Ship Collision, Risk analysis - Emergency systems - Collision dynamics

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1 Abstract

Some offshore wind farms in Europe have been built and numerous projects are on the drawing tables. It is necessary to study the effects of these wind farms with respect to the safety of shipping in order to estimate the related risks to people, ship traffic and the environment. Here the formal risk definition is the product of collision frequency (collision rate) and collision consequence (size of ship damage or emission of harmful substances). This paper puts emphasis on the determination of the consequences. For offshore wind farms within the German Exclusive Economical Zone (EEZ) the so-called "Collision Friendly Foundation Design (CFFD)" is required by the responsible authorities. In case of a ship collision with such a foundation type, the ship will not be damaged or more generally spoken emission of harmful substances will be minimal.

Within this paper results from research projects SafeShip [9] and TUHH[10] are summarised concerning consequence modelling. Collision simulations for 4 different ship types and 3 different foundation designs have been performed by means of Finite Element Models considering the structural behaviour of wind turbine and ship. The calculated collision mechanisms will be discussed. Finally the question of the "Collision Friendly Foundation Design" will be discussed for each foundation type.

2 Introduction

A number of offshore wind farms are currently being planned in Europe, USA and Canada. E.g. for German areas in the North Sea and the Baltic Sea, it is proposed to install wind turbines of up to 5 MW rated power and up to 25,000 MW total power. It is necessary to study the effects of those wind farms with respect to the safety of shipping in order to estimate the related risks to people, ship traffic and the environment. A guideline for risk analysis for offshore wind farms has been issued by GL in 2002 [7].

In general risk R is defined as the product of collision frequency f and consequence c of undesired events:

$$R = f \times c$$

Considering the ship collision risks for an offshore wind farm f is the ship collision frequency and c is loss of harmful substances, e.g. oil spill.

Within the framework of the approval process, detailed risk analyses have to be submitted, which enable the responsible authorities to carry out an evaluation on the basis of comprehensible criteria. Measures for risk minimization such as the provision of additional salvage tugs or ship traffic control can be evaluated with respect to their efficiency in order to achieve the highest safety standard for people and the environment. Additionally, risk analyses provide the necessary safety information for insurers and operators of wind farms.

During the approval process, the responsible authority will examine compliance with acceptance levels for collision frequency and risk. On the basis of the calculated period between collisions (1/f) and quantity of harmful substances an evaluation is possible. By comparing the acceptance levels with the calculated values, a decision regarding the approval can be made. The effects of risk reducing measures can be demonstrated and thus have a direct influence on the acceptance of the planned wind farm.

For offshore wind farms in the German Exclusive Economical Zone (EEZ) acceptance criteria have been defined [8], see table 1. The calculated collision frequencies to be compared against the below mentioned acceptance criteria shall include state of the art risk minimization methods, e.g. collision friendly design, AIS, radar control, existing tugs, etc.

Furthermore important calculation parameters are described in [8].

	Time (years) between two collisions
acceptable	> 100 a – 150 a
“from Case to Case”, enhanced analysis required	> 50 a and <100 a
not Acceptable	< 50 a

Table 1: Acceptance Criteria for wind farms in the German EEZ [8].

A comprehensive elaboration of methods to calculate and minimize ship collision risks is given in [9] summarizing the results of the EU-funded research project SAFESHIP.

Another research project aiming at a numerical evaluation of several collision scenarios between different ship types and three exemplary types of foundation structures was initiated by the German Federal Ministry for Environment. It was performed by Hamburg University of Technology (TUHH). The resulting conclusions were supposed to lead to an evaluative scheme to determine the mechanical properties of offshore wind turbines (OWT) foundation structures concerning their crashworthiness and their ability to conserve hull integrity in ship collisions. This scheme shall be used in the approval of OWTs. The scheme was applied to three exemplary OWT foundation designs and selected types of ships in the research project [10].

A stochastic analysis of the collision frequency was not the aim of the project although it is necessary to link both collision frequency and consequence analysis to determine the risk.

In an investigation of the Federal Environmental Agency on preventive actions in the events of failure in offshore wind farms, a single hull oil-tanker of 160,000 dwt was proposed to be the design ship in accidental limit state (ALS). Also, a damage of three cargo tanks was estimated as being likely, which means an amount of 54,400 tons of spilled oil to calibrate necessary preventive action to be taken into consideration.

