degrees, since this will lead to lower energy efficiency. In addition, no current design is available on the market, meaning heavy research and development is needed for the foldable concept to succeed.

Possible challenges for the FLEX-hose concept that have been established through this research include instability occurring due to buckling and a pressure drop becoming larger than 0.6 bar, thereby significantly reducing the net power of the OTEC plant. The maximum allowed angle of inclination of the sheet to stay below 0.6 bar is calculated to be 7.5 degrees at a flow speed of 2 m/s. During pumping a discharge of 20.000 kg/s is pumped through a thin walled pipe with a diameter of 3.5 m, which leads to a radial displacement of the nylon sheet. Collapse and too significant deformations of the thin walled sheet are prevented by applying 10 MN of pre-tension in the thin walled sheet. However, in order for the nylon sheet to stay in the linear elastic regime, the calculated wall thickness is 0.04 m, thereby making foldability questionable. A total of 200 concrete rings is present in the design, one every 5 m over the total length of 1000 m of the pipe.
In addition, a large clump weight of 12 MN is needed at the bottom of the pipe. The total system weight of the foldable pipe with concrete rings is calculated to be 1840 mT, which could be installed by an offshore installation vessel. Finally, creep has also been established to be a challenge due to the life-time of 30 years for the cold water pipe. A synthetic plastic material such as nylon experiences relaxation of the material when stressed for a longer period of time, leading to large deformations.

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European Wind Energy Master
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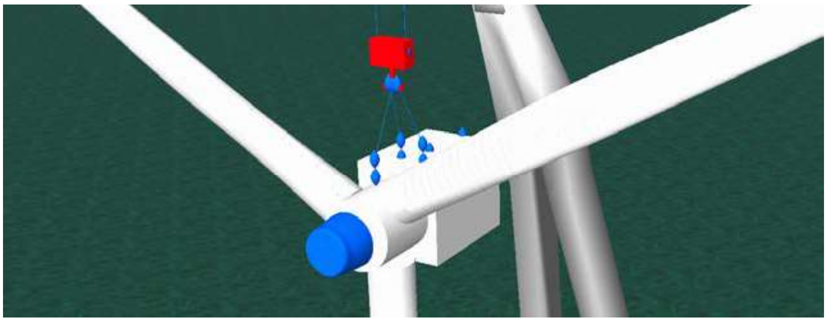
Modelling the dynamic behaviour of a rotor nacelle assembly during installation using a floating vessel

The offshore wind energy industry has been developing rapidly due to the ever increasing demand for renewable energy. As a result, offshore wind turbines are increasing in mass and height and are installed at larger water depths, further away from shore. Jack-up vessels can lift themselves above the water, eliminating the influence of the waves on the vessel motions, but are limited by water depth, soil conditions and crane capacity. A floating vessel on the other hand, is not limited by this, but is sensitive to wave-induced motions. Heerema Marine Contractors (HMC) developed a new installation method using a floating vessel, where the rotor nacelle assembly (RNA) of a wind turbine is assembled on a dummy tower on deck and is installed in one lift on top of the tower. In this way the number of critical lifts is changed to one lift, being it a challenging one. The research objective is to gain a better understanding of the dynamic behaviour of a rotor nacelle assembly, particularly due to the wind, focusing on the horizontal motions of the RNA, when it is hanging in the crane above the tower. To examine the dynamic behaviour of the RNA, separate models are made to assess the effect of the wind and waves individually. This is done to identify which motions are due to the wind, and which motions are due to the waves. Finally, the wind and waves are coupled and the insight gained in these models is used to improve the workability of the installation. In the final model, a case study is performed to prove its applicability for assessing the workability of the installation using tugger lines. *Model 1 – Wind only* is performed in OrcaFlex using time domain simulations, in which the effect of wind turbine blade pitch angle, length of the hoist wires and wind speed and wind direction on the RNA response is examined. It is concluded that a 0 deg blade pitch and a short as possible pendulum, result in the smallest motions. The main responses are a pendulum motion in the direction of the wind and a slow yaw motion, due to the wind that is dominant in the low frequency region. Moreover, the RNA response heavily depends on wind direction and wind speed. For some wind directions, the responses are above limiting criteria, proving the importance of including wind in the model. In *Model 2 – Waves only*, frequency domain analyses are performed in Liftdyn to observe the influence of wave conditions and crane configuration on the RNA response. It is shown that head sea and crane pointing to port side yield the smallest motions, while the optimal crane tip height depends on the wave peak period. The main response of the RNA due to waves is a sideward pendulum (in the direction of the waves) coupled with vessel pitch motion. The magnitude of the pendulum increases with wave peak period and is significantly larger than wind. In *Model 3 – Wind & Waves* the wind and waves are coupled, performed in OrcaFlex using time domain simulations. It is concluded that wave-induced motions are governing and that the wind has negligible effect on the sideward pendulum. Depending on the wave conditions, the RNA responses are beyond the limits and thus it is required to reduce the motions to safely install the RNA. In the case study, constraints that represent tugger lines, are implemented to examine the effect on the RNA motions and to assess if the model can be used for developing concepts to reduce the motions. It is shown that providing stiffness in the horizontal plane helps to reduce the sideward pendulum. However, a roll motion of the RNA is still excited. Hence, roll stiffness is added. For higher peak periods, the RNA response is too large, because the vessel pitch motion is excited. Therefore, more research is required to develop a concept that can keep the RNA within limits, focusing on reducing the RNA sideward pendulum and roll response that is coupled with vessel pitch motion.



