TITLE : **Investigation of ship impact against wind turbine foundations in the Dutch part of the North Sea.**

DOCUMENT NO. : 081.R030.M006-Rev.4

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Version	Description	Author	Date
0	Original issue	Ir J.H.A. van Rooij	9 December 2020
1	Comments Marin included	Ir J.H.A. van Rooij	17 December 2020
2	Soil failure results updated (marked in border)	Ir J.H.A. van Rooij	17 May 2023
3	Final version	Ir J.H.A. van Rooij	25 January 2024
4	Table 1.1 updated	Ir J.H.A. van Rooij	5 March 2024

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APPENDICES

1. Introduction.

Due to the increase in the number of offshore wind farms (OWF) in the North Sea, during the last 15 years and still to be expected for the next 15 years, and due to the increase in ship traffic in the waterways alongside these wind farms, see lit. [1], Rijkswaterstaat (RWS) wants to assess the scenario of potential collisions between ships and wind turbines. Based on this and when feasible RWS then wants to issue guidelines/rules for the design of future windfarms in order to minimize the effect of these collisions for the ships and its crew and passengers, the environment and for the foundations.

In 2005 the project SAFESHIP (https://cordis.europa.eu/project/rcn/86899/factsheet/en), lit. [1], was carried out to address the issue of ship collisions against wind turbines. Since the finishing of the SAFESHIP project, new studies and analysis techniques have been executed, thus it is necessary to align both the theoretical background and the analysis method established in 2005 for the SAFEHSIP project with the latest developments.

For this reason RWS has asked MARIN and HVR Engineering to execute a literature review to the latest state of the art concerning ship/wind turbine collision, focusing in particular on the calculation methods currently available to assess this scenario. Also HVR Engineering has been asked to repeat the 2005 calculations using the design information of the most recently established wind farms in the Dutch part of the North Sea and ship sizes presently sailing these waters as following from studies executed by MARIN. A review of the windfarms in the Dutch part of the North Sea, already realized, being build or planned, is presented in Table 1.1. Finally MARIN was asked to organise an expert meeting in order to discuss the results and possible ways forward.

This study should not only be based on ships presently sailing through the Dutch windfarms, but should concentrate on ships sailing the Dutch waters in the neighbourhood of the wind farms and that could accidentally sail into the windfarm or that could drift into the windfarm in case an emergency happens with the ship.

Wind farm	**Country**	**Owner**	**Capacity (MW)**	**Turbines (nrs)**	**Status**	**Year operational**
Prinses Amaliawindpark	Nederland	Eneco	120	60	Realized	2008
Luchterduinen	Nederland	Eneco	129	43	Realized	2015
Windpark Borssele (Borssele III t/m IV)	Nederland	Blauwwind Consortium	731.5	77	Realized	2021
Gemini	Nederland	Gemini	600	150	Realized	2017
Windpark Borssele (Borssele I t/m II)	Nederland	Ørsted	752	94	Realized	2020
Windpark Borssele (Borssele V Leegwat	Nederland	Two Towers (van Oord, e.a.)	19	2	Realized	2021
NoordzeeWind (OWEZ)	Nederland	Vattenfall	108	36	Realized	2008
Windpark Hollandse Kust Zuid (1 t/m 2)	Nederland	Vattenfall	770	70	Realized	2023
Windpark Hollandse Kust Zuid (3 t/m 4)	Nederland	Vattenfall	770	70	Realized	2023
Hollandse Kust (noord) I, II	Nederland	CrossWind (Shell en Eneco)	700		Realized	2023
Hollandse Kust (west) VI	Nederland	Ecowende (Shell en Eneco)	756		Planned	2026
Hollandse Kust (west) VII	Nederland	Oranje Wind Power II (RWE)	700		Planned	2026
Waddeneiland Noord	Nederland		700		Planned	2026
IJmuiden Ver	Nederland		4000		Planned	2027

Table 1.1: Windfarms in the Dutch part of the North Sea.

In this report a summary is given of the investigations carried out by HVR Engineering. The results of this study are preliminary and give insight in the possible failure scenarios that can occur when a ship impacts a wind turbine foundation. The study is presently limited to mono pile foundations as this is the only foundation presently used in the Dutch part of the North Sea and hence only as-build information of this kind of foundations will be available.

In Section 2 a brief summary of the literature survey results will be presented. Next, in Section 3, the results of the search for as-build information is discussed. Then, in Section 4, the assumptions made for the simulation model will be discussed and their possible effect on the simulation results. In Section 5 the investigated wind turbine foundations is presented and the main properties of the ships used for the investigation are presented. The results of the simulations will be presented in Section 6 and the main conclusions will finally be summarised in Section 7.

2. Literature survey.

The results of the literature survey are presented in lit. [4]. The main conclusions following from this study are presented below.

1. The ship impact risk is of particular importance for the offshore wind industry since it can cause structural damage or collapse of the wind turbine, ship's structural damage, pollution generated from oil/chemicals spillages due to ship damages and injuries and/or loss of life of ship crew and passengers.
2. The main factors that can contribute to the ship collision event are human errors, mechanical breakdowns and prohibitive weather conditions.
3. Different types of wind turbine foundations are currently present in the market (e.g. mono pile, jacket, tripod, floating) and every structural layout will respond differently to a ship impact event.
4. Different industry standards address the topic to some extent, with the most comprehensive method for the assessment of this accidental scenario found in the NORSOK N-004 document, which is also incorporated in the DNVGL-RP-C204 standard.
5. Three possible assessment methods are available to perform the study of the consequences of a wind turbine/ship collision event:
    a. Simplified methods based on risk analyses and probabilistic assessments.
    b. Analytical models, able to reasonably describe the deformation modes of a wind turbine subjected to ship collision. These models are particularly useful in the foundation pre-design stage but they might be difficult to implement for complex structural layouts of the foundation (e.g. jackets).
    c. Advanced numerical models, in which the FE method is applied to accurately describe the deformation and failure modes of the wind turbine foundation, also accounting for soil-structure interaction and a proper flexibility of the impacting vessel.
6. The analytical assessments developed through the years mostly focused on the structural behaviour of the foundations and neglected the soil failure consideration. These models were initially developed for oil and gas offshore platforms, and for these structures it holds that base shears and overturning moments caused by collision forces are normally smaller than those generated by extreme waves.
7. Neglecting the soil-structure interaction will produce non-realistic deformations in the foundations as found in the several numerical investigations reported in the literature review.
8. From the numerical investigations reported in the literature review, it is clear that the impact velocity at which the ship collides against the foundation is particularly important as it can define the damage mode experienced by the foundation. For example, in one literature source the limit impact velocity resulting in a global collapse of the foundation has been calculated as 5 m/s for a 5,000 tonnes vessel impacting on a mono pile. Different impact velocity limits might be calculated for different vessels.
9. Considering a rigid colliding ship will produce excessive deformations in the foundations by neglecting the possible energy dissipation in the ship impact region. For example, in one literature source it is mentioned that the flexibility of the striking ship reduces the deformations of the wind turbine by a factor 2 for the analysed load scenarios.

10. By comparing the numerical analyses performed in 2005 for the SAFESHIP project with the latest analyses performed in recent years, it is possible to notice that the “simplified” approaches used for the SAFESHIP project produced consistent results in terms of deformation patterns with the latest calculations. The SAFESHIP models can also give an indication about the soil failure, useful for estimating the post-impact serviceability of the wind turbine under investigation.
11. A refinement of the SAFESHIP FE models is suggested to incorporate the latest development of the current FE analysis software to produce more accurate results, especially in the local dent region.
12. A possible implementation of a more refined model for the impacting region of the ship could provide more insight on the failure modes of the ship, and in particular indicating if fracture of the hull would be likely or not under the analysed impact scenario.

This study shows that various studies to the effects of ship impact have been carried out. Most studies however concentrated on relatively small ships up to a displacement of c.a. 5000 tonnes. One study also investigated larger ships up to 250000 tonne and concluded that the investigated mono pile was not able to withstand the impact.

The results of these studies are interesting and give background information for the issue at hand. However, none of these studies gives the information that RWS is looking for in order to be able to base future legislation on. Hence, more detailed and coordinated studies are required in order to investigate the effects of various collision scenario’s.

3. Survey for technical data.

To be able to repeat the ship impact simulations as performed in 2005 during the SAFESHIP project for the present wind farms, detailed technical information of the wind turbine foundations are required. Therefore the owners, building contractors and turbine manufacturers have been contacted with the request to provide this information. In lit. [3] a background description and general description of the required information is presented that has been send to all parties involved with the wind farm construction. A more detailed specification in order to align the information provided by each wind farm is presented in lit. [6].

This search for information started by the end of 2019 and up to now no as-build information has been received from any wind farm in the Dutch part of the North Sea. Partly this was caused by the Corona situation, but it turned out that all parties involved are bound by NDA's that prevent the provision of as-build information to 3rd parties. Most parties do see the need for the study proposed by RWS and they also see the need to be involved in order to have some influence on future legislation that might be developed by RWS in the near future based on the results of this study. However, the urgency for this matter is lacking and also parties are afraid that they will provide more detailed information than other parties and therefore they are afraid to come in an unfavourable position.

It also didn't help that in the period that MARIN and HVR Engineering were requesting information from the various windfarms similar requests were made from other governmental parties, e.g. ' Staatstoezicht op de Mijnen (SodM). Parties became irritated and didn't understand why they had to provide information twice.

Presently the activities to get as-build information are still on going, but in the near future it would help to get this information from all wind farms when a coordinated governmental effort is put into this so that it is guaranteed that all windfarms provide the same as-build information and no party gets the feeling of coming into an unfavourable position. For future windfarms it might be wise to include in the concession conditions that the parties are obliged to present the as-build information of the wind farms to the government in order to facilitate this kind of studies.

Presently from one party the conceptual design of 2 wind turbine foundations has been received. The provided information covers the requested information as detailed in lit. [6]. This foundation is for an offshore wind turbine with a power in the order of 10 MW. This information will be used for the simulations as presented in Section 5.

4. Discussion of model assumptions.

In lit. [5] a review is given of the ship impact simulation programs as they were developed for the SAFESHIP project in 2005. Below the main assumptions will be discussed briefly, together with an impression of the expected effects on the simulation results.

4.1. Finite element program.

All simulations have been carried out with ANSYS rev. 2020, using implicit calculations. This means that the simulations are stopped when large plastic deformations occur in the elements and the numerical solution becomes unstable. So post failure calculations during collapse of the foundation can not be carried out with this model.

To achieve this it is required to transfer to the explicit formulation within ANSYS. However, for the present model that is based on beam elements this is not feasible as the accuracy of beam elements in the post failure conditions is überhaupt limited.

4.2. Foundation model.

1. The foundation, consisting of mono pile, transition piece and tower for traditional designs and consisting of mono pile and tower for more recent design, is modelled using beam elements. The model is presented in Figure 4.1.

   In this document, when reference is made to the 'foundation' then the complete structure supporting the nacelle consisting of mono pile, transition piece (when present) and tower is meant.

   The beam elements used during 2005 where semi-3-dimension elements that support elasto-plastic material models and that allow the stress calculation at various locations around the circumference of the pile using integrated postprocessing in the element formulation. A limitation of these elements was the circumferential cross-sections remain circular, even under large deformations. This means that ovalisation of a pipe that occurs during bending is not included in the element formulation.

   For the present investigation a new element type has been used that in addition to the properties of the previously used element also includes the formulation to describe the ovalisation of the pile during bending. This will result in more accurate simulation of the actual pile behaviour.

2. The most recent pile foundations for wind turbines are not often equipped anymore with grout connections, but are using flanges to connect the T-piece or tower with the mono pile. Also between tower and transition piece and between the various tower segments flanges are used. These flanges are steel rings with a total thickness of 2 flanges in the range of 250 a 300 [mm] and a width in the range of 250 [mm]. These flanges increase the stiffness of the mono pile, T-piece or tower against ovalisation and hence will increase the resistance against failure. These flanges are presently included in the FE-model as short beams with a locally increased wall thickness equal to the flange width.

3. The mass of the foundation consists of:

   a. Steel mass of all tubulars.

      This is included by the foundation dimensions used for the model and the specified steel density.

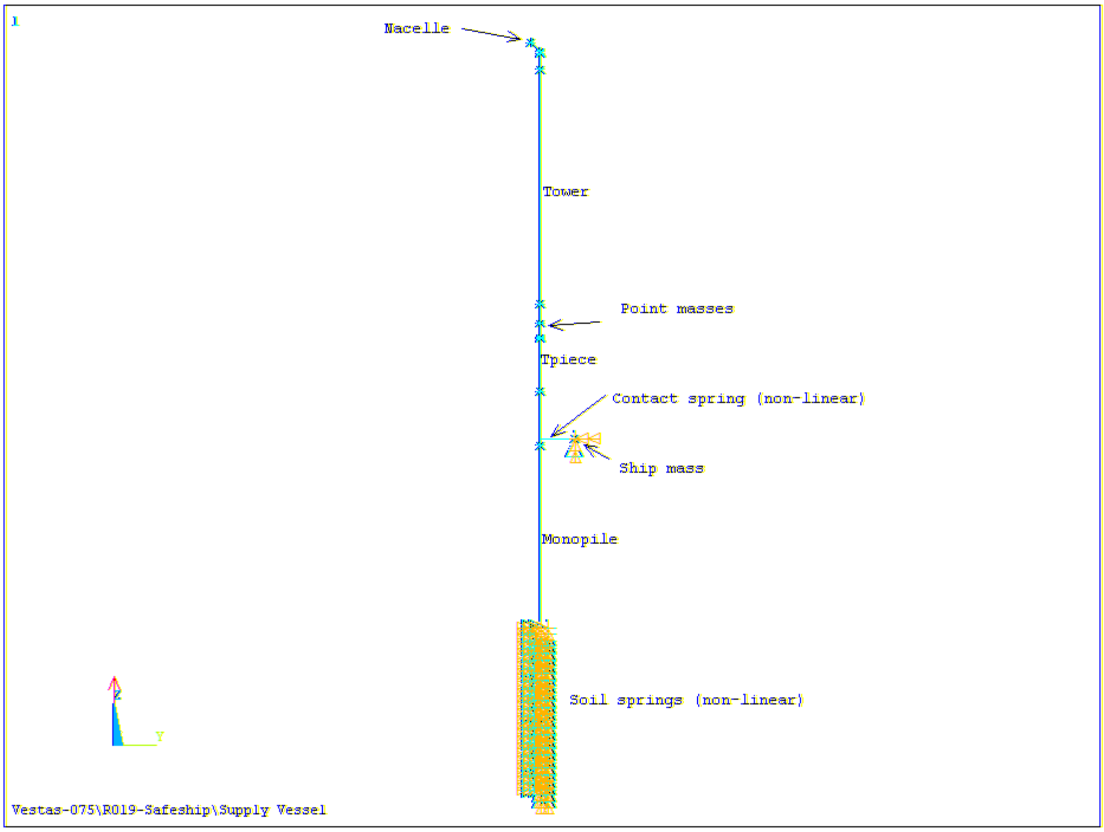

Figure 4.1: ANSYS model for ship impact against an offshore wind turbine foundation, build-up out of beam elements.

b. Concentrated masses, e.g. of flanges, platforms, equipment in the tower, etc.

   When specified by the wind farm representatives, these masses are included as mass points located at the centre line of the foundations. These mass points don’t have mass moments of inertia.

c. Nacelle and rotor.

   The nacelle and rotor are modelled as separate mass points when provided as such by the wind farm representatives. These mass points can have mass moments of inertia when this information is available. The mass points are located at the specified locations of the Centre of Gravity and are connected to each other and the tower top by stiff massless beams.

d. Marine growth.

   Marine growth can be included when desired to account for the added mass caused by this. For the simulations presented in this report, marine growth has not been taken into account.

e. Water inside and outside the pile.

   The water inside and outside the pile is taken into account as an addition to the dynamic mass of the foundation.

4. Secondary steel at the outside of the foundation is not included in the model. In general this is no problem as the secondary steel is not structural and the mass, dimensions, stiffness and strength are negligible in comparison to a ship.

   The exception in this is the main platform, which is in general located somewhere between 15 and 25 [m] above LAT. For the smaller ships the platform is located outside the main impact area but might collide with the upper part of the ship. For the larger ships, e.g. large tankers, passenger vessels and container ships, the main platform might be the first part of the foundation coming in contact with the ship. The interaction between ship and platform will not sink the ship, but the platform might penetrate the ship hull or the upper part of the ship an cause severe damage and can possibly lead to injuries or death of personnel and passengers.

4.3. The soil.

The lateral stiffness of the soil has been modelled by P-Y-curves determined for the calculation of the foundation stability under lateral loading. An example of such P-Y-curves valid for the conceptual design investigated in this document is presented Figure 4.2 for various penetration depths. The penetration depth is relative to LAT, with in this case the soil level being located at -25.6 [m].

P-Y curves are numerical models used to simulate the response of the soil resistance (p, soil resistance per unit length of the pile) to the pile deflection (y) for piles under lateral loading. With this approach, the soils are represented by a series of nonlinear springs varying with the depth and soil type in the analysis for laterally loaded piles. The P-Y curves are derived from soil test data, e.g. Cone Penetration Tests (CPT) data, that are determined from bore holes located at the actual locations where the turbines are going to be placed. Nowadays CPT data are derived typically for every turbine location in a wind farm. There exist various methods to transfer the measurement data to P-Y curves, for example as specified in API RP2A 21st Edition (2000).

The curves show that when the lateral displacement becomes too large, the gradient decreases to zero and the soil will fail. For the upper soil layers failure will already occur after a displacement of ca. 250 [mm], whereas deeper soil layers fail after a displacement of 1 [m] or more.

