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

**DOCUMENT NO. : 081.R030.M011-Rev.2**

**HVR ENGINEERING**

Achtseweg Zuid 157A
5651 GW EINDHOVEN
The Netherlands
**T** +31 (0)88 0155700
**E** info@hvrengineering.com
**WWW.HVRENGINEERING.COM**

| Version | Description | Author | Date |
|---|---|---|---|
| 0 | Original issue | Ir J.H.A. van Rooij | 6 December 2023 |
| 1 | Final version | Ir J.H.A. van Rooij | 25 January 2024 |
| 2 | Table 3.1 updated | Ir J.H.A. van Rooij | 5 March 2024 |
| | | | |
| | | | |
| | | | |
| | | | |

INDEX

# 1. Samenvatting.

Vanwege de toename van het aantal offshore windmolenparken (OWF) in de Noordzee gedurende de afgelopen 15 jaar en de verwachtingen voor de komende 15 jaar, en vanwege de toename van het scheepvaartverkeer in de waterwegen langs deze windmolenparken, zie lit. [1], wil Rijkswaterstaat (RWS) het scenario van mogelijke botsingen tussen schepen en windturbines beoordelen. Op basis van de resultaten van deze beoordeling en indien haalbaar, wil RWS vervolgens richtlijnen/voorschriften opstellen voor het ontwerp van toekomstige windmolenparken om het effect van deze botsingen op schepen en de bemanning, passagiers en lading, het milieu en de funderingen te minimaliseren.

In 2005 werd het project SAFESHIP (https://cordis.europa.eu/project/rcn/86899/factsheet/en), zie lit. [2], uitgevoerd om het probleem van aanvaringen tussen schepen en windturbines aan te pakken. Sinds de afronding van het SAFESHIP-project zijn er nieuwe studies en analyses uitgevoerd, dus het is noodzakelijk om zowel de theoretische achtergrond als de analysemethoden die in 2005 zijn vastgesteld voor het SAFESHIP-project af te stemmen op de laatste ontwikkelingen.

Om deze reden heeft RWS MARIN en HVR Engineering gevraagd om een literatuuronderzoek uit te voeren naar de laatste stand van zaken met betrekking tot aanvaringen tussen schepen en windturbines, met name gericht op de huidige berekeningsmethoden die beschikbaar zijn om dit scenario te beoordelen, zie lit. [3]. Ook is aan HVR Engineering gevraagd om de berekeningen van 2005 te herhalen met behulp van de ontwerpinformatie van de meest recentelijk gebouwde windmolenparken in het Nederlandse deel van de Noordzee en de afmetingen van de schepen die momenteel deze wateren bevaren, zoals blijkt uit studies uitgevoerd door MARIN. Deze studie zou zich moeten concentreren op schepen die in de buurt van de windmolenparken in de Nederlandse wateren varen en die per ongeluk in het windmolenpark kunnen varen of erin kunnen drijven in geval van een noodsituatie met het schip.

In het eerste deel van deze studie, zie literatuur [5], is een vooronderzoek uitgevoerd op basis van het conceptuele ontwerp van 2 funderingen voor een 10 MW windturbine in het Noordzeegebied, omdat er op dat moment geen informatie was ontvangen over bestaande funderingen voor windturbines in het Nederlandse deel van de Noordzee.

Later, toen de vereiste technische informatie was ontvangen voor 2 windmolenparken, Windmolenpark 1 en Windmolenpark 2, zijn dezelfde analyses uitgevoerd voor de werkelijk bestaande funderingen van Windmolenpark 1 en Windmolenpark 2.

De resultaten van dit onderzoek geven inzicht in mogelijke scenario's van falen die kunnen optreden wanneer een schip botst met een fundering van een windturbine. Het onderzoek is beperkt tot monopile-funderingen, omdat dit momenteel de enige gebruikte fundering is in het Nederlandse deel van de Noordzee. In dit rapport is het model zoals ontwikkeld in lit. [2] bijgewerkt, en het effect van verschillende parameters is gedetailleerder onderzocht. Deze parameters omvatten het grondmodel, de impactrichting van het schip ten opzichte van de rotor-as van de turbine, de effecten van wind, golven, stroming en belasting door de turbine op de fundering, het effect van de voortstuwingsbelasting op het schip (door wind, golven en stroming in het geval van een drijvend schip, of door de scheepsmotor in het geval van een varend schip), en de faalcriteria die van toepassing zijn op de fundering van de windturbine, zoals falen als gevolg van plastische deformatie of falen als gevolg van plooien.

Een beknopt literatuuronderzoek naar de huidige stand van zaken van onderzoeken met betrekking tot de impact van schepen tegen funderingen van windturbines, zoals beschreven in lit. [3], leverde de volgende resultaten op:

1. Er zijn drie mogelijke beoordelingsmethoden beschikbaar om de gevolgen van een botsing tussen een windturbine en een schip te bestuderen:
    a. Vereenvoudigde methoden op basis van risicoanalyses en probabilistische beoordelingen.
    b. Analytische modellen die redelijk het deformatie gedrag van een windturbine onderhevig aan een botsing met een schip kunnen beschrijven. Deze modellen zijn nuttig in de pre-ontwerpfase van de fundering, maar kunnen moeilijk te implementeren zijn voor complexe structuren (bijvoorbeeld jackets).
    c. Geavanceerde numerieke modellen, waarbij de eindige-elementenmethode wordt toegepast om nauwkeurig de vervormings- en faalmodi van de fundering van de windturbine te beschrijven, rekening houdend met grond-fundatie interactie en de juiste modellering van het bezwijkgedrag van het botsende schip.
2. Het verwaarlozen van bodem-fundatie interactie leidt tot niet-realistische vervormingen van de funderingen, zoals duidelijk wordt uit verschillende numerieke onderzoeken zoals opgenomen in het literatuuroverzicht.
3. Het beschouwen van een botsend schip als een star lichaam zal overmatige vervormingen in de funderingen veroorzaken door het verwaarlozen van mogelijke energie dissipatie in het impact gebied van het schip. Bijvoorbeeld in een literatuur bron wordt aangegeven dat de flexibiliteit van het botsende schip de vervormingen van de windturbine fundatie met een factor 2 vermindert voor de geanalyseerde belastingscenario's.

Het literatuuronderzoek toont verder aan dat de resultaten van deze studies interessant zijn en achtergrondinformatie bieden over zaken welke relevant zijn voor het onderzoek naar de effecten van botsingen tussen schepen en windturbine fundaties. Echter, geen van deze studies geeft de informatie die RWS zoekt om toekomstige wetgeving op te baseren. Daarom zijn meer gedetailleerde en gecoördineerde studies nodig om de effecten van verschillende botsingsscenario's te onderzoeken.

De simulatieresultaten die in dit rapport worden gepresenteerd, zijn gebaseerd op de eindige-elementenmethode, zoals beschreven onder punt 1c hierboven. De gebruikte methode modelleert echter niet de geometrie van het schip en de fundering in volledig 3D, waarmee gedetailleerd inzicht kan worden verkregen in de lokale vervorming die zal optreden in het contactgebied tussen het schip en de fundering. Het nadeel van dergelijke 3D-modellen is dat ze zo gedetailleerd zijn dat de modelleringstijd en berekeningstijden uitgebreid zijn, en het moeilijk is om snel een overzicht te krijgen van het hele scala aan mogelijke scenario's voor schip-fundatie interacties. Analyses met dit soort modellen zullen deel uitmaken van een volgende fase van deze studie.

Het EEM-model dat in dit rapport wordt gebruikt voor de simulaties is een 3D-balkmodel dat het globale faalgedrag van een fundering bepaalt ten gevolge van plastische deformatie of schaal knik. Het houdt ook rekening met de flexibiliteit van het botsende schip en het elasto-plastisch gedrag van de bodem-fundatie interactie. Met dit model kan de schip-fundatie interactie ter plaatse van het impactpunt niet in detail worden onderzocht. Het is met dit model echter wel mogelijk om snel een overzicht te krijgen van mogelijke scenario's welke zich kunnen voordoen bij botsingen tussen schepen en windturbinefundaties aanwezig in de Noordzee.

Het EEM-model houdt geen rekening met secundaire constructies zoals J-buizen, bootlandingen, ladders, enzovoort. Over het algemeen is dit geen probleem omdat het secundaire staal niet structureel is en het gewicht, de afmetingen, stijfheid en sterkte verwaarloosbaar zijn in vergelijking met een schip of de primaire staalstructuur.

De uitzondering hierop is het hoofdplatform, dat doorgaans ergens tussen 15 en 25 [m] boven LAT (laagwaterstand) is geplaatst. Voor kleinere schepen bevindt het platform zich buiten het belangrijkste impactgebied maar het kan in botsing komen met het bovenste deel van het schip. Voor grotere schepen, zoals grote tankers, passagiersschepen en containerschepen, kan het hoofdplatform het eerste deel van de fundering zijn dat in contact komt met het schip. De interactie tussen schip en platform zal het schip niet laten zinken, maar het platform kan de scheepswand penetreren of het bovenste deel van het schip beschadigen, wat ernstige schade kan veroorzaken en bovendien tot verwondingen of overlijden van personeel en passagiers kan leiden.

De twee onderzochte windmolenparken verschillen aanzienlijk. De fundering van Windmolenpark 1 heeft een conventioneel ontwerp bestaande uit een toren, overgangsstuk en paal, terwijl de fundering voor Windmolenpark 2 alleen bestaat uit een toren en paal. Bovendien zijn er verschillen in diameter, wanddikte en lengtes van conische en buisvormige secties. Binnen elk windmolenpark is een fundering geselecteerd op minimale waterdiepte en een fundering op maximale waterdiepte. Het blijkt dat binnen een windmolenpark de verschillende funderingen dezelfde diameter en wanddikte hebben tot ongeveer LAT. Onder LAT zijn er verschillen in diameter en wanddikte voor de funderingspaal. Dit betekent dat de palen zijn geoptimaliseerd voor de waterdiepte en de grondomstandigheden.

Het moet worden opgemerkt dat de funderingsdiameter en wanddikte van de bestaande windmolenparken 1 en 2 aanzienlijk verschillen van de conceptuele ontwerpen die zijn geanalyseerd in het eerste deel van deze studie, zie lit. [5]. De conceptuele ontwerpen zijn over het algemeen stijver dan de ontwerpen voor de bestaande windparken, wat leidt tot verschillen in faalgedrag, vooral voor kleinere schepen. Ook verschillen de grondeigenschappen en daarmee de sterkte van de grond die zijn gebruikt voor deze conceptuele ontwerpfunderingen aanzienlijk van de grondsterkte die is gebruikt voor de bestaande windmolenparken 1 en 2. Daarom verschillen sommige van de faalmodi die zijn geïdentificeerd voor de conceptuele funderingsontwerpen van de faalmodi die zijn geïdentificeerd voor de bestaande windmolenparken 1 en 2.

De geselecteerde schepen voor het onderzoek dat in dit rapport wordt gepresenteerd, zijn gedeeltelijk afkomstig uit het SAFESHIP-onderzoek in 2005, zie lit. [2]. Het 'Very Large Container Carrier' is toegevoegd. Deze schepen vormen een ruwe dwarsdoorsnede van de schepen die varen in de wateren nabij de Nederlandse windmolenparken.

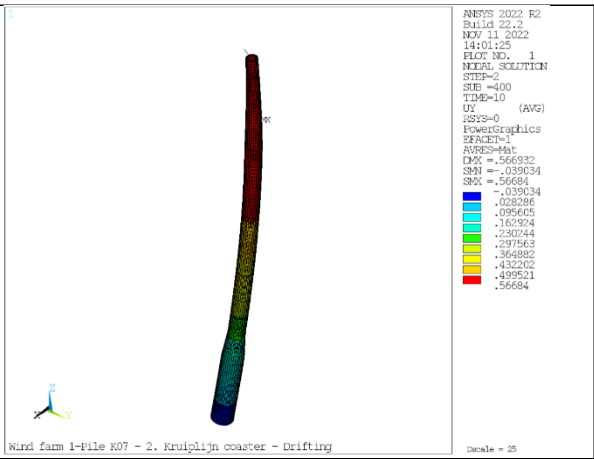
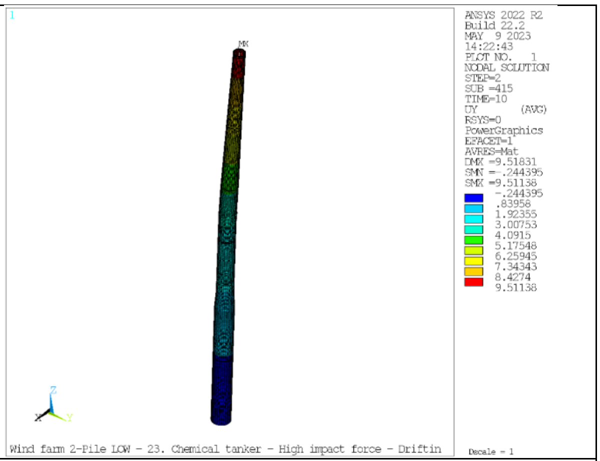
De simulaties om het gedrag van alle schepen en funderingen te bestuderen, zijn uitgevoerd voor de volgende condities:

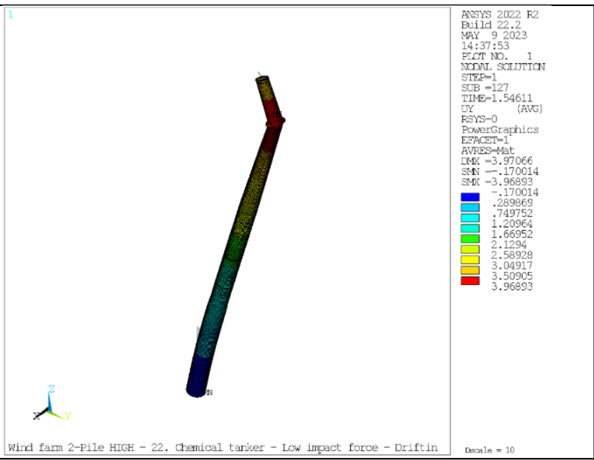
1. Een drijvend en een varend schip.
2. Impact waarbij het schip in dezelfde richting beweegt als de wind en de fundatie onder de rotor treft.
3. Impact waarbij het schip in tegen de wind in vaart en de fundatie onder de gondel treft
4. Zijdelingse impact van de fundering door een varend schip.
5. Variatie in het grondmodel, dat wil zeggen het Full reversible' grondmodel zonder energie dissipatie door de grond en het Non reversible' grondmodel met energie dissipatie door de bodem. Dit heeft met name invloed op de elastische terugveercapaciteit van de fundering na de impact.
6. Verminderde sterkte van het schip om mogelijke onnauwkeurigheden in de schatting van de faalbelastingen van de schepen die zijn geëxtrapoleerd uit DNV standaard te onderzoeken.
7. Verminderde drijf- en vaarsnelheid van het schip om het effect van de impactsnelheid te onderzoeken.
8. Het effect van wind-, golf- en stromingsbelastingen op de fundering en de turbine gedurende de botsing.

9. Het effect van wind-, golf- en stromingsbelastingen op een drijvend schip, respectievelijk de motorvoortstuwingsbelasting op een varend schip.
10. Het effect van het faalcriterium van de fundering, plastische deformatie resp. plooien. In het laatste geval neemt de faalbelasting voor de fundering aanzienlijk af.

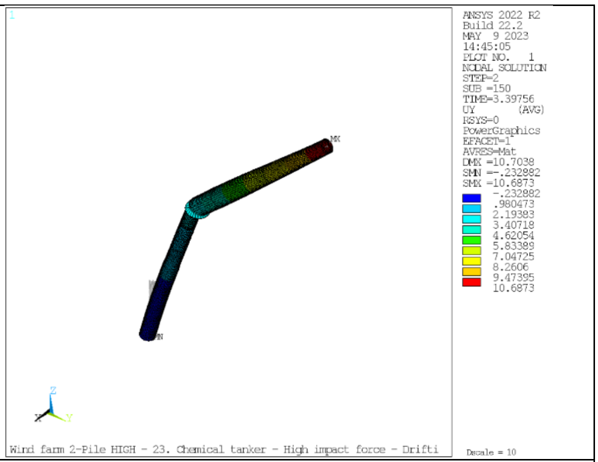
De analyses van alle simulatieresultaten leidden tot de volgende 8 belangrijkste faalmodi van de funderingen van de windturbines:

1. Geen paal- of torenfalen, alleen elastische vervorming van de fundering, de fundering blijft staan en oscilleert in zijn eerste eigenmode, zie Tabel 1.1, mode 1.
2. Torenfalen (plastische vervorming) maar geen toreninstorting, zie Tabel 1.1, mode 2.
3. Torenfalen/instorting, de turbine beweegt naar het schip toe, zie Tabel 1.1, mode 3.
4. Torenfalen/instorting, de turbine beweegt zich van het schip af, zie Tabel 1.1, mode 4.
5. Grond falen, de turbine beweegt naar het schip toe, zie Tabel 1.1, mode 5. Vanwege het falen van de grond beweegt de fundering weg van het schip, terwijl door het falen van de toren de gondel naar het schip toe neigt te bewegen. Welke van de twee tegenwerkende bewegingen dominant wordt, kan niet worden gesimuleerd door het huidige model en hangt af van de snelheid waarmee elk falen zich ontwikkelt. Het is dus niet mogelijk te voorspellen of het falen van de toren zal resulteren in het vallen van de turbine op het schip, of dat het falen van de grond uiteindelijk zal leiden tot het bewegen van de turbine weg van het schip.
6. Grondfalen, de turbine beweegt zich van het schip af, zie Tabel 1.1, mode 6.
7. Fundatiefalen in de grond, torenfalen als gevolg van de massatraagheid van de gondel, de turbine beweegt naar het schip toe, zie Tabel 1.1, mode 7.
8. Fundatiefalen in de bodem, torenfalen als gevolg van de massatraagheid van de gondel, de turbine beweegt zich van het schip af, zie Tabel 1.1, mode 8.