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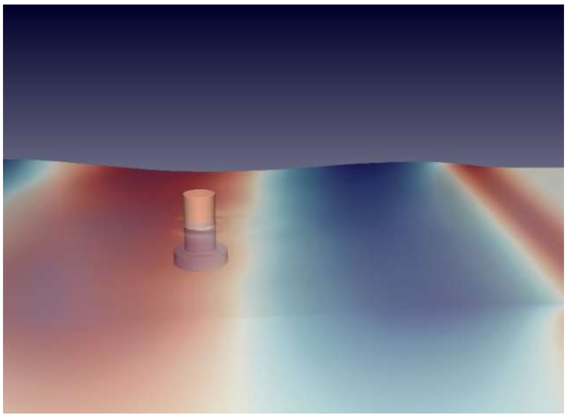
Comparison of potential flow and CFD for a column with heave plate

Floating offshore wind turbines can only withstand a limited amount of (heave) motions before the equipment fails. In order to reduce the heave motion, the DeepCwind floater for offshore floating wind turbines makes use of heave plates. This semi-submersible floater consists of three cylindrical columns with a heave plate attached to the bottom of each column. Often potential flow models are used in order to assess the response. However, potential flow theory does not take into account the viscosity and the vorticity of the fluid. Therefore, this thesis examines the effect of a heave plate on a cylindrical column moving in heave direction and subjected to wave loads with both a potential flow model and a fully nonlinear numerical wave tank (CFD). Specifically, the difference between a potential flow model and a fully nonlinear numerical wave tank (CFD) is examined.

The CFD simulations with the fully nonlinear numerical wave tank have been carried out using the opensource software package OpenFOAM (version 1606+). An unresolved DNS approach is used throughout this work. Best practices for the dimensions of the wave tank, the mesh and settings of the solver where obtained from Bruinsma (2016) and Rivera-Arreba (2017). The OpenFOAM waves2Foam toolbox (developed by Jacobsen et al. (2012)) has been used to generate waves in the wave tank. The two phase solver interDyMFoam for moving bodies was coupled to the waveFoam solver from the waves2Foam toolbox in order to simulate a moving body under wave loads. The simulations in OpenFoam where carried out on a 1:50 scale. The potential flow model WAMIT has been used in order to obtain the RAO, added mass, damping and wave excitation forces from potential flow theory.

A single cylindrical column has been tested in the numerical wave tank both with and without heave plate. Firstly, a heave decay test has been carried out. Thus, the linear damping ratio and the linear and quadratic damping coefficients have been determined. Secondly, the structure was exposed to incoming waves. The response of the structure has been assessed under three different wave periods, which were selected in order to align with Rivera-Arebba (2017). The response of the structure was measured, filtered on the frequency of the incoming wave and compared with the RAO from the potential flow model. Also, the wave excitation forces of the potential flow model have been compared with wave loads from the numerical wave tank, based on simulations where heave motion of the structure was constrained.
It was found that both the wave excitation forces and the RAO of the potential flow model are in agreement with the CFD model results. The viscous effects included in the CFD model affect the response of the structure only very lightly. The largest differences between the potential flow and CFD model were found around the heave cancellation wave frequency. At the heave natural period of the structure, the heave plate increases the linear damping coefficient with ca. 50%. The damping at this period was dominated by viscous effects. In general, the potential flow model produces an accurate RAO, due to the fact that the system is lightly damped and the damping therefore plays a minor role in the structure's response.



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Offshore & Dredging Engineering

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Ice wear and abrasion of marine concrete

Since the construction of offshore platforms, bridges and other structures in cold regions, abrasion of concrete due to ice has been experienced. However, the characterisation of this process and the correct estimation of the abrasion rate has proved to be a complex challenge. Ice abrasion is the process of wearing down or rubbing away due to friction at a surface over time. This study is a part of the ICEWEAR program of the University of Newfoundland to determine the effects of ice- concrete bonding on concrete abrasion due to ice. This thesis aimed to evaluate existing methods to determine long term abrasion resistance on concrete by ice and on gathering more experimental data using relatively easy methods of concrete structures exposed to ice abrasion. These new methods need to be less complicated, but still qualitatively proper enough to represent other actual experiments.

Three designs were made to improve existing experimental methods with two different approaches to determine the abrasion resistance on concrete. The first approach is "absolute wear" as a function of various experimental and material parameters. This second approach is "relative wear" an empirical method of determining the performance of mix design to known benchmarks or simply comparing two alternative designs. Three experiments have been successfully designed to simulate real concrete structures exposed to ice abrasion in the field. Only two experiments have been executed due to the closing of the University because of the COVID-19 Virus. However, the unfinished experiment has already shown that it is not complicated to replicate the experiment and has the possibility to be valuable to be a new test module for ice wear projects in the future.

The results of the other two experiments showed significant signs of abrasion wear and were able to be analysed and discussed. It can be concluded that all three experiments have the potential to be a new method to determine the long-term effects of wear in the concrete-ice abrasion process. All experiments simulate simplified concrete structures interaction with ice-abrasion. The three experiments resulted in the ability to perform multiple test sequences in order to explore the long-term effects of concrete-ice abrasion. After evaluating the three experiments, each experiment has its own benefits and can be used in future research.

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Two-dimensional ice-structure interactions for offshore wind turbines

With the Paris climate accords signed in 2016, most countries have committed themselves to ambitious climate targets during the next decades. One of these targets is a dramatic increase in the overall energy portfolio's market share of renewable energies. This increase in renewable market share will, for a large part, consist of newly built offshore wind farms. In turn, this rise in offshore wind energy projects is expected to be especially dramatic in northern regions, where high and constant wind speeds prevail. However, as offshore wind farm projects move further north, additional challenges need to be faced. One of these is the technical challenge to design offshore wind farms for possible encounters with drifting sea ice. To tackle this challenge, a proper understanding of the mechanics associated with encounters of drifting sea ice with offshore wind turbines is essential.