One of the uncertainties in these P-Y models with respect to the ship impact analysis is how the soil behaves when the ship motion has stopped and the foundation starts to spring back elastically. Especially in the case that no plastic deformation occurs in the foundation. One can either assume that the unloading path is the same as the loading path in which case the stored energy in the nonlinear springs is at least partly returned to the ship, pushing it back until contact is lost between ship and foundation. The remaining elastic energy is transferred into kinetic energy of the foundation, causing the foundation to vibrate in its own frequency. Another possible assumption is that the elastic return path follows the same slope as the slope of the P-Y curve at zero displacement. This return path is shown in Figure 4.3 by the red line. In this case the energy returned to the ship and remaining in the vibrating foundation is much less as it is assumed that most energy is taken up by the plastic, permanent, deformation of the soil.

It will be shown in this document that the difference in behaviour of the foundations for these two methods can be considerable. The reality will most probably somewhere in between those two extremes.

The PZ-curves that model the vertical soil resistance are not included in the model. Instead it is assumed that the pile tip cannot move in vertical direction.

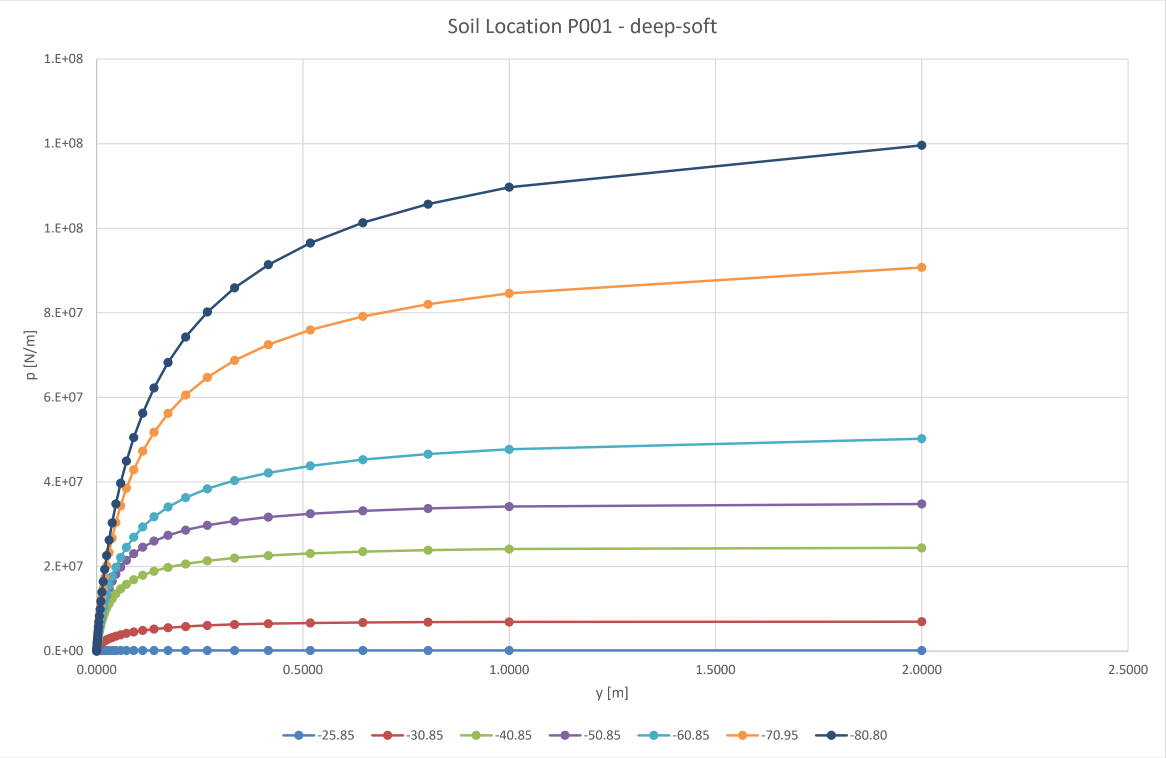

Figure 4.2: PY curves of example soil location P001 – deep-soft.

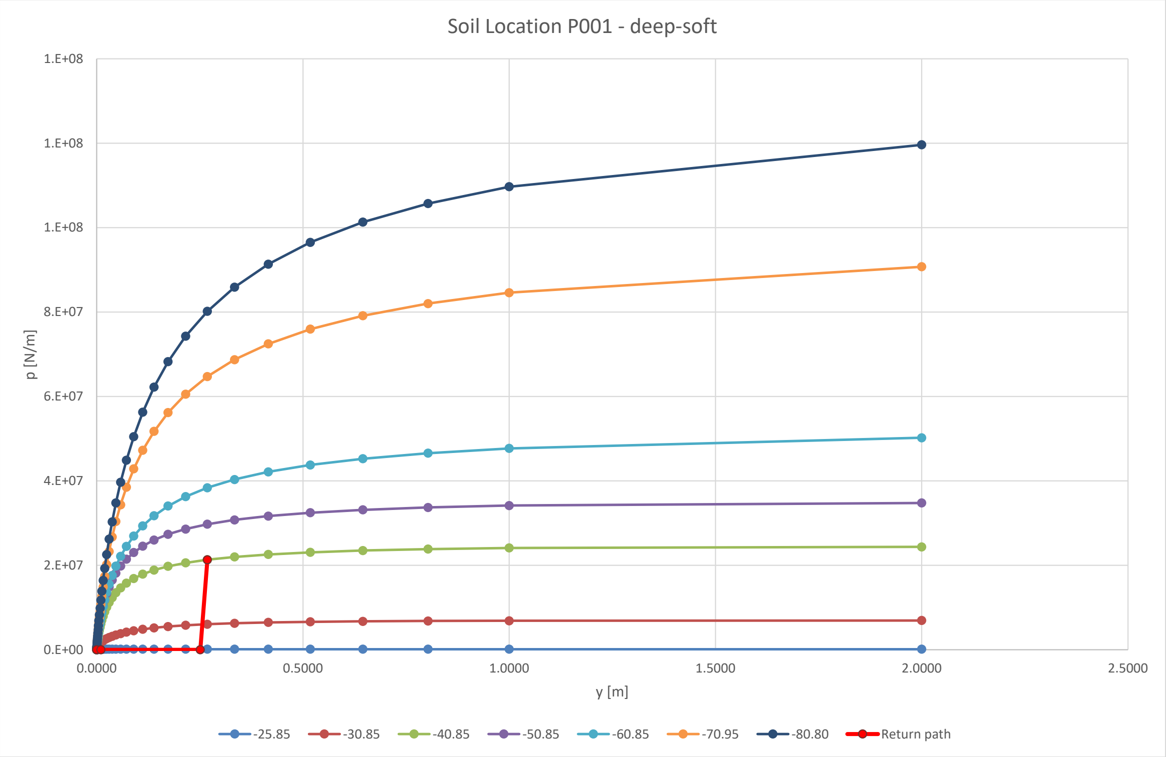

Figure 4.3: PY curves of example soil location P001 – deep-soft, with possible return path (in red).

4.4. External loads acting on the foundation.

The wind turbine foundations are of course continually loaded by current, wave and wind loads and when the turbines are operating of course also by the loads applied by the wind turbine. These loads can be derived by separate simulations programs and can be applied as constant or time-varying loads to the FE model used for the ship impact simulations. This is option already has been implemented in the present FE-model, but is presently not used as the loads acting on the foundation are presently not known.

For the simulations presented in this document these loads have not been included. The main reason for this is that these loads are not available for the conceptual design that is used for these simulations. Another consideration is that this study is aimed at ships normally not operating inside the wind farm, e.g. supply ships or maintenance vessels, but at ships accidentally sailing or drifting into the wind farm. Early warning systems are present that can warn the wind farm when a ship tends to sail or drift into the wind farm so that that the turbines can be shut down before the ship actually enters the wind farm. Apart from storm conditions, the normal wind, wave and current loads without the turbine being operational are small in comparison with ship impact loads, so the error made by neglecting these loads are small for the present study.

During the expert meeting it was noted that the new windfarms can be shut down in ca. 20 [minutes]. The present early warning systems give out a warning when a ship is within 500 [m] of a windfarm. This is thus too short to shut down the windfarm in time. Shortly however, a new AIS system will come online that allows a more early detection of ships nearing the windfarms.

Results presented in the literature survey, see lit. [4], show that for supply ships impacting against the wind turbine foundation the wind direction in case of an operating wind turbine indeed has an effect on the failure mode. Collapse of the wind turbine foundation will occur at lower impact velocity if the ship sails against the wind when impacting the foundation.

Furthermore, for the large container ships and passenger vessels there is the danger that the blades of an operating wind turbine will hit the superstructure of the ship, with possible severe consequences for crew and passengers.

4.5. Damping.

Hydraulic and aerodynamic damping have not been taken into account. Investigative calculations have shown that the effect of this is negligible in case of ship impact.

The gyroscopic effect of a rotating rotor has not been taken into account either. Investigative calculations have shown that the gyroscopic effect of the rotating rotor in combination with the rotation of the nacelle+rotor due to the bending of the tower, results in a yaw motion of the rotor+nacelle. This yaw motion does not contribute to the bending loads on the tower or on the connection nacelle-tower. Due to the yaw motion of the nacelle only the direction of the bending load on the connection nacelle-tower changes. This should be considered when analysing the strength of this connection.

Structural damping in the steel material has also not been taken into account in this model as its effect is very small.

It must be noted that the absence of damping limits the accuracy of the simulation results after impact when no collapse of the foundation or the soil takes place. The foundation will then start vibrating in its 1st eigenmode and this motion will not dampen out anymore. However, as this post-impact period is presently not of interest, no effort has been made yet to include damping in the model.

4.6. The ship.

The ship is modelled as a point mass. This point mass is divided as a number of masses equally divided over the height of the impact area, as shown in Figure 4.4. The mass points of the ship are linked with respect to their horizontal displacement, so all points will always have the same horizontal displacement. The ship velocity at the moment of impact is the input for the simulation.

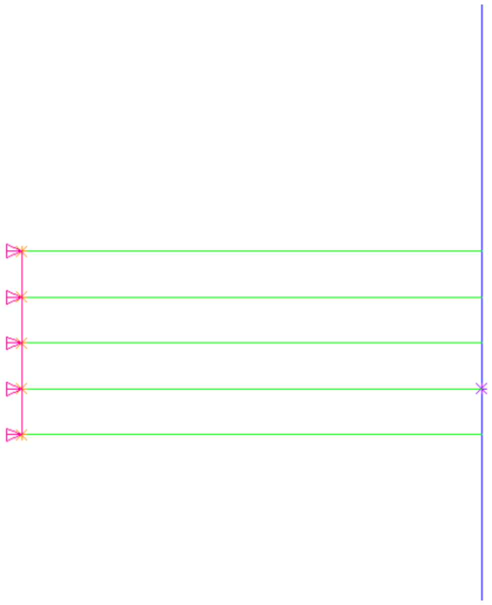

Figure 4.4: Ship modelled as a number of masses equally divided over the height of the impact area.

The parameters presently taken into account are as follows:

1. The ship mass.

   This mass is defined as the displacement of the ship, multiplied with a factor for taking into account the added water mass. The correction factors for the added water mass are:

   a. Sailing, frontal impact : Correction factor = 1.1

   b. Sideways drifting, broadside impact : Correction factor = 1.4

2. The mass moment of inertia of the ship.

   The program has the possibility to take into account the mass moment of inertia of the ship, including added water mass, around the vertical axis, in order to take into account the yaw motion of the ship when the impact between ship and foundation does not occur exactly in the centre of the ship and a sort of grazing impact occurs.

   In lit. [2] and [5] it has been explained that when the ship is modelled as a point mass, this effect results in an adaptation of the effective ship mass and thus of the kinetic energy of the ship. In general the effective ship mass will be lower than the displacement, so a grazing impact is less severe than a broad side impact directly at the location of the COG of the ship.

   In this study this effect has not yet been taken into account.

3. The impact velocity of the ship.

   In case of drifting, the impact velocity is taken as the drifting velocity of the ship due wind and current. It is based on information derived during the SAFESHIP study in 2005. In case of sailing, the impact velocity is taken as the normal cruising velocity of the ship as found in literature.

   In case of sailing impact, the propulsion force of the ship is not taken into account. It is assumed that impact occurs at a certain ship velocity and that at the moment of impact the propulsion is directly switched off so that the ship will come to a halt due to the impact with the foundation. When this is not the case and the propulsion force will keep on pushing the ship forward, then this will of course have an effect on the failure mode of the foundation. Especially for the larger ships this means that it is more likely that the foundation is pushed over and that the nacelle and rotor will drop away from the ship. For the smaller ships this effect is less easily to judge, but it is quite possible that this might have a negative effect on the failure mode of the foundation and might result in the nacelle and rotor dropping down towards the ship.

   In case of drifting impact the effects of the wind, current and wave forces pushing the ship forward is not taken into account yet either. It is assumed that these forces are negligible with respect to the forces introduced by the impact.

4. The vertical location of impact at the foundation relative to LAT and the height of the impact area.

   The water level is selected as the water level at MSL and using this level the impact position is estimated from the available ship dimensions.

   When this impact location moves upward due to changes in water level or due to the ship size, then this can of course have an effect on the failure mode of the foundation. First of all the bending moment acting on the pile part inside the soil increases when the impact point moves upward and thus failure of the pile part inside the soil might occur at an earlier moment. Also, when the impact area moves upward the wall thickness of the foundation in general decreases. This means that the foundation becomes more susceptible to local denting at the impact area.

   This last effect is however not possible to investigate in much detail using the beam model.

5. The angle of impact of the ship relative to the orientation of the nacelle and rotor.

   The mass moment of inertia of the nacelle and rotor differs along the various axes. This means that the impact direction of the ship relative to the nacelle and rotor orientation will have an effect on the dynamic motion of the nacelle and rotor. This might influence the failure modes of the foundation, although it is expected that the overall effect will be limited.

   The model has been set-up in such a way that the rotor plane is parallel to the YZ-plane so that the rotation axis of the rotor is parallel to the X-axis. Furthermore the ship is default located along the X-axis and is moving in the X-direction. So the impact is default taking place along the X-axis. However, by varying the angle of impact the impact direction can be changed to for example being along the Y-axis.

   For the simulations presented in this report the impact angle is equal to 0^o and impact takes place along the X-axis.

6. The impact force between ship and foundation.

The impact force between ship and foundation is determined by the resistance of the foundation and by the deformation of the ship body. The present model does not facilitate modelling the failure of the ship body. For this a full three dimensional model must be made that takes into account the actual ship geometry near the impact area and the actual foundation geometry so that also local denting effects can be included.

For this investigation reference is made to DNVGL-RP-C204 in which the impact force of a ship is defined as function of the ship indentation. Examples of these curves as used in this analysis are presented in Figure 4.5 to Figure 4.8. These curves will be used for the various investigated ships, scaled based on the actual ship displacement.

The non-linear force-displacement curves are just as the soil resistance modelled by non-linear springs. An example of such a modelled force-displacement curve is presented in Figure 4.9. This Figure shows that the curve consists of 3 parts:

a. Blue line : The force-displacement curve during impact.

b. Red line : The force relaxation curve. It is assumed that the ship deformation is permanent and that the elastic relaxation is small and has the same slope as the impact curve for zero displacement.

c. Green line : When the ship rebounds and loses contact with the foundation, the force remains zero.

The non-linear springs are shown in Figure 4.4 as the blue lines connecting the mass points with the foundation. The non-linear stiffness is equally divided over the modelled spring elements so that the sum of all elements is equal to the overall curve as shown in Figure 4.9.

The impact points on the foundation are fixed. This means that due to a large deformation of the pile a difference occurs in the vertical position of the mass points of the pile and the connection points on the foundation. This however does not affect the impact force as the impact force is a function of the horizontal displacement.

The mass points of the ship are linked with respect to their horizontal displacement, so all points will always have the same horizontal displacement. The displacement of the corresponding points on the foundation however can be different due to the bending of the foundation. The higher points will get a slightly larger displacement than the lower points when the foundation bends. As a result the impact force for the lower non-linear spring will become larger than the impact force for the higher springs. This is somewhat in agreement with what will happen in reality, although it will only be a crude approximation.

It must be noted that the impact force for broadside impact rises very steeply. This is probably due to the fact that for broadside impact the contact height is fairly large and that the stiffness of intermediate decks is quite high. Although the drift velocity of a ship is small, in the order of 1 to 2 [m/s] (2 to 4 [knots]), this high stiffness can lead to high accelerations of the foundation during impact.