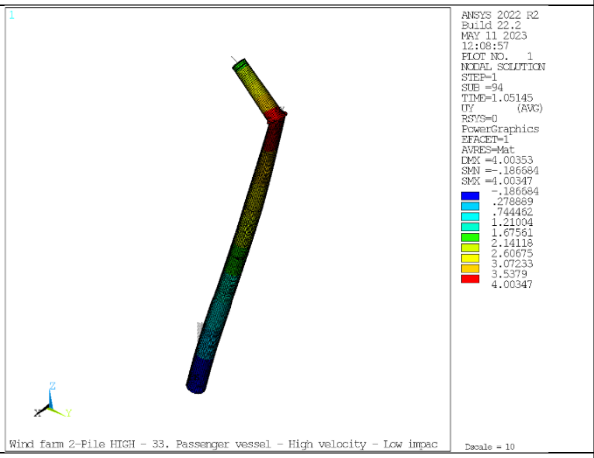
| | |
|---|---|
|  |  |
| 1. Geen paal- of torenfalen. | 2. Torenfalen (plastische vervorming) maar geen toreninstorting. |



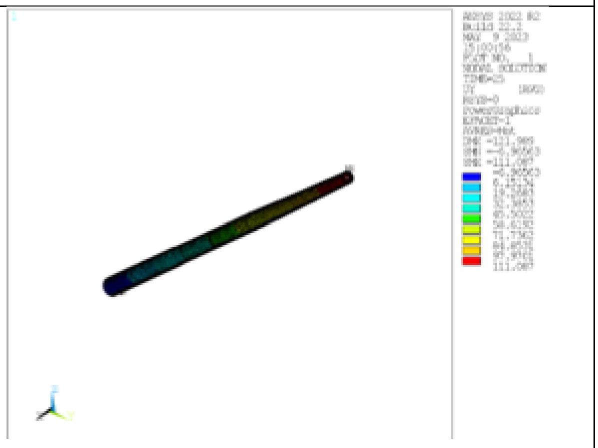

3. Torenfalen/instorting, de turbine beweegt naar het schip toe.



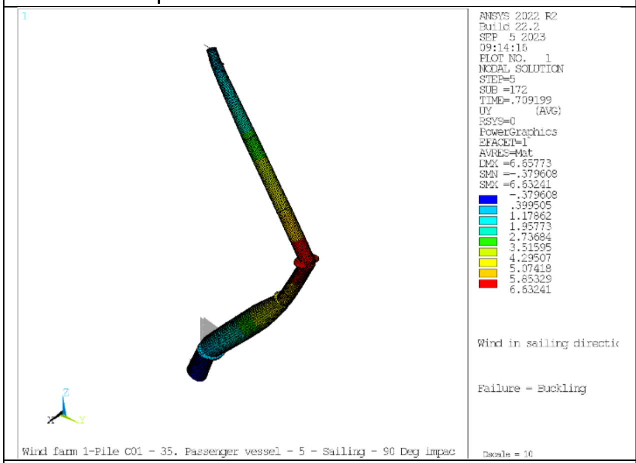

4. Torenfalen/instorting, de turbine beweegt zich van het schip af.



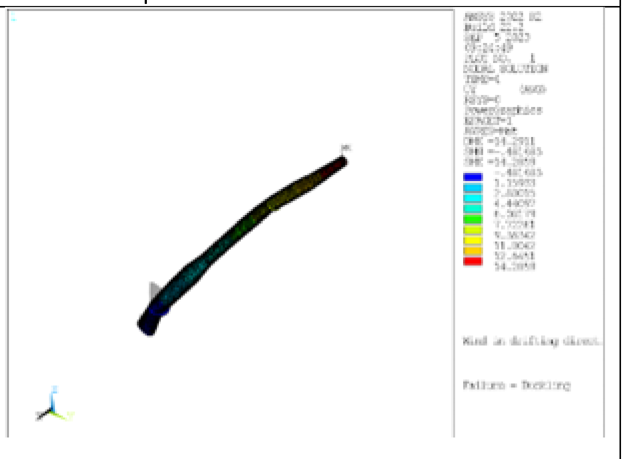

5. Grond falen, de turbine beweegt naar het schip to.



6. Grondfalen, de turbine beweegt zich van het schip af.




7. Fundatiefalen in de grond, torenfalen als gevolg van de massatraagheid van de gondel, de turbine beweegt naar het schip toe.



8. Fundatiefalen in de bodem, torenfalen als gevolg van de massatraagheid van de gondel, de turbine beweegt zich van het schip af.

Tabel 1.1: Grafische presentatie van de gedetecteerde faalmodi.

De meest geschikte simulaties om de belangrijkste faalmodi van de fundering te identificeren, zijn de simulaties die zijn uitgevoerd met wind-, golf-, stromings- en turbinebelastingen op de fundering, zonder externe belastingen op het schip met nominale sterkte-eigenschappen van het schip en nominale drijvende en varende snelheden. Het faalcriterium voor de fundering in deze simulaties is ofwel plastische deformatie of plooi.

De belangrijkste geïdentificeerde faalmodi worden weergegeven in Tabel 1.2. Uit deze resultaten volgt dat de funderingen van de Windmolenparken 1 en 2 alleen in staat zijn om een drijvende impact van schepen tot ongeveer 3000 ton waterverplaatsing te overleven, zoals de onderzochte Kruiplijn coaster, wanneer plooi het dominante faalcriterium is. Wanneer plastische deformatie het dominante faalcriterium is, kan ook impact door drijvende schepen tot ongeveer 7000 ton, zoals het bevoorradingsschip, overleefd worden door de fundering zonder instorting van de toren.

Bij varende impact door deze schepen leidt dit in de meeste gevallen tot funderingsfalen, met het gevaar dat de turbine op het schip valt. Voor de grotere schepen, zoals chemicaliëntankers, passagiersschepen en containerschepen, treedt bijna altijd catastrofaal falen van de fundering op, met het gevaar dat de turbine op het schip valt.

In Tabel 1.3 worden de maximale versnellingen voor de turbine gepresenteerd. Deze zijn relevant voor de sterkteverificatie van de verbinding tussen de gondel en de bovenflens van de toren. Het volgt dat voor de Kruiplijn coaster, het bevoorradingsschip en de chemicaliëntanker de versnellingen over het algemeen maximaal +/-10 [$m/s^2$] zijn. Voor het passagiersschip en voor het grote containerschip nemen de maximale versnellingen toe tot +/-20 [$m/s^2$].

Het mogelijke falen van de verbinding tussen de bovenflens van de toren en de gondel is niet onderzocht. Dit is een moeilijke kwestie, aangezien de analyse van deze mogelijke faalmode afhankelijk is van zeer vertrouwelijke informatie van de turbinefabrikanten die ze zeer waarschijnlijk niet zullen delen. De evaluatie van het effect van deze versnellingen op de verbinding tussen de gondel en de toren moet daarom worden uitgevoerd door de turbinefabrikanten.

| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 1 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 6 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

Met wind, plastische deformatie als faalcriterium.

| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 4 | 4 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 4 | 3 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 2 | 3 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 3 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 7 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 8 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

Met wind, plooi als faalcriterium.

Tabel 1.2: Samenvatting van de gedetecteerde faalmodi gedurende drijvende/varende impact, met wind belasting werkend op de fundatie en plastische deformatie of plooi als faalcriterium.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -2.19 | 4.81 | -2.36 | 3.50 | -2.56 | 3.76 | -2.80 | 3.68 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.36 | 9.76 | -5.44 | 5.55 | -4.81 | 5.03 | -7.84 | 6.77 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -4.75 | 4.09 | -4.89 | 4.04 | -6.02 | 3.53 | -5.18 | 4.54 |
| | | | | | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.06 | 7.98 | -4.54 | 6.42 | -5.60 | 5.26 | -4.88 | 6.60 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 12.69 | -1.08 | 8.83 | -4.52 | 9.18 | -3.24 | 10.19 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -3.36 | 7.96 | -2.68 | 7.87 | -5.59 | 7.91 | -5.73 | 7.51 |
| | | | | | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.67 | 10.28 | -7.98 | 9.92 | -7.79 | 7.89 | -5.91 | 9.03 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 10.99 | -2.10 | 10.03 | -6.25 | 9.87 | -4.21 | 9.97 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -6.90 | 6.86 | -10.42 | 8.68 | -6.79 | 8.12 | -5.67 | 6.92 |
| | | | | | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -14.66 | 22.47 | -12.17 | 15.97 | -11.03 | 13.25 | -10.26 | 12.47 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -13.35 | 15.78 | -8.44 | 15.10 | -10.07 | 14.10 | -10.87 | 15.27 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -16.48 | 15.84 | -10.77 | 20.22 | -8.69 | 12.42 | -8.77 | 12.18 |
| | | | | | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -11.31 | 17.22 | -11.02 | 16.43 | -9.47 | 10.71 | -9.40 | 10.33 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.59 | 11.50 | -2.83 | 11.02 | -6.21 | 9.54 | -2.83 | 9.81 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -10.28 | 9.30 | -5.76 | 9.11 | -6.25 | 8.61 | -6.95 | 6.84 |
| **Overall extremes** | | | | | | | **-16.48** | **22.47** | **-12.17** | **20.22** | **-11.03** | **14.10** | **-10.87** | **15.27** |

Tabel 1.3: Samenvattende maximale turbine versnellingen.

## 2. 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 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 the results of this assessment 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, passengers and cargo, the environment and for the foundations.

In 2005 the project SAFESHIP (https://cordis.europa.eu/project/rcn/86899/factsheet/en), lit. [2], was carried out to address the issue of ship collisions against wind turbines. Since the finishing of the SAFESHIP project, new studies and analyses 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, see lit. [3]. 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.

In the first part of this study, see lit. [5], a preliminary investigation has been carried out, based on the conceptual design of 2 wind turbine foundations for a 10 MW wind turbine in the North Sea area, because at that moment no information about existing wind turbine foundations in the Dutch part of the North Sea had been received.

Later, when the required technical information had been received for 2 wind farms, Wind farm 1 and Wind farm 2, the same analyses have been executed for the really existing foundations of the Wind farms 1 and 2.

The results of these investigation give insight in the possible failure scenarios that can occur when a ship collides with a wind turbine foundation. The study is limited to mono pile foundations as this is the only foundation presently used in the Dutch part of the North Sea. In this report the model as developed in lit. [2] has been updated and the effect of various parameters has been investigated in more detail. Such parameters are the soil model, the impact direction of the ship relative to the rotor axis of the turbine, the effect of the wind, wave, current and turbine load acting on the foundation, the effect of the propulsion load acting on the ship, either due to wind, wave and current in case of a drifting ship or due to the ship motor in case of a sailing ship and the failure criterion applicable for the wind turbine foundation, e.g. failure due to yield of the material or failure due to shell buckling.

A brief literature survey to the present state of the art of investigations concerning the impact of ships against wind turbine foundations, see lit. [3], 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 scenarios.

The simulation results presented in this report are based on the FE method as described under item 1c above. The method used does however not model the geometry of the ship and the foundation in full 3D giving detailed insight in the local deformation that will occur in the contact area between ship and foundation. The disadvantage of these 3D 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. Analyses using this kind of models will be part of a next phase of this study.

The FE model used for the simulations in this report is a 3D beam model that captures the global failure modes of a foundation due to for example global yield or shell buckling. Also, it takes into account the flexibility of the impacting ship and the elasto-plastic behaviour of the soil-structure interaction. With this model the detailed ship-foundation interaction at the impact point cannot be investigated, but it is possible to get 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 structures 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 resp. the primary steel structure.
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 into 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 and cause severe damage and in addition can possibly lead to injuries or death of personnel and passengers.

The two investigated Wind farms are quite different. The foundation of Wind farm 1 has a conventional design consisting of a tower, transition piece and pile, whereas the foundation for Windfarm 2 consists of only a tower and pile. Furthermore, there are differences in diameter, wall thickness and lengths of conical and tubular section. Within each Wind farm a foundation located at minimum water depth and a foundation located at maximum water depth has been selected. It turns out that within a Wind farm the various foundations have the same diameter and wall thickness up to approximately LAT. Below LAT, for the foundation pile, there are differences in diameter and wall thickness. This means that the piles have been optimized for the water depth and the soil conditions.

It must be noted that the foundation diameter and wall thickness of the existing wind farms 1 and 2 differ considerably from the conceptual designs analysed in the first part of this study, see lit. [5]. The conceptual designs are in general stiffer than the actual designs, leading to differences in failure behaviour, especially for the smaller ships. Also, the soil properties and the soil strength used for these conceptual design foundations is very large in comparison with the actual soil strength used for the existing wind farms 1 and 2. Therefore some of the failure modes identified for the conceptual foundation designs differ from the failure modes identified for the existing wind farms 1 and 2.

The selected ships for the investigation presented in this report 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.

The simulations to study the behaviour of all the ships and foundations has been carried out for the following conditions and circumstances.

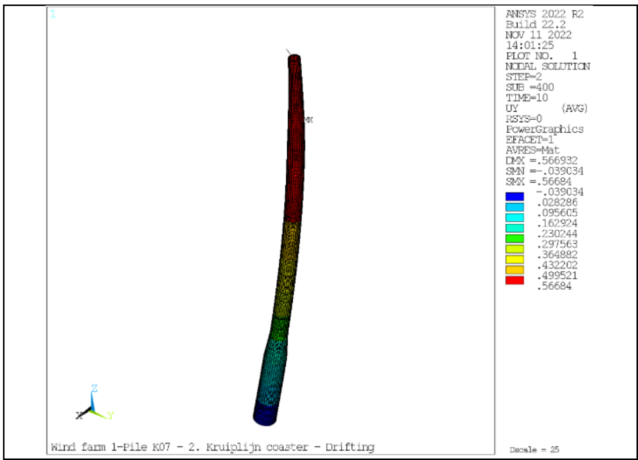
1. A drifting and a sailing ship.
2. Impact when moving with the wind, so hitting the foundation below the rotor.
3. Impact when moving against the wind, so hitting the foundation below the nacelle, when sailing.
4. Side impact of the foundation, when sailing.
5. Variation in soil model, e.g., the 'Full reversible' soil model with no energy dissipation by the soil and the 'Non reversible' soil model with energy dissipation by the soil. This affects especially the elastic rebound capacity of the foundation after impact.
6. Reduced ship strength to investigate possible inaccuracies in the estimation of the ship failure loads that have been extrapolated from standard DNV curves.
7. Reduced drifting and sailing velocity of the ship to investigate the effect of the impact velocity.
8. The effect of wind, wave, current loads acting on the foundation and the turbine.
9. The effect of wind, wave and current loads acting on a drifting ship, resp. the motor propulsion load acting on a sailing ship.
10. The effect of the failure criterion of the foundation, e.g., Yield or shell buckling. In the latter case, the failure load for the foundation is considerably reduced.

The analyses of all simulation results led to the following 8 main failure modes of the wind turbine foundations:

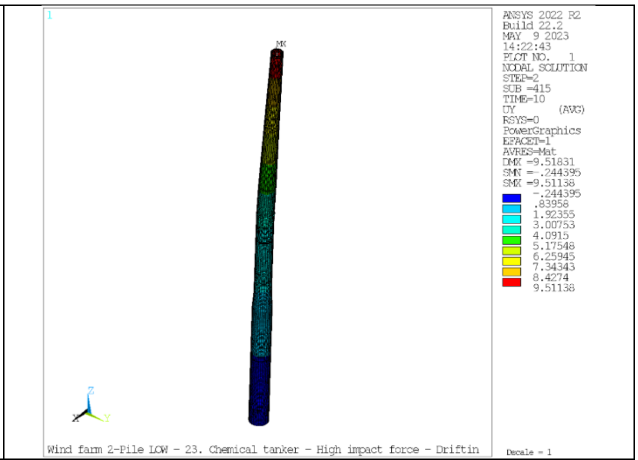
1. No pile or tower failure, just elastic foundation deformation, the foundation remains standing and oscillates in its 1$^{st}$ eigenmode, see Table 2.1, mode 1.
2. Tower failure (plastic deformation) but no tower collapse, see Table 2.1, mode 2.
3. Tower failure/collapse, turbine moving towards the ship, see Table 2.1, mode 3.
4. Tower failure/collapse, turbine moving away from the ship, see Table 2.1, mode 4.
5. Soil collapse, turbine moving towards the ship, see Table 2.1, mode 5.