Such encounters are currently primarily understood phenomenologically, and the associated models simulating these encounters – or ice-structure interactions – therefore are phenomenological as well. Moreover, most ice-structure interaction models are fundamentally one-dimensional, whereas ice-structure interactions are generally not one-dimensional. This mismatch holds especially for ice-structure interactions with offshore wind turbines, where wind loads are generally misaligned with ice loads causing highly two-dimensional ice-structure interaction problems.

Therefore, the first half of this work sets out to extend one of the industry-leading phenomenological one-dimensional models – the Hendrikse (2017) model – to a two-dimensional environment. The ultimately developed Zero-friction contact Area variation Model By Omnidirectional Numerical Ice (ZAMBONI) attempts to do so by introducing practical extensions rather than introducing new assumptions. Nevertheless, one extension does entail a shift from current one-dimensional ice-structure interaction models. Namely, the assumption that ice experiences neither friction at the ice-structure interface nor internal shear forces. Consequently, much of the correctness of this model hinges on this extension. To assert the correctness of ZAMBONI. A comprehensive verification campaign is performed as well as a simple order-of-magnitude validation campaign. Although both confirm the extensions' correctness, further validation is required, especially concerning the zero-friction principle.

Upon developing and discussing this two-dimensional ice-structure interaction model, the second half of this work couples ZAMBONI to an offshore wind turbine model to gain further insight into ice-structure interactions. These dynamically coupled two-dimensional simulations serve two purposes. Firstly, to compare one- and two-dimensionally simulated load cases of aligned ice and wind. Secondly, to perform newly simulable load cases of misaligned ice and wind. Four primary findings are discussed. Firstly, as hypothesized, introducing a disturbing wind load lowers the ice-structure contact area, causing smaller loads and displacements due to ice loads. This effect is especially well observable for misaligned wind loads and low far-field ice velocities. Secondly, a new ice-structure interaction regime is observed where ice and structure synchronize in the structure's first bending mode. This synchronization occurs most dominantly for two-dimensional ice. Thirdly, frequency lock-in occurs solely in the second bending mode and is terminated at lower ice indentation speeds for two-dimensional than for one-dimensional ice. Finally, small ice-wind misalignments, which are most common, appear highly similar to load cases of fully aligned ice and wind.

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Offshore & Dredging Engineering

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Improving seismic foundation models of jack-ups

Jack-up designers, owners and operators are expanding their activities into seismically active areas such as Japan and Taiwan. Further development of expertise in seismic analysis of jack-ups is required to improve safety and reduce costs. At present, a linear elastic foundation model is used in seismic assessments. Improved understanding of foundation behaviour can lead to a significant reduction in conservatism. In this thesis a brief comparison of available foundation models is made. The radiation damping model has been improved, which is found to have minor effect on jack-up response. To capture non-linear foundation behaviour, a hypoplastic macro-element has been implemented in seismic simulation software OpenSees. This results in reduced non-linear resonance and an amplitude-dependent resonance-shift. The modelled loads at critical locations in the structure consistently decrease more than 25% as a result. Plastic displacements and hardening are found to be significant for highly non-linear soils and severe earthquakes. This thesis demonstrates significant conservatism in the linear foundation model. Implementation of the proposed hypoplastic macro-element can thus reduce costs and increase demonstrated capabilities of jack-ups significantly.

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Offshore & Dredging Engineering

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Workability Analysis of a Floating XL-Monopile Installation – A vessel motion study

In order to meet the climate goals to minimize the global temperature rise, an accelerated growth of renewable energy sources is necessary. Within the renewables market, the offshore wind sector takes a big part and has experienced a rapid growth over the past years. Around 80% of offshore wind turbines have a monopile foundation, (a large diameter tubular support structure). In present time, monopiles are installed by using either a jack-up or a floating vessel. Due to the trend in the offshore industry that wind turbines increase in size and that wind locations move to deeper waters, an installation with floating vessels may become the most cost-effective option.
Jumbo Maritime has designed a new vessel to expand its offshore fleet: HLCV Stella Synergy. This heavy lift crane vessel will be used to install monopiles. Multiple installation methods are under consideration and this thesis focuses on the method with mooring lines to provide station-keeping during the installation. Due to the footprint of the vessel relative to an earth-fixed position, a motion compensated pile gripper is used to maintain upright position of the monopile.
During the early driving phase (see Figure 1.1) of the installation, the monopile has limited interaction with the soil and acts as an unstable inverted pendulum. The upright position of the monopile is maintained by the gripper frame. The forces applied by the gripper frame on the monopile are reaction forces on the vessel. These reaction forces on the vessel can cause an increased vessel footprint. A workability assessment is performed for a moored floating monopile installation, and the influence of the gripper frame reaction forces on this workability is analyzed.
During the early driving phase (see Figure 1.1) of the installation, the monopile has limited interaction with the soil and acts as an unstable inverted pendulum. The upright position of the monopile is maintained by the gripper frame. The forces applied by the gripper frame on the monopile are reaction forces on the vessel. These reaction forces on the vessel can cause an increased vessel footprint. A workability assessment is performed for a moored floating monopile installation, and the influence of the gripper frame reaction forces on this workability is analyzed.