The goal of the study is that, knowing about the mechanical performance of the OWT in case of a collision and depending on the particular conditions, the probability of environmental damage can be estimated more precisely than it could be before. This leads to a more favorable evaluation of the environmental risk. Especially the increase of passive safety against collisions is considered. To allow for maximum safety, provisions concerning active safety against collision and fault events respectively (redundant navigation and control systems, ban on close parting for certain kinds of ships, training of crews, traffic management systems, monitoring of the wind farms, providing tug boats for emergencies, etc.) are to be considered in order to prevent collisions and emergency situations before they occur.

3 Collision Model

3.1 General

The aspect of collision safety is mostly treated in connection with the design of tankers. For this type of vessels, there is an international binding agreement (MARPOL 73/78 Annex I, Directive 13F), which determines the minimum dimensions of double bottoms and double hulls. Additionally, the European Union decided to phase out single hull tankers more quickly to reduce the environmental impact of collisions with tankers.

The state of the art in simulating collision and grounding events were enhanced by scientific projects, which were initiated after the spectacular tanker wreckings of “Exxon Valdez” and “Braer” and set forth e. g. in connection with the construction of the Great–Belt–Crossing. In these projects, both, empirical, analytical, and numerical methods were applied and many experiments were executed. Several experiments and analyses are described in Zhang’s dissertation [1], which also features an extensive reference list on the field of collision analysis.

Between 1995 and 1999 two projects were conducted at Germanischer Lloyd and Hamburg University of Technology (TUHH) that dealt with the safety of double hull tankers concerning collision and grounding [2], [3]. Apart from this, there is a worldwide interest in the limitation of risks in collisions. An overview on the actual state can be found in the ICCGS conference proceedings [4].