   Due to the collapse of the soil, the foundation moves away from the ship, while due to the failure of the tower the nacelle tends to move towards the ship. Which of the 2 counteracting motions becomes dominant cannot be simulated by the present model and depends on the velocity with which each failure develops. It is thus not possible to predict whether the tower failure will result in the turbine dropping down on the ship or that the soil failure will ultimately lead to the turbine moving away from the ship.

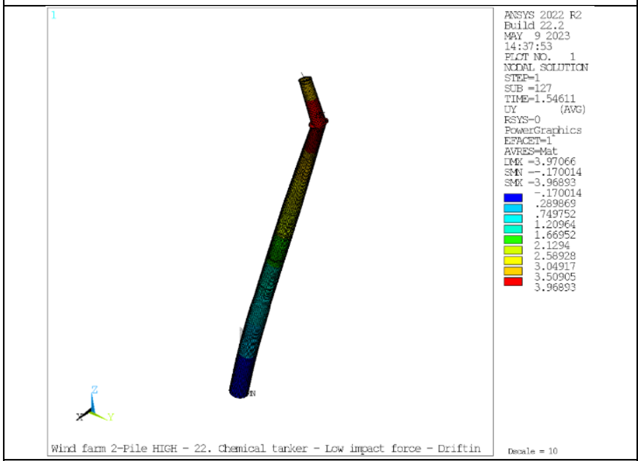
6. Soil collapse, turbine moving away from the ship, see Table 2.1, mode 6.
7. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving towards the ship, see Table 2.1, mode 7.
8. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving away the ship, see Table 2.1, mode 8.



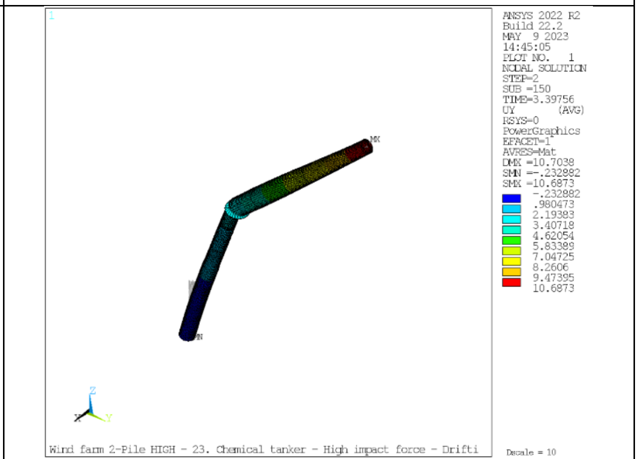

1. No pile or tower failure.




2. Tower failure (plastic deformation) but no tower collapse.




3. Tower failure/collapse, turbine moving towards the ship.




4. Tower failure/collapse, turbine moving away from the ship.

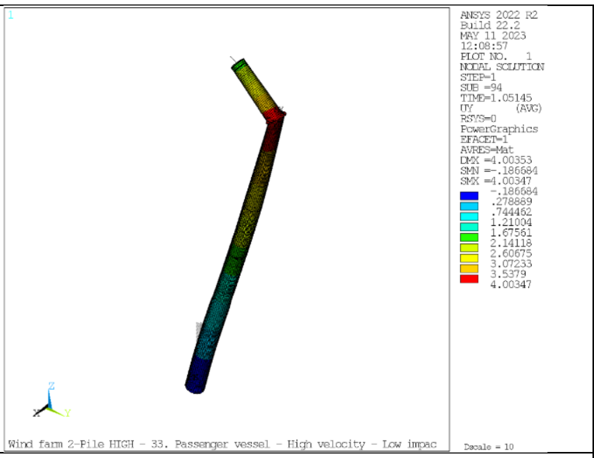
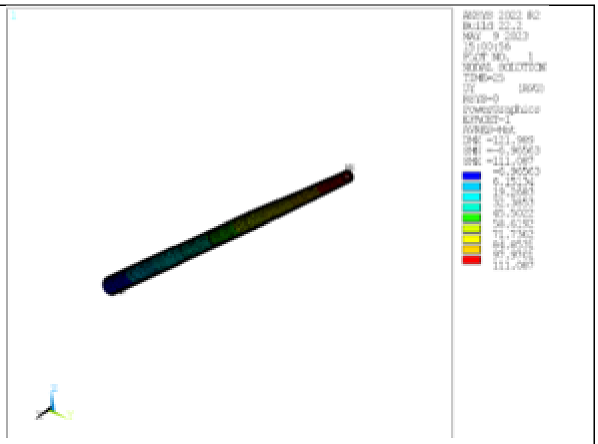
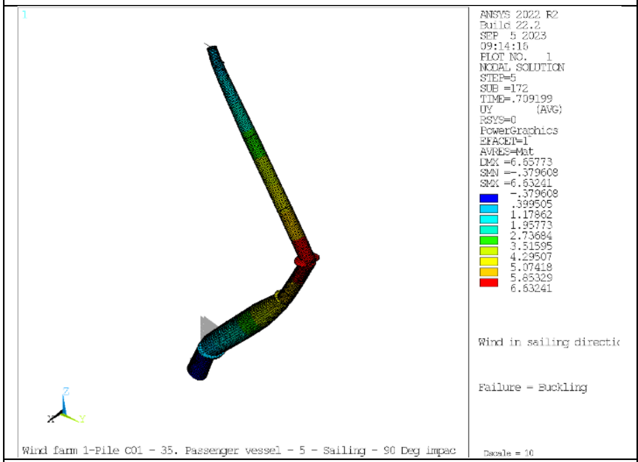
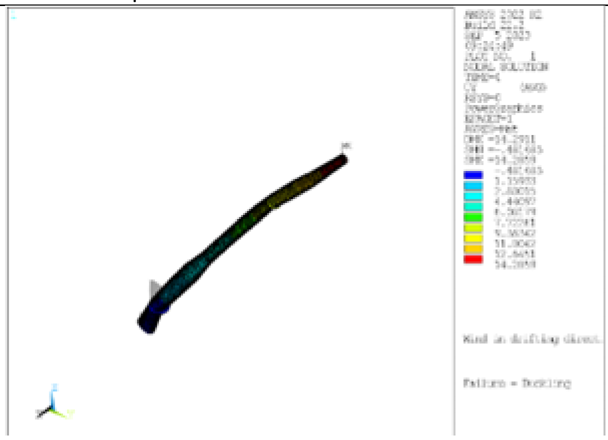
<table>
<tr>
<td>
</td>
<td></td>
</tr>
<tr>
<td>5. Soil collapse, turbine moving towards the ship.</td>
<td>6. Soil collapse, turbine moving away from the ship.</td>
</tr>
<tr>
<td>
</td>
<td></td>
</tr>
<tr>
<td>7. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving towards the ship.</td>
<td>8. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving away the ship.</td>
</tr>
</table>

Table 2.1: Graphical presentation of detected failure modes.

The simulations that are most appropriate to identify the main failure modes of the foundation are the simulations that have been carried out with the wind, wave, current and turbine loads acting on the foundation, no external loads acting on the ship using nominal ship strength properties and nominal drifting and sailing velocities. The foundation failure criterion for these simulations is either Yield or shell buckling.

The main identified failure modes are in Table 2.2. From these results it follows that the foundations of Wind farm 1 and 2 are only able to survive drifting impact for ships up to c.a. 3000 tonnes displacement, such as the investigated Kruiplijn coaster, when buckling is the dominant failure criterion. When yield is the dominant failure criterion, also impact by drifting ships up to c.a. 7000 tonnes, e.g. the Supply vessel, can be survived by the foundation without tower collapse.
Sailing impact by these ships in most cases leads to foundation failure, with the danger of the turbine dropping down on the ship.

For the larger ships, e.g., Chemical tankers, Passenger vessels and Container ships catastrophic failure of the foundations does almost always occur, with the danger of the turbine dropping down on the ship.

In Table 2.3 the maximum accelerations for the turbine are presented. These are relevant for the strength verification of the connection between nacelle and tower top. It follows that for the Kruiplijn coaster, the

Supply vessel, and the Chemical tanker the accelerations are in general maximal +/-10 [m/s$^2$]. For the Passenger vessel and for the large Container ship the maximum absolute acceleration increases to +/-20 [m/s$^2$].

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 manufacturers that they is very unlikely to share. Evaluation of the effect of these accelerations on the connection between nacelle and tower must therefore be carried out by the turbine manufacturers.

| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 1 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 6 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

With wind, yield failure criterion.

| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 4 | 4 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 4 | 3 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 2 | 3 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 3 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 7 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 8 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

With wind, shell buckling failure criterion.

Table 2.2: Summary of detected failure modes during drifting/sailing with wind load and using Yield or shell buckling as failure criterion.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| **Foundation** | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -2.19 | 4.81 | -2.36 | 3.50 | -2.56 | 3.76 | -2.80 | 3.68 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.36 | 9.76 | -5.44 | 5.55 | -4.81 | 5.03 | -7.84 | 6.77 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -4.75 | 4.09 | -4.89 | 4.04 | -6.02 | 3.53 | -5.18 | 4.54 |
| | | | | | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.06 | 7.98 | -4.54 | 6.42 | -5.60 | 5.26 | -4.88 | 6.60 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 12.69 | -1.08 | 8.83 | -4.52 | 9.18 | -3.24 | 10.19 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -3.36 | 7.96 | -2.68 | 7.87 | -5.59 | 7.91 | -5.73 | 7.51 |
| | | | | | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.67 | 10.28 | -7.98 | 9.92 | -7.79 | 7.89 | -5.91 | 9.03 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 10.99 | -2.10 | 10.03 | -6.25 | 9.87 | -4.21 | 9.97 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -6.90 | 6.86 | -10.42 | 8.68 | -6.79 | 8.12 | -5.67 | 6.92 |
| | | | | | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -14.66 | 22.47 | -12.17 | 15.97 | -11.03 | 13.25 | -10.26 | 12.47 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -13.35 | 15.78 | -8.44 | 15.10 | -10.07 | 14.10 | -10.87 | 15.27 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -16.48 | 15.84 | -10.77 | 20.22 | -8.69 | 12.42 | -8.77 | 12.18 |
| | | | | | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -11.31 | 17.22 | -11.02 | 16.43 | -9.47 | 10.71 | -9.40 | 10.33 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.59 | 11.50 | -2.83 | 11.02 | -6.21 | 9.54 | -2.83 | 9.81 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -10.28 | 9.30 | -5.76 | 9.11 | -6.25 | 8.61 | -6.95 | 6.84 |
| **Overall extremes** | | | | | | | **-16.48** | **22.47** | **-12.17** | **20.22** | **-11.03** | **14.10** | **-10.87** | **15.27** |

Table 2.3: Overall extremes for the turbine accelerations.

# 3. 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 the results of this assessment 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, passengers and cargo, the environment and for the foundations.

In 2005 the project SAFESHIP (https://cordis.europa.eu/project/rcn/86899/factsheet/en), lit. [2], 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 study, see lit. [3], to the latest state of the art concerning ship/wind turbine collision, focusing 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 3.1.

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 3.1: Windfarms in the Dutch part of the North Sea.

In the first part of this study, see lit. [5], a preliminary investigation has been carried out, based on the conceptual design of 2 wind turbine foundations for a 10 MW wind turbine in the North Sea area, because at that moment no information about existing wind turbine foundations in the Dutch part of the North Sea had been received. In the 2$^{nd}$ and 3$^{rd}$ part of the study, see lit. [6] and [7], this analysis has been repeated for 2 existing windfarms that have recently been put into operation in the Dutch North Sea area. These wind farms are being identified by the following names:

1. Wind farm 1.
2. Wind farm 2.

In Section 4 first a summary is given of the results of the literature study. Next, in Section 5, the assumptions made for the simulation model are discussed. In Section 6 the investigated wind turbine foundations and the main properties of the ships used for the investigation are presented and in Section 7 is summarized which effects have not been included in the analyses. The results of the simulations are discussed in Section 8 for the conceptual wind turbine foundation designs and in Section 9 for the wind turbine foundation designs for Wind farm 1 and 2. The main conclusions are finally summarised in Section 10.

## 4. Literature survey.

The results of the literature survey are presented in lit. [3]. 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, see lit. [22].
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 5000 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, see lit. [2], 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 tonnes 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 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 scenarios.

# 5. Discussion of model assumptions.

In lit. [4] a review is given of the ship impact simulation programs as they were developed for the SAFESHIP project in 2005, see lit. [2]. These programs have been adapted and extended to be able to use them efficiently for the investigation of the ship impact analysis for the existing windfarms in the Dutch part of the North Sea.

In the next sections the main assumptions that have been made for the development of these programs will be discussed briefly, together with an impression of the expected effects on the simulation results.

## 5.1. Finite element program and solution method.

All simulations have been carried out with ANSYS APDL rev. 2022, using the implicit formulation and 'large displacement' set to on. Gravity is also considered and the fact that 'large displacement' has been set to on means that when the foundation is pushed over the moment caused by the gravity load acting on the rotor and the nacelle increases when the inclination angle of the foundation increases.

The fact that the implicit formulation has been used means that the simulations are stopped when large plastic deformations occur in the elements or when the foundation is pushed over due to soil failure. When this happens, the numerical solution becomes unstable, and the program is stopped. So, post failure calculations during collapse of the foundation cannot be carried out with this model!

To investigate the actual collapse of a foundation 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 limited anyway.

The elements selected to model the ship-foundation interaction are such that the impact force always acts parallel to the horizontal plane, even when the foundation rotates when it is being pushed over. However, the height of the impact point on the foundation is fixed, so the fact that when the foundation is pushed over the contact point between ship and foundation actually moves towards a lower point on the foundation is not included in the analysis. This results in an underestimation of the results when collapse of the soil occurs.

## 5.2. The coordinate system.

The coordinate systems used to describe the model is presented in Figure 5.1, they are:

1. A coordinate system with the origin located **at LAT** and lying on the centre line of the foundation.

2. A coordinate system with the origin located **at top of the tower flange** that connects the tower with the nacelle and lying on the centre line of the foundation.

Both coordinate systems have parallel axis with the XZ-plane being parallel with the rotor blades and the direction of those axis is as follows:

1. The X-axis is running parallel with the area formed by the rotor blades.

2. The Y-axis is pointing in the direction of the nacelle, so away from the rotor blades.

3. The Z-axis is point upwards.

In general, this means that the COG of the rotor and nacelle is lying at the negative Y-axis.

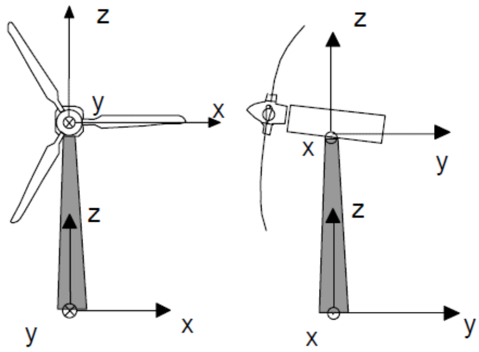



Figure 5.1: Coordinate systems used to describe the model.

## 5.3. 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 5.2.

   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 ovalising 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 ovalising 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 ovalising 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.

   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 executed during this study, marine growth has not been considered.

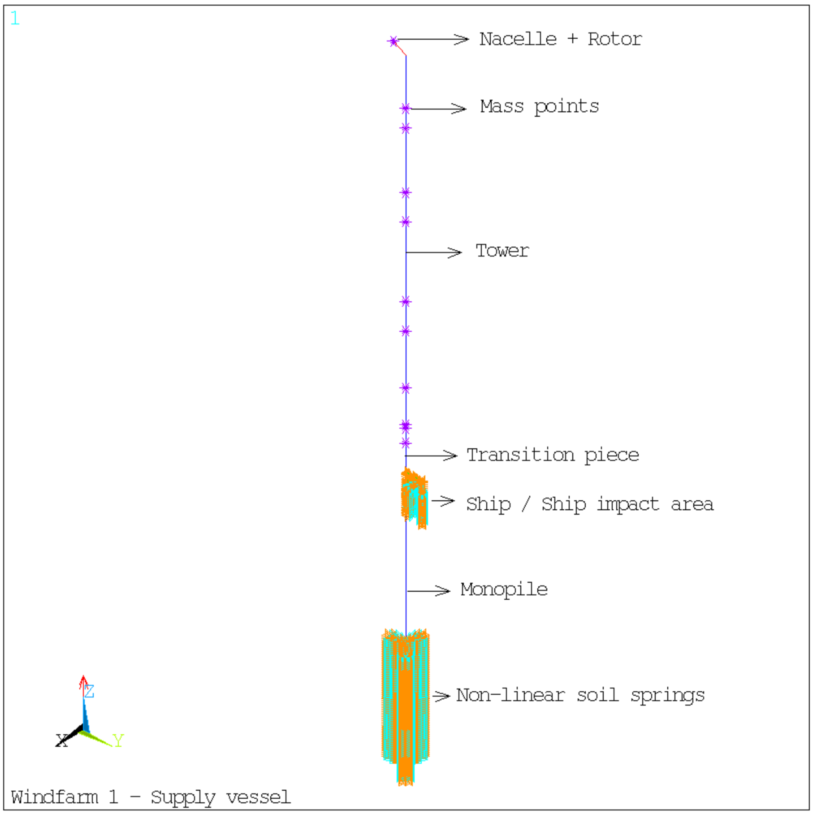



Figure 5.2: ANSYS model for ship impact against an offshore wind turbine foundation, build-up out of beam elements.

e. Water inside and outside the pile.