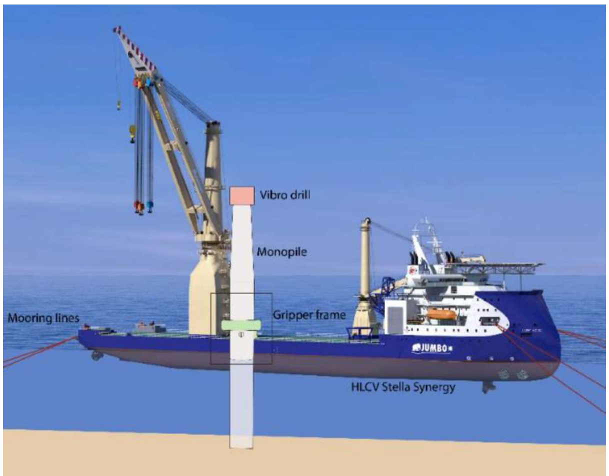

Figure 1.1 - Early Driving phase of a monopile installation

Considering nonlinear phenomena in the installation system, such as a gripper frame control system and viscous drag forces, a time-domain simulation model is made in AnySim XMF for which a hydrodynamic database is used as input. The provided hydrodynamic database is based on the results of a scale model test in a water basin, for one specific loading condition. The provided hydrodynamic database is also compared with an AQWA calculation. The reaction forces from the gripper frame are determined with a MATLAB/Simulink model which generates a gripper force time series based on the behavior of the monopile and the gripper frame due to environmental loading. This gripper force time series is applied to the vessel as an external force during the time-domain simulations. During these 3 hour simulations, the vessel is subjected to co-linear environmental conditions from two different incoming directions, while the vessel is moored to the seabed. The workability is calculated for sea conditions in the North Sea. In a second simulation model, the same simulations are performed but without the gripper frame force time series applied to the vessel to determine its influence on the total workability of the installation.
The gripper frame forces have no significant influence on the workability of a monopile installation. In beam waves, the workability is limited by excessive roll motions for longer waves and by insufficient station-keeping from the mooring lines for higher waves. The loading condition addressed in this research proves unfavorable due to its low roll natural frequency. Investigation is needed whether this loading condition is representative of a loading condition which is likely to occur during a monopile installation. In head waves, the system performs satisfactory and is mildly limited by excessive roll and pitch motions.

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European Wind Energy Master
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Monopile Installation Using a Motion-Compensated Gripper Frame on a DP Vessel

Offshore wind energy is one of the solutions to meet the growing demand for renewable energy. The offshore wind turbines producing this energy keep increasing in size and, as a result, the monopile foundations are becoming larger and heavier. The traditional jack-up installation vessels have limited crane capacity and many of these vessels are unable to install the XXL monopiles. Therefore, the offshore industry is currently investigating a new installation method using a motion-compensated gripper frame on floating vessel with a dynamic positioning system. The gripper frame is attached to the vessel and encloses the monopile with a ring to keep it vertical during the installation. In addition, the gripper frame compensates for the vessel motions such that the vessel motions do not influence the monopile motions.

The purpose of this thesis is to investigate the feasibility of such a motion-compensated gripper frame and to determine what control settings minimise the monopile inclination and the force exerted on the monopile. The system is composed of three main bodies: the vessel, the gripper frame and the monopile. The monopile and PID controller, which controls the amount of force exerted on the monopile to keep it vertical, have been modelled in the frequency domain to gain insight in the effect of changing the control parameters. To model the dynamics of the coupled system an OrcaFlex model has been set-up. The system has been tested for various values of proportional and derivative gain, k_P and k_D respectively, in various wave conditions. First the perfect control system is tested, where the force to keep the monopile vertical is applied instantly and the vessel motions are fully compensated. However, as the real world is never perfect, the system tested for sensor lag and imperfect motion compensation as well. The results are judged based on three criteria regarding the maximum monopile inclination, actuator force and actuator stroke.

Resonance is observed in case a value of k_P is selected such that the natural frequency of the monopile and controller matches the wave forcing frequency. Adding derivative gain k_D limits the monopile motions and force exerted in this case. To limit the monopile motion the proportional gain should be selected such that resonance is avoided. Two different control settings are investigated and it has been found that a relatively high value of k_P of 10,000 kN/m in combination with a k_D of 11,000 kNs/m is a suitable setting based on the three criteria. Furthermore, bow quartering waves is the favourable wave direction compared to head waves for the system considered in this thesis, as the force on the monopile is more evenly distributed over the actuator in x- and y-direction. Introducing a sensor lag into the system results in higher monopile motions and forces on the monopile. If the sensor lag exceeds 0.3 s it leads to instability of the monopile for both settings. The effect of not fully compensating the vessel motions is found to be limited due to the fact that these motions are slowly varying.

The results of this work contribute to a better understanding of the dynamics of the system in various wave conditions. Furthermore, it provides insight in the effect of sensor lag and imperfect motions compensation, contributing to the design of a motion-compensated gripper frame for the installation of XXL monopiles.