For sailing impact, when contact either occurs at the ship bow or bulb, the impact force rises much more gently and the maximum impact force is in general also lower than for broadside impact, although it keeps

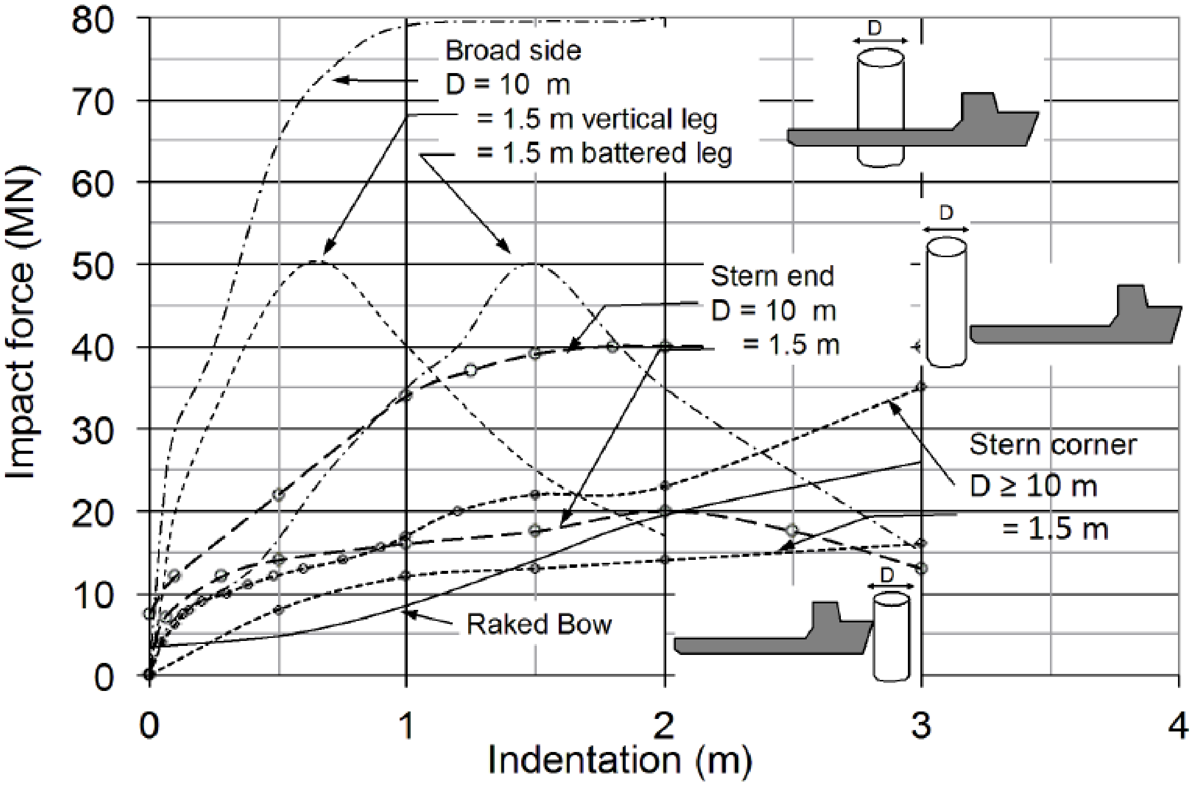

Figure 4.5: Force-deformation curve for standard supply vessels with a displacement of 6500 to 10000 [tonnes], for broadside, bow and stern impact.

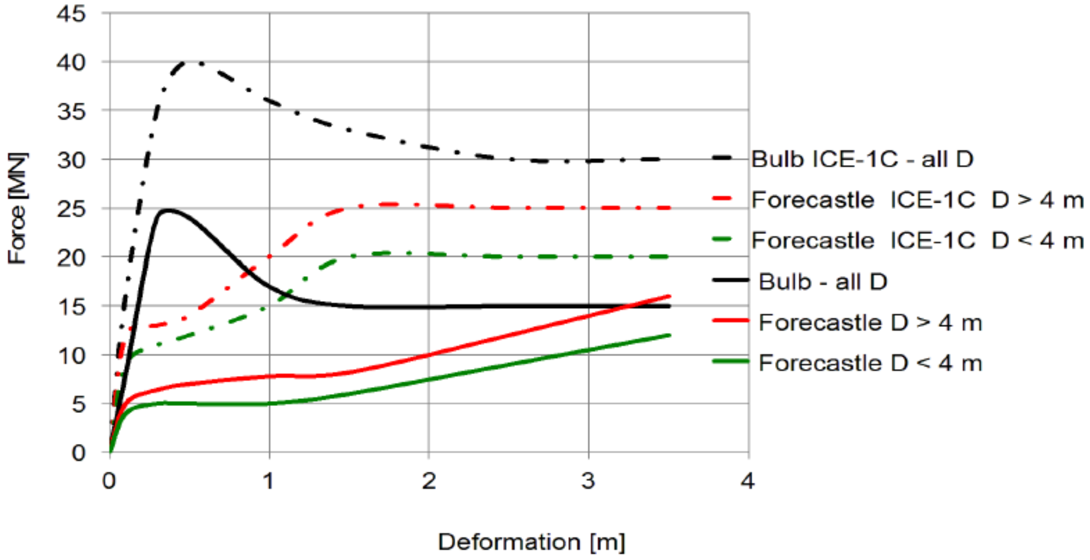

Figure 4.6: Force-deformation curve for the bow impact of supply vessels with a displacement of 5000 to 10000 [tonnes], for standard no reinforced bulbous bow and for reinforced bulbous bows according to class Ice(1C).

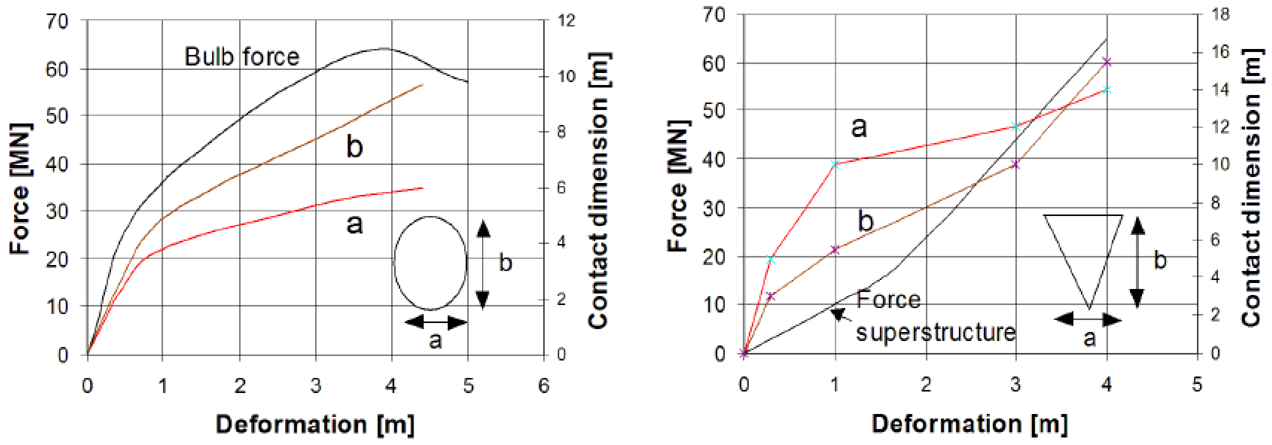

Figure 4.7: Force-deformation curve and contact area for tanker bow impact (~125000 dwt)

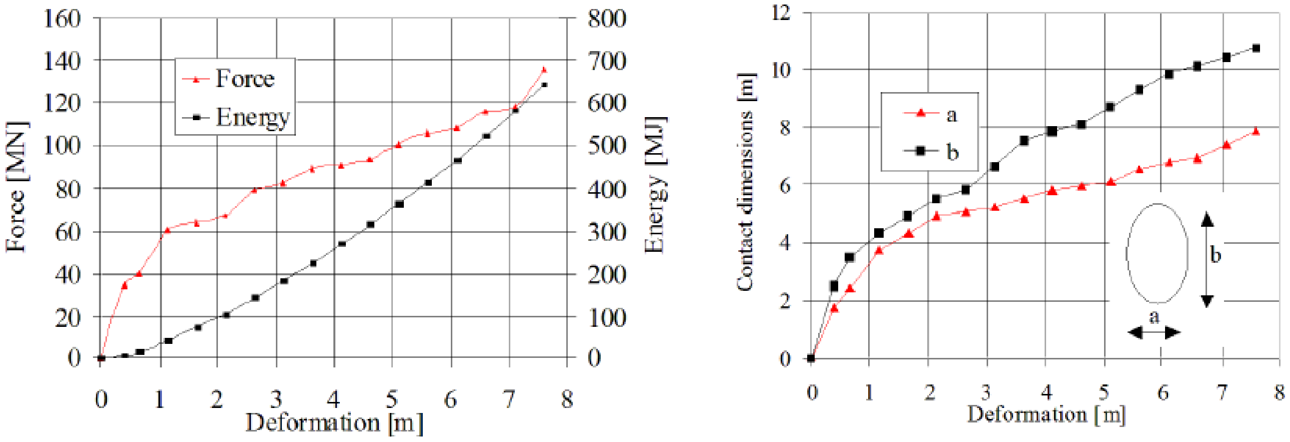

Figure 4.8: Force-deformation curve and contact area for the bulbous bow of a VLCC (~340000 dwt)

on rising when the deformation progresses. Whether the initial accelerations of the foundation are lower than for broadside impact is depended on the sailing velocity at impact.

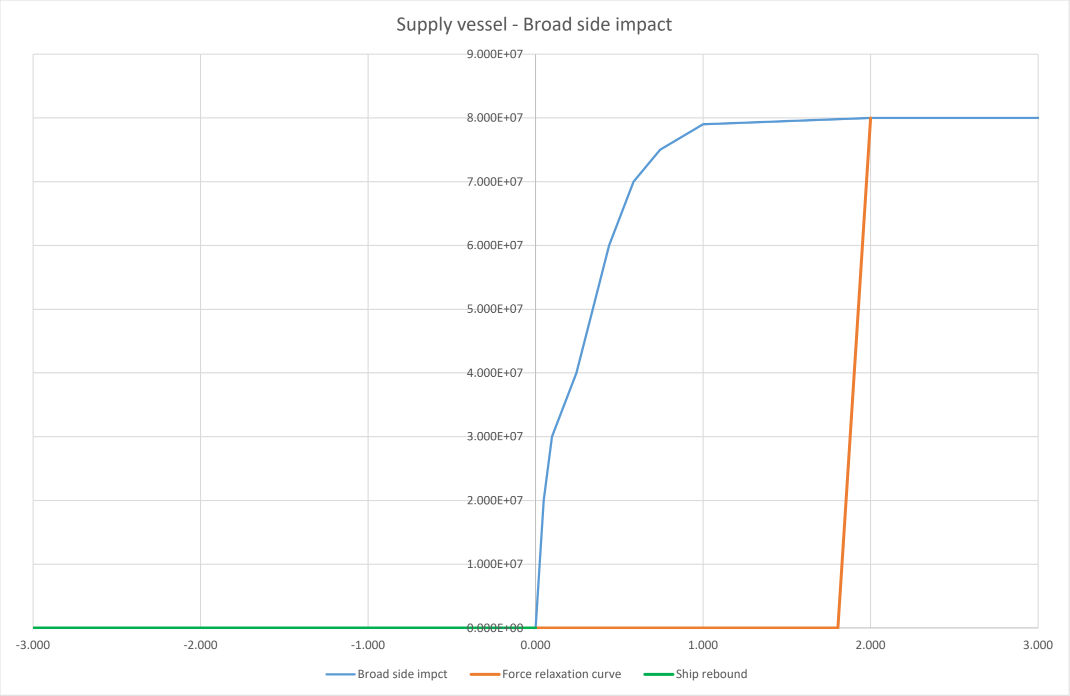

Figure 4.9: Modelled force-deformation curve for a supply vessel.

4.7. Foundation material properties and failure modes.

The material properties, modulus of elasticity, poisson constant and density, used for the foundation are the normal properties for standard construction steel. For the failure mode of the foundation presently the elements have a non-linear elasto-plastic material curve. This curve is presented in Figure 4.10. The material behaves elastically until a limit is reached and when the strain becomes larger than the elastic limit, the stress remains constant. When this happens at a cross-section of the foundation, the plastic zone will quickly develop over the whole circumference and the foundation will collapse. This will be indicated by the simulation becoming unstable and the calculation will stop.

The present model is thus not suitable for the simulation of the post-collapse behaviour.

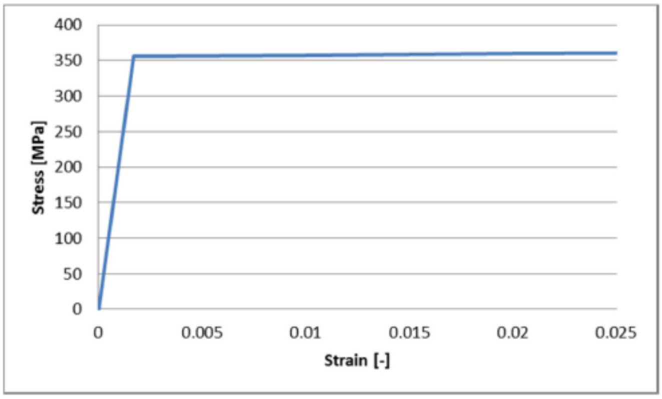

Figure 4.10: Non-linear material curve.

The limiting stress can be freely selected. Possible options are for example:

1. The nominal yield limit of the material, taking into account the reduction of this limit with increasing wall thickness. An example for construction steel S-355 is presented in Table 4.1.
2. The shell buckling strength of the foundation. The shell buckling strength is lower than the nominal yield limit and thus will lead to an earlier collapse of the foundation.

For the simulation presented in this document which are aimed at comparing the different failure modes for various windfarms, the nominal yield limit has been selected as the failure criterion. The material selected is according to the specifications for the windfarm under consideration. No material factor has been applied to these data that decreases the yield limit to an ‘ allowable’ limit.

Material S355 ML		
t_{min}	**t_{max}**	**σ_{yield}**
[mm]	**[mm]**	**[MPa]**
0	16	355
16	40	345
40	63	335
63	80	325
80	100	325
100	150	320

Table 4.1: Material properties for S-355.

5. Investigated configurations.

5.1. Foundations.

At the writing of this report no actual as-build data have been received from the windfarm representatives. Only from one entity a conceptual design has been received of 2 windturbine foundations for a future North Sea windfarm. These foundations are identified as P001 and P002. The received data include all specified data as described in lit. [6].

A summary of the received data as used for the simulations is presented in Table 5.1. It must be noted that the foundation in this case only consists of the pile and the tower. So no transition piece between pile and tower is present.

The P-Y curves for the soils at both locations are presented in Figure 5.1. The P-Y lines at the same penetration depth have the same colour and a different marker to identify P001 and P002. The diameter-wall thickness layout of both foundations is shown in Figure 5.2 and Figure 5.3. If follows that the pile diameter and maximum wall thickness below the mudline are larger at Location P001 than at Location P002. The penetration depth at Location P001 is however lower. Altogether it results in the same dynamic characteristics of the two foundations.

Figure 5.2 and Figure 5.3 show that at the most likely contact area between ship and foundation during a collision, e.g. between -6 [m LAT] and +20 [m LAT] the wall thickness of the foundation is fairly large. It further shows that the wall thickness of the tower, above 20 [m], is fairly small, with a thickness in the range of 30 [mm].

It must be noted that the flange dimensions are not available. This means that the ring stiffening effects of these flanges are not included in this analysis!

In Figure 5.4 the failure force of the soil is shown as function of the displacement at the contact point, together with the displacement at seabed and at the pile tip. It follows that the failure force for both configurations is almost the same. A numerical summary of the soil failure data is presented in Table 5.2. It follows that the soil failure force is equal to 46.4 [MN] for foundation P001 and 43.3 [MN] for foundation P002. It furthermore shows that the total energy that is required to push the foundation over is equal to 1357 [MJ] for foundation P001 and 1244 [MJ] for foundation P002.

Identification			P001	P002
Turbine	Rated power	[MW]	~10	~10
	Nacelle plus rotor mass	[tonnes]	644	644
	Hub height	[m LAT]	126	126
Tower	Top elevation	[m LAT]	122	122
	Bottom elevation	[m LAT]	17.5	17.5
	Top diameter	[mm]	4940	4940
	Bottom diameter	[mm]	7000	7000
	Maximum wall thickness	[mm]	59	59
	Steel quality		S-355	S-355
Pile	Top elevation	[m LAT]	17.5	17.5
	Bottom elevation	[m LAT]	-51	-50
	Top diameter	[mm]	7000	7000
	Mudline diameter	[mm]	8000	7500
	Maximum wall thickness	[mm]	94	82
	Main platform	[m LAT]	15	15
	Mudline	[m LAT]	-26	-23
	Water depth	[m]	26	23
	Pile penetration	[m]	25	27
	Steel quality		S355	S355
	Soil		Deep-soft	Representative
Water level	MSL	[m LAT]	1.1	1.1
Resonance frequency	1st mode	[Hz]	0.17	0.168

Table 5.1: Turbine, foundation and soil data.

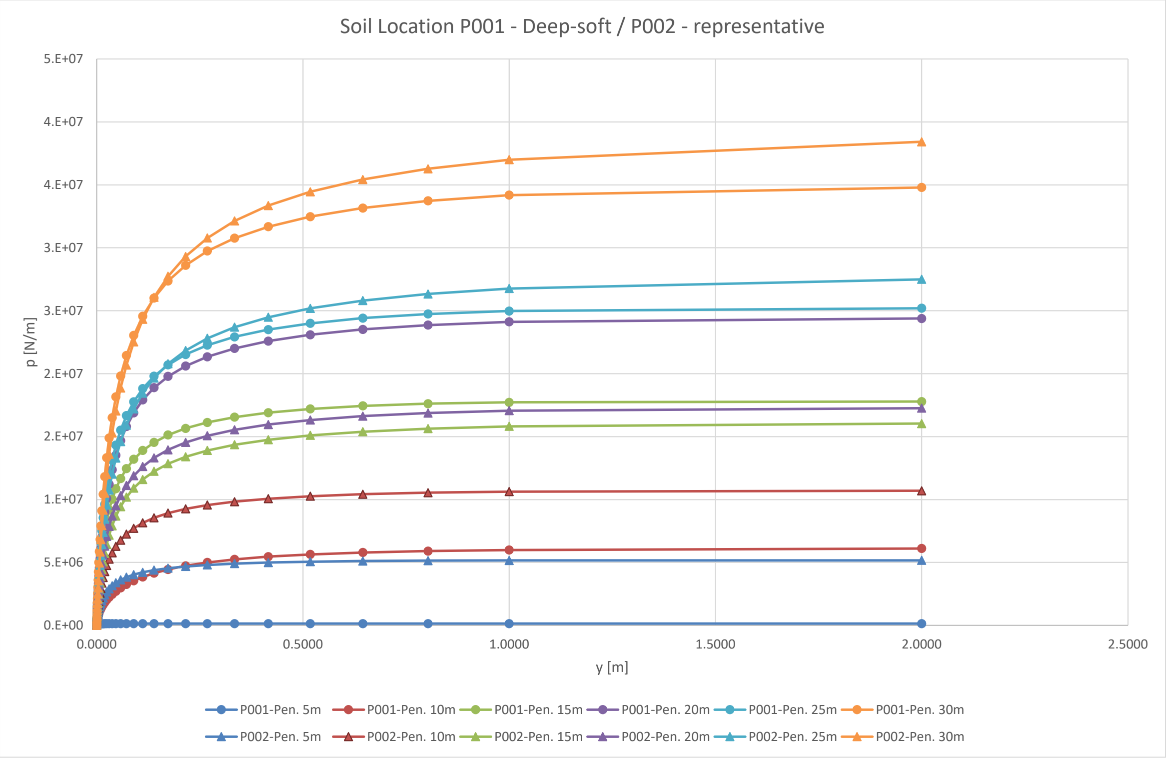

Figure 5.1: P-Y curves for location P001 and P002.