To account for the effect of the water mass at the inside and at the outside of the foundation during impact, these water masses have been included in the analyses as follows:

i. Water at the inside of the foundation.

It has been assumed that the water level at the inside of the foundation is the same as at the outside of the foundation. This water level is assumed to be equal to MSL.

The total mass of the water inside the foundation has been considered and has been added to the mass of the pile.

ii. Water at the outside of the foundation.

The water level at the outside of the foundation is assumed to be equal to MSL. The added water mass factor used is equal to 1.2.

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 encountered by 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 and cause severe damage and can possibly lead to injuries or death of personnel and passengers.

   This effect cannot be simulated by the present models and programs and will require a dedicated study.

## 5.4. The soil.

### 5.4.1. Introduction.

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 in lit. [5] is presented Figure 5.3 for various penetration depths. The penetration depth is relative to LAT, with in this case the soil level being located at -25.6 [m].

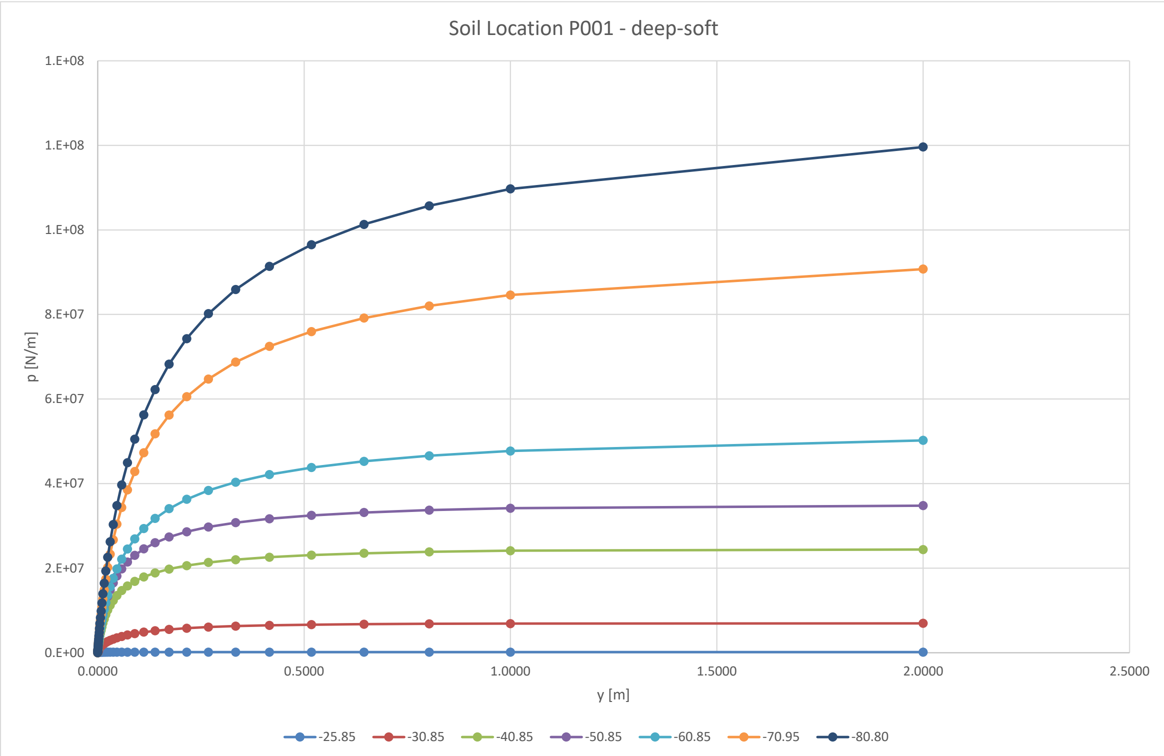



Figure 5.3: PY curves of example soil location P001 – deep-soft.

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 c.a. 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. This will be discussed in the following sections.

### 5.4.2. Theory of the py-curves under alternating loading.

The design of laterally loaded monopiles in current design regulations i.e. Det Norske Veritas, lit. [9], and American Petroleum Institute, lit. [10] is done by means of the p-y curve method, see lit. [11]. The pile-soil behaviour is modelled by a Winkler model approach where the pile is modelled as a beam supported by uncoupled springs, as for example shown in Figure 5.4, lit. [12]. The drawing in Figure 5.5 shows a cylindrical pile under lateral loading. Unloaded, there is a uniform distribution of unit stresses normal to the wall of the pile as shown in Figure 5.5b. When the pile deflects over a distance of y1 at a depth of z1, the distribution of stresses looks similar to Figure 5.5c with a resisting force of p1. The stresses will have decreased on the backside of the pile and increased on the front, where some unit stresses contain both normal and shearing components as the displaced soil tries to move around the pile. When it comes to this type of analysis, the main parameter to take from the soil is a reaction modulus. It is defined as the resistance from the soil at a point along the depth of the pile divided by the horizontal deflection of the pile at that point. This can for example be expressed by the reaction modulus, Epy, using the secant of the p-y curve, as shown in Figure 5.6. p-y curves are developed at specific depths, indicating the soil reaction modulus is both a function of pile deflection (y) and the depth below the ground surface (z). More information about how to derives p-y curves for various soil types is presented in lit. [12].

The springs as shown in Figure 5.4 represent the response of the soil and the spring stiffnesses are modelled by p-y curves which account for the non-linear relationship between soil resistance and lateral deflection of the pile. The p-y curve theory was initially developed for piles in the oil and gas industry and is based on test results from slender, flexible piles. Thus, the curves were not developed for piles with diameters of 4 to 10 m which are often used for the foundation of wind turbines today. No approved method exists for the design of large diameter piles and therefore the p-y curve method is still the applied method today and has also been used for the design of the wind farms being investigated in this study.

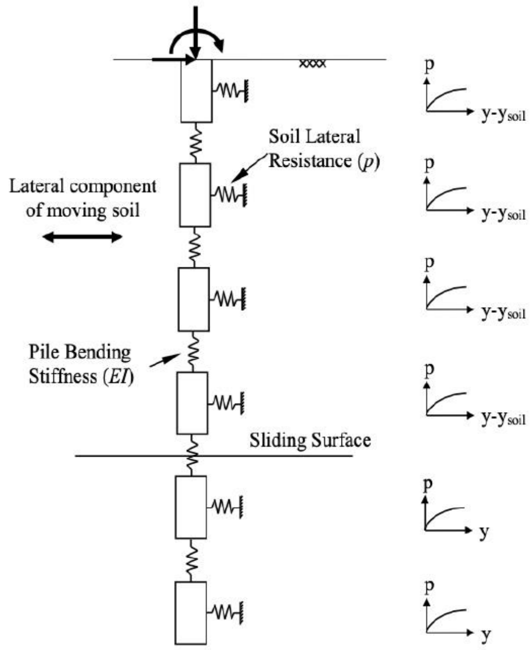



Figure 5.4: Spring mass model used to compute lateral response of loaded piles (lit. [8]).

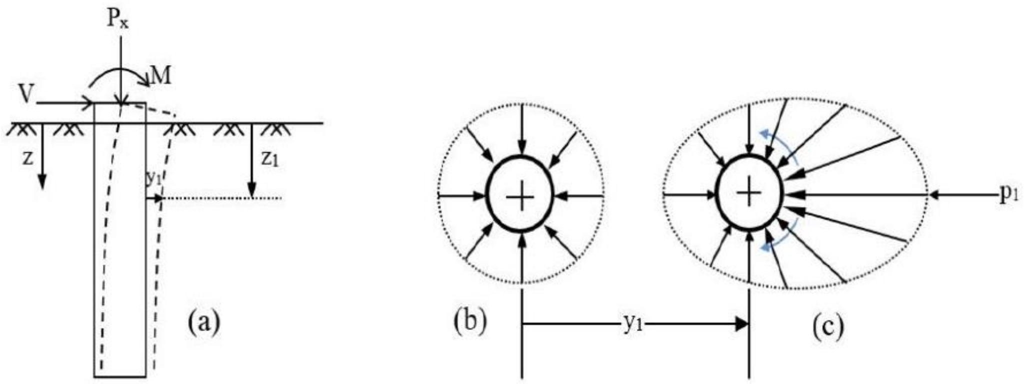



Figure 5.5: Unit stress distribution in a laterally loaded pile (Lit. [8]).

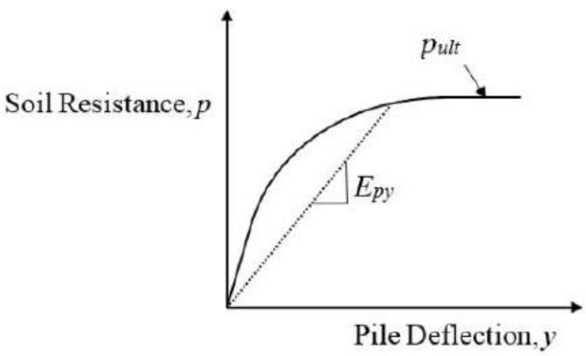



Figure 5.6: Generic p-y curve defining soil reaction modulus (Lit. [8]).

The p–y curve is commonly assumed to be reversible, lit. [9]. This is generally not the case for real soils, for which irreversible displacements are observed during unloading. This irreversibility can also be accompanied by the formation of a gap between the pile and the soil behind during loading in a given direction. To explain what happens during loading and unloading in case of gapping, see lit. [13], in the following example elastic unloading of the p–y curve is assumed, with a modulus equal to the initial slope of the loading branch, E0, see Figure 5.7.

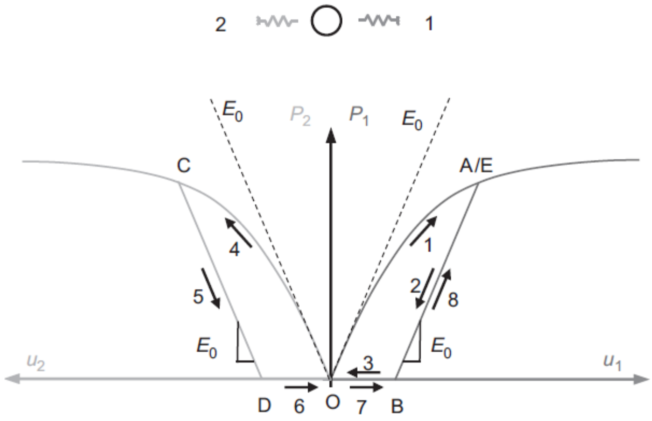



Figure 5.7: The response in unloading of a generic p-y curve with gapping (Lit. [9]).

Depending on the soil behaviour, the pile stiffness, and the stress state around the pile after installation, gapping can occur and significantly affect the response of the pile. The extent of the gap will vary with depth along the pile. For example, in the pile tests for the PISA project, the extent of a gap was analysed in lit. [14] for stiff clay and in lit. [15] for sand. To explain the modelling procedure in the presence of gapping, first the case is considered of unidirectional loading simulated with two opposite springs, number 1 and number 2, see Figure 5.7. Consider a loading sequence consisting of loading and unloading of spring number 1 followed by loading and unloading of spring number 2 in the opposite direction and finally reloading of spring number 1. After the first loading/unloading cycle applied on spring number 1 (paths 1 and 2 in Figure 5.7, the irreversible displacement is represented by segment OB. The pile moves towards its initial position (zero displacement) without mobilising the soil reaction (path 3). Spring number 2 starts to be compressed only when the displacement of the pile changes sign. The second loading and unloading cycle applied on spring number 2 is represented in Figure 5.7 by paths 4 and 5, which generate irreversible displacement OD. Spring number 1 is now reloaded only after the pile returns to point B (paths 6 and 7). By contrast, when no gapping occurs spring number 2 is compressed directly from point B, even though the spring displacement is negative (negative load in the spring is never permitted). It is generally assumed that the response of spring number 2 is not affected by the previous loading/unloading cycle of spring number 1. This is a strong assumption because pile loading affects the soil behind when no gapping occurs. However, the model could be extended to account for soil remoulding due to pile loading, but this would require additional complexity in the constitutive model of the soil.

So, summarizing; for soil modelling with p-y curves and non-gapping soil behaviour the p-y curve can be represented by one non-linear spring, see Figure 5.8. The spring definition should extend stiffness through both sides of the p-y relationship, and the hysteretic model should be selected as Kinematic, as shown in Figure 5.10.

The kinematic hysteresis model is based upon kinematic hardening behaviour that is commonly observed in metals. This model dissipates a significant amount of energy and is appropriate for ductile materials. Under the rules of kinematic hardening, plastic deformation in one direction 'pulls' the curve for the other direction along with it. Matching pairs of points are linked, see Figure 5.11. No additional parameters are required for this model. So, upon unloading and reverse loading, the curve follows a path made of segments parallel to and of the same length as the previously loaded segments and their opposite-direction counterparts until it re-joins the backbone curve when loading in the opposite direction. This behaviour is shown in Figure 5.10 and Figure 5.11 for cycles of increasing deformation.

For soil with gapping behaviour, only compression should be specified, and the p-y curve must be represented by two non-linear springs, see Figure 5.9. Tensile stiffness should be set to zero, and the hysteretic model should be selected as Takeda, as shown in Figure 5.12.

The Takeda hysteresis model is very similar to the kinematic model, but uses a degrading hysteretic loop based on the Takeda model, as described in lit. [17]. This simple model requires no additional parameters and is more appropriate for reinforced concrete than for metals. Less energy is dissipated than for the kinematic model.

Unloading is along the elastic segments, similar to the kinematic model. When reloading, the curve follows a secant line to the backbone curve for loading in the opposite direction, see Figure 5.12 and Figure 5.13. The target point for this secant is at the maximum deformation that occurred in that direction under previous load cycles. This results in a decreasing amount of energy dissipation with larger deformations. Unloading is along the elastic segments.

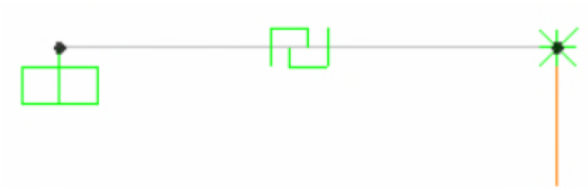


Figure 5.8: Non-gapping soil behaviour (Lit. [12]).

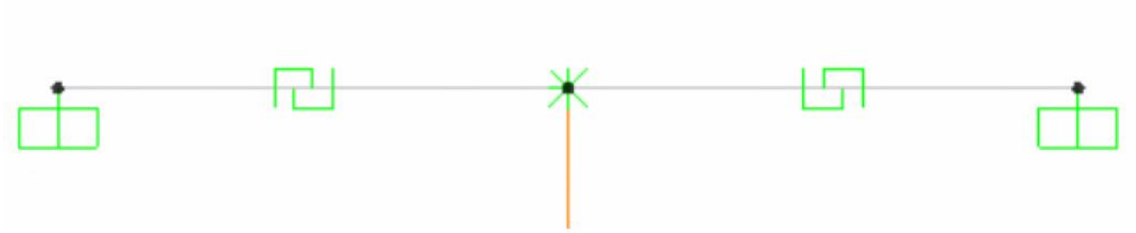


Figure 5.9: Gapping soil behaviour (Lit. [12]).

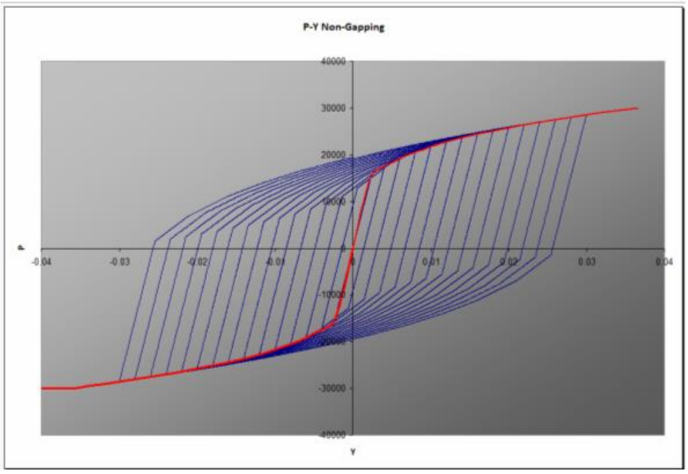



Figure 5.10: Kinematic model simulating non-gapping soil behaviour (Lit. [12]).

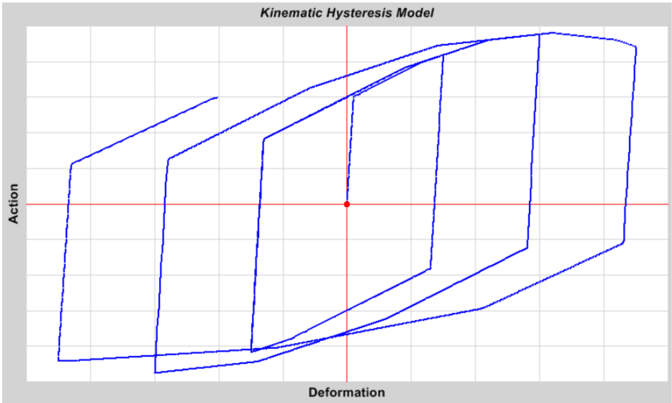



Figure 5.11: Kinematic hysteresis model.