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Offshore & Dredging Engineering

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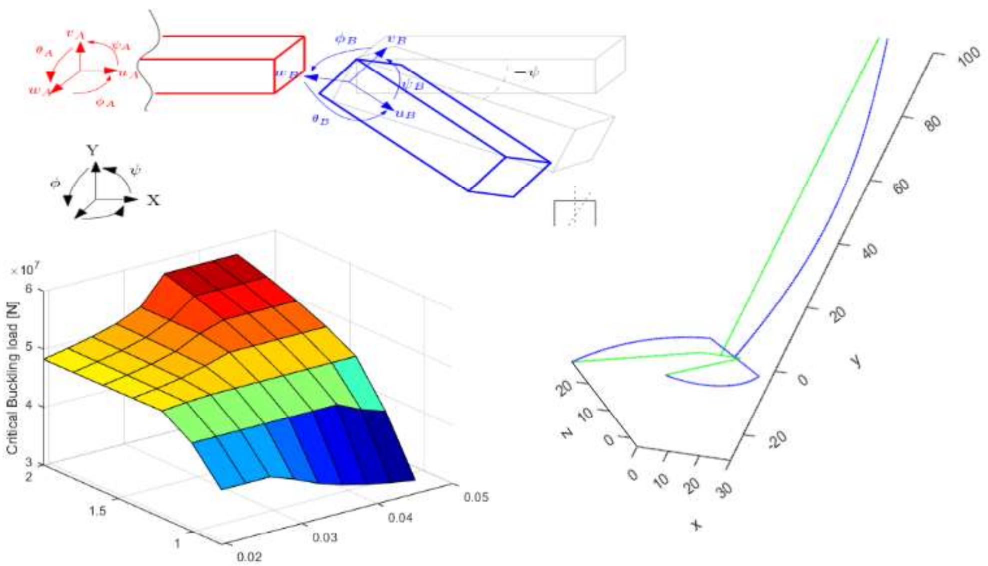
Buckling Stability of the Tetrahedron Crane

This thesis aims to provide insight into the conceptual design phase of Tetrahedron B.V. with regards to buckling stability. Currently, Tetrahedron B.V. assumes an effective length factor of one for determining the cross-section profiles of the Tetrahedron Crane. In this thesis, Euler-Bernoulli beams are used to model every member of this crane, where each element's compressive force is related to the applied cargo load of the crane. The crane has various aspects to it that are assumed as ideal boundary conditions or partial restraints, some of these assumed boundary conditions are then modelled by partial restraints to see its effect on the critical buckling load. The critical buckling load of Euler-Bernoulli beams, also known as the linear bifurcation point, is found by solving the eigenvalue problem, which results in the load under which the system fails from buckling instability. The current crane, the version zero design, was assessed. The buckling model created in this thesis is verified through limit cases of simplified models and the results from a FEM software, whilst always remaining critical to all comparisons.

This crane design is deemed to be stable from buckling failure within the intended safe working load of the crane. With this crane design, using an effective length factor of one in the conceptual design phase is suitable. However, the Tetrahedron crane design has changed quite dramatically since this thesis began, so the thesis also adapted to understand and analyse the general trends that appear when key structural or geometrical inputs change. This is done through a sensitivity analysis where the critical buckling load is determined for a variety of geometrical and section properties to see at how the critical load changes given input changes. This uncovered some changes in the critical buckling load and eigenmode of the crane given certain conditions. Most significantly, a sharp decrease in critical buckling load when the crane heel girder's (which is one of the members) is greater than eleven meters. This decrease in critical buckling load would in fact mean that the crane would fail from buckling instability within its safe working load and means that the effective length factor is not related to the shape of the crane itself. As there are so many geometrical and structural parameters in the crane, not all of them could be assessed in the sensitivity analysis. But ultimately, the model in this thesis, programmed in MATLAB, can be used by Tetrahedron B.V. for future iterations to the crane in the conceptual design phase.



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Offshore & Dredging Engineering

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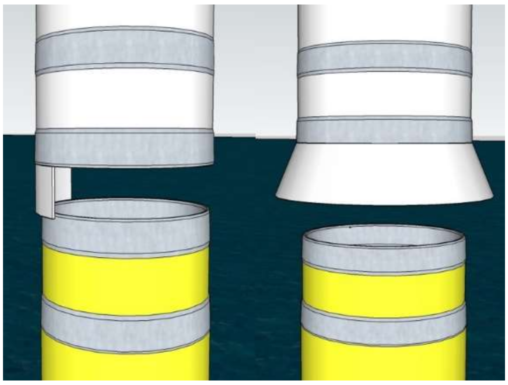
Limits of Installation with the Double Slip Joint using Catchers

Offshore Wind Turbine Tower Installation by the Double Slip Joint Connection using Catchers. A determination of Installation Limits and Exploration of Workability

The Double Slip Joint is a promising innovation as a connection between a WTG tower and the support structure. It is visualized by the steel grey rings in the figure that connect the WTG tower (white) to the support structure (yellow). In current offshore WTG tower installations, bolted flange connections are common. These connections however generally do not allow for large motions between the tower and foundation. This limits the workability of installation and as such, the CAPEX for an installation vessel is relatively high due to the necessary downtime. This research explores the motion and collision limits for WTG tower installation on an MP and focuses on the lowering and catcher mating. A first exploration of workability is provided. Two types of catchers are studied, the vertical asymmetrical catcher and the conical catcher, seen on the left and right in the figure, respectively.



A model is developed that simulates the lowering and catcher mating of a WTG tower with a MP. This model includes physical phenomena that affect the motion and collision behavior of the WTG tower. Specific attention is paid to collisions between the catcher and MP. With the use of finite element analysis, a stiffening non-linearity, caused by the local deformation of the mating elements, was observed in the lumped contact element do describe collisions.
Installation limits are determined by the requirements that an installation should comply to. These installation requirements aim to prevent slack wires, axial impact, and plastic deformation of the catcher due to contact with the MP. It is also required that the side-lead angle remains below a maximum allowable value.