Figure 1 Ship to Ship Collision Test

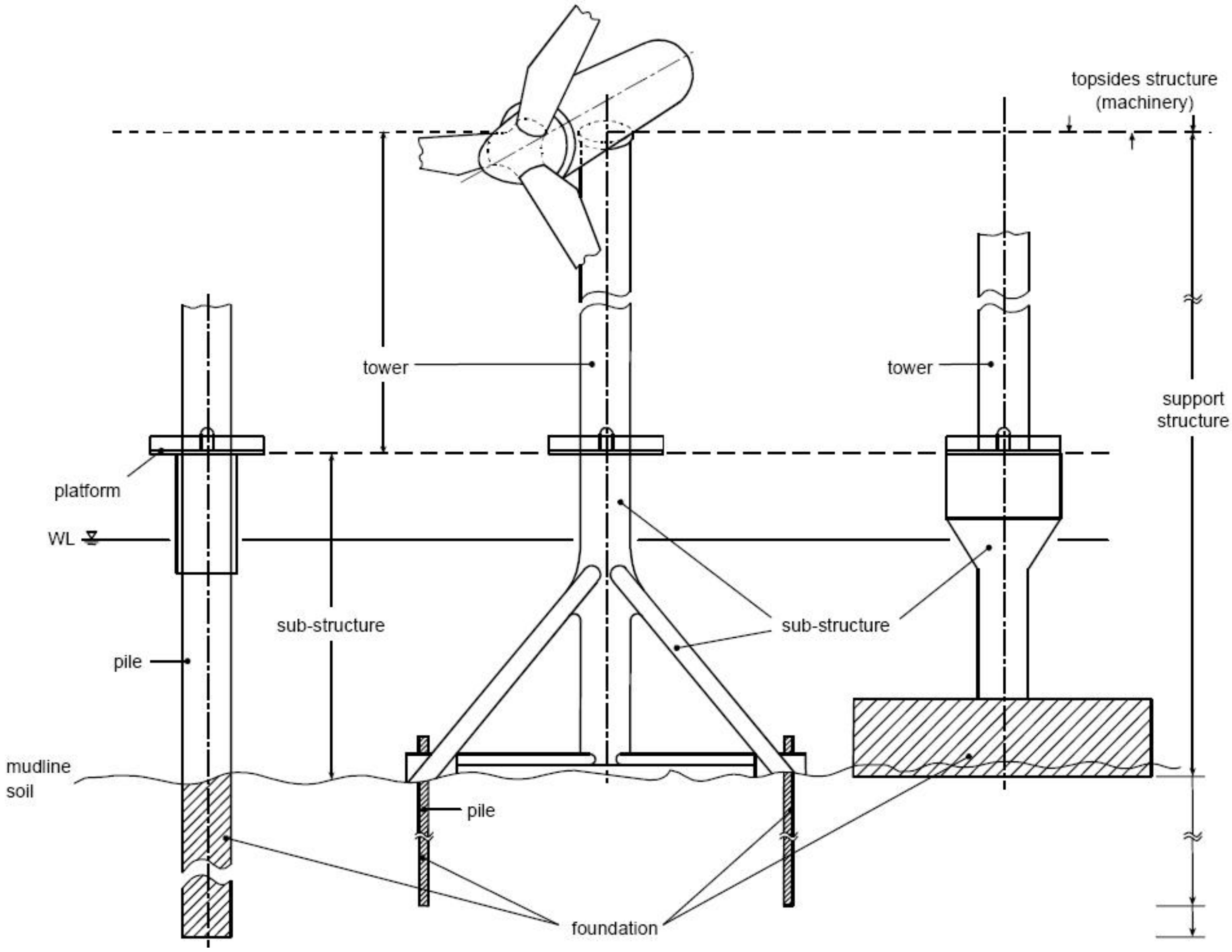

Figure 2 Definition of offshore wind turbine sections

Numerical analysis of ship to OWT-collisions basically is an extension of the calculation of ship to ship-collisions. When considering ship bow toship side collisions, the bow of the colliding ship can be assumed to be rigid [3]. Both structures in a ship to OWT collision are to be considered deformable. Additionally, the interaction of the support structure and the foundation soil is to be taken into consideration.

The numerical model for the collision analyses consists of two main parts:

1. the OWT comprising machinery and support structure including soil-foundation interaction, see fig. 2
2. the colliding ship including the surrounding water.

Only side impacts of the ship with the OWT were taken into account due to two reasons. Firstly the ship side is of lower strength and stiffness and thus more vulnerable compared to the bow. Secondly it is more likely that the colliding ship is a drifting ship and thus ramming the OWT sideways. Motions (rotations) of the ship around the OWT were not considered. These are conservative assumptions leading to more severe damages than in reality.

3.2 TUHH Project

3.2.1 Selction of Ship and Support Structure Types

Calculations were carried out for four different OWT support structures: A mono pile, a jacket, and two tripod foundations (North Sea and Baltic Sea locations).