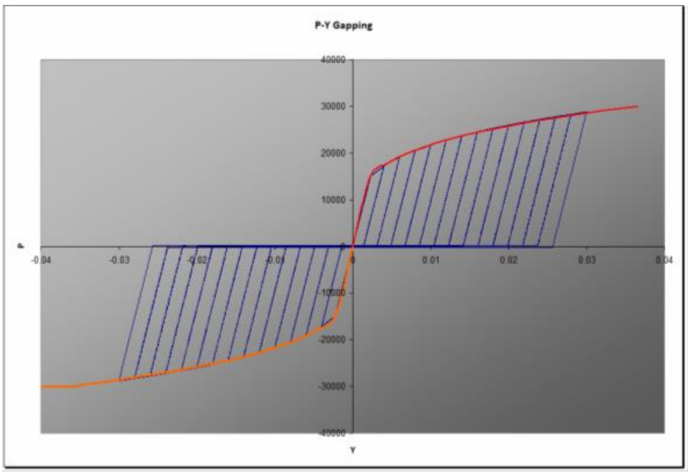



Figure 5.12: Takeda model simulating gapping soil behaviour (Lit. [12]).

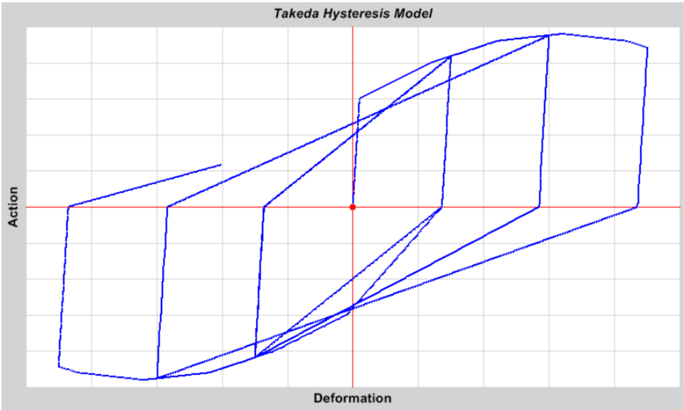



Figure 5.13: Takeda hysteresis model.

Gapping behaviour may be applied during time-history analysis, effective when load reversal occurs, see for example lit. [18], while non gapping behaviour is appropriate for nonlinear static-pushover analysis. Gapping mainly occurs at the rear of laterally loaded pile shafts in cohesive soil. Under repeated cyclic loading the gap grows wider at the ground surface and becomes deeper during cycling. For non-cohesive soils, e.g. sand and loamy sand, in general no gapping does occur. It is assumed that when a gap occurs, the sand immediately fills up the gap and when the pile springs back immediately the soil at the rear side of the pile is mobilised, as explained for the kinematic hysteresis model discussed above.

The design of piles subject to lateral loading is generally undertaken assuming that the loads act only in one direction, see lit. [9]. However, there are several situations in which a pile is subjected to lateral loads with varying direction, such as when acting as the foundations of offshore or onshore wind turbines, or of offshore oil and gas structures. For example, lit. [19] shows the wave rose and the wind rose at the Hornsea wind farm in the North Sea showing that the loading from wind and waves is far from being unidirectional and indicates the range of angular variation for both types of loading. As wind turbines and other offshore structures are dynamically loaded structures, they should be designed with particular attention to control cumulative rotations at the mudline and to avoid resonance problems. Such design needs accurate estimation of the global stiffness of the structure, and thus the stiffness of the foundation; the latter can be influenced by the changes in the direction of the lateral loading, see lit. [20]. Therefore, it is important to consider the impacts of multi-directional loading in the analysis and design of laterally loaded foundations.

In lit. [13] a new model is presented that enables better characterization of multi-directional laterally loaded piles. The model is based on the classical approach of p–y curves used to calculate laterally loaded pile response and extended to consider multi-directional loading, see Figure 5.14. The advantage of the approach is its simplicity, as it provides a semi-analytical method that only requires information from unidirectional p–y curves. The p–y curves for multi-directional loading are deduced from the p–y curves for unidirectional loading by assuming equality of the external work required for the two models. The model permits including irreversible nonlinear p–y curves and the phenomenon of gapping.

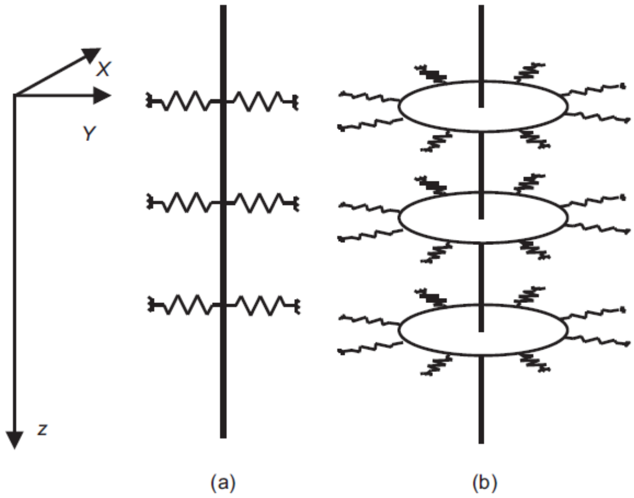



Figure 5.14: Comparison of unidirectional and multi-directional models.

Pile foundations are often subjected to lateral loading due to forces on the supported structure. The horizontal loads at the pile head can be the governing design constraint for single piles and pile groups supporting different types of structures in many situations including environmental loading (wind, water, and earthquakes) and machine loading on structures such as buildings, bridges, wind turbine foundations and offshore platforms. Most building and bridge codes use factored static loads to account for the dynamic effects of pile foundations. Although very low frequency vibrations may be accurately modelled using factored loads, the introduction of nonlinearity, damping, and pile–soil interaction during transient loading may significantly alter the response. The typical frequency ranges of interest are 0–10 Hz for earthquakes 0–1 Hz for offshore environmental loading, and 5–200 Hz for machine foundations. Especially for earthquake analysis a more detailed damping analysis is required, see lit. [21].

### 5.4.3. Implementation of the soil model in the ship impact analysis in Part 1 and 2.

For the FE model used during Part 1 and 2 of the project, as discussed in lit. [4], [5] and [6], the p-y curves representing the soil resistance were modelled by single springs. For the spring behaviour under cyclic loading 2 different models were applied:

1. ‘Full reversible’ soil model, see Figure 5.15.

   In this case the unloading path of the spring in the 1st quadrant is along the same curve as the loading path. This means that the load path of the springs representing the soil resistance is reversed when the spring relaxes, returning all energy stored inside the soil springs back to the ship and the foundation. So, no hysteresis is present, but all stored energy is returned to the foundation and the ship. This is clearly shown in Figure 5.16. The applied load with positive displacement follows the compression curve during loading and unloading and when the load reverses and the displacement becomes negative, the applied load follows the tensile curve in the 3rd quadrant which is the reflected compression curve. In both cases no hysteresis does occur, and all energy is fully returned to the foundation and the ship.

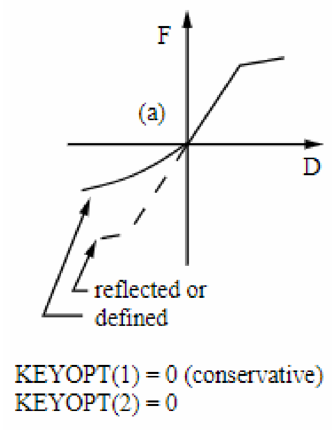



Figure 5.15: Full reversible soil model.

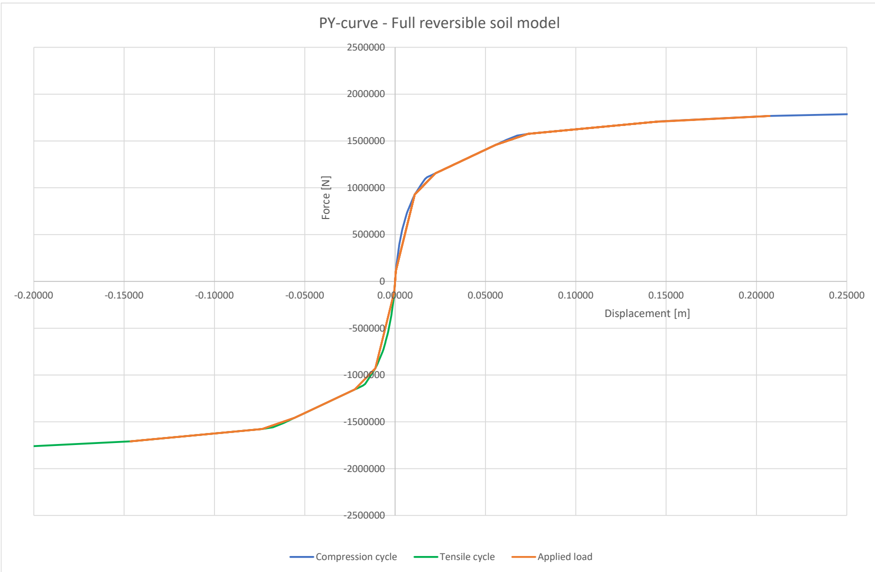



Figure 5.16: Full reversible soil model, loading and unloading curve.

2. 'Non reversible' soil model, see Figure 5.17.

   In this case the unloading path of the spring in the 1st quadrant is along a line parallel to the slope at origin of the loading curve. This means that when the springs representing the soil resistance relax the force reduces along the same slope as at zero displacement. So, hysteresis does occur and only a limited amount of energy stored in the soil springs is returned to the foundation and the ship.

   This is clearly shown in Figure 5.18. The applied load with positive displacement first follows the compression curve during loading. During unloading the load decreases with the same slope as the slope at zero displacement. Then, when the load has returned to zero again and the displacement reduces further it follows the shifted tensile curve that is shown in the 3rd quadrant of Figure 5.17. When the loading again reverses, it first increases with the same slope as the slope at zero displacement and then follows the shifted compression curve, and so forth. So, in this case hysteresis occurs. Comparing Figure 5.18 with Figure 5.10 to Figure 5.13 and the description given in Section 5.4.2 shows that the model presented in Figure 5.18 agrees with the kinematic hysteresis model used for non-gapping soils.

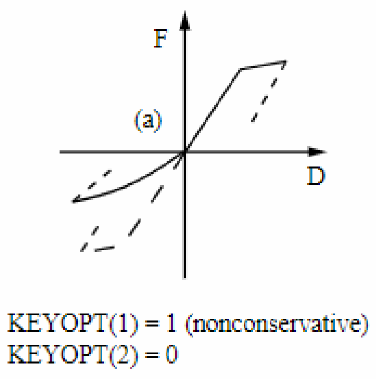



Figure 5.17: Non reversible soil model.

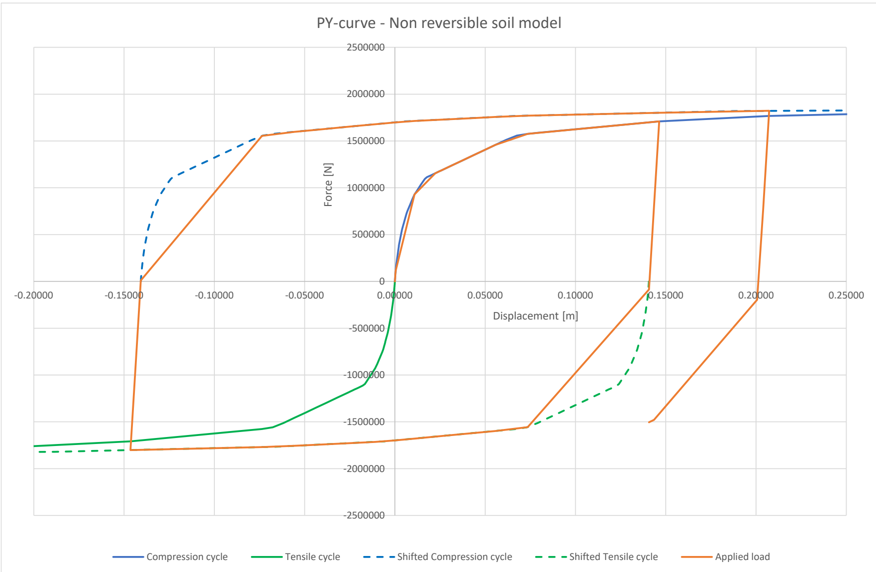



Figure 5.18: Non reversible soil model, loading and unloading curve.

### 5.4.4. Implementation of the soil model in the ship impact analysis for Part 3.

Based on the theory presented in Section 5.4.2 and the soil model implementation used in Part 1 and 2 of the project, see Section 5.4.3, for Part 3, as discussed in lit. [7], the following soil model has been proposed:

1. Gapping or non-gapping soils.

   The soil in the Dutch part of the North Sea consists mainly of non-cohesive soils that are non-gapping. Hence the kinematic hysteresis soil model will be used to model the soil behaviour.

2. Unidirectional versus multidirectional soil model.

   The behaviour of the soil during ship impact is mainly governed by the motion of the ship itself, with the wind and wave loading in general having a limited effect. The ship motion is highly unidirectional and therefore it is decided to keep the analysis in this Part 3 unidirectional, so that the soil model used will be a unidirectional soil model. The direction of the unidirectional ship impact can however be varied between 0°, 90°, 180° and 270°, see Figure 5.19.

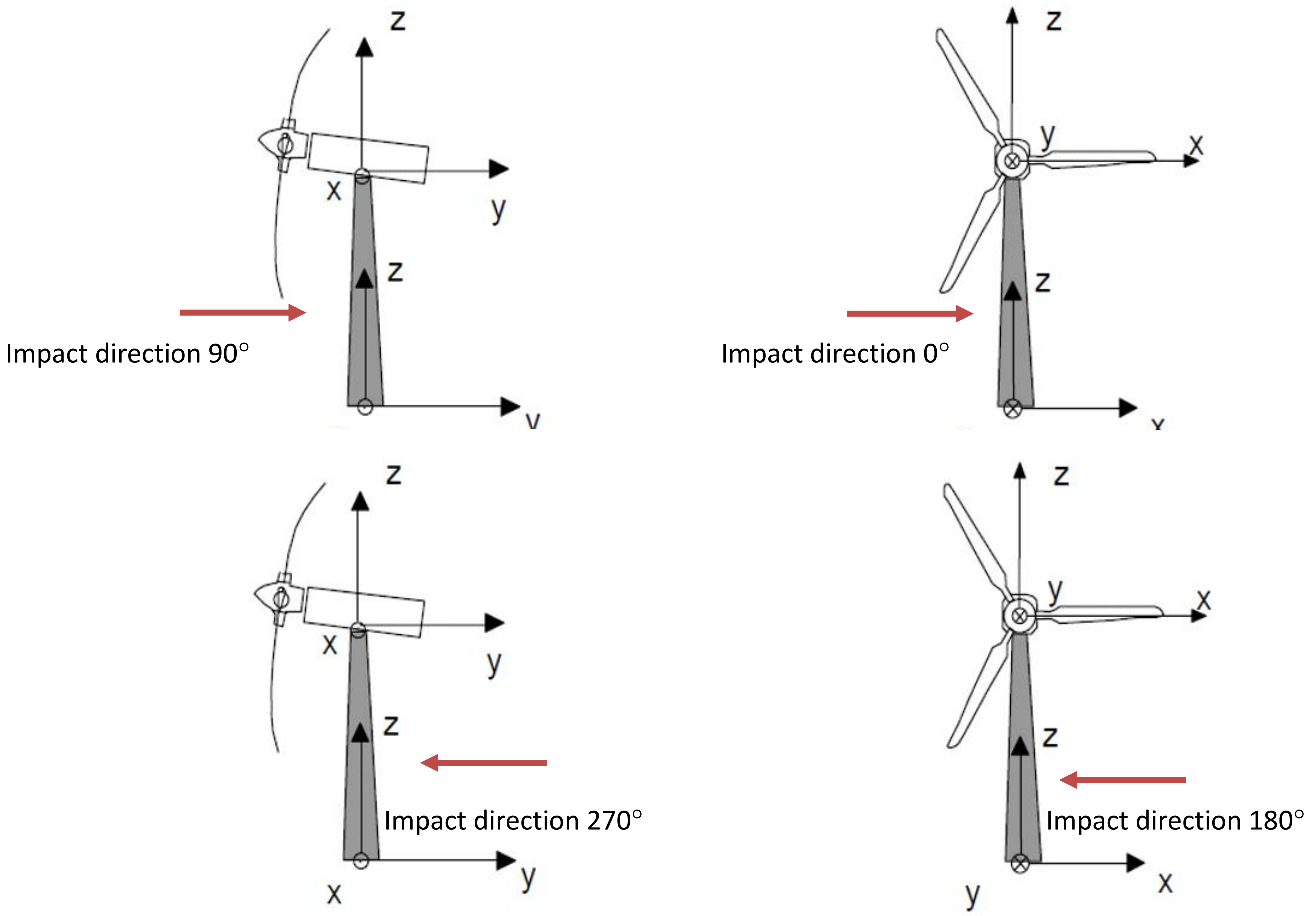



Figure 5.19: Impact direction between ship and foundation.