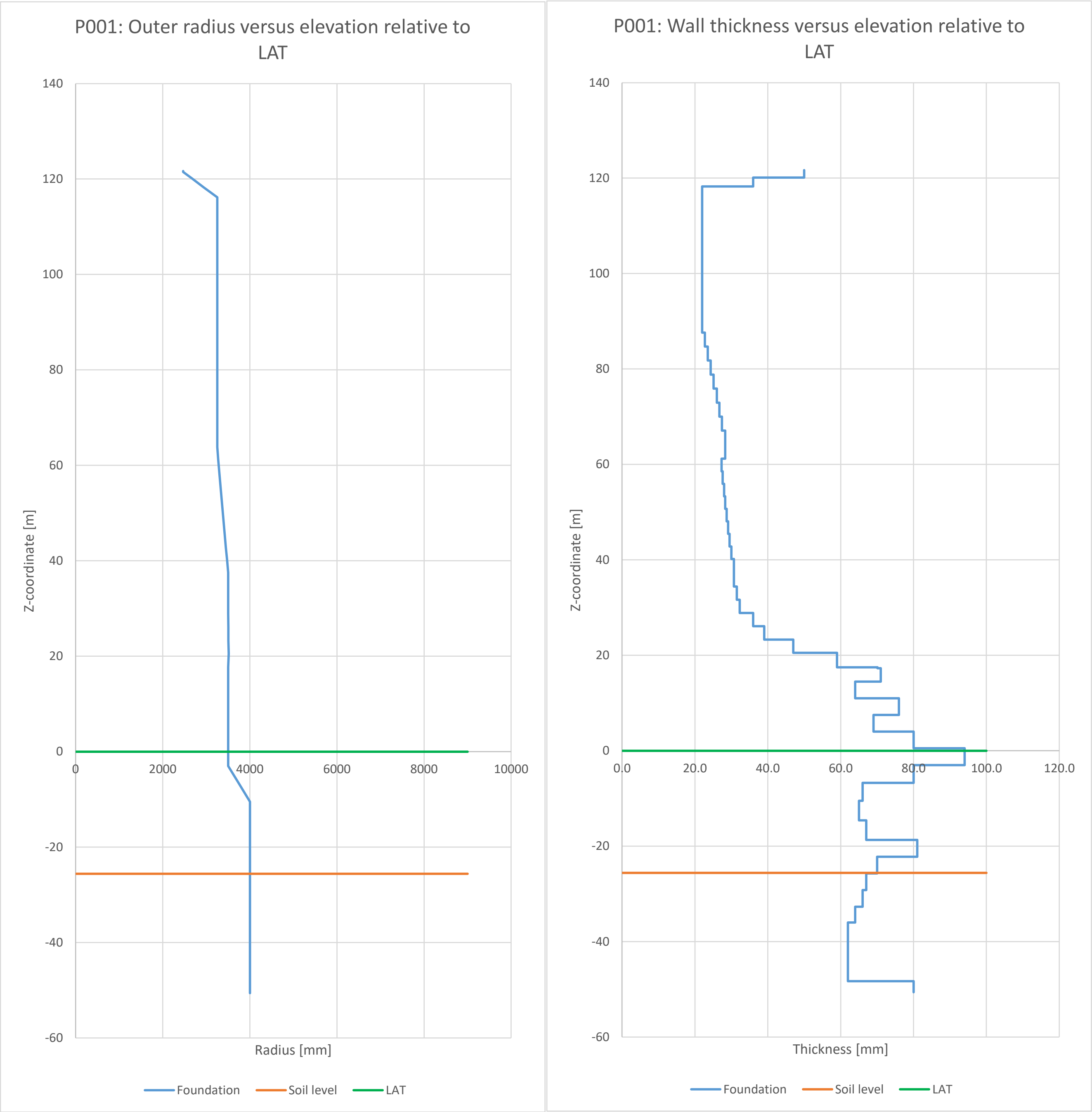

Figure 5.2: Outer diameter and wall thickness layout foundation P001.

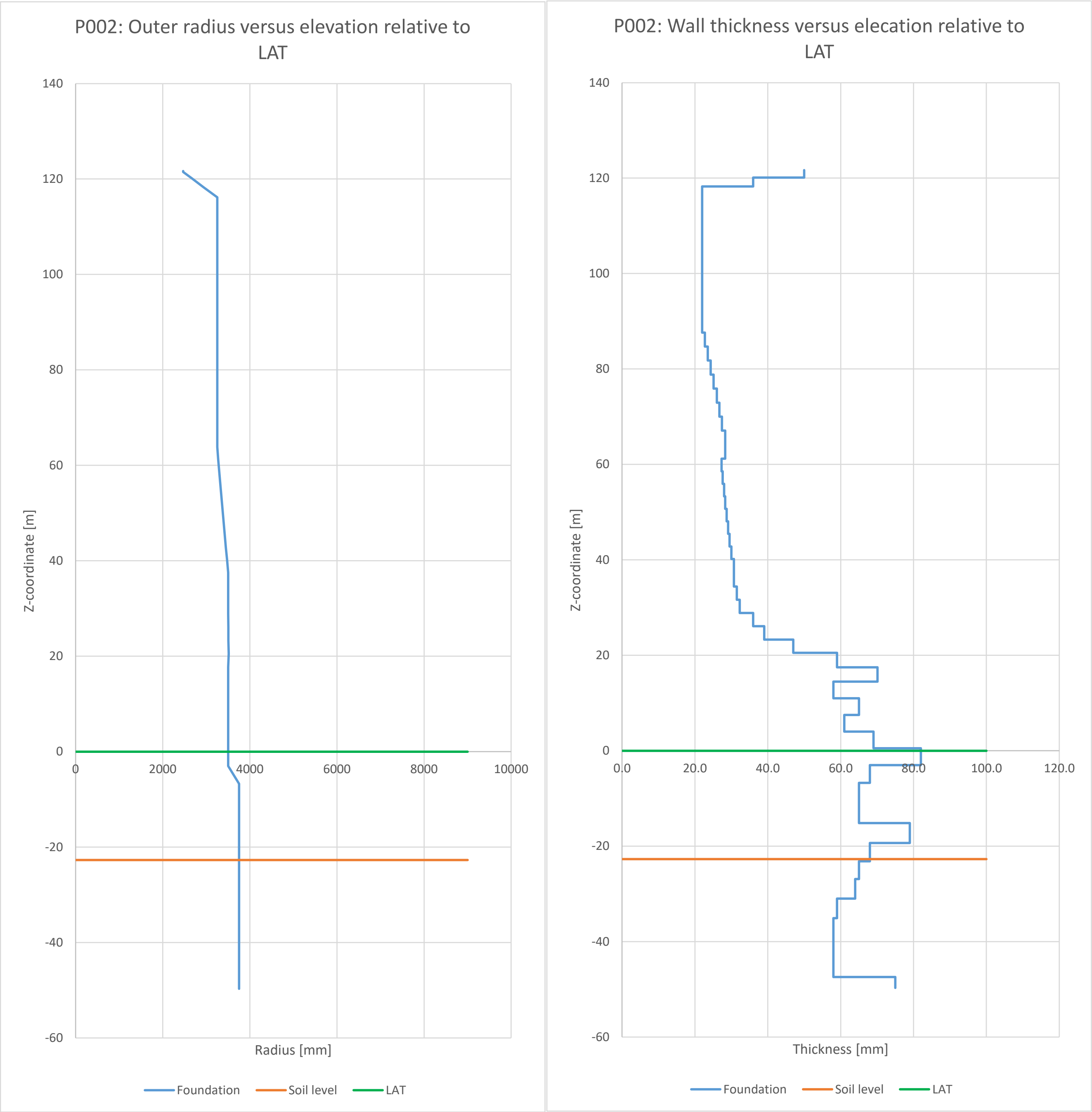

Figure 5.3: Outer diameter and wall thickness layout foundation P002.

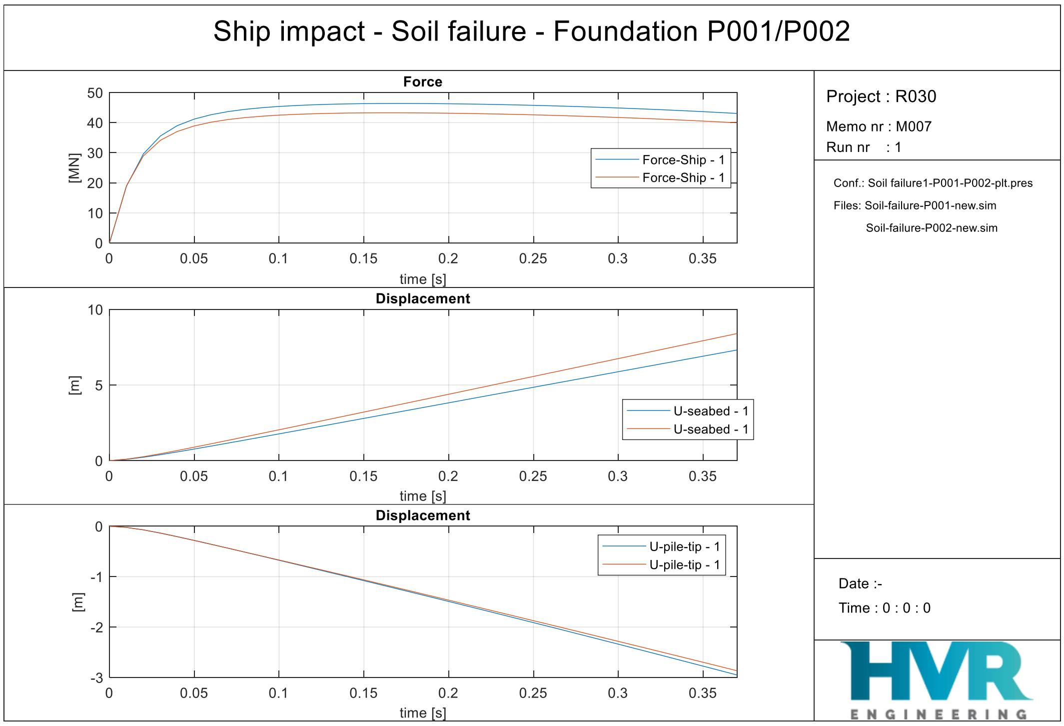

Figure 5.4: Soil failure

(Blue line = P001, Red line = P002).

Soil failure load		Conceptual designs	
		P001	P002
Water depth	[m]	26.0	23.0
Pile penetration	[m]	25	27
MSL	[m LAT]	1.1	1.1
Soil failure load at MSL	**[MN]**	**46.4**	**43.3**
Energy dissipation capacity	**[MJ]**	**1356.8**	**1243.8**

Table 5.2: Soil failure data.

5.2. Ships.

In Table 5.3 a summary is given of the main properties of the ships that have been used for the investigation presented on this document. These ships are partly taken from the SAFESHIP investigation in 2005, see lit. [2]. A Very Large Container Carrier, has been added. These ships are a rough cross-section of the ships sailing the waters near the Dutch windfarms.

This Table shows:

1. The ship displacement, which is governing for the impact energy, varies from 2853 [tonnes] to 223000 [tonnes]. The difference thus being almost a factor 10.
2. The impact energy when drifting varies from 4 [MW] to 192 [MW], for a drift velocity in the range of 1.1 to 1.7 [m/s].
3. The impact energy when sailing varies from 46 to 5000 [MJ], so a ratio of almost 100. The highest value does not occur for the largest container ship due to its low sailing velocity, but for a large passenger vessel that is sailing at quite a high velocity.
4. The location of impact has been estimated from some indicative ship dimensions, but must at this moment be regarded as an educated guess.
5. Based on the energy required to fully push over the foundations, see previous Section 5.1, and the kinetic energy of the investigated ships, it can be determined whether ultimately the foundations P001 and P002 will be able to stop the ship. This is presented in Table 5.4. It follows that all investigated drifting ships can be stopped by the foundations. For the sailing ships this is only true for the Kruiplijn coaster, the Supply vessel and the Chemical tanker. The Passenger vessel and the Container ship will sail over the foundation.

Typical dimensions.		**Kruiplijn Coaster**	**Supply vessel**	**Chemical & Product tankers**	**Passenger vessels**		**Container ship**
Gross Tonnage	**GT**	**1554 GT**	**3200 GT**	**10000 GT**	**100000 GT**		**192784 GT**
Length Lpp	m	77.40	76.20	135.00	242.00		379.40
Width B	m	11.30	19.70	23.00	36.00		59.00
Design Draught D	m	5.33	7.45	12.00			
Maximum depth T	m	3.73	6.10	8.30	8.30		16.00
Lightweight	ton	807.00	2,555.00	4,800.00			
Deadweight	ton	2,046.00	4,300.00	16,200.00			199,272.00
Displacement	ton	2,853.00	6,855.00	21,000.00	42,700.00		223,000.00
Displacement plus added water mass frontal	ton	3,138.30	7,540.50	23,100.00	46,970.00		245,300.00
Displacement plus added water mass broadside	ton	3,994.20	9,597.00	29,400.00	59,780.00		312,200.00
Bulb below water	m	n.v.t.	2.70	1.50	1.80		
Stem above water	m	3.65	8.44	9.00	16.20		
Drifting							
Combined Wind drift and eq. Current velocity	knots	2.78	2.78	2.62	3.40	2.20	2.22
	m/s	1.39	1.39	1.31	1.70	1.10	1.11
Typical drifting kinetic energy	MJ	3.87	9.29	25.15	86.29	36.17	192.01
Impact height relative to water level: Top	m	3.00	6.00	9.00	16.00		20.00
Impact height relative to water level: Bottom	m	0.00	0.00	0.00	0.00		0.00
Normal sailing							
Normal sailing velocity (1 knot ~ 0,5 m/s)	knots	10.80	15.00	14.00	29.00		7.60
	m/s	5.40	7.50	7.00	14.50		3.80
Normal sailing kinetic energy	MJ	45.76	212.08	565.95	4,937.72		1,771.07
Impact height relative to water level: Top	m	3.00	-1.70	-0.50	-0.80		-1.00
Impact height relative to water level: Bottom	m	0.00	-3.70	-2.50	-2.80		-3.00

Table 5.3: Review of ship properties for the ships used in the investigation.

Stopping power foundation		
Drifting ship	**Conceptual designs**	
	P001	**P002**
Kruiplijn coaster	Yes	Yes
Supply vessel	Yes	Yes
Chemical tanker	Yes	Yes
Passenger vessel	Yes	Yes
Container ship	Yes	Yes

Stopping power foundation		
Sailing ship	**Conceptual designs**	
	P001	**P002**
Kruiplijn coaster	Yes	Yes
Supply vessel	Yes	Yes
Chemical tanker	Yes	Yes
Passenger vessel	**No**	**No**
Container ship	**No**	**No**

Table 5.4: Stopping capacity of the foundations P001 and P002.
(Yes = the foundation can stop the ship; No = the foundation is run over by the ship)

6. Summary of simulation results.

6.1. Introduction.

For the foundations presented in Section 5.1 and the ships presented in Section 5.2 the sailing and drifting impact against foundation P001 have been simulated. The results of these simulations will be presented first in the Section 6.2. The graphical results of these simulations is presented in Appendix A. Hereafter some parameter variations to investigate certain phenomena have been executed and these will be discussed in Section 6.3. The graphical results for these simulations are presented in Appendix B.

It must be noted that for these simulations the ship motion is always in the +X-direction.

The main numerical results of the simulations is summarised in Table 6.1.

6.2. Initial results.

6.2.1. Kruiplijn coaster.

6.2.1.1. Drifting.

1. Ship behaviour.
   - The ship comes to a halt and rebounds due to the elasticity of the foundation and soil. The rebound velocity is slightly lower than the impact velocity.
   - For the ship deformation curve only the maximum positive value is relevant. The maximum ship deformation is limited to ca. 0.31 [m].
   - The maximum impact force is in the range of 11 [MN], so still in the steep part of the impact force curve.
   - The total collision lasts ca. 1.2 [sec].
2. Foundation behaviour.
   - The maximum nacelle displacement is equal to ca. +0.64 [m].
   - The nacelle acceleration varies from -3 to +2 [m/s^2].
   - At the impact level the displacement is in the order of -0.1 to +0.2 [m].
   - At seabed level the maximum deformation is in the order of +/-0.04 [m].
   - The pile tip only displaces a few [mm].
   - No failure of the foundation or the soil occurs. The maximum stress level of the steel remains below the yield limit.
   - The foundation keeps on vibrating after impact in its 1st resonance frequency.

6.2.1.2. Sailing.

1. Ship behaviour.
    - The ship comes to a halt and only rebounds very little due to the elasticity of the foundation and soil. The rebound velocity is ca. -0.8 [m/s].
    - For the ship deformation curve only the maximum positive value is relevant. The maximum ship deformation is equal to ca. 4.2 [m].
    - The maximum impact force is in the range of 18 [MN], so just in the more or less linearly increasing part of the impact force curve.
    - The total collision lasts ca. 1.57 [sec].
2. Foundation behaviour.
    - The maximum nacelle displacement is equal to ca. +1.55 [m] in the impact direction, and after rebound it reaches a maximum value of ca. -1.51 [m].
    - The nacelle acceleration varies from -3.7 to +3.9 [m/s^2]. This is larger than for the drifting impact.
    - At the impact level the displacement is in the order of -0.22 to +0.25 [m].
    - At seabed level the maximum deformation is in the order of -0.05 to +0.07 [m].
    - The pile tip moves in the order of -20 to +10 [mm].
    - No failure of the foundation or the soil occurs. The maximum stress level of the steel remains below the yield limit.
    - The foundation keeps on vibrating after impact in its 1st resonance frequency.