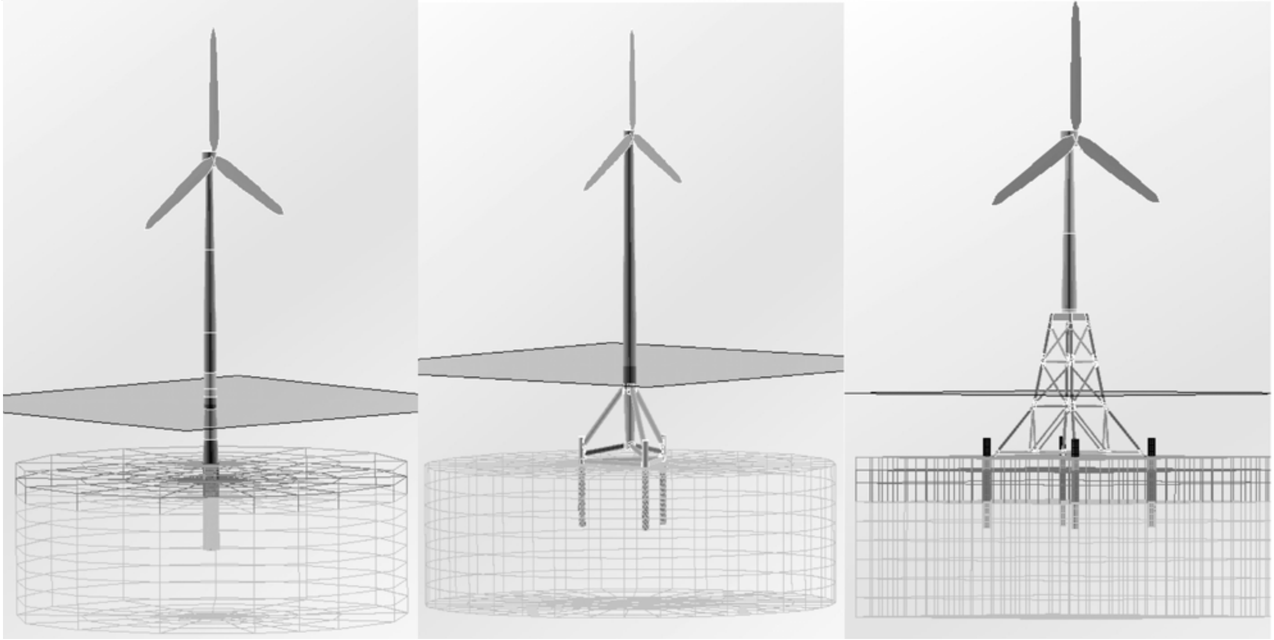

Figure 3: OWT Support Structures

In cooperation with Germanischer Lloyd, ship types were selected for the analysis of the collision scenarios. The decisive factor was the commonness of the types. As a basis for this, results from Germanischer Lloyd regarding maritime movement on the North and the Baltic Seas were used [5]. The percentage of the different ship types was calculated for the years 1995 to 1999 and extrapolated to the year 2010. The absolute number of maritime movements rises from 373,023 per year in the time between the years 1995 and 1999 (mean value) to 450,086 in 2010 (estimated).

A 31,600 tdw double-hull tanker, a single-hull (150,000 tdw) tanker, a container ship (2,300 TEU) and a bulk carrier (170,000 tdw) were selected.

Figure 4 Ship types used in analysis

3.2.2 Analysis Procedure

All calculations were performed using LS-DYNA, a nonlinear (explicit) finite element program widely used in crash applications. For static and quasi-static procedures, a nonlinear (implicit) equation solver implemented in LS-DYNA was used. The movement of the ship was calculated by a user supplied subroutine implemented in the code.

3.2.3 Idealization of the Ships and their Motion

The ship types considered are very long (up to 300 meters) compared to the width of the OWT foundation (up to 30 meters). Therefore, the ships were not fully discretized. Only one or two holds were modelled with finite elements. The rest of the ship was modeled as a rigid body connected to the FE-model at the outer nodes of the most forward and rear section of the FE model (see Fig. 5).

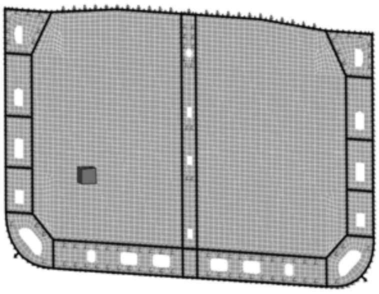

Figure 5 Connection of deformable and rigid parts, connection nodes are drawn in black.

In addition to this, the ship's motion before and during the collision which is driven by hydrodynamic forces was taken into consideration. According to the potential theory, the hydrodynamic forces are determined quite easily in a harmonic agitation of the hull. The procedure has already been implemented in the present version of LS-DYNA. The calculating method used here is similar to the procedure in [6].

3.2.4 Dynamic Simulation

For the calculations, the following boundary conditions were set up:

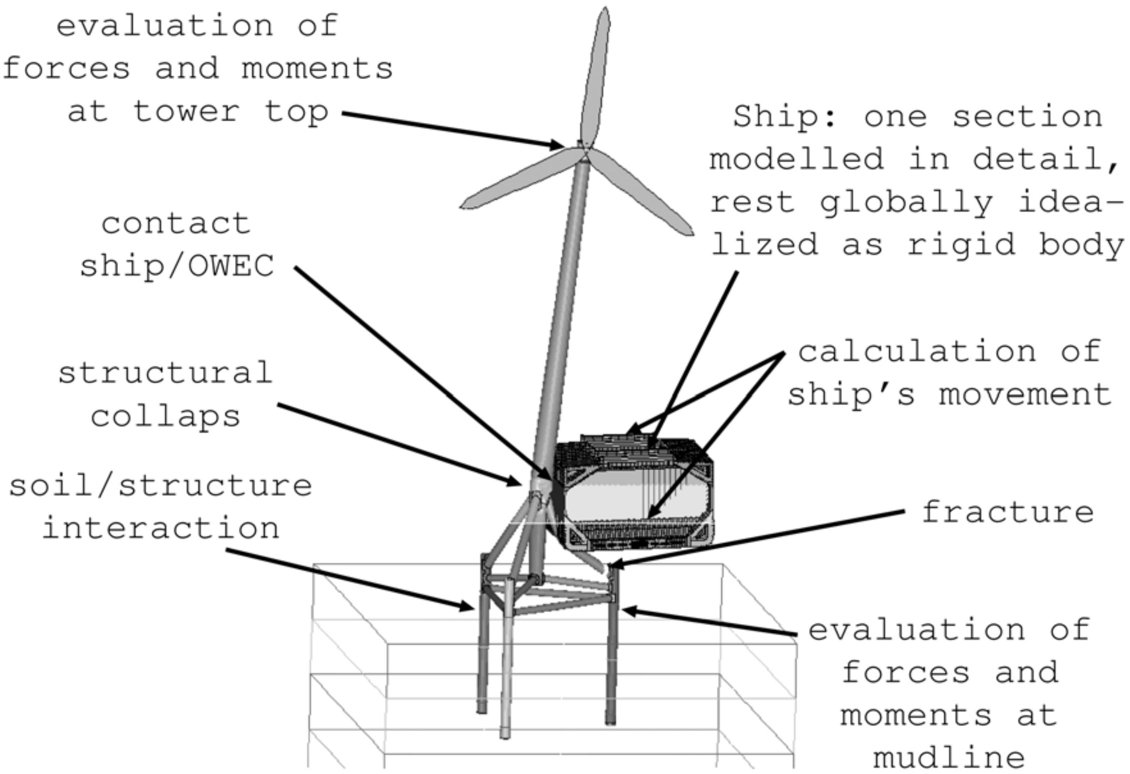

Figure 6: collision: input data, parameters, and output data

For standard cases, a drift velocity of 2 m/s (approx. 4 knots) has been assumed, in individual cases, collisions with 3 or 4 m/s were simulated to evaluate the influence of a variation in initial kinetic energy. The drift angle was set to 90°. Sea conditions were not taken into account.
Failure of individual modules is the decisive part in the simulation. There are three failure modes:

Ultimate Strength: In the constitutive model for steel, a failure criterion is implemented that considers an element ruptured if a certain amount of effective plastic strain is reached. This failure strain depends on the initial geometry of the finite element. Peschmann [3] gives values for certain element length/thickness ratios. These values were obtained by tensile tests and proved to be a good estimate.

Stability: Buckling can occur even within the elastic range, i. e. mostly without rupture. In fully nonlinear finite element codes like LS-DYNA, buckling phenomena are calculated by using nonlinear geometric stiffness. As a result, already deformed (buckled) areas of the model will be greatly deformed even with small extra loadings and thus will be unstable.

Foundation soil: The immense loading, which is inserted into the soil, may lead to large-scale deformations. Heavy plastic deformations can only be introduced by modifications of the granular structure (e. g. shear bands), i. e. the soil loses its bearing capacity and collapses. Mechanisms of soil collapse cannot be considered in the present model because of its simplifications. Too much rigidity of the soil may lead to conservative results in the calculation. This is due to the foundation simulating more resistance and thus tending to cause more damage to the ship.

3.3 SAFESHIP Research Project

The SAFESHIP project "Reduction of Ship Collision Risks for Offshore Wind Farms" was initiated with EU support to investigate potential risk reducing technologies and to develop risk assessment methodologies. Within the project, methods to assess the risks in connection with simulation of the consequences of potential collisions of ships with offshore wind farms were investigated. Herein the support structure was assumed to be a steel tower and a monopile.

The mechanical collision model was based on the approach used in the TUHH project but in some aspects it was modified, e. g. modeling of soil-structure interaction was simplified by using nonlinear-elastic springs based on the API approach (py-curves).

As it was already known that the mono pile foundation would not be a threat to hull integrity, more emphasis was laid upon calculating the reaction forces and moments at the tower top and blade root in order to evaluate the possibility of failure of these parts and subsequent impacts of parts onto the ship's deck. Therefore the ships were modeled entirely rigid to save calculation time.