Model simulations have been performed for two different crane tip excitations that in terms of frequency correspond to a jack-up and a floating installation vessel. This research indicates that the conical catcher yields higher allowable wind velocities than the vertical asymmetrical catcher in installation. This is supported by the findings that the conical catcher has higher allowable contact forces, requires no crane operator action during catcher mating and the side-lead angle varies less than with the vertical asymmetrical catcher.
Another important observation is that the installation limits are often reached through installation requirements related to the motions and collisions of the mating elements. This study suggests that applying linear damping to the horizontal motions of the bottom of the WTG tower increases the allowable mean wind velocity of installation and therefore, it increases the workability of installation.
The focus in this study is kept on motion and collision limits in installation as well as on installation requirements. To this end, with regards to workability, only a first exploration has been performed. It is therefore recommended for future research to workability to analyze the entire system consisting of vessel, load, and foundation. As such wind and waves are considered separately as a source of excitation and vessel-load interaction is incorporated. Second, it is recommended to investigate to which extent heave motions can be compensated for increasingly heavy structures. Third, it is recommended to investigate the extent to which active tugger winches can be controlled to serve as linear dampers to the horizontal motions of the WTG tower bottom. Fourth, it is recommended for future research to investigate the timing and accuracy with which the crane operator can displace the crane tip. Finally, this study is performed with in-plane motions and collisions. It is recommended for future research to study 3D motions and collisions of the WTG tower in installation. Specifically, it is recommended to study how the motions of the bottom of the tower, which may exhibit Lissajous-like motion behavior in 3D, can be controlled or damped. It is also recommended to study the inclined collision responses resulting from the aforementioned motion behavior.

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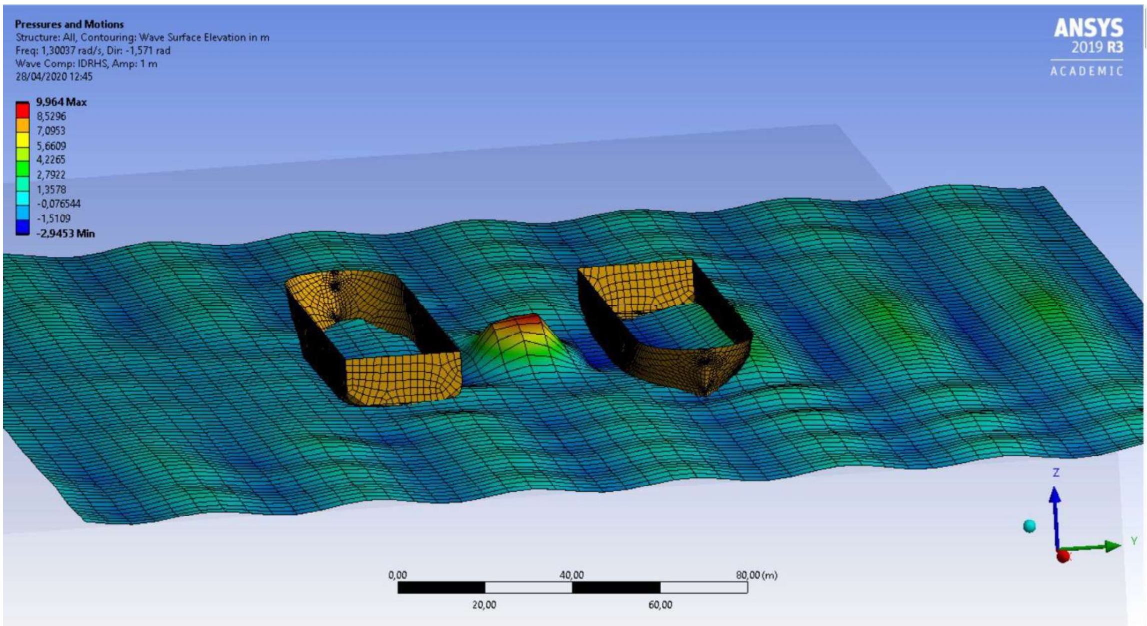
Offshore & Dredging Engineering

QUAD lift workability analysis.
Evaluating the dynamic interaction between two dual-crane vessels using a frequency domain modelling technique.

A QUAD lift is a new lifting method in which dual crane vessels combine their vessel capability to increase their offshore lift performance. The use of the Jumbo J-Class vessels in a QUAD lift creates the opportunity to increase the offshore lift capacity and to install structures with larger dimensions. When floating vessels are close to each other in an offshore environment, their motion will be different than in the freely-floating situation because of hydrodynamic coupling and wave diffraction forces.

The main objective of this thesis is to create a model of the QUAD Lift method which predicts the vessel and load motions and evaluate the workability such a lift. Both potential solvers AQWA and OrcaWave are used to assess the hydrodynamic parameters of the interacting vessels. The gap between the vessels is 40 m and the vessel configuration is such that the cranes are parallel to each other. In between the vessels, transversal wave resonance induces peaks in the frequency dependent radiation forces of the vessels. An additional damping lid in between the vessels effectively reduces the resonance behaviour, which is overestimated by potential solvers. The damping lid has an negligible effect on the final workability of the QUAD lift. A 18-DoF linear Matlab model is created which includes the mechanical connection between the vessels and the load.
The cranes and the cables are modelled as linear springs. The natural frequencies and eigenvectors show large coupling between the vessel roll and the load sway motion. Tugger lines between the vessel and load are added to shift the natural frequencies of the system and to decrease the large horizontal responses of the load. A parametric study is done on the effect of the load mass, cable lengths and wave directions on the system motion in the most probable wave condition in the Central North Sea. An increase of the mass of the load leads to larger vessel and load motions. The shorter the cable length, the larger the vessel and load motions. The motions are most severe in beam and quarter waves. Depending on the stiffness of the tugger lines the workability can be improved up to 85, 55 and 24 % in respectively head, quarter and beam waves. The limiting factor for the workability is the off-lead angle of the cranes. Broadening of the off-lead angle limit of the crane shows great potential to further increase the workability.