6.2.2. Supply vessel.

6.2.2.1. Drifting.

1. Ship behaviour.
    - The ship comes to a halt and rebounds due to the elasticity of the foundation and soil. The rebound velocity is slightly lower than the impact velocity.
    - For the ship deformation curve only the maximum positive value is relevant. The maximum ship deformation is very small, in the order of 0.1 [m]. This is due to the high stiffness of the construction, indicated by the steep incline of the impact force of the ship at zero deformation.
    - The maximum impact force is in the range of 30 [MN], so still at the steepest part of the impact force curve.
    - The total collision lasts ca. 1.4 [sec].

2. Foundation behaviour.
    - The maximum nacelle displacement is equal to ca. +2.0 [m].
    - The nacelle acceleration varies from -7.5 to +5 [m/s^2].
    - At the impact level the displacement is in the order of -0.15 to +0.4 [m].
    - At seabed level the maximum deformation is in the order of +0.11 [m].
    - The pile tip displaces in the order of -35 [mm].
    - No failure of the foundation or the soil occurs. The maximum stress level of the steel remains below the yield limit.
    - The foundation keeps on vibrating after impact in its 1st resonance frequency.

6.2.2.2. Sailing.

1. Ship behaviour.
    - The ship comes to a halt and only rebounds very little due to the elasticity of the foundation and soil. The rebound velocity is ca. -1 [m/s].
    - The maximum ship deformation is in the order of 7 [m].
    - The maximum impact force is in the range of 45 [MN], so just in the more or less linearly increasing part of the impact force curve.
    - The total collision lasts ca. 2.3 [sec].
2. Foundation behaviour.
    - The maximum nacelle displacement is equal to ca. +6.3 [m] and is still increasing. The nacelle moves away from the ship.
    - The nacelle acceleration varies from -19 to +7 [m/s^2].
    - At the impact level the maximum displacement is equal to +0.85 [m].
    - At seabed level the maximum deformation is in the order of +0.32 [m].
    - The pile tip displaces maximal -100 [mm].
    - No failure of the soil occurs, although the maximum impact force is in the range of the failure force of the soil. This is due to the fact that this high impact force is mainly caused by the inertia and stiffness of the foundation and is not directly acting at the soil.
    - Failure does occur in the foundation, in the tower above the impact point, at +37.5 [m LAT], just at a cone transition. Due to this failure the nacelle drops away from the ship.

      Failure occurs just after the ship has been stopped completely. The relaxation of the soil and the pile inside the soil then start pushing back the ship. The ship loses contact with the foundation briefly and then the foundation hits the ship again. This in combination with the nacelle still moving away from the ship due to its inertia causes an overload of the tower and the sudden acceleration of the nacelle.

6.2.3. Chemical tanker.

6.2.3.1. Drifting.

1. Ship behaviour.
    - The ship comes to a halt and rebounds due to the elasticity of the foundation and soil. The rebound velocity is slightly lower than the impact velocity.
    - For the ship deformation curve only the maximum positive value is relevant. The maximum ship deformation is very small, in the order of 0.08 [m]. This is due to the high stiffness of the construction, indicated by the steep incline of the impact force of the ship at zero deformation.
    - The maximum impact force is in the range of 48 [MN], so just at the end of steepest part of the impact force curve.
    - The total collision lasts ca. 2.1 [sec].
2. Foundation behaviour.
    - The maximum nacelle displacement is equal to ca. +6.7 [m] and is still increasing. The nacelle still moves away from the ship, but the velocity is decreasing to zero.
    - The nacelle acceleration varies from -15 to +8.5 [m/s^2].
    - At the impact level the maximum displacement is equal to +0.86 [m].
    - At seabed level the maximum deformation is in the order of +0.26 [m].
    - The pile tip displaces maximal -82 [mm].
    - No failure of the soil occurs, although the maximum impact force is larger than the soil failure force. The reason for this is that the high impact force is mainly taken up by inertia and stiffness of the foundation.
    - Failure does occur in the foundation, in the tower above the impact point, at +37.5 [m LAT], just at a cone transition. Due to this failure the nacelle drops away from the ship.

    The behaviour of the foundations is almost the same as for the impact due to the sailing Supply vessel. The above characteristic values of displacements and accelerations are comparable.

    Failure occurs just after the ship has been stopped completely. The relaxation of the soil and the pile inside the soil then start pushing back the ship. The ship loses contact with the foundation briefly and then the foundation hits the ship again. This in combination with the nacelle still moving away from the ship due to its inertia causes an overload of the tower and the sudden acceleration of the nacelle.

    At the moment of failure the nacelle is still moving away from the ship and the velocity is again increasing. It is thus likely that the nacelle will drop away from the ship.

6.2.3.2. Sailing.

1. Ship behaviour.
    - The foundation is not able to stop the ship. The end velocity of the ship at the moment of the foundation failure is still 6.2 [m/s].
    - The maximum ship deformation is in the order of 4.2 [m].
    - The maximum impact force is in the range of 65 [MN], so in the more or less linearly increasing part of the impact force curve.
    - The collision time until failure of the foundation is equal to ca. 1.0 [sec].
2. Foundation behaviour.
    - The maximum nacelle displacement is equal to ca. +0.7 [m] and is still increasing. The nacelle moves away from the ship.
    - The nacelle acceleration varies from -11 to +16 [m/s^2].
    - At the impact level the maximum displacement is equal to +2.0 [m] and is still increasing.
    - At seabed level the maximum deformation is in the order of +0.5 [m] and is gradually increasing.
    - The pile tip displaces maximal -160 [mm] and decrease to 0 again after failure of the foundation.
    - No complete failure of the soil occurs, but the pile inside the soil collapses and above this failure point the soil fails too. Below the failure point the soil relaxes because the pile does not give any resistance anymore and this explains the fact that the displacement of the pile tip reduces to zero again. This will probably not be fully realistic.
    - The foundation fails at 2 locations.
        a. First failure occurs in the tower above the impact point, at +37.5 [m LAT], just at a cone transition. Due to this failure the nacelle moves towards the ship.

           Due to the high ship velocity the displacement of the foundation at the impact point increases fast. This high acceleration can not be followed by the nacelle due to its inertia. At a certain moment the nacelle stays so much behind that the bending moment in the tower reaches the failure limit. At the moment of failure, the displacement of the tower at the impact point is significantly higher than the displacement of the nacelle.
        b. Secondly, failure occurs in the soil at 8 [m] below seabed level. Due to this failure the foundation is pushed over and the part between the impact point and the failure point is pushed forward by the ship. Failure inside the soil occurs quickly after the failure inside the tower.

      With respect to the motion of the nacelle both failure modes are working against each other. Due to the tower failure the nacelle will move towards the ship accelerated by gravity, whereas due to the pile failure inside the soil the nacelle is pushed away from the ship. Considering the remaining ship velocity of 6.2 [m/s] at the end of the simulation, it is likely that the overall movement of the nacelle will be away from the ship, as shown by the displacement and velocity curve of the nacelle. In the end it is likely that the pile will break inside the soil and the vessel will sail over the foundation.

6.2.4. Passenger vessel.

6.2.4.1. Drifting.

1. Ship behaviour.

    - The passenger vessel is drifting with a fairly high velocity of 1.7 [m/s]. The foundation is not able to stop the ship. The end velocity of the ship at the moment of the foundation failure is still 0.87 [m/s].
    - The maximum ship deformation is in the order of 0.04 [m].
    - The maximum impact force is in the range of 67 [MN], so in the more or less linearly increasing part of the impact force curve.
    - The collision time until failure of the foundation is equal to ca. 1.4 [sec].

2. Foundation behaviour.

    - The maximum nacelle displacement is equal to ca. +2.6 [m] and is still increasing. The nacelle moves away from the ship.
    - The nacelle acceleration varies from -13 to +13 [m/s^2].
    - At the impact level the maximum displacement is equal to +1.93 [m] and is still increasing.
    - At seabed level the maximum deformation is in the order of +0.36 [m] and is gradually increasing.
    - The pile tip displaces maximal -160 [mm] and decrease to 0 again after failure of the foundation.
    - The failure mode of the foundation is comparable with the failure that occurs for the Chemical tanker sailing against the foundation. Also the characteristic parameters presented above are of the same order of magnitude.
    - No complete failure of the soil occurs, but the pile inside the soil collapses and above this failure point the soil fails too. Below the failure point the soil relaxes because the pile does not give any resistance anymore and this explains the fact that the displacement of the pile tip reduces to zero again. This will probably not be fully realistic.
    - The foundation fails at 2 locations.

        a. First failure occurs in the tower above the impact point, at +60 [m LAT]. This is at a higher position than for the Chemical tanker. Due to this failure the nacelle moves towards the ship.

        As the passenger vessel is quite heavy and drifting at a relatively high speed, the foundation at and above the impact point is accelerated fast. The nacelle can not follow this fast acceleration and stays behind. At a certain moment the bending moment in the tower becomes that large that the bending stress exceeds the failure limit. The failure point lies higher up in the tower than for the sailing Chemical tanker due to the differences in impact velocity.

        b. Secondly, failure occurs in the soil at 8 [m] below seabed level. Due to this failure the foundation is pushed over and the part between impact point and the failure point is pushed forward by the ship. Failure inside the soil occurs quickly after the failure inside the tower.

With respect to the motion of the nacelle both failure modes are working against each other. Due to the tower failure the nacelle will move towards to ship accelerated by gravity, whereas due to the pile failure inside the soil the nacelle is pushed away from the ship. Considering the remaining ship velocity of 0.87 [m/s] at the end of the simulation, it is likely that the overall movement of the nacelle will be away from the ship, as shown by the displacement and velocity curve of the nacelle. In the end it is likely that the pile will break inside the soil and the vessel will drift over the foundation.

6.2.4.2. Sailing.

1. Ship behaviour.
    - The foundation is not able to stop the ship. The end velocity of the ship at the moment of the foundation failure is still 13.4 [m/s].
    - The maximum ship deformation is in the order of 4.8 [m].
    - The maximum impact force is in the range of 145 [MN], so in the more or less linearly increasing part of the impact force curve.
    - The collision time until failure of the foundation is equal to ca. 0.51 [sec].
2. Foundation behaviour.
    - The maximum nacelle displacement is equal to ca. -0.04 [m], so towards the ship! This is caused by the reaction loads due to the very high impact speed of the ship and the sudden movement of the impact point of the foundation. Hereafter the displacements decreases to 0 again and the nacelle will start to move away from the ship.
    - The nacelle acceleration varies from -8 to +18 [m/s^2].
    - At the impact level the maximum displacement is equal to +2.4 [m] and is still increasing.
    - At seabed level the maximum deformation is in the order of +0.83 [m] and is still increasing.
    - The pile tip displaces maximal -230 [mm] and decrease to 0 again after failure of the foundation.
    - No complete failure of the soil occurs, but the pile inside the soil collapses and above this failure point the soil fails too. Below the failure point the soil relaxes because the pile does not give any resistance anymore and this explains the fact that the displacement of the pile tip reduces to zero again. This will probably not be fully realistic.
    - The foundation fails at 2 locations.
        a. First failure occurs in the tower above the impact point, at +26 [m LAT].

           Due to the very high velocity of the ship, the deformation of the foundation at the impact point goes very fast. Even that fast that the nacelle not only stays behind, but due to the deformation of the top part of the tower even moves slightly towards the ship before being pushed over due to the failure of the foundation inside the soil.

b. Secondly, failure occurs in the soil at 8 [m] below seabed level. Due to this failure the foundation is pushed over and the part between impact point and the failure point is pushed forward by the ship. Failure inside the soil occurs quickly after the failure inside the tower.

With respect to the motion of the nacelle both failure modes are working against each other. Due to the tower failure the nacelle will move towards to ship accelerated by gravity, whereas due to the pile failure inside the soil the nacelle is pushed away from the ship. Considering the remaining ship velocity of 13.4 [m/s] at the end of the simulation, it is likely that the overall movement of the nacelle will be away from the ship, as shown by the displacement and velocity curve of the nacelle. In the end it is likely that the pile will break inside the soil and the vessel will sail over the foundation.

Failure occurs due to plastic deformation or buckling of the foundation wall. In this case the velocity of the ship is that high that the nacelle in first instance moves towards the ship. It is quite likely that when local denting of the foundation due to the impact is included in the analysis, this effect will be exaggerated and that this will eventually lead to the nacelle dropping towards the ship.

6.2.5. Container vessel.

6.2.5.1. Drifting.

1. Ship behaviour.
   - The container vessel is drifting with a velocity of 1.1 [m/s]. Due to its high mass, the foundation is however not able to stop the ship. The end velocity of the ship at the moment of the foundation failure is still 0.8 [m/s].
   - The maximum ship deformation is in the order of 0.01 [m].
   - The maximum impact force is in the range of 88 [MN], so at the lower end of the steeply increasing impact force curve. This curve has been scaled based on the ship displacement, but it must be questioned whether this scaling with the very high displacement of the ship is still applicable.
   - The collision time until failure of the foundation is equal to ca. 3.4 [sec].
2. Foundation behaviour.
   - The maximum nacelle displacement is equal to ca. +12.5 [m] and is still increasing. The nacelle moves away from the ship.
   - The nacelle acceleration varies from -18 to +14 [m/s^2].
   - At the impact level the maximum displacement is equal to +4.2 [m] and is still increasing.
   - At seabed level the maximum deformation is in the order of +0.75 [m] and is gradually increasing.
   - The pile tip displaces maximal -176 [mm] and decrease to 0 again after failure of the foundation.
   - The failure mode of the foundation is comparable with the failure that occurs for the Chemical tanker sailing against the foundation.
   - No complete failure of the soil occurs, but the pile inside the soil collapses and above this failure point the soil fails too. Below the failure point the soil relaxes because the pile does not give any resistance

anymore and this explains the fact that the displacement of the pile tip reduces to zero again. This will probably not be fully realistic.

- The foundation fails at 2 locations.

  a. First failure occurs in the tower above the impact point, at +37.5 [m LAT], just at a cone transition. Due to this failure the nacelle moves towards the ship.

     As the container vessel is very heavy, the foundation is hardly able to decelerate the ship. This becomes clear from the very small decrease in velocity until failure occurs. The foundation is pushed over and the nacelle more or less moves with the impact point, but still remains slightly behind. At a certain moment the bending stress becomes higher than the failure limit and the tower fails. However, the failure of the foundation inside the soil is dominating the overall movement of the foundation.

  b. Secondly, failure occurs in the soil at 8 [m] below seabed level. Due to this failure the foundation is pushed over and the part between impact point and the failure point is pushed forward by the ship. Failure inside the soil occurs quickly after the failure inside the tower and is dominating the overall movement of the foundation, pushing the nacelle away from the ship.

  With respect to the motion of the nacelle both failure modes are working against each other. Due to the tower failure the nacelle will move toward the ship, whereas due to the pile failure inside the soil the nacelle is pushed away from the ship. In this case, due to the large ship displacement, this latter motion is dominating and the nacelle is pushed away from the ship. In the end it is likely that the pile will break inside the soil and the vessel will sail over the foundation.

6.2.5.2. Sailing.

1. Ship behaviour.
   - The foundation is not able to stop the ship. The end velocity of the ship at the moment of the foundation failure is still 3.5 [m/s], while the impact velocity was 3.8 [m/s]. Hence the ship is way to heavy for the foundation.
   - The maximum ship deformation is in the order of 3.4 [m].
   - The maximum impact force is in the range of 56 [MN], so in the more or less gradually increasing part of the impact force curve.
   - The collision time until failure of the foundation is equal to ca. 1.6 [sec].
2. Foundation behaviour.
   - The maximum nacelle displacement is equal to ca. 2.9 [m], so away from the ship and it keeps increasing.
   - The nacelle acceleration varies from -13 to +18 [m/s^2].
   - At the impact level the maximum displacement is equal to +2.5 [m] and is still increasing.
   - At seabed level the maximum deformation is in the order of +0.68 [m] and is still increasing.

- The pile tip displaces maximal -150 [mm] and decreases to 0 again after failure of the foundation.
- No complete failure of the soil occurs, but the pile inside the soil collapses and above this failure point the soil fails too. Below the failure point the soil relaxes because the pile does not give any resistance anymore and this explains the fact that the displacement of the pile tip reduces to zero again. This will probably not be fully realistic.
- The foundation fails at 2 locations.

  a. First failure occurs in the tower above the impact point, at +37.5 [m LAT], just at a cone transition.

     Due to the high velocity of the ship and its very large displacement, the deformation of the foundation at the impact point goes very fast. It goes that fast that the nacelle can not follow this motion and stays behind until the bending moment becomes that large that the pile stress becomes higher than the failure stress and the tower collapses.

  b. Secondly, failure occurs in the soil at 8 [m] below seabed level. Due to this failure the foundation is pushed over and the part between impact point and the failure point is pushed forward by the ship. Failure inside the soil occurs quickly after the failure inside the tower.

  With respect to the motion of the nacelle both failure modes are working against each other. Due to the tower failure the nacelle will move towards to ship accelerated by gravity, whereas due to the pile failure inside the soil the nacelle is pushed away from the ship. Considering the remaining ship velocity of 3.5 [m/s] at the end of the simulation, it is likely that the overall movement of the nacelle will be away from the ship, as shown by the displacement and velocity curve of the nacelle. In the end it is likely that the pile will break inside the soil and the vessel will sail over the foundation.

6.2.6. Summary.

A summary of the main results is presented in Table 6.1.