In this simplified approach, no damping effect of the large soil mass and no friction interface between the mono pile and the soil were taken into consideration. This approach led to conservative forces and moments at the tower top.

In a case study, five different ship types and three different drift velocities were investigated. The impact location was also varied according to the local tidal range. Altogether, 22 calculations were carried out.

4 Collision Consequences

4.1 TUHH Research Project

Comparing the energy absorption of the three foundation structures during the collision with the double hull tanker, it was shown that the mono pile fails before the smallest ship's kinetic energy of approx. 90 MJ is consumed. The mono pile also fails in any collision with one of the other ships. Due to its weakness, the damage level of the side structures of all ship types is low.

Although the ship comes to a full stop in the collision with the jacket structure, damage is not much more severe compared to the mono pile. High global and small local stiffness of the jacket allows the collision force to be transferred into the jacket using much deformation work.

Collisions with a tripod foundation cause more severe damage to the ship: If the ship drifts onto one of the diagonal legs all the energy will be transferred through this contact point until eventually the side structure of the ship reaches the central column of the support structure. The strength of the diagonal and the tripod structure in general may lead to penetration of both the outer and the inner hull of a double hull tanker.

4.2 Safe Ship Research Project

Calculation results confirmed the TUHH results of the mono pile foundation. Following conclusions can be drawn:

- The chronology in case of a failure is generally yaw bearing, main shaft, rotor blade and mono pile below the mudline
- The calculations show that the yaw bearing is highly sensitive.
- The mono pile often fails below the mudline.
- At a drifting velocity of 4 knots the section loads in nearly all considered parts exceed the maximum design loads of the wind turbine.
- With the considered drifting velocities of 1, 2, and 4 kn, the mono pile is pushed away and does not fall towards the ship.

5 Collision Friendly Design

5.1 Mono Pile

Mono pile foundations exhibit lowest risk in case of collisions. Only local buckling occurs without rupture of the ship hull. Much of the impact energy is transformed into deformation at the mono pile.

5.2 Steel Tripod

If a ship hits the diagonal chord and the central joint of the tripod severe consequences may occur. To minimize this risk the central joint of a tripod should be located lower than the maximum draught of a ship that travels regularly in the area.