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Offshore & Dredging Engineering

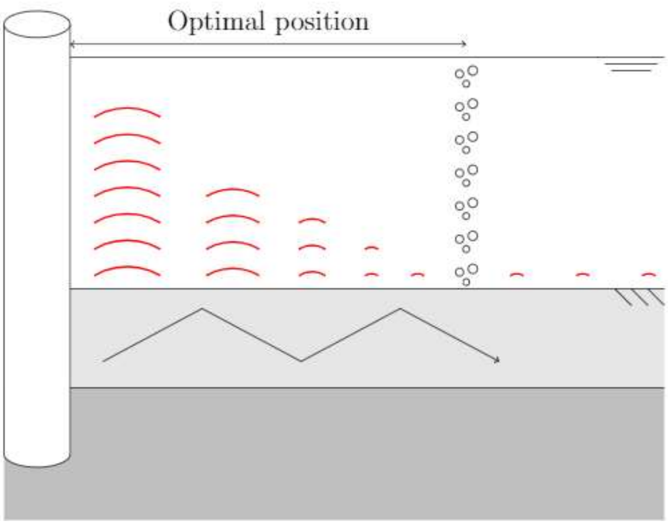
Underwater noise - *An analysis to the relevant criteria for positioning a bubble curtain*

Wind turbines are growing in size and therefore their foundations, become larger as well. Additionally, they are placed in deeper waters. This results in the industry being at the limit of underwater noise levels generated by impact piling during the installation phase of monopiles. The most common installation method for monopiles is impact piling. This installation method comes with high impulse noise emissions which can be harmful for the aquatic environment. Larger piles require more energetic hammer impacts which, in turn, generate more noise. Given the size of the monopiles installed nowadays, noise limits imposed by governmental organisations are exceeded in all cases.

The noise due to impact piling can be reduced by applying noise mitigation measures. Several systems have been developed, the most common of which is the Big Bubble Curtain (BBC). Although the working principle of the BBC has been proven in practice, the most effective deployment configuration, i.e. distance from the pile, air-flow volume and pressure, etc., has not been thoroughly investigated. In current projects, the BBC is typically placed at twice the water depth.

This study aims to identify the parameters that determine the optimum position of the BBC to achieve maximum noise reduction. First, free-field predictions (without the BBC) using the TU Delft software SILENCE have been carried out for model validation purposes. The accuracy of the noise predictions were found to be within 2 dB (re 1µPa) both for the SEL and the $L_{p,pk}$. Second, the BBC was implemented by assuming a depth and frequency-dependent transmission loss (TL) factor at the position of the BBC. Noise predictions including the modelling of the BBC were validated against measured data.

The key findings in this research are that the location of the bubble curtain is determined by the energy leakage from the soil into the water column. Depending on the damping characteristics of the BBC, this leakage is significant up to a point where the energy does not leak back to the water column anymore. In the examined case, and for blocking the waterborne path, this optimal position is found to be around 70m. The figure below shows the trend of the energy leakage in a schematic way. It shows that if the bubble curtain is placed too close to the pile, noise leaks back into the water column behind the bubble curtain. Thus, depending on the specific geometrical configuration, water depth and soil conditions, it is argued that an optimum position can always be found using the analysis presented in this work.



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Offshore & Dredging Engineering

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Creating a local residual curvature during S-lay pipeline installation by lowering the stinger

Marine pipelines are often operated at high internal pressure and temperature. This loading condition results in the development of axial compressive forces that can cause the pipeline to buckle globally. Global buckling occurs when significant lateral motion is present in the pipeline and excessive feed-in occurs at that specific location, which in turn forms into a sharp curve that can initiate destructive structural failure. Research has been conducted addressing the control of buckle development.

The "buckle initiation" techniques were invented to mitigate the uncontrolled buckling of the pipelines on the seabed. These techniques involve the creation of less stiff sections in the pipeline (imperfections), so that buckling occurs in these locations. The most common buckle initiation techniques used in S-lay installation so far, are the "snake lay" method, the "artificial vertical out-of-straightness" and the "distributed buoyancy" method. However, these techniques require the addition of subsea structures on the seafloor or larger pipeline length, which can increase the pipelaying cost dramatically.

A beneficial buckle initiation technique is the "residual curvature" method. The residual curvature method (RCM) principle is based on creating intermittent residual curvature sections in the pipeline so that buckling can be initiated at these locations. The curvature sections are created by adjusting the settings of the already existing installation equipment. So far, this method is only used in reel-lay installation. It is particularly urgent to examine if the local residual curvature method can successfully be applied in pipelines laid by S-lay vessels, since S-lay is considered the most common and frequently used technique due to its adequacy on different water depths and pipe diameters.

The scope of this master thesis is to assess the feasibility of creating local residual curvatures in the pipeline by lowering the stinger during S-lay. The assessment is accomplished by simulating numerically the pipelaying process and the creation of the residual curvature, by analysing the behaviour of the pipeline while being lowered (in particular, looking at its twist/rotational behaviour) and by verifying if the alterations to the normal pipelaying procedure still respect the integrity of the pipeline and installation equipment.

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Offshore & Dredging Engineering

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Advanced Constitutive Models for Offshore Applications on Suction Pile Foundation

The suction pile foundation is a large steel cylinder with an open end and sealed top. This foundation type is widely used in the oil&gas industry and wind energy. Experimental investigation and numerical investigation are the main two methods to understand the performance of the suction bucket foundation. The experimental studies are important and basal for design, but it is time-consuming and costly compared to numerical studies. However, the accuracy of the finite element method(FEM) in geotechnical problems highly depends on whether the soil constitutive models can correctly predict soil behaviour.