3. Soil damping.

   Soil damping is mainly relevant during continuous motion of the foundation pile, e.g., under continuous wind and wave loading. During ship impact the soil behaviour will be mainly governed by the non-linear elastic and plastic soil behaviour and less by the soil damping. Only during the vibration of the foundation after the impact, when the foundation pile is still standing and there is no contact with the ship anymore, soil damping might play a role again. However, the phase after the impact is not part of this investigation as then also other aspects as the effect of the local indentation of the foundation under wind and wave loading play a role that cannot be investigated with the present beam model. For this reason, soil damping will not be accounted for during this Part 3.

Considering the above and taking into account that the Non-reversible soil model as used in Part 1 and 2 is identical to the kinematic hysteresis soil model as is valid for non-gapping non-cohesive soils, the Non-reversible soil model has also been used in Part 3 of the project.

During Part 1 and 2 of the project, the Non-reversible soil model was compared to the Full reversible soil model and the main difference with the Full reversible soil model occurs for the smaller ships that do not lead to significant plastic deformation of the soil. In those cases, the energy release of the Full reversible soil model during the rebound phase can lead to failure of the tower due to the inertia of the turbine, even when this failure did not occur during the initial impact. The release of energy by the Non-reversible soil model is much less and thus the loading of the foundation during the rebound phase is smaller. For the larger ships that do lead to significant soil failure the initial impact is governing the foundation failure and for both the Full reversible and the Non reversible soil model the initial impact behaviour is mostly the same.

## 5.5. External loads acting on the foundation.

### 5.5.1. Introduction.

The wind turbine foundations are of course continually loaded by current, wave and wind load 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.

During part 1 and part 2 of the study, see lit. [5] and [6], the current, wave, wind and turbine loads have not been considered because these loads were not available yet. However, these loads can influence the behaviour of the foundation and the turbine as is shown in the literature survey, see lit. [3]. It shows 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. When the motion of the ship is in the same direction as the wind load, which is quite likely in case of a drifting ship, then the wind load will contribute to the overturning motion of the foundation. On the other hand, when the ship is sailing against the wind when impacting with the foundation and considering that collapse of the foundation towards the ship is most likely, then the wind load will magnify the effect of the impact and might lead to collapse of the foundation at lower ship velocities. For this reason the effect of the current, wave, wind and turbine loads has been investigated in Part 3 of the study, see lit. [7].

The effect of the wind load has been investigated for the following situations, see Figure 5.20 to Figure 5.22:

1. A drifting ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation. The wind turbine is assumed to be operating, meaning that the forces acting on the turbine add to the wind forces acting on the foundation.
2. A sailing ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation. The wind turbine is assumed to be operating, meaning that the forces acting on the turbine add to the wind forces acting on the foundation.
3. A sailing ship with impact below the nacelle and a wind load in the direction opposite to the ship motion acting on the foundation. The wind turbine is assumed to be operating, meaning that the forces acting on the turbine add to the wind forces acting on the foundation.

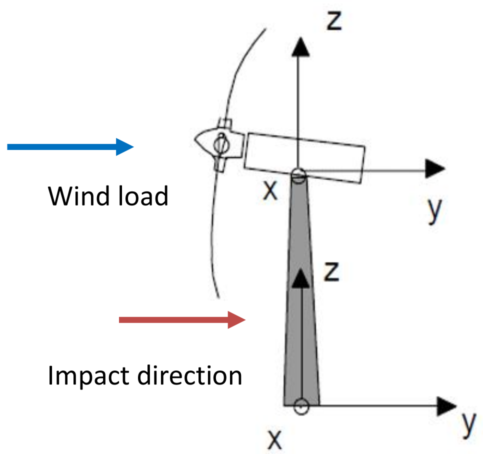



Figure 5.20: Drifting ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation.

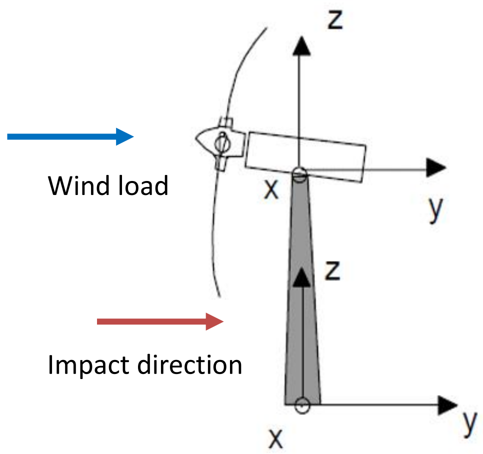



Figure 5.21: Sailing ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation.

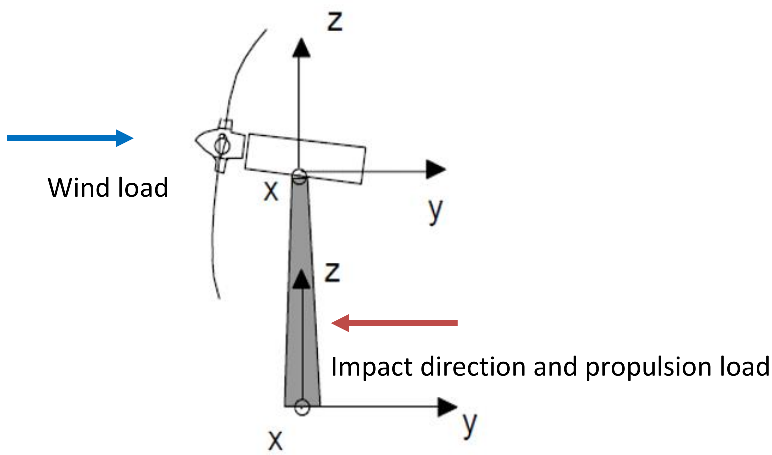



Figure 5.22: Sailing ship with impact below the nacelle and a wind load in the direction opposite to the ship motion acting on the foundation.

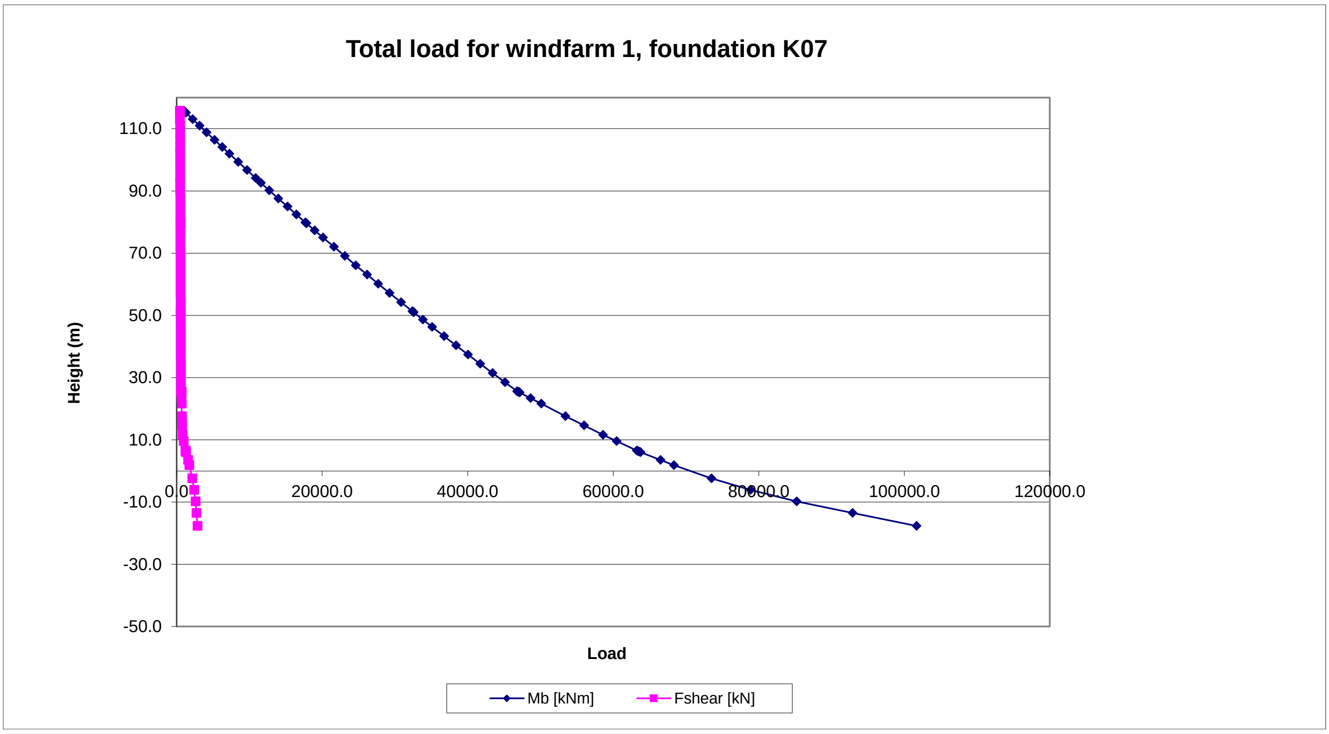
### 5.5.2. Load derivation.

Detailed design information for the foundations of the 2 investigated windfarms is not available. For this reason, generic load data will be used that are derived from literature to estimate the load applied to the foundations by the wind, waves, current and the turbines. The loads found in literature have been scaled to match the different foundation dimensions and have been derived for a nominal wind speed at hub height of 25 [m/s], which is the cut-out speed of the turbines.

The load curves, shear force and bending moment, are presented in Figure 5.23 and Figure 5.24 as function of the vertical position in [m LAT]. The loads will be applied as a static load acting in a direction parallel to the rotor axis, see Figure 5.25. The deformation of the foundations due to these loads are presented in Figure 5.26 to Figure 5.29. The nacelle displacement under these loads for all foundations and the maximum bending stress level are presented in Table 5.1.

| Foundation | Nacelle displacement [m] | Bending stress [MPa] |
|---|---|---|
| K07 | 0.76 | 53.1 |
| C01 | 0.62 | 55.7 |
| HIGH | 0.44 | 42.9 |
| LOW | 0.71 | 63.3 |

Table 5.1: Nacelle displacement and foundation bending stress under operational load.



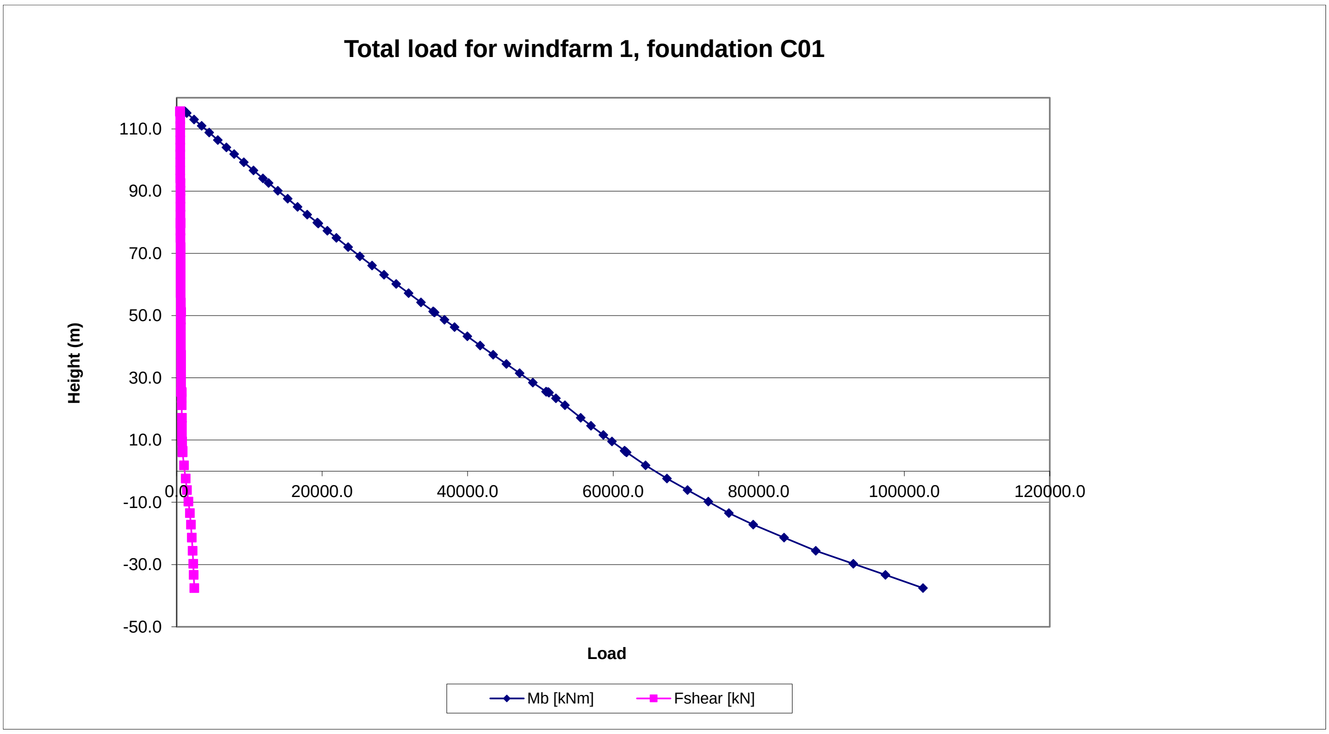
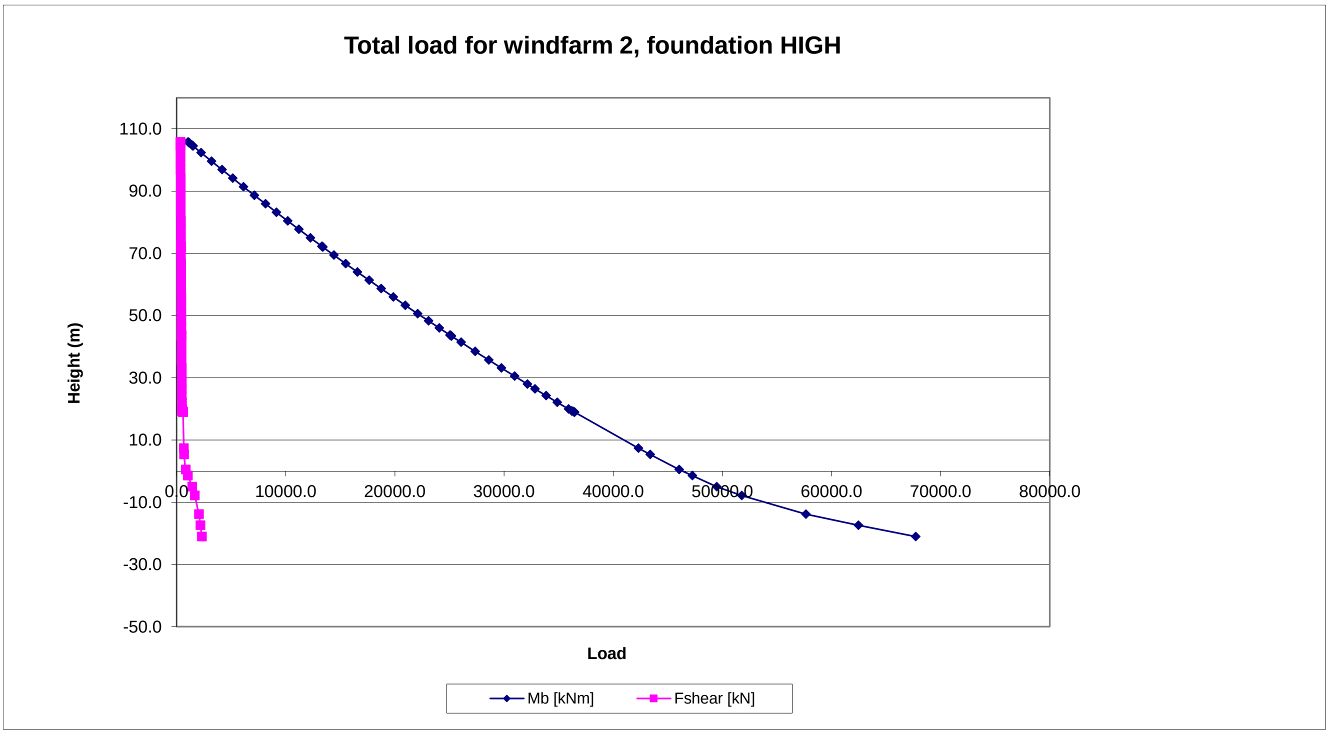




Figure 5.23: Operational loads for Windfarm 1, Foundations K07 and C01.