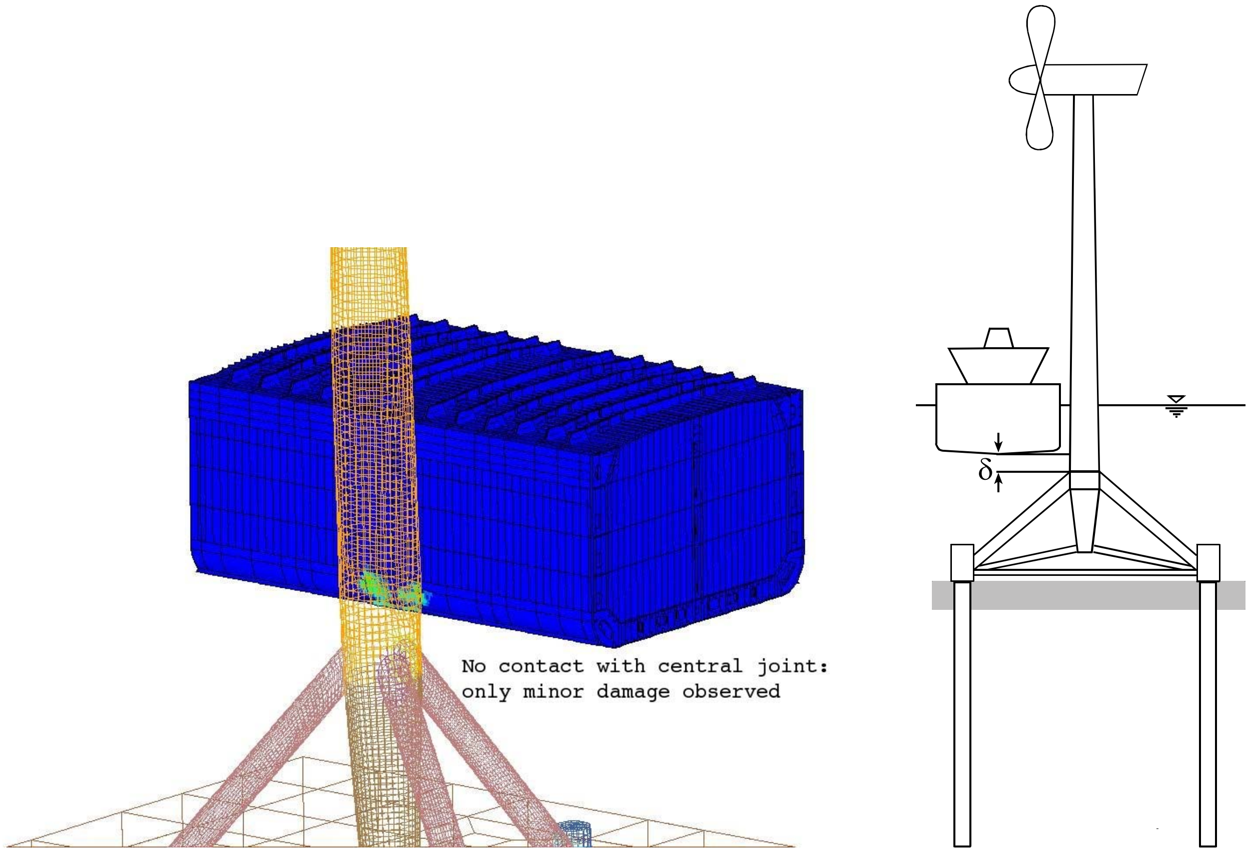

Figure 7: Tripod with central joint below ship bottom (δ >0)

5.3 Jacket

The work of the collision force can be transformed into large deformations within the jacket structure as far as the structure is able to withstand the ship long enough without being torn off the foundation piles.

Local damage in the model caused by the jacket's joints should not lead to widely damaged areas of the ship's hull. As the joints were modeled very stiff this condition leads to higher damage to the ship as it would probably occur in a real collision.

Although large damaged areas at the ship hull in the contact zone are unlikely, it is possible that the wind turbine falls towards the ship, since the damaged jacket structure acts like a plastic hinge.

5.4 Gravity Based Foundation

This foundation type is set onto the soil without piles or other types of anchors. Horizontal forces have to be transmitted by friction only. Moments can lead to rotation of the whole foundation including separation of parts of the interface between concrete and soil. Thus a ship impact may lead to failure of the friction interface and the foundation is pushed away provided the contact zone is high enough.

Two effects seem to be dominant for gravity based structures:

1. In case the central column is made of concrete, this will lead to a more rigid behavior of the support structure and thus lower the amount of absorbed collision energy within the first second of contact.
2. Impact energy can be transformed into sliding energy. The foundation tilts and is pushed away after some “activation time”.

5.5 *Rating of Results*

From the results discussed before the following matrix was developed. The matrix considers ship type/size and foundation type.

GRAVITY BASED	▨ ( )[1]	▨ ( )[1]	▨ (✓)[1]	▨ ( )[1]
STEEL TRIPOD	(✓)[1]	(✓)[1]	(✓)[1]	(✓)[1]
JACKET	✓	✓	-	-
MONO PILE	✓	✓	✓	✓
	DOUBLE HULL 31.600 tdw	CONTAINER 50.000 tdw	SINGLE HULL 150.000 tdw	BULK CARRIER 170.000 tdw

Table 1: Results of Collision Simulations:

Legend:

✓	Calculation of collision scenarios did not show major hazards with this type of OWT support structure and this vessel type. The design may be regarded as collision friendly for this vessel type.
(✓)	Certain hazardous scenarios could be identified by numerical simulation. Countermeasures were given. The design may be regarded as conditionally collision friendly for this vessel type.
-	Hazardous scenarios were identified and no practicable countermeasures have been developed yet. So far, the design has to be considered unsafe.
▨	Not enough investigations have been made to verify the given results.
)[1]	see 5.2.for tripod and 5.4 for gravity based foundation

6 Outlook

Direct analysis of collision friendly foundation design of OWT structures using complete 3D-FE models is time consuming and expensive. Further research has the goal to simplify parts of the calculation model as soil-structure-interaction, ship impact, and OWT design in order to give a tool to enable to estimate collision friendly foundation design parameters in a global design phase of a project.