In our study, we investigate four constitutive models: the Mohr-Coulomb model, the hardening soil model, the NGI-ADP model, and the hypoplastic model. To some extent, advanced soil models can better present soil behaviour than traditional ones. However, it needs more laboratory test data to calibrate the advanced model parameters. The NGI-ADP model is mainly used for undrained analysis, and it is an anisotropic model which can exact match with undrained shear strength and stiffness for various failure surfaces. The hypoplastic model has no distinguishing between elastic and plastic strain. It is an inelastic(dissipative) and incrementally nonlinear soil model without the requirement of a yield surface.

A soil investigation report of Block 17 offshore Angola is used to calibrate the aforementioned constitutive models. The cone penetration test(CPT), ball penetration test(BPT) and a series of laboratory tests(i.e. direct simple shear, triaxial, and oedometric tests) are exacted from the soil report and interpreted for calibration. Parameter determination procedures for constitutive models are explained. Subsequently, the consistency of the parameter set is validated by numerical simulation of direct shear and triaxial tests, where the NGI-ADP model obtains the best fit for the stress-strain relationship.

The numerical experiments for a suction pile foundation whose out diameter equals four and aspect ratio equals three are carried out. Four loading cases (i.e. horizontal, vertical tension, vertical compression and vertical-horizontal-moment(VHM) combining loadings) are included in the finite element analysis. The suction pile performance (i.e. deformation and capacity) are compared among the using of different constitutive models. Additionally, the compliance matrices of the suction pile for different soil models are obtained for the structural engineer.
The analyses indicated that NGI-ADP model could be the best choice for undrained analysis of suction pile foundation. This model has a robust calibration process, and well simulate the an-isotropic strain-stress relationship. Additionally, the finite element results are conservative when modelling by NGI-ADP model. However, this model cannot predict the right pore pressure build-up and stress-path, which may be improved by using a well-calibrated hypoplastic model.

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Offshore & Dredging Engineering

Earth-Fixed Heave Compensation

With a global growing demand of energy, more offshore wind farms are installed, further away and in deeper waters. Nowadays, offshore wind turbines are mostly installed by jack-up installation vessels. Most existing jack-up vessels have legs that are becoming too short for these water depths while offshore wind turbines are increasing in size year after year. Since 2014, the turbine capacity of newly installed wind turbines has increased by 16% every year. Therefore, larger jack-up crane vessels are needed and installation by floating crane vessels is being considered. Heerema Marine Contractors aims to be one of the leaders in the offshore wind installation with her large crane vessels such as HLV Aegir, SSCV Thialf and SSCV Sleipnir.

The challenge of floating installation of offshore wind turbines is that motions of the vessel are transferred to the rotor-nacelle assembly (RNA) while low tolerances apply for the installation of an RNA. Vertical motions can be reduced by means of a heave compensation system. Such systems are available but come with certain drawbacks: they are difficult to retrofit to a vessel, use a large amount of energy and are rather expensive. A possible solution to these problems could be a novel concept called earth-fixed heave compensation. In this concept, the crane wire is connected to the seabed via a transmission on board of the vessel, transforming an upward motion of the vessel into a downward motion of the RNA and vice versa. At present, it is unclear if such a system is technically feasible. In this research, an analytical model of an earth-fixed heave compensation system is developed.

The objective of the model is to gain insight in the influence of design parameters such as the transmission and stiffness of the system. The model is set up in three stages: Stage 1 comprising one degree of freedom for the transmission; Stage 2 comprising two additional degrees of freedom for the sheaves that connect the earth-fixed wire from the seabed to the transmission; Stage 3 comprising all other sheaves, crane reeving and payload are added, resulting in a sixteen degrees of freedom model.

A first finding is that wire damping has a negligible influence on the results because natural frequencies of the system are found to lie outside the wave frequency range. However, the first natural frequency is close to the wave frequency range, resulting in a larger response amplitude for both transmission and vertical payload motion in the higher frequencies. Furthermore, it is shown that the inertia of the sheaves of the earth-fixed wire can be neglected for a range of transmission inertias and earth-fixed wire stiffnesses. On top of this, the model confirms that the inertia of the other sheaves can be modelled by means of an equivalent inertia block, to simplify the model for time-domain simulations.

The losses in wire tension due to wire-sheave interaction were approximately 6% and it is shown that they can be modelled accurately by means of a sigmoid function. Frequency-domain simulations showed that the heading of the vessel, or wave direction, has a significant influence on the vertical RNA motions. On top of that, increasing peak periods generally result in larger vertical RNA motions. A time-domain simulation for typical North Sea environmental conditions, head waves and a fixed crane slew angle without the heave compensator is made to compare results with. These simulations have shown that it is in principle possible to reduce vertical RNA motions.

For a given sea state, 80% motion reduction is achieved by tuning the transmission ratio of the system. It is shown that the location of the earth-fixed wire has an impact on the vessel and payload motions. When located on the starboard side of the vessel, rather than reducing the vertical payload motions that are induced by vessel roll, those motions of the vessel itself are actually increased. Further simulations show that the stiffness of the earth-fixed wire and the losses occurring due to wire-sheave interaction determine the performance for a large part. Although the overall performance of the system can be considered promising, additional research is needed to confirm whether earth-fixed heave compensation can be competitive relative to existing passive and active heave compensation systems with a performance of 80% to 95%. Also, it is recommended that the behavior of the system for different sea states is investigated. Sensitivity analyses already show that shorter wave periods result in a significant drop in performance. The vessel heading seems to have a limited influence on the performance of the heave compensator.

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