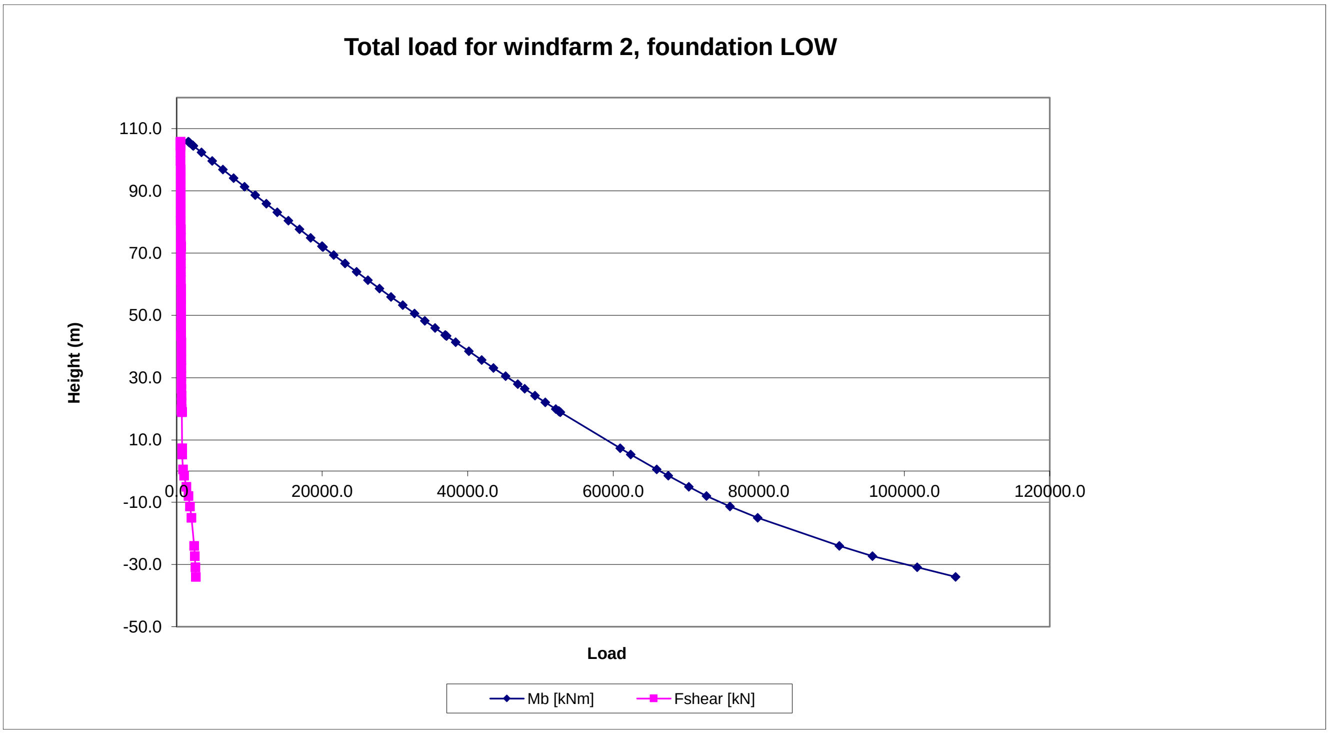




Figure 5.24: Operational loads for Windfarm 2, Foundations HIGH and LOW.

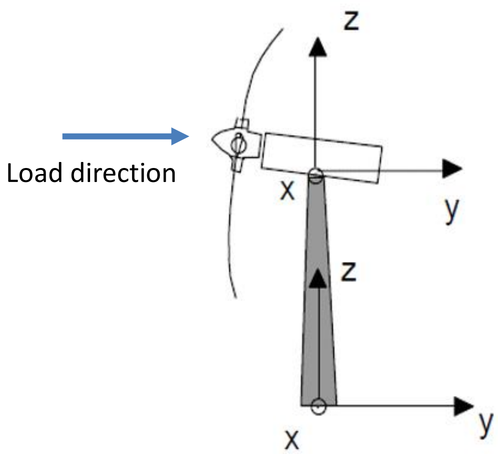



Figure 5.25: Direction of the wind, current, wave and turbine load.

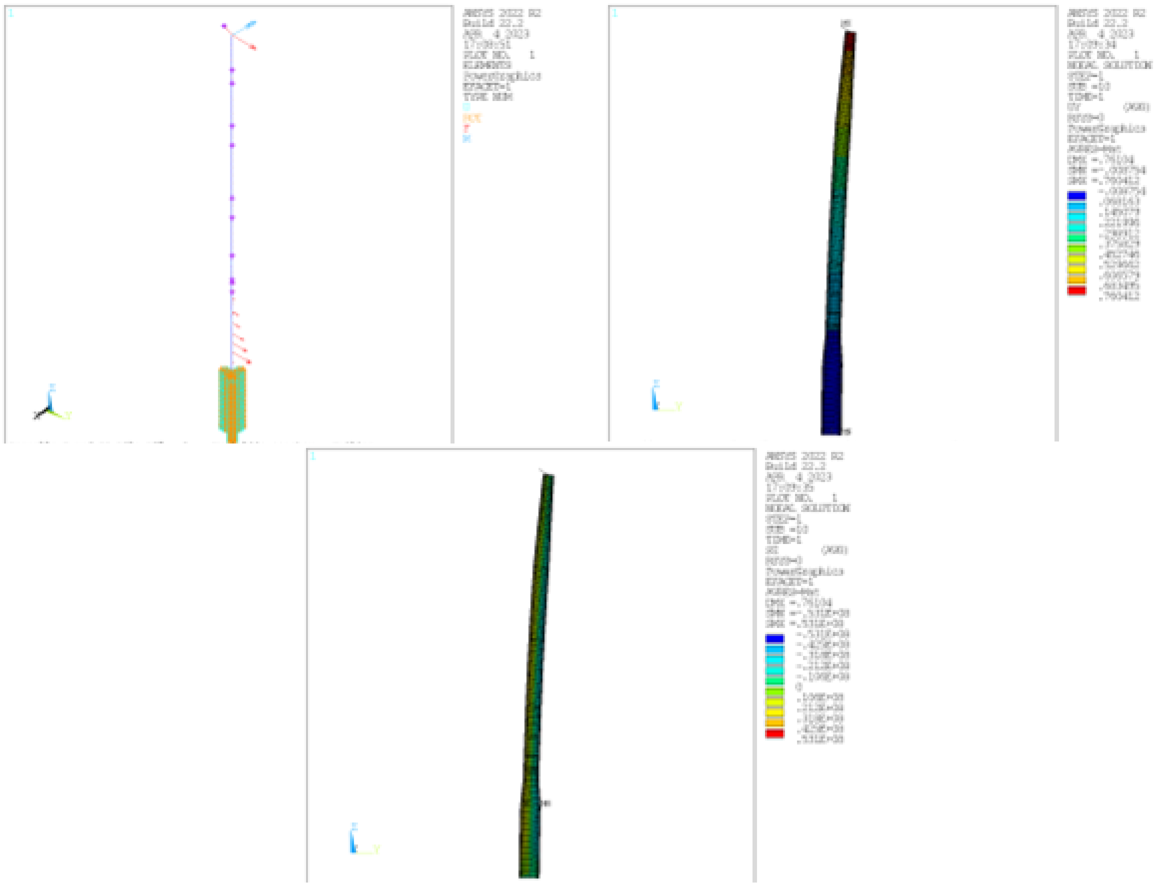


Figure 5.26: Applied loads and deformation and stress level of the foundation under operational load, Windfarm 1, Foundations K07.

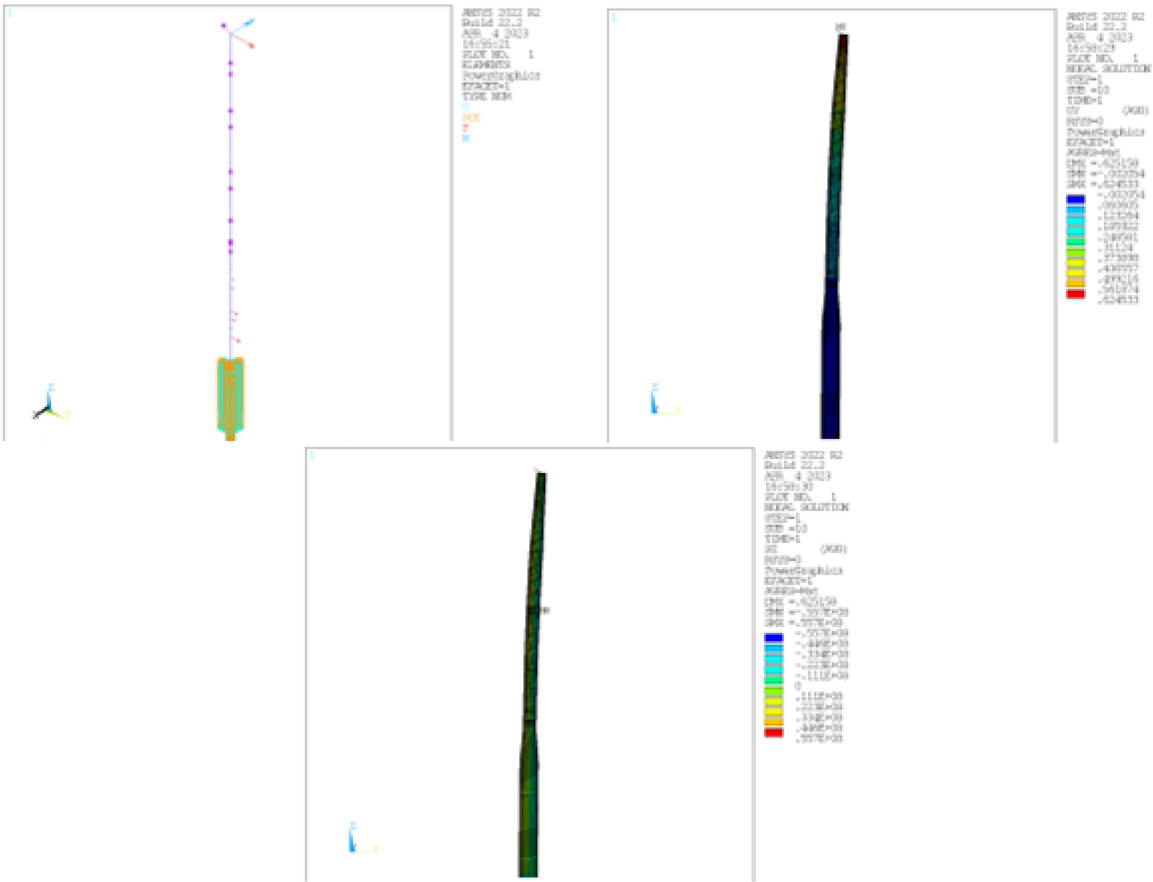


Figure 5.27: Applied loads and deformation and stress level of the foundation under operational load, Windfarm 1, Foundations C01.

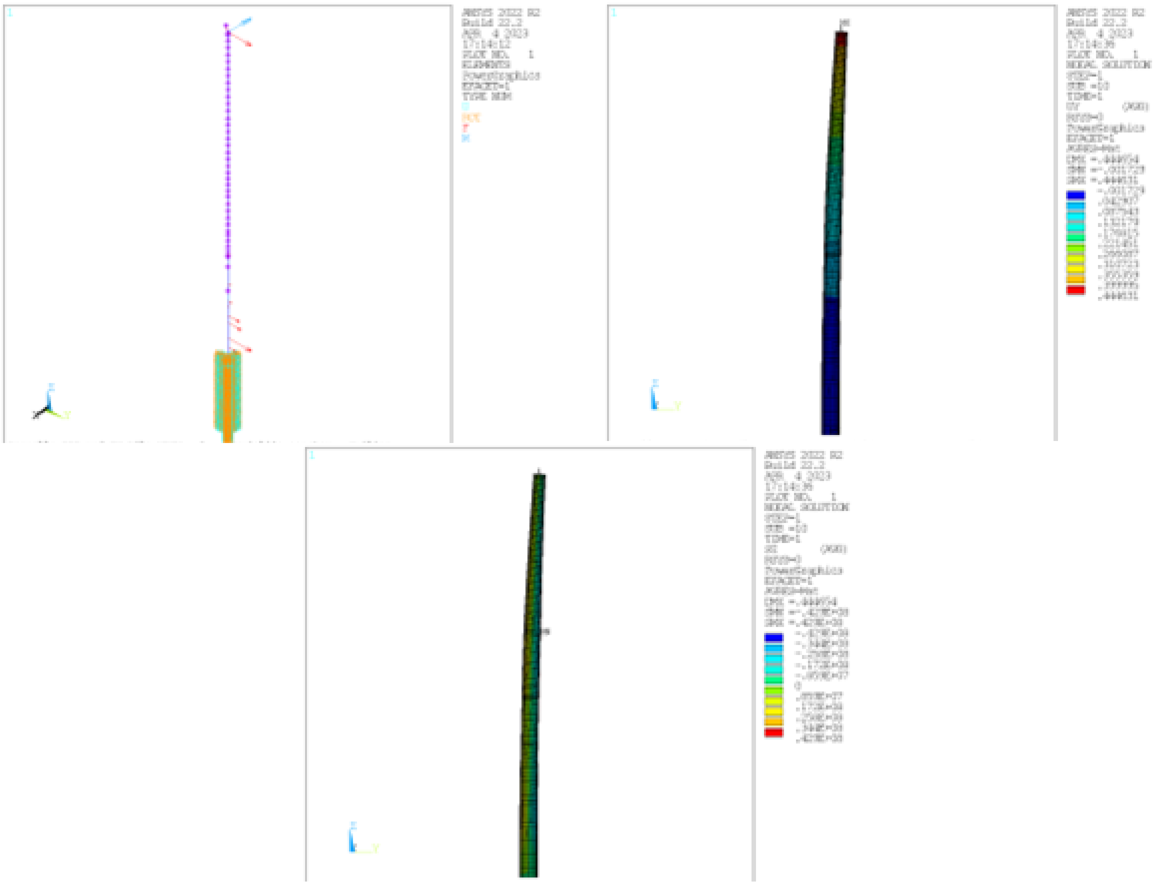


Figure 5.28: Applied loads and deformation and stress level of the foundation under operational load, Windfarm 2, Foundations HIGH.

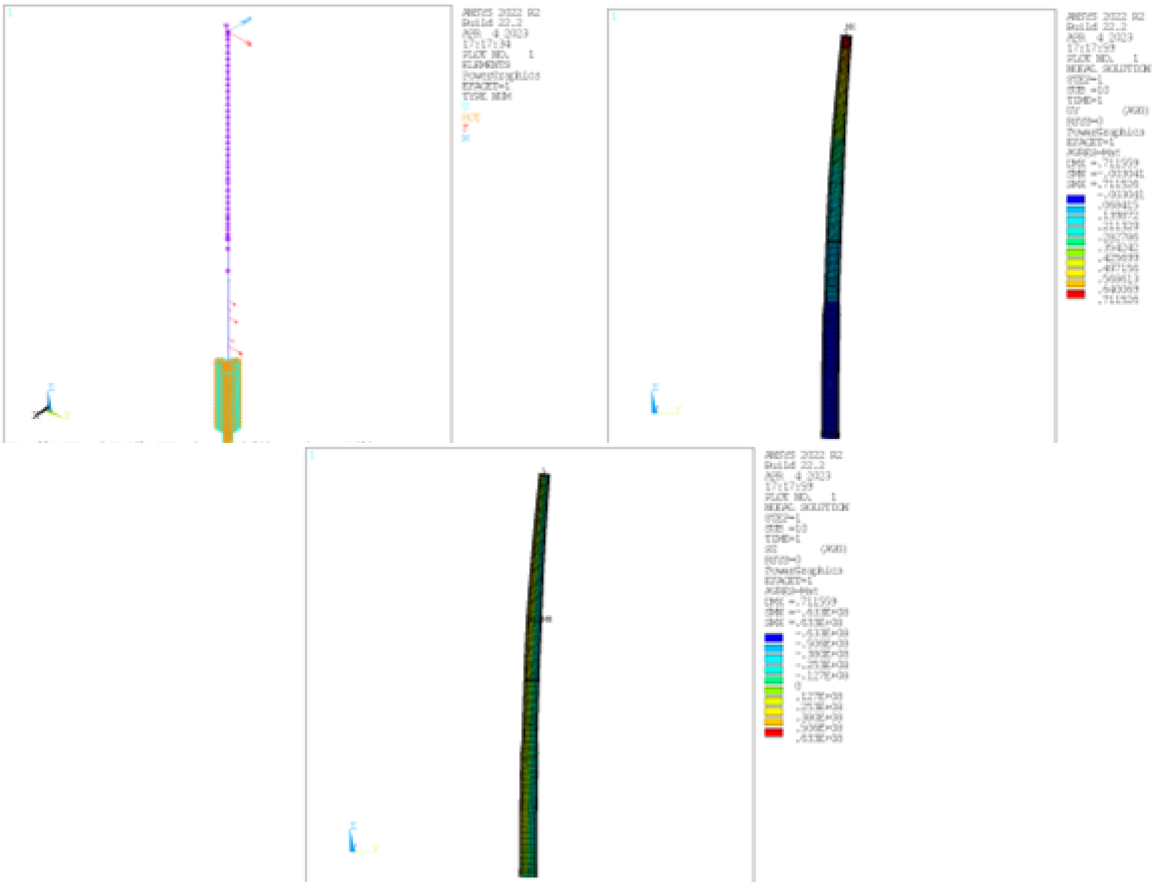


Figure 5.29: Applied loads and deformation and stress level of the foundation under operational load, Windfarm 2, Foundations LOW.

## 5.6. The ship.

### 5.6.1. Introduction.

The ship is modelled as a point mass. This point mass is divided over a number of masses equally divided over the height of the impact area, as shown in Figure 5.30. 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.

The parameters considered during the analyses are presented in the following sections.