The failure modes that have been identified until now are as follows:

1. No pile or tower failure, just elastic foundation deformation.
   - Kruiplijn coaster, drifting
   - Kruiplijn coaster, sailing.
   - Supply vessel, drifting.
2. Tower failure,

   When the ship stops, the foundation springs back and during this process contacts again with the ship. Due to the accelerations and the inertia of the nacelle this leads to tower failure. The nacelle will probably drop away from the ship.
   - Supply vessel, sailing.
   - Chemical tanker, drifting.

3. Failure in the tower first and next pile failure inside the soil.

   Failure in the tower occurs because the inertia of the nacelle prevents it from following the impact point displacement, resulting in the bending stresses in the tower exceeding the failure limit. The ship keeps moving on and next the pile fails inside the soil.
   The nacelle can either fall onto the ship or drop away from the ship, depending on the ship displacement and velocity and whether or not fracture of the tower wall will occur.

   For the investigated configurations, it seems most likely that the nacelle will drop away from the ship.

   - Chemical tanker, sailing.
   - Passenger vessel, drifting.
   - Container ship, sailing

4. Failure in the tower first, the top part of the tower moves towards the ship and next pile failure inside the soil, causing the nacelle to move away from the ship.

   For the investigated configurations it is most likely that the nacelle will drop away from the ship.

   - Passenger vessel, sailing.
   - Container ship, drifting.

Finally it must be noted that the difference in behaviour of the foundation between a sailing Kruiplijn coaster with an impact energy of 46 [MJ] and a drifting Chemical tanker with an impact energy of 25 [MJ] is quite significant. The Kruiplijn coaster leaves the foundation intact while the Chemical tanker results in failure of the foundation. The reason for this difference will become clear in Section 6.3.2.

Regarding the various failure modes, the following must be noted.

1. Failure in the tower is mostly governed by the acceleration loads acting on the foundation. When these accelerations are too high, the nacelle can not follow this due to its inertia and stays behind. Eventually this can lead to such high bending moments that the bending stresses exceed the failure limit and collapse of the tower occurs.

2. It has been found that especially cone transition are susceptible to this. Of course, the stiffening flanges present at these cone transition are not included because their information is missing, but nevertheless it can be concluded that cone transition in a tower are susceptible to failure.

3. Failure below the impact point in this case always occurs inside the seabed. This failure is mostly governed by the sheer impact load caused by the impact velocity and energy. Accelerations have not much effect at this failure mode.

4. Local deformation of the foundation at the impact point can not be analysed with this model. It is likely that for certain conditions, e.g. ship sizes and impact velocity, local denting can be significant and can influence the actual failure modes observed. Also it can result in the nacelle dropping down on the ship instead of away from the ship.

Typical dimensions.		**Kruiplijn Coaster**	**Supply vessel**	**Chemical & Product tankers**	**Passenger vessels**	**Container ship**
Gross Tonnage	**GT**	**1554 GT**	**3200 GT**	**10000 GT**	**100000 GT**	**192784 GT**
Displacement	**ton**	**2853**	**6855**	**21,000**	**42,700**	**223,000**
			Drifting			
Kinetic energy	[MJ]	3.9	9.3	25.2	86.3	192.0
Start velocity	[m/s]	1.39	1.39	1.31	1.70	1.11
End velocity	[m/s]	<0	<0	<0	0.87	0.8
Foundation failure		No	No	Yes	Yes	Yes
Time of instability after impact	[sec]	--	--	2.30	0.74	0.93
Nacelle motion after impact		Oscillating	Oscillating	Away from ship	Probably away from ship	Away from ship
Maximum impact force	[MN]	11	30	48	67	88
Collision time	[sec]	1.2	1.4	2.1	1.4	3.4
Maximum ship deformation	[m]	0.31	0.1	0.08	0.04	0.01
Maximum nacelle displacement	[m]	0.64	2	6.7 and increasing	2.6 and increasing	12.5 and increasing
Maximum nacelle acceleration	[m/s^2]	-3 to +2	-7.5 to +5	-15 to +8.5	-13 to 13	-18 to 14
Displacement at impact level	[m]	-0.1 to +0.2	-0.15 to +0.4	0.86	1.93 and increasing	4.2 and increasing
Displacement at seabed level	[m]	-0.04 to +0.04	0.11	0.26	0.36 and increasing	0.75 and increasing
Displacement at pile tip	[mm]	-10 to +5	-35	-82	-160	
			Sailing			
Kinetic energy	[MJ]	46	212	566	4938	1771
Start velocity	[m/s]	5.4	7.50	7	14.5	3.8
End velocity	[m/s]	<0	<0	6.2	13.4	3.5
Foundation failure		No	Yes	Yes	Yes	Yes
Time of instability after impact	[sec]	--	2.48	0.69	0.35	0.95
Nacelle motion after impact		Oscillating	Away from ship	Probably away from ship	Probably away from ship	Probably away from ship
Maximum impact force	[MN]	18	45	65	145	56
Collision time	[sec]	1.57	2.3	1	0.51	1.6
Maximum ship deformation	[m]	4.2	7	4.2	4.8	3.4
Maximum nacelle displacement	[m]	-1.51 to +1.55	6.3 and increasing	0.7 and increasing	-0.04	2.9
Maximum nacelle acceleration	[m/s^2]	-3.7 to +3.9	-19 to +7	-11 to +16	-8 to +15	13 to 18
Displacement at impact level	[m]	-0.22 to +0.25	0.85	2 and increasing	2.4 and increasing	2.5 and increasing
Displacement at seabed level	[m]	-0.05 to +0.07	0.32	0.5 and increasing	0.83 and increasing	0.68 and increasing
Displacement at pile tip	[mm]	-20 to +10	-100	-160	-230	-150

Table 6.1: Summary of main results of the initial simulations.

6.3. Parameter variations.

6.3.1. The soil properties.

All simulations in Section 6.2 have been carried out with soil P001 and the corresponding foundation. In this Section the soil P002 and its corresponding foundation will be investigated for a limited number of ships.

The ships being investigated are:

1. Supply vessel, drifting and sailing.
2. Chemical tanker, drifting and sailing.

The results are presented in Appendix B, Section 1.1 and 1.2. In these graphs the results for these vessels impacting against foundation P001 and against foundation P002 are compared in 1 graph. From these results it follows:

1. The overall behaviour of both foundations is almost identical. There are small differences, but these are fairly small. The largest differences occur after the moment that failure of the foundation occurs.

2. This effect can be explained by the fact that although the configuration of the foundation, mainly the pile, and the soil are different, they are both designed to take up the same loads and they must fulfil the same dynamic requirements with respect the eigenfrequencies. Hence the strength and dynamic properties of these two foundations are comparable and therefor the reaction against ship impact can be expected to be comparable too.
3. In Figure 5.2 and Figure 5.3 the layout of the two foundations is shown. When comparing these layouts, it becomes clear that the wall thickness of the two foundations at the impact location, e.g. between -6 and +20 [m LAT] is different. This means that the local behaviour at the point of impact can be different for both configurations and this of course might affect the global behaviour too.

6.3.2. The rebound properties of the soil.

All simulations in Section 6.2 have been carried out with the assumption that when rebound occurs, the force follows the same curve backwards as during the impact. This might be true for small displacements, but for large displacements when plastic deformation of the soil layers occurs, this might not be the case. The problem is however that from the P-Y-curves it can not be determined when this change in behaviour will occur.

To investigate its effect the formulation of the non-linear elements representing the P-Y curves has been adapted, so that during rebound the force-displacement curve follows a line that has the same slope as the slope of the P-Y curve at displacement zero. This is indicated by the red line in Figure 4.3.

With these assumptions, the impact simulations for the following ships have been repeated:

1. Supply vessel, sailing.
2. Chemical tanker, drifting.
3. Container ship, drifting and sailing.

The results are presented in Appendix B, Section 2.1 to 2.3. In these graphs the results for these vessels impacting against the foundation with the standard rebound properties and against the foundation with the adapted rebound properties are compared in 1 graph. The numerical results are summarised in Table 6.2. From these results it follows:

1. Supply vessel, sailing.

   This combination has been selected as failure of the foundation occurs in the tower after the ship has been halted and rebound of the structure occurs. This rebound is affected by the elasticity of the foundation and by the rebound behaviour of the soil.

   The results in the graphs in Appendix B, Section 2.1 and in Table 6.2 show:

   a. Up to the moment of failure of the foundation for the original configuration, the results are identical. Only after the ship has been stopped and rebound occurs, the results are different.
   b. For the original configuration failure occurs in the tower above the impact point as the nacelle can't follow the rebound motion and in between renewed impact with the ship occurs, whereas with the adapted rebound behaviour no failure in the tower occurs and the foundation starts oscillating in its 1st eigenmode.
   c. In this case the rebound velocity of the ship is -0.84 [m/s] instead of -1.28 [m/s].

Typical dimensions.		**Supply Vessel**		**Chemical & Product tankers**		**Container ship**	
Gross Tonnage	**GT**	**3200 GT**	**3200 GT**	**10000 GT**	**10000 GT**	**192784 GT**	**192784 GT**
Displacement	**ton**	**6855**	**6855**	**21,000**	**21,000**	**223,000**	**223,000**
		Original	**Adapted rebound**	**Original**	**Adapted rebound**	**Original**	**Adapted rebound**
Drifting							
Kinetic energy	[MJ]	--	--	25.2	25.2	192.0	192.0
Start velocity	[m/s]	--	--	1.31	1.31	1.11	1.11
End velocity	[m/s]	--	--	-0.81	-0.45	0.8	0.78
Foundation failure		--	--	Yes	No	Yes	Yes
Time of instability after impact	[sec]	--	--	2.30	--	0.93	0.93
Nacelle motion after impact		--	--	Probably away from ship	Oscillating	Away from ship	Away from ship
Maximum impact force	[MN]	--	--	48	47	88	75
Collision time	[sec]	--	--	2.1	2.06	3.4	4.04
Maximum ship deformation	[m]	--	--	0.08	0.08	0.01	0.01
Maximum nacelle displacement	[m]	--	--	6.7 and increasing	6.3	12.5 and increasing	17 and increasing
Maximum nacelle acceleration	[m/s^2]	--	--	-15 to +8.5	-7.2 to 6.8	-18 to 14	-18 to 15
Displacement at impact level	[m]	--	--	0.86	0.88	4.2 and increasing	4.9 and increasing
Displacement at seabed level	[m]	--	--	0.26	0.26	0.75 and increasing	1.10 and increasing
Displacement at pile tip	[mm]	--	--	-82	-82		
Sailing							
Kinetic energy	[MJ]	212	212	--	--	1771	1771
Start velocity	[m/s]	7.50	7.50	--	--	3.8	3.8
End velocity	[m/s]	-1.28	-0.84	--	--	3.5	3.5
Foundation failure		Yes	No	--	--	Yes	Yes
Time of instability after impact	[sec]	2.48	--	--	--	0.95	0.95
Nacelle motion after impact		Away from ship	Oscillating	--	--	Probably away from ship	Probably away from ship
Maximum impact force	[MN]	45	45	--	--	56	59
Collision time	[sec]	2.3	2.15	--	--	1.6	1.8
Maximum ship deformation	[m]	7	7	--	--	3.4	3.7
Maximum nacelle displacement	[m]	6.3 and increasing	6.79	--	--	2.9	3.8
Maximum nacelle acceleration	[m/s^2]	-19 to +7	-8 to +7	--	--	-13 to 18	-13 to 15
Displacement at impact level	[m]	0.85	0.9	--	--	2.5 and increasing	2.95 and increasing
Displacement at seabed level	[m]	0.32	0.33	--	--	0.68 and increasing	1.04 and increasing
Displacement at pile tip	[mm]	-100	-106	--	--	-150	-243

Table 6.2: Summary of results for different soil rebound properties.

2. Chemical tanker, drifting.

   This combination has been selected as failure of the foundation in this case also occurs in the tower after the ship has been halted and rebound of the structure occurs but now during drifting instead of sailing. This rebound is affected by the elasticity of the foundation and by the rebound behaviour of the soil.

   The results in the graphs in Appendix B, Section 2.2 and in Table 6.2 show:

   a. Up to the moment of failure of the original configuration, the results are almost identical.

   b. The differences start to occur when the ship velocity reaches 0 [m/s]. The rebound of the ship is much less and the rebound velocity is equal to -0.45 [m/s] instead of the -0.81 [m/s] for the original configuration.

   c. The maximum displacements for the nacelle, the impact point, at seabed level and for the pile tip are the same as for the original configuration. However, the deformations at seabed level and of the pile tip, so the pile displacement inside the soil remains more or less constant after impact, instead of bouncing back to a virtually 0 displacement.

   d. The foundation above seabed does not fail in this case because the acceleration loads acting on the nacelle directly after the ship has been halted are lower, thus limiting the bending moment in the tower and preventing failure of the tower.

   e. In this case the foundation thus does not fail, but remains oscillating after impact.

3. Container ship, drifting.

   This combination has been selected because in this case foundation failure occurs due to the sheer mass of the container ship and the rebound effect of the soil is expected to have not much effect on the results.

   The results in the graphs in Appendix B, Section 2.3 and in Table 6.2 show:

   a. For both configurations failure of the foundation, both in the tower and inside the soil, occurs at the same time. The soil rebound behaviour has no effect on this.

   b. In the period before failure some differences are visible in the force-time curve, because the impact is somewhat oscillatory due to the small ship velocity. Due to these oscillations there is some effect of the rebound behaviour of the soil, but this effect is not large. E.g. de peak impact force is 13 [MN] lower.

   c. The displacements at the end of the simulation of the foundation above seabed level, when the calculation becomes instable, are larger than for the original soil rebound behaviour. However, this is mainly due to the fact that this numerical instability occurs 0.64 [sec] later.

   d. The maximum accelerations acting at the nacelle are more or less the same for both investigated configurations.

   e. The displacement of the foundation part inside the soil behaves differently from the situation with the soil having the original rebound behaviour. The pile tip does not rebound back to zero, but more or less keeps its position and, just as the displacement at seabed level, very gradually increases with time. This is probably more realistic than the original behaviour.

   f. In both cases, the ship will keep on moving forward and eventually the foundation inside the soil will break off and the ship will drift over the foundation.

4. Container ship, sailing.

   This combination has been selected because in this case foundation failure occurs due to the sheer mass of the container ship in combination with the high impact velocity.

   The results in the graphs in Appendix B, Section 2.3 and in Table 6.2 show:

   a. In this case the difference between the two configurations is less than for the drifting container ship.

   b. The differences start to occur at the moment that foundation failure inside the soil occurs. When that happens, the pile part inside the soil does not bounce back due to the relaxation of the soil, but keeps on displacing further, caused by the forward motion of the ship. At a certain moment when the pile is behaving fully plastically, the pile tip displacement remains more or less constant.

   c. The slightly different behaviour of the pile inside the soil after failure causes the simulation to become unstable at a slightly later time. This explains the differences in displacement of the foundation above seabed level.

   d. In both cases, the ship will keep on moving forward and eventually the foundation inside the soil will break off and the ship will sail over the foundation.

The main conclusion of this analysis is that the influence of the rebound properties of the soil is significant when the foundation is just able to stop the ship motion without failure inside the soil. At that moment, when the ship motion is stopped the foundation will rebound due to its own elasticity and due to the relaxation of the soil. When this rebound is significant repeated contact with the ship can occur and the nacelle will not be able to follow the accelerations and the bending stress inside the tower will reach the failure limit and collapse of the tower will occur. For the investigated configurations this will lead to the nacelle dropping away from the ship.

6.3.3. The impact force.

For the simulations in Section 6.2 the impact force as function of the displacement has been scaled from the data presented in the DNVGL-RP-C204 standard. In case of drifting, e.g broadside impact, and for the very large ships, e.g. Chemical tankers, Passenger vessels and Container ships it can be questioned whether such scaling is correct as it results in force-displacement curves with a very large slope for zero displacement and a very high failure force.

To investigate this, the impact force has been decreased with a certain arbitrary factor in order to get a lower failure limit and a more gradual slope for zero displacement. The shape of the curve has however not been adapted. In fact this means of course that the ship construction is assumed to be weaker than for the original configuration.

This effect has been investigated for the following ships:

1. Chemical tanker, drifting, force reduction factor 3.
2. Passenger vessel, drifting, force reduction factor 3.
3. Container ship, drifting, force reduction factor 10.

The results are presented in Appendix B, Section 3.1 to 3.3. In these graphs the results for these vessels impacting against the foundation with the standard impact force curve and against the foundation with the reduced impact force curve are compared in 1 graph. The numerical results are summarised in Table 6.3. From these results it follows:

1. Chemical tanker, drifting.

   The results in the graphs in Appendix B, Section 3.1 and in Table 6.3 show:

   a. As the ship is weaker, the deceleration of the ship takes slightly longer, e.g. 1.4 [sec] versus 1.21 [sec] for the original configuration.

   b. Also the deformation of the ship is now larger, ca. 0.4 [m] versus 0.1 [m] for the original configuration.

   c. The maximum impact force is lower too, 40 [MN] versus 48 [MN] for the original configuration. This force is still lower than the force at which complete ship failure occurs. This means that the noticed effects are mainly due to the less stiff behaviour of the ship construction simulated by the reduction factor.

   d. The foundation generally reacts in the same way as with the original input data. The ship is stopped by the foundation and at the moment of rebound the bending stresses in the tower reach the failure limit and collapse of the tower occurs. Considering the displacements and velocities it is likely that the nacelle will drop on the ship.