Sophistication of the model should allow adjustment of the model complexity to obtain more reliable results during different planning phases.

7 Summary and Conclusions

A number of offshore wind farms are currently being planned. It is necessary and mandatory to study the effects of those wind farms with respect to the safety of shipping in order to estimate the related risks to people, ship traffic and the environment. Germanischer Lloyd's Guideline for Risk Analysis for Offshore Wind Farms [7] outlines requirements and methodology to calculate ship collision risks. Risk is defined here as the product of collision frequency and collision consequence.

Within this paper emphasis has been set to the consequences for different wind turbine foundation designs considering different ship types. Foundation types are mono pile, steel tripod, jacket and gravity type foundation. Ship types considered are a 31,600 tdw double - hull tanker, a single - hull (150,000 tdw) tanker, a container ship (2,300 TEU) and a bulk carrier (170,000 tdw). These are large vessels with a length of up to 300 m compared to the width of a wind turbine foundations with the magnitude of up to 30 m.

Which of the foundation types can be considered a "Collision Friendly Foundation Design"? To answer this question results from research projects SAFESHIP[9] and TUHH [10] have been incorporated as well as new simulation studies. All results have been derived from numerical simulations using the Finite Element Method. Both the ship and the wind turbine were modeled as deformable structures. Within SAFESHIP the ship was simplified as a non deformable body, since only the reaction forces and deformations of the wind turbine were investigated with respect to wind turbine parts falling onto the ship.

The mono pile has revealed to be of the CFFD-type, since no major hazards occurred at the ship during collision. The impact energy of the ship is very high and leads to a complete destruction of the wind turbine. It is likely that the wind turbine is pushed down by the ship in a way that the wind turbine falls onto the sea floor in the drifting direction of the ship. Due to the round shape and the large diameter of the foundation in the contact zone, the ship collision will form a local hull deformation, but it is unlikely that a crack appears. The collision leads to a high bending moment in the tower top region, it is not designed for. Therefore it is possible that buckling in the tower top region takes place or the tower to nacelle connection fails. In this case it is difficult to predict whether the nacelle could fall onto the ship.

For the tripod designs investigated, certain hazardous scenarios were identified by numerical simulation. In case the central tripod joint lies below the ship bottom, the steel tripod can be considered a CFFD-type and shows a behavior similar to that of a mono pile. In case the central joint and upper braces are in the depth of the ship hull's contact area, this can lead to substantial damage in the hull structure and should be investigated thoroughly in each individual case.

Within the jacket foundation the impact energy can be transformed into large deformations as far as the structure is able to withstand the ship's impact long enough without being torn off the foundation piles. Local damage in the model caused by the jacket's joints should not lead to widely damaged areas of the ship's hull. As the joints were modeled very stiff higher damage of the ship occurred as it would in a real collision. Although large damaged areas at the ship hull in the contact zone are unlikely, it is possible that the wind turbine tilts towards the ship, since the damaged jacket structure acts like a plastic hinge for the OWT.

For gravity based foundations first preliminary simulation results show the tendency, that it will be a CFFD-type, if the foundation base is below the ship hull bottom line. In this case the collision mechanisms are comparable to that of the mono pile. The results indicate that overturning of the foundation does not take place. Further investigations are necessary to study the behavior of gravity based foundations. What about other structures, e.g. combined types like a concrete tripod? For a concrete tripod the authors assume a similar behavior than for the steel tripod. Obviously the concrete tripod is of higher local stiffness and will absorb less impact energy than the steel tripod. But more important is that the central joint lies below the ship hull bottom line, so that the central column with it's smooth round shape builds the collision contact point in order to avoid a torn open ship hull.

A "Collision Friendliness Matrix" has been developed on basis of the a.m. results considering different ship types and different foundation types. Purpose of this matrix is to bring a foundation designer in the position to get a first impression, whether his design may be of the CFFD-type. But the authors recommend performing a collision analysis for the final foundation design by use of FEM, since the "Collision Friendliness Matrix" can only give a rough indication.

Further investigations are necessary to develop simplified analysis tools. More research is needed to analyze consecutive faults. Is it likely that a wind turbine nacelle topples down, falls onto the ship and perforates the top side and the hull bottom with large oil quantities spilling out or is this an extreme unlikely scenario?

8 References

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