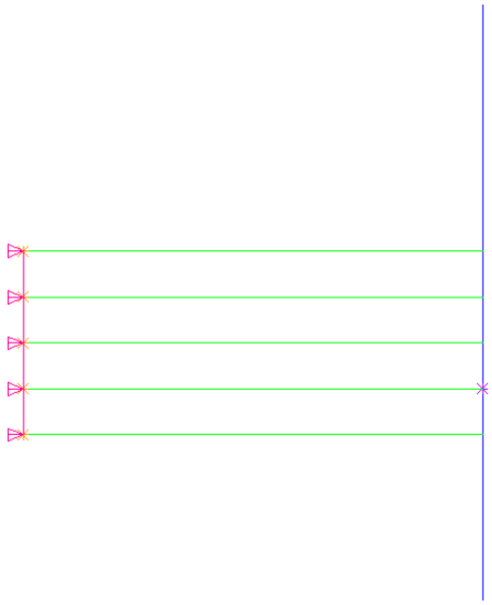


Figure 5.30: Ship modelled as a number of masses equally divided over the height of the impact area.

### 5.6.2. 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

### 5.6.3. 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 [4] 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 been taken into account.

### 5.6.4. The impact velocity of the ship and the loads acting on 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, lit. [2]. In case of sailing, the impact velocity is taken as the normal cruising velocity of the ship as found in literature.

During Part 1 and 2 of this study, the propulsion force of the ship has not considered in case of sailing impact. It was assumed that impact occurs at a certain ship velocity and that at the moment of impact the motor 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.

During Part 1 and 2 of this study the effects of the wind, current, wave and loads pushing the ship forward in case of drifting impact, is not taken into account either. It is assumed that these forces are negligible with respect to the forces introduced by the impact.

The effect of **the loads acting on the ship** during the impact, e.g., the ship propulsion load or the wind, wave, current and turbine loads were taken into account during the 3rd part of the study. The following situations have been investigated, see Figure 5.31 to Figure 5.33:

1. A drifting ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation, with the wind/current load pushing the ship forward. The wind turbine is assumed to be operating.
2. A sailing ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation, with the ship motor pushing the ship forward. The wind turbine is assumed to be operating.
3. A sailing ship with impact below the nacelle and a wind load in the direction opposite to the ship motion acting on the foundation, with the ship motor pushing the ship forward. The wind turbine is assumed to be operating.

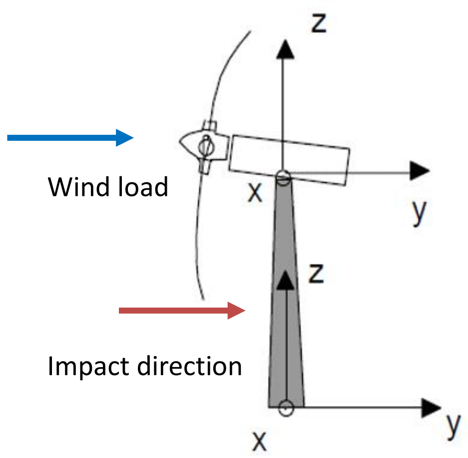



Figure 5.31: Drifting ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation and on the ship.

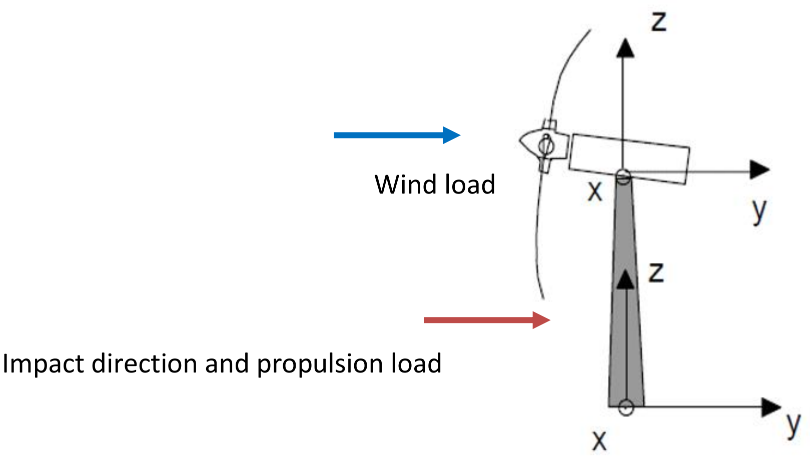



Figure 5.32: Sailing ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation, with the ship motor pushing the ship forward.

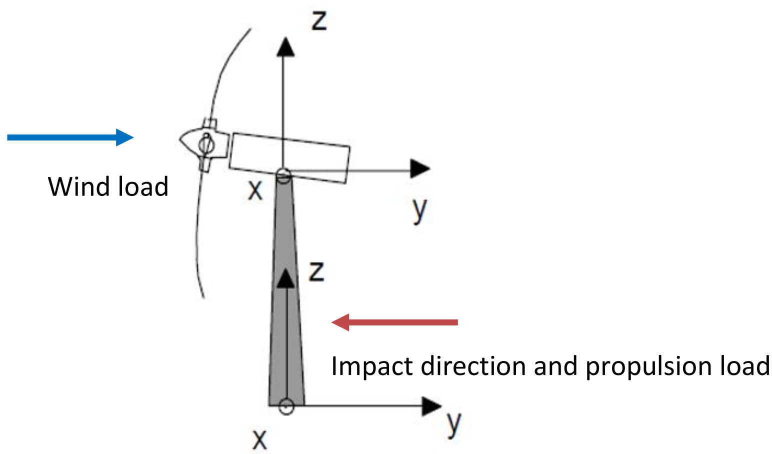



Figure 5.33: Sailing ship with impact below the nacelle and a wind load in the direction opposite to the ship motion acting on the foundation, with the ship motor pushing the ship forward.

These situations have also been investigated without any loads acting on the ship and thus those 2 sets of results can be compared to each other.

The wind, current, wave and loads resp. the propulsion load acting the ships are derived in Section 5.6.8.

### 5.6.5. 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.

### 5.6.6. 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 XZ-plane so that the rotation axis of the rotor is parallel to the Y-axis. Furthermore, the ship is default, impact angle equal to 0°, located along the X-axis and is moving in the +X-direction. So, the impact is default, impact angle equal to 0°, 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.

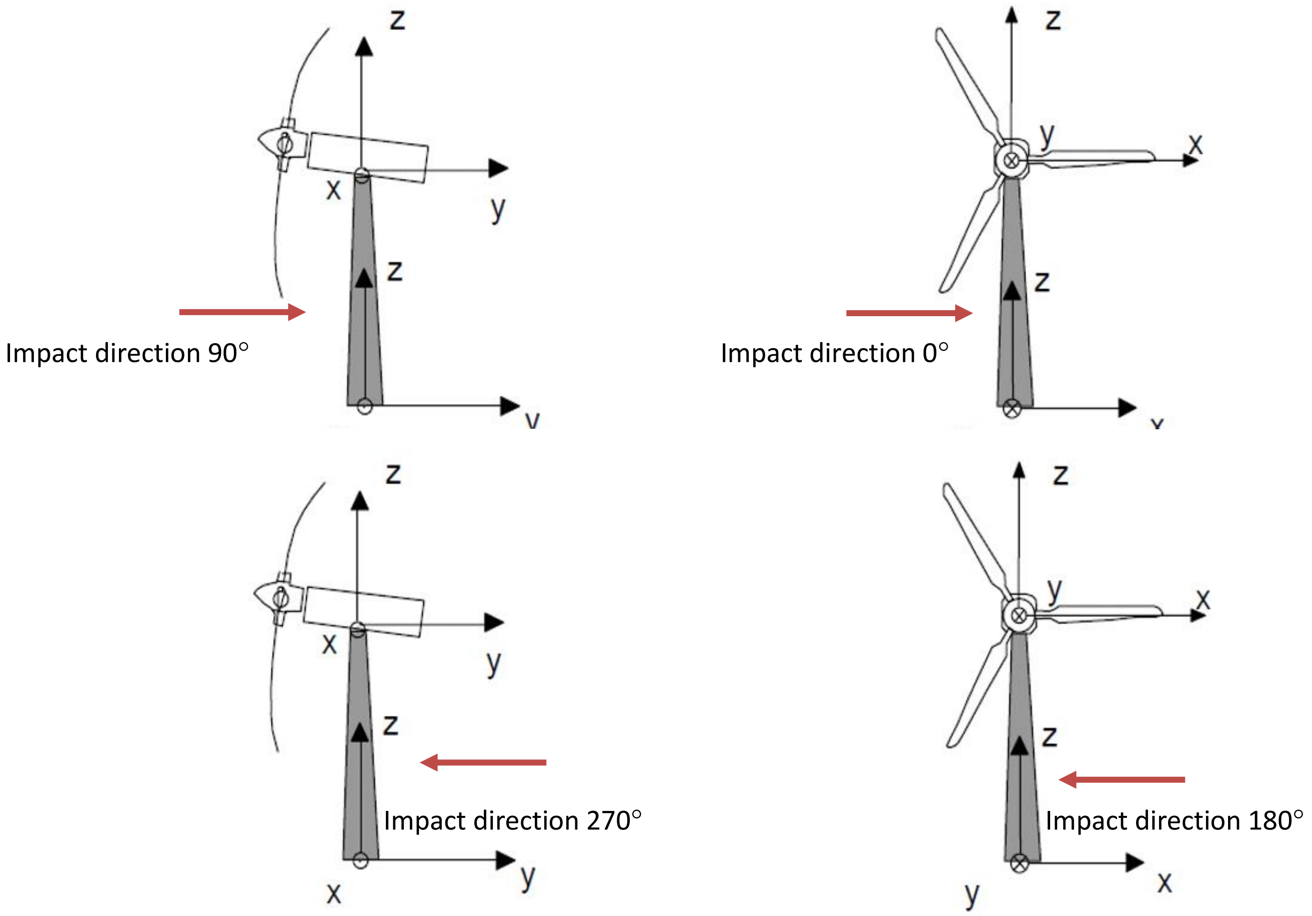



Figure 5.34: Impact direction between ship and foundation.

In first instance, during Part 1 and 2 of the project, the simulations have been carried out with **the impact angle being equal to 90º** so that impact takes place along the Y-axis, with the ship moving in the +Y-direction. This is consistent with a drifting ship being pushed by the wind towards the turbine and the rotor blades being turned into the wind by the Yaw system. Later, during Part 3 of the study, the impact angle has been changed to 180° and 270°, see Figure 5.34, so that also side impact and impact below the nacelle is simulated.

### 5.6.7. 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 hull. The present model does not facilitate modelling the failure of the ship hull. 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, see lit. [22], 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 5.36 to Figure 5.39. 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 5.35. 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 5.30 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 5.35. It must be noted that due to the nature of the elements available within Ansys, the modelled springs are tensile springs. This means that the springs are modelled as elements pointing away from the foundation and the ship pulling on the foundations during impact. During rebound, when the springs tend to be compressed their stiffness drops to zero so that during rebound no force is executed on the foundation as discussed above.

The force executed by the springs is always acting parallel to the horizontal plane, even when during collapse the foundation rotates. The point of impact relative to LAT does however remain constant, so the fact that when the foundation is pushed over the contact point between ship and foundation moves towards a higher point on the foundation is not included in the analysis. This means that the impact points on the foundation are fixed and when the foundation rotates when the soil collapses these points on the foundation will rotate and move downward while the ship points will remain at a constant height. The elements representing the ship stiffness will therefore not remain horizontal anymore. However, this will not affect the direction of their force executed on the foundation. This force will remain parallel to the horizontal plane.

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.

Figure 5.36 to Figure 5.39. show the force-deformation curves executed on the foundation during impact. In case of drifting impact there will be broadside impact, whereas in case of sailing impact there will be impact with the ship bulb or bow.

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 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 the moment of impact.

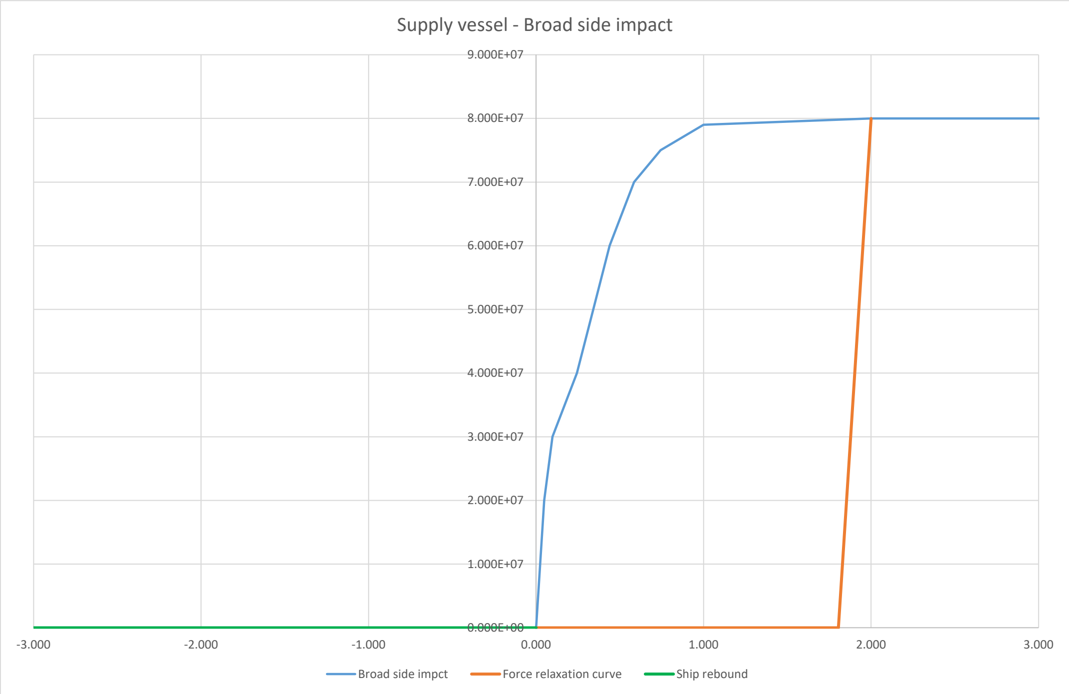



Figure 5.35: Modelled force-deformation curve for a supply vessel.

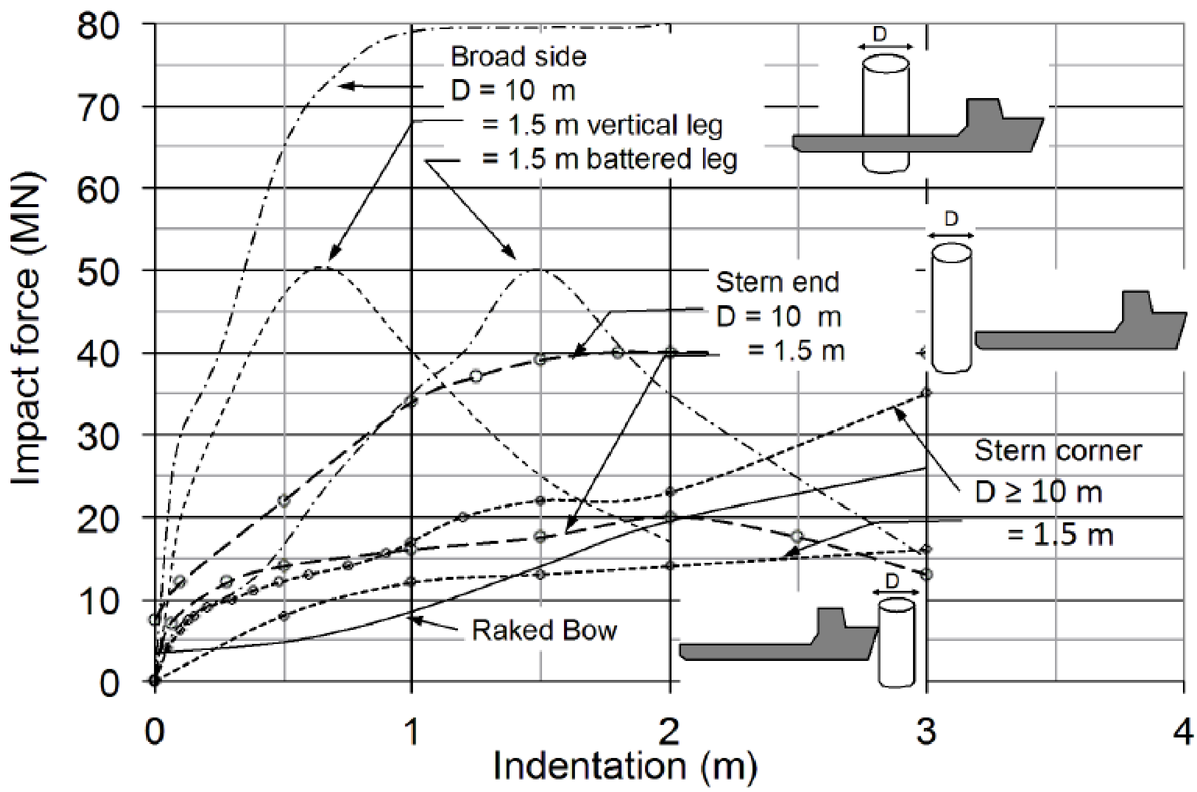



Figure 5.36: Force-deformation curve for standard supply vessels with a displacement of 6500 to 10000 [tonnes], for broadside, bow and stern impact.