Typical dimensions.		Chemical & Product tankers		Passenger vessels		Container ship	
Gross Tonnage	GT	10000 GT		100000 GT		192784 GT	
Displacement	ton	21,000		42,700		223,000	
Drifting							
		High force	Low force	High force	Low force	High force	Low force
Kinetic energy	[MJ]	25.2	25.2	86.3	86.3	192.0	192.0
Start velocity	[m/s]	1.31	1.31	1.70	1.70	1.11	1.11
End velocity	[m/s]	-0.81	-0.65	0.9	0.45	0.8	0.82
Foundation failure		Yes	Yes	Yes	Yes	Yes	Yes
Time of instability after impact	[sec]	2.30	2.80	0.74	0.92	0.93	1.95
Nacelle motion after impact		Probably away from ship	Probably away from ship	Probably away from ship	Probably away from ship	Away from ship	Away from ship
Maximum impact force	[MN]	48.0	40.0	67	51	88	53
Collision time	[sec]	2.1	2.4	1.4	3.5	3.4	3.5
Maximum ship deformation	[m]	0.1	0.4	0.04	0.18	0.01	0.09
Maximum nacelle displacement	[m]	6.7 and increasing	5.48, slightly decreasing	2.6 and increasing	12.3 and increasing	12.5 and increasing	17 and increasing
Maximum nacelle acceleration	[m/s^2]	-15 to +8.5	-12.5 to 11	-13 to 13	-18 to 15	-18 to 14	-11 to 21
Displacement at impact level	[m]	0.9	0.7	1.93 and increasing	3.63 and increasing	4.2 and increasing	3.99 and increasing
Displacement at seabed level	[m]	0.3	0.2	0.36 and increasing	0.66 and increasing	0.75 and increasing	0.67 and increasing
Displacement at pile tip	[mm]	-82.0	-68.0	-160	-340	-176	-177

Table 6.3: Summary of results for different impact force curves.

2. Passenger vessel, drifting.

   The results in the graphs in Appendix B, Section 3.2 and in Table 6.3 show:

   a. The failure mode is the same as for the original configuration. The nacelle can not follow the acceleration imposed by the ship at the impact point, remains behind and collapse of the tower occurs when the bending stresses reach the failure limit. Due to the lower stiffness of the ship, this moment now occurs 0.92 [sec] after impact instead of 0.74 [sec] after impact. Soon hereafter failure of the pile inside the soil occurs.

   b. Due to the applied reduction the ship reacts less stiff, resulting in a larger ship deformation and a somewhat smaller maximum impact force. This force is however still smaller than the force at which the ship fully collapses.

   c. The graphs in Appendix B, Section 3.2 show that the behaviour of foundation is the same, only the whole process lasts a little longer due to the larger weakness of the ship.

3. Container vessel, drifting.

   The results in the graphs in Appendix B, Section 3.3 and in Table 6.3 show:

   a. The failure mode is almost the same as for the original configuration. The foundation fails inside the soil and is pushed over by the ship. Only in this case no failure in the tower above the impact point occurs because due to the weaker ship and thus lower stiffness, the acceleration induced by the ship on the foundation is lower and can be followed by the nacelle without the bending stress in the tower becoming larger than the failure stress.

   b. Due to the applied reduction the ship reacts less stiff, resulting in a somewhat larger ship deformation and a smaller maximum impact force. This force is however still smaller than the force at which the ship fully collapses.

   c. The graphs in Appendix B, Section 3.2 show that the behaviour of foundation is virtually the same, only the whole process lasts a little longer due to the larger weakness of the ship.

The main conclusion of this analysis is that when these large ships behave less stiff than originally assumed, the overall failure mode remains more or less the same. Only the failure mode of the tower due to the accelerations acting on the structure might be different when the accelerations decrease or no failure in the tower at all occurs. For the larger ships still failure of the foundation inside the soil will occur, only the process last slightly longer.

Of course a less stiff ship construction will affect the local deformation of the foundation occurring at the impact and this will also have an effect on the global failure mode.

6.3.4. The impact velocity.

To investigate the effect of the impact velocity, some simulations have been carried out with a reduced impact velocity. Apart from this all input data have been kept the same.

This analysis has been done for the following ships:

1. Chemical tanker, drifting, reduction of the impact velocity with a factor √2, so reduction of the impact energy with a factor 2.
2. Passenger vessel, drifting, reduction factor of the impact velocity with a factor ~√2, so reduction of the impact energy with a factor ~2.

The results are presented in Appendix B, Section 4.1 and 4.2. In these graphs the results for these vessels impacting against the foundation with the standard impact force curve and against the foundation with the reduced impact force curve are compared in 1 graph. The numerical results are summarised in Table 6.4. From these results it follows:

1. Chemical tanker, drifting.

   The results in the graphs in Appendix B, Section 4.1 and in Table 6.4 show:

   a. Due to the lower impact velocity the required deformation of the foundation to stop the ship is smaller. Also the maximum impact force is lower, just as the maximum deformation of the ship.

   b. As a result the rebound effect at the moment that the ship has been stopped is also smaller and this results in lower acceleration forces on the foundation. Also no 2nd impact with the ship occurs.

      Due to this the nacelle is now able to follow these accelerations without the bending stresses reaching the failure limit. As a result no failure of the foundation occurs and after the impact the foundation starts to oscillate in its 1st resonance mode.

2. Passenger vessel, drifting.

   The results in the graphs in Appendix B, Section 4.2 and in Table 6.4 show:

   a. Due to the lower impact velocity/energy, the foundation is now able to stop the ship. The maximum impact force is lower, just as the maximum deformation of the ship. As a result, the impact duration is now longer.

   b. At 2 [sec] after impact the motion of the ship has stopped and rebound of the foundation occurs. Contact between foundation and ship is lost again after ca. 2.5 [sec]. The rebound velocity of the ship is equal to -0.23 [m/s].

   c. At 2.36 [sec] after impact, so when the ship motion has already been stopped, failure of the foundation occurs inside the soil because the nacelle keeps on moving forward due to its inertia.

Hereafter rebound of the pile part inside the soil occurs, but this does not affect the motion of the foundation above seabed level anymore.

d. The nacelle however keeps moving away from the ship due to its inertia and at ca. 3 [sec] after impact the bending stress in the tower reaches the failure limit and foundation failure also occurs in the tower above the impact point.

e. After failure of the tower, the nacelle keeps on moving away from the ship and even accelerates again due to the gravity force. Finally the foundation will collapse at the tower and the nacelle will drop down, away from the ship.

Typical dimensions.		**Chemical & Product tankers**		**Passenger vessels**	
Gross Tonnage	**GT**	**10000 GT**		**100000 GT**	
Displacement	**ton**	**21,000**		**42,700**	
Drifting					
		Normal velocity	**Reduced velocity**	**Normal velocity**	**Reduced velocity**
Kinetic energy	[MJ]	25.2	12.6	86.3	40.9
Start velocity	[m/s]	1.31	0.92	1.70	1.17
End velocity	[m/s]	-0.81	-0.57	0.9	-0.23
Foundation failure		Yes	No	Yes	Yes
Time of instability after impact	[sec]	2.30	--	0.74	2.36
Nacelle motion after impact		Probably away from ship	Oscillating	Probably away from ship	Away from ship
Maximum impact force	[MN]	48.0	40.0	67	53
Collision time	[sec]	2.1	2.0	1.4	2.54
Maximum ship deformation	[m]	0.08	0.06	0.04	0.03
Maximum nacelle displacement	[m]	6.7 and increasing	4.0	2.6 and increasing	9.9 and increasing
Maximum nacelle acceleration	[m/s^2]	-15 to +8.5	-7.4 to 7.5	-13 to 13	-16 to 13.5
Displacement at impact level	[m]	0.9	0.57	1.93 and increasing	1.5 and increasing
Displacement at seabed level	[m]	0.3	0.17	0.36 and increasing	0.36 and increasing
Displacement at pile tip	[mm]	-82.0	-48.0	-160	-117

Table 6.4: Summary of results for different impact velocities.

The main conclusion of this analysis is that a reduction in impact velocity and thus impact energy results in less severe consequences for foundation and ship. Whether or not the foundation will collapse or not of course depends on the ship size and the impact velocity/energy. In general it can be stated that with a lower impact velocity/energy the chance that the foundation will survive increases.

6.3.5. Summary.

The investigations in this Section 6.3 together with the initial results in Section 6.2 leads to following identified global failure modes.

1. No pile or tower failure, just elastic foundation deformation, foundation remains standing and oscillates in its 1st eigenmode.
    - Kruiplijn coaster, drifting
    - Kruiplijn coaster, sailing.
    - Supply vessel, drifting.
    - Supply vessel, sailing, small soil rebound.
    - Chemical tanker, drifting, high impact force/stiff ship, small soil rebound.

- Chemical tanker, drifting, high impact force/stiff ship, large soil rebound, low impact velocity.

2. Tower failure,

   When the ship stops, the foundation bounds back and during this process contacts again with the ship. The resulting acceleration loads can not be followed by the nacelle and this leads to tower failure above the impact point. The nacelle will probably drop away from the ship.

   - Supply vessel, sailing, large soil rebound.
   - Chemical tanker, drifting, high impact force/stiff ship, large soil rebound.
   - Chemical tanker, drifting, low impact force/weak ship, large soil rebound.

3. Failure in the tower first and next failure of the pile inside the soil.

   Failure in the tower occurs because the inertia of the nacelle prevents it from following the impact point displacement. The nacelle remains behind and tower failure occurs with the upper tower part folding towards the ship. The ship keeps moving on and next the pile fails inside the soil and the foundation is pushed over by the ship. The nacelle can either fall onto the ship or drop away from the ship, depending on the ship displacement and velocity and whether or not fracture of the tower wall will occur.

   For the investigated configurations, it seems most likely that the nacelle will drop away from the ship.

   - Chemical tanker, sailing.
   - Passenger vessel, drifting, high impact force/stiff ship, high drift velocity.
   - Passenger vessel, drifting, low impact force/weak ship, high drift velocity.
   - Passenger vessel, sailing.
   - Container ship, drifting, high impact force/stiff ship, large soil rebound.
   - Container ship, drifting, high impact force/stiff ship, small soil rebound.
   - Container ship, sailing.

4. Pile failure inside the soil first and next tower failure due to the inertia of the nacelle.

   The pile fails inside the soil just after the ship stops due to the continuing motion of the nacelle. Hereafter the nacelle keeps on moving forward, finally leading also to failure of the tower. The nacelle will drop away from the ship.

   - Passenger vessel, drifting, high impact force/stiff ship, low drift velocity.

5. Failure in the tower first, the top part of the tower moves towards the ship and next pile failure inside the soil, causing the nacelle to move away from the ship.

   For the investigated configurations it is most likely that the nacelle will drop away from the ship.

   - Container ship, sailing, high impact force/stiff ship, small soil rebound.

6. Pile failure inside the soil.

   Only failure inside the soil occurs. The inertia loads are that small that the nacelle can follow the motion imposed by the ship without failure in the tower above the impact point occurring. The nacelle drops away from the ship.

   - Container ship, drifting, low impact force/weak ship.

The present simulations show that failure either occurs in the tower due to the accelerations being too large for the nacelle to following, leading eventually to too high bending stresses in the tower wall and collapse of the tower. In general the top part of the tower will move towards the ship, together with the nacelle. Whether this will lead to the nacelle dropping onto the ship or away from the ship depends in the 2nd failure mode.

The other failure mode is failure of the pile inside the soil. The foundation is pushed over by the ship and when the combination of ship mass and velocity is sufficient, the ship might move over the foundation with the pile breaking off inside the soil. This might of course lead to damage to the bottom of the ship.

The for investigated ship-foundation combinations the combination of both failure modes leads most likely to the nacelle dropping away from the ship.

The effects of local deformations at the impact point can not be investigated by this FE-model. These local deformations most likely will affect the identified global deformation modes and might lead to collapse of the foundation at the point of impact. This might result in the nacelle dropping on to the ship.

6.4. Nacelle failure.

In the previous Sections the possible failure of the connection between tower top and nacelle has not been investigated. This is a difficult issue as the analysis of this possible failure mode depends on highly proprietary information of the turbine manufacturer that he is very unlikely to share.

The simulations presented in this document show that the accelerations acting at the nacelle can in the range from -20 to +20 [m/s^2] as an upper limit. These values are somewhat higher than found during the safeship analysis in 2005, see lit. [2].

At this moment nothing can be said about the nacelle-tower connection, but when looking to the tower top geometry and the simulation results of the investigated foundations, then it follows that the geometry of the conceptual tower design is not advantageous for the nacelle support. From Figure 5.2 and Figure 5.3 it follows that the top part of the tower consists of a short conical section that connects the tower to the nacelle. Such a conical section is susceptible to local shell buckling under larger bending moment. Almost all simulations show that in that region high stresses occur that are up to and above the yield limit, see for example Figure 6.1. These stresses that are above the yield limit do not extend over the whole circumference, so not a total collapse of this connection occurs. Also it must be noticed that the stabilising effect of the flanges connecting those parts is not included because the information about the flanges is missing. It can however be concluded that such a conical transition close to the nacelle connection is not advantageous and should preferably be avoided.

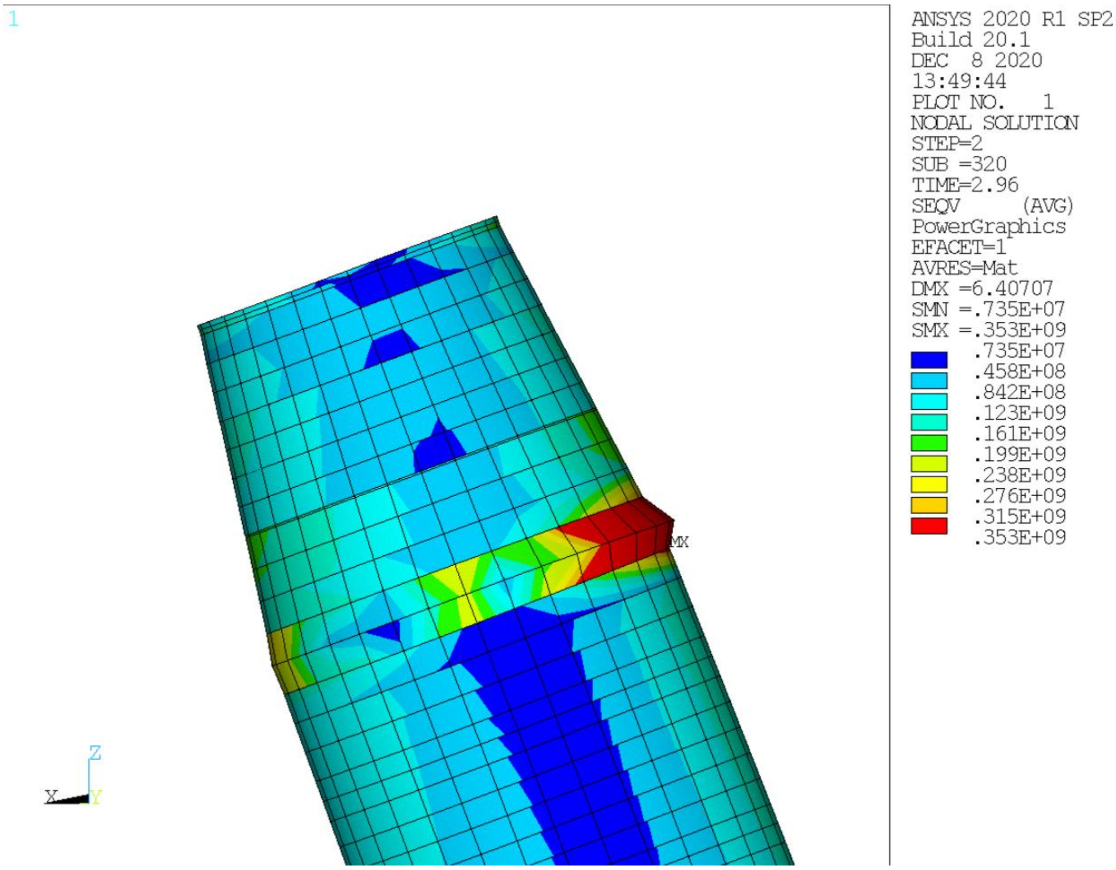

Figure 6.1: Tower top cone connecting tower with nacelle – results for drifting Chemical tanker.

7. Summary and conclusions.

7.1. Summary.

Due to the increase in the number of offshore wind farms (OWF) in the North Sea, during the last 15 years and still to be expected for the next 15 years, and the increase in ship traffic in the waterways alongside these wind farms, see lit. [1], Rijkswaterstaat (RWS) wants to assess the scenario of potential collisions between ships and wind turbines and when feasible come to issue guidelines/rules for the design of future windfarms in order to minimize the effect of these collisions for the ships and its crew and passengers, the environment and for the foundations.

In 2005 the project SAFESHIP (https://cordis.europa.eu/project/rcn/86899/factsheet/en), lit. [1], was carried out to address the issue of ship collisions against wind turbines. Since the finishing of the SAFESHIP project, new studies and analysis techniques have been executed, thus it is necessary to align both the theoretical background and the analysis method established in 2005 for the SAFEHSIP project with the latest developments.

For this reason RWS has asked MARIN and HVR Engineering to execute a literature review to the latest state of the art concerning ship/wind turbine collision, focusing in particular on the calculation methods currently available to assess this scenario. Also HVR Engineering has been asked to repeat the 2005 calculations using the design information of the most recently established wind farms in the Dutch part of the North Sea and ship sizes presently sailing these waters as following from studies executed by MARIN. This study should concentrate on ships sailing the Dutch waters in the neighbourhood of the wind farms and that could accidentally sail into the windfarm or that could drift into the windfarm in case an emergency happens with the ship.

Finally MARIN was asked to organise an expert meeting in order to discuss the results and possible ways forward.

In this report a summary is given of the investigations carried out by HVR Engineering. The results of this study are preliminary and give insight in the possible failure scenarios that can occur when a ship impacts a wind turbine foundation. The study is presently limited to mono pile foundations as this is the only foundation presently used in the Dutch part of the North Sea and hence only as-build information of this kind of foundations will be available.

Unfortunately, up to now, it has not been possible to get detailed design information of the wind farms presently operable in the Dutch part of the North Sea. Only from one entity two conceptual foundation designs for a future windfarm in the North Sea have been received. Therefore the results presented in this report are based on the investigation of these two conceptual designs.

A brief literature survey to the present state of the art of investigations concerning the impact of ships against wind turbine foundations lead to the following results:

1. Three possible assessment methods are available to perform the study of the consequences of a wind turbine/ship collision event:
    a. Simplified methods based on risk analyses and probabilistic assessments.

   b. Analytical models, able to reasonably describe the deformation modes of a wind turbine subjected to ship collision. These models are particularly useful in the foundation pre-design stage but they might be difficult to implement for complex structural layouts of the foundation (e.g. jackets).
   c. Advanced numerical models, in which the FE method is applied to accurately describe the deformation and failure modes of the wind turbine foundation, also accounting for soil-structure interaction and a proper flexibility of the impacting vessel.
2. Neglecting the soil-structure interaction will produce non-realistic deformations in the foundations as found in several numerical investigations reported in the literature review.
3. Considering a rigid colliding ship will produce excessive deformations in the foundations by neglecting the possible energy dissipation in the ship impact region. For example, in one literature source it is mentioned that the flexibility of the striking ship reduces the deformations of the wind turbine by a factor 2 for the analysed load scenarios.

The literature study further showed that the results of these studies are interesting and give background information for the issue at hand. However, none of these studies gives the information that RWS is looking for in order to be able to base future legislation on. Hence, more detailed and coordinated studies are required in order to investigate the effects of various collision scenario's.

The results presented in this report are based on the FE method as tinplated under item 1c. The model used does however not model in full 3D shell models the geometry of the ship and the foundation giving detailed insight in the local deformation that will occur in the contact area between ship and foundation. The disadvantage of these models is that they are so detailed that the modelling time and calculation times are extensive and that it is difficult to get a quick overview over the whole range of possible ship-foundation impact scenarios. For this reason the FE model used for this investigation is a 3D beam model that captures the global failure modes of a foundation due to for example global yield or shell buckling, that does take into account the effects of the flexibility of the impact ship and that includes also the soil-structure interaction. With this model the detailed ship-foundation interaction can not be investigated, but it is possible to getfalry quick an overview of the possible ship-foundation impact scenarios and to compare the behaviour of the various windfarm foundations that are present in the North Sea.

The FE-model does not take into account secondary steel such as J-tubes, boat landing, ladders, etc.. In general this is no problem as the secondary steel is not structural and the mass, dimensions, stiffness and strength are negligible in comparison to a ship.
The exception in this is the main platform, which is in general located somewhere between 15 and 25 [m] above LAT. For the smaller ships the platform is located outside the main impact area but might collide with the upper part of the ship. For the larger ships, e.g. large tankers, passenger vessels and container ships, the main platform might be the first part of the foundation coming in contact with the ship. The interaction between ship and platform will not sink the ship, but the platform might penetrate the ship hull or the upper part of the ship an cause severe damage and in addition can possibly lead to injuries or death of personnel and passengers.

The main assumptions made for the simulations presented in this report are as follows:

1. The foundation – soil interaction is modelled by non-linear spring representing P-Y curves that are derived to model the lateral stability of pile foundations. The results in this document show that especially the unloading behaviour of the soil, e.g. merely elasto-plastic or more elastic, can under certain conditions

have a significant effect on the simulation results. It can determine whether foundation failure will occur or not.

2. It has been assumed that the wind turbines are not operating when impact of ship occurs. It is assumed that early warning systems will detect when a ship is nearing the windfarm so that the windfarm can be shut down before the ship enters the windfarm. It takes ca. 20 [minutes] to shut down a windfarm and the present early warning systems only give a warning when a ship is closer within 500 [m] of a windfarm. This is too late to be able to shut down a windfarm in time. Shortly however, a new SIS system will come online that might mitigate this problem.

   Some studies have shown that when a ship hits an operating wind turbine then collapse of the wind turbine foundation will occur at lower impact velocity if the ship sails against the wind when impacting the foundation.

   Also, for the large container ships and passenger vessels, there is the danger that the blades of an operating wind turbine will hit the superstructure of the ship, with possible severe consequences for crew and passengers.

   Finally, it must be noted that it has never been investigated what happens dynamically with the rotor blades when a ship hits an operating wind turbine, even when there is no direct contact between blades and ship.

3. Damping has not yet been considered in the simulations, nor is the gyroscopic effect of a rotating rotor on the behaviour of the nacelle in case the turbine is still operating when impacted by a ship. Investigative analyses have indicated that the effect is probably limited for the overall behaviour of the foundation, but it might affect the failure mode of the nacelle-tower connection of the failure mode of the blades itself. Also it can play a role when the post-impact behaviour of the foundation has to be analysed in more detail.

4. The ship is modelled as a series of mass points equally divided over the modelled impact height. For the simulations presented in this report it is assumed that contact between ship and foundation will occur at the COG of the ship. Grazing impact, which occurs when the ship hits the foundation at a distance from the COG and which will result in a rotation of the ship, can be included, but has not been done for this study. In general a grazing impact is less severe than a broad side impact at the location of the COG.

5. The failure of the ship is modelled by non-linear springs representing the failure load of a ship by non-linear force displacement curves. Such curves are for example specified in the standard DNVGL-RP-C204. These curves will be used for the various investigated ships, scaled based on the actual ship displacement. It is however questionable whether this scaling is still valid for the very large ships.

6. The modelling of the mass points of the ship and the non-linear springs is such that the centre of the applied force will move downward when the foundation undergoes large displacements. This is crudely in line with what is expected to happen in practice.

7. The input for the simulation is the velocity of the ship at the moment of impact.

   For drifting impact the effects of the wind, current and wave forces pushing the ship forward is not taken into account. It is assumed that these forces are negligible with respect to the forces introduced by the impact.

In case of sailing impact, the propulsion force of the ship is not taken into account. It is assumed that the propulsion is directly switched off at impact so that the ship will come to a halt due to the impact with the foundation. When this is not the case and the propulsion force will keep on pushing the ship forward, then this will of course have an effect on the failure mode of the foundation, especially for the larger ships.

8. The material model used for the foundation is a non-linear elasto- ideal plastic material mode. The material behaves elastically until a limit is reached and when the strain becomes larger than the elastic limit, the stress remains constant. When this happens at a cross-section of the foundation, the plastic zone will quickly develop over the whole circumference and the foundation will collapse.

   As the plastic limit either the yield limit can be selected or the shell buckling limit. The latter one is generally lower. For the simulations presented in this document the nominal yield limit has been used as the failure criterion. No material factor has been applied to these data.

In continuing study it will be required to investigate in more detail the effect of the above assumptions on the observed foundation failure modes as presented in this report by executing a parameter study. Based on this parameter study and the results presented in this report a sort of representative base case must be defined that can be used to compare the various failure scenarios for the windfarms presently operating in the Dutch part of the North Sea.

The two investigated foundation – soil combinations, P001 and P002, are quite different. They are designed for the same windfarm, but the soil conditions differ that much that the design for the mono pile is different for both locations. The designs are different with respect to the diameter inside the soil and the wall thickness division. The tower design is the same for both configurations. It should be noted that these two different foundations are designed to support the same turbine and that therefore the loads acting on the structure are comparable and that also the dynamic requirements will be the same. This means that the strength and the dynamic characteristics of the two foundations will be more or less the equal. This is typical for foundations within one windfarm. The failure force for the soil assuming an infinitely strong foundation is in the order of 40 to 50 [MN].

The selected ships for the investigation presented in this report are partly taken from the SAFESHIP investigation in 2005. The Very Large Container Carrier has been added. These ships are a rough cross-section of the ships sailing the waters near the Dutch windfarms. It must be noted that the impact height has been estimated from the available information, but might not be accurate.

7.2. Main results.

The main results from the simulations presented in this report can be summarized as follows:

1. Based on energy considerations, it can be concluded that the conceptual foundation designs P002 and P002 are able to stop all investigated **drifting** ships without being run-over. For the **sailing** ships this is only true for the Kruiplijn coaster, the Supply vessel and the Chemical tanker. The Passenger vessel and the Container ship will sail over the foundation.

2. Failure in the tower is mostly governed by the acceleration loads acting on the foundation. When these accelerations are too high, the nacelle can not follow this due to its inertia and stays behind. Eventually this can lead to such high bending moments that the bending stresses exceed the failure limit and collapse of the tower occurs.

3. It has been found that especially cone transition are susceptible to this. Of course, the stiffening flanges present at these cone transition are not included because their information is missing, but nevertheless it can be concluded that cone transition in a tower are susceptible to failure.
4. Failure below the impact point in this case always occurs inside the seabed. This failure is mostly governed by the sheer impact load caused by the impact velocity and energy. Accelerations have not much effect at this failure mode.
5. For the investigated foundations, pure soil failure does not occur. Instead failure of the pile inside the soil, at ca. 8 [m] below seabed level, occurs. Hereafter the soil layers above this pile failure point do fail.
6. Local deformation of the foundation at the impact point can not be analysed with this model. It is likely that for certain conditions, e.g. ship sizes and impact velocity, local denting can be significant and can influence the actual failure modes observed. Also it can result in the nacelle dropping down on the ship instead of away from the ship.
7. Comparison of the behaviour of the two configurations P001 and P002 when impact with the same ship and under the same conditions shows:
    a. The overall behaviour of both foundations is almost identical. There are small differences, but these are fairly small. The largest differences occur after the moment that failure of the foundation occurs.
    b. This effect can be explained by the fact that although the configuration of the foundation, mainly the pile, and the soil are different, they are both designed to take up the same loads and they must fulfil the same dynamic requirements with respect the eigenfrequencies. Hence the strength and dynamic properties of these two foundations are comparable and therefor the reaction against ship impact can be expected to be comparable too.
    c. When comparing these layouts, it becomes clear that the wall thickness of the two foundations at the impact location, e.g. between -6 and +20 [m LAT] is different. This means that the local behaviour at the point of impact can be different for both configurations and this of course might affect the global behaviour too.
8. The influence of the rebound properties of the soil is significant when the foundation is just able to stop the ship motion without failure inside the soil. At that moment, when the ship motion is stopped the foundation will rebound due to its own elasticity and due to the relaxation of the soil. When this rebound is significant repeated contact with the ship can occur and the nacelle will not be able to follow the accelerations and the bending stress inside the tower will reach the failure limit and collapse of the tower will occur. This happens when it is assumed that upon rebound the soil force follows the same path backwards as during impact.

    When it is assumed that the rebound of the soil goes along a line with the same slope as for zero displacement, then less energy is transferred back to the foundation and the ship. In that case the tower failure might not occur and the foundation will survive the impact.

    It needs therefore be investigated which soil behaviour is most likely, or maybe it should be a mix of both methods depending on the actual displacement of the pile inside the soil.

    For the large ships this effect is not relevant as in that case failure of the foundation inside the soil will occur and the overall rebound effect is very limited.

9. For the large ships the force-displacement curves for broadside impact simulating the plastic deformation of the ship has been scaled from the data presented in the DNVGL-RP-C204 standard. For the very large ships, e.g. Chemical tankers, Passenger vessels and Container ships it can be questioned whether such scaling is correct as it results in force-displacement curves with a very large slope for zero displacement, so a high ship stiffness, and a very high failure force.

   To investigate this, the impact force has been decreased with a certain arbitrary factor in order to get a lower failure limit and a more gradual slope for zero displacement.

   It follows that when these large ships behave less stiff than originally assumed, the overall failure mode remains more or less the same. Only the failure mode of the tower due to the accelerations acting on the structure might be different when the accelerations decrease or no failure in the tower at all occurs. The failure behaviour of the pile inside the soil is not affected by this.

   Of course a less stiff ship construction will affect the local deformation of the foundation occurring at the impact and this will also have an effect on the global failure mode.

10. Evaluation of the effect of the impact velocity on the failure mode of the foundation shows that a reduction in impact velocity and thus impact energy results in less severe consequences for foundation and ship. Whether or not the foundation will collapse or not of course depends on the ship size and the impact velocity/energy. In general it can be stated that with a lower impact velocity/energy the chance that the foundation will survive increases.

11. The possible failure of the connection between tower top and nacelle has not been investigated yet. This is a difficult issue as the analysis of this possible failure mode depends on highly proprietary information of the turbine manufacturer that he is very unlikely to share.

    The simulations presented in this document show that the accelerations acting at the nacelle can in the range from -20 to +20 [m/s^2] as an upper limit. These values are somewhat higher than found during the safeship analysis in 2005.

12. It has already been concluded that cone transitions in the tower are susceptible to failure by either plasticity of shell buckling. This also accounts for a cone transition close to the tower top as is the case for the investigated foundations. Such a cone transition close to the tower top is not advantageous for the support and stability of the nacelle during a ship impact and is therefore best avoided.

7.3. Summary of global failure modes.

The following global failure modes have been identified

1. No pile or tower failure, just elastic foundation deformation, the foundation remains standing and oscillates in its 1st eigenmode.
   - Kruiplijn coaster, drifting
   - Kruiplijn coaster, sailing.
   - Supply vessel, drifting.
   - Supply vessel, sailing, small soil rebound.
   - Chemical tanker, drifting, high impact force/stiff ship, small soil rebound.

- Chemical tanker, drifting, high impact force/stiff ship, large soil rebound, low impact velocity.

2. Tower failure,

   When the ship stops, the foundation bounds back and during this process contacts again with the ship. The resulting acceleration loads cannot be followed by the nacelle and this leads to tower failure above the impact point. The nacelle will probably drop away from the ship.

   - Supply vessel, sailing, large soil rebound.
   - Chemical tanker, drifting, high impact force/stiff ship, large soil rebound.
   - Chemical tanker, drifting, low impact force/weak ship, large soil rebound.

3. Failure in the tower first and next pile failure inside the soil.

   Failure in the tower occurs because the inertia of the nacelle prevents it from following the impact point displacement. The nacelle remains behind and tower failure occurs with the upper tower part folding towards the ship. The ship keeps moving on and next the pile fails inside the soil and the foundation is pushed over by the ship. The nacelle can either fall onto the ship or drop away from the ship, depending on the ship displacement and velocity and whether or not fracture of the tower wall will occur.

   For the investigated configurations, it seems most likely that the nacelle will drop away from the ship.

   - Chemical tanker, sailing.
   - Passenger vessel, drifting, high impact force/stiff ship, high drift velocity.
   - Passenger vessel, drifting, low impact force/weak ship, high drift velocity
   - Passenger vessel, sailing.
   - Container ship, drifting, high impact force/stiff ship, large soil rebound.
   - Container ship, drifting, high impact force/stiff ship, small soil rebound.
   - Container ship, sailing.

4. Pile failure inside the soil first and next tower failure due to the inertia of the nacelle.

   The pile fails inside the soil just after the ship stops due to the continuing motion of the nacelle. Hereafter the nacelle keeps on moving forward, finally leading also to failure of the tower. The nacelle will drop away from the ship.

   - Passenger vessel, drifting, high impact force/stiff ship, low drift velocity

5. Failure in the tower first, the top part of the tower moves towards the ship and next pile failure inside the soil, causing the nacelle to move away from the ship.

   For the investigated configurations it is most likely that the nacelle will drop away from the ship.

6. Pile failure inside the soil.

   Only pile failure inside the soil occurs. The inertia loads are that small that the nacelle can follow the motion imposed by the ship without failure in the tower above the impact point occurring. The nacelle drops away from the ship.

   - Container ship, drifting, low impact force/weak ship.

The present simulations show that failure either occurs in the tower due to the accelerations being too large for the nacelle to following, leading eventually to too high bending stresses in the tower wall and collapse of the tower. In general the top part of the tower will move towards the ship, together with the nacelle. Whether this will lead to the nacelle dropping onto the ship or away from the ship depends in the 2nd failure mode.

The other failure mode is failure of the pile inside the soil. The foundation is pushed over by the ship and when the combination of ship mass and velocity is sufficient, the ship might move over the foundation with the pile breaking off inside the soil. This might of course lead to damage to the bottom of the ship.

For the investigated ship-foundation combinations the combination of both failure modes leads most likely to the nacelle dropping away from the ship.

The effects of local deformations at the impact point cannot be investigated by this FE-model. These local deformations most likely will affect the identified global deformation modes and might lead to collapse of the foundation at the point of impact. This might result in the nacelle dropping on to the ship.

Regarding the survivability of the foundation of the turbine under ship impact, the following can presently be concluded:

1. For ships up to ca. 3000 tonnes the foundation will survive drifting and sailing impact.
2. For ships up to 7000 tonnes the foundation will survive drifting impact and, depending on the actual soil rebound behaviour, most likely can also survive sailing impact.
3. For ships between 7000 tonnes up to 20000 tonnes the foundation can survive drifting impact depending on the actual drift velocity and the soil rebound behaviour.
4. For ships between 7000 tonnes up to 20000 tonnes the behaviour under sailing conditions is still unclear. Depending on the actual sailing velocity, a foundation can survive or will fail.
5. For ships above 20000 tonnes, foundation failure under drifting and sailing impact is likely.

These global results can of course still be affected by the effect of the local deformation at the point of impact.

In comparison with the SAFESHIP results as presented in lit. [2] it follows that the latest foundations are likely to survive impact with larger ships than the 2005 foundations.

7.4. Continuation of the project.

For the continuation of the project, the following steps are foreseen:

1. Continuation of the efforts to get the design data of all the windfarms in the Dutch part of the North Sea. Probably RWS in combination with other governmental departments should take a coordinated role in this.
2. Evaluation of the assumptions made in this report and execution of some further investigations to eliminate these assumptions, e.g. the rebound properties of the soil, in order to build a base case for the comparison of the behaviour of the foundations in the different windfarms, using the present version of the FE-model.

   This will give an overview of the overall behaviour of the modern mono pile wind turbine foundations.
3. Based on the results of item 2 select specific combinations of ships and foundations to investigate in more detail their dynamic behaviour, including their post-impact behaviour, using full 3D finite element models that are able to simulate the actual plastic deformation of the ship and foundation at the impact point and actual behaviour of the soil. For the selection of the ships to be analysed also attention must be paid to more novel ships with for example and X-bow or an Axe bow.
4. Detailed investigation of the failure modes of the connection nacelle-tower top. For this investigation active cooperation of the turbine manufacturers is required.

8. Literature.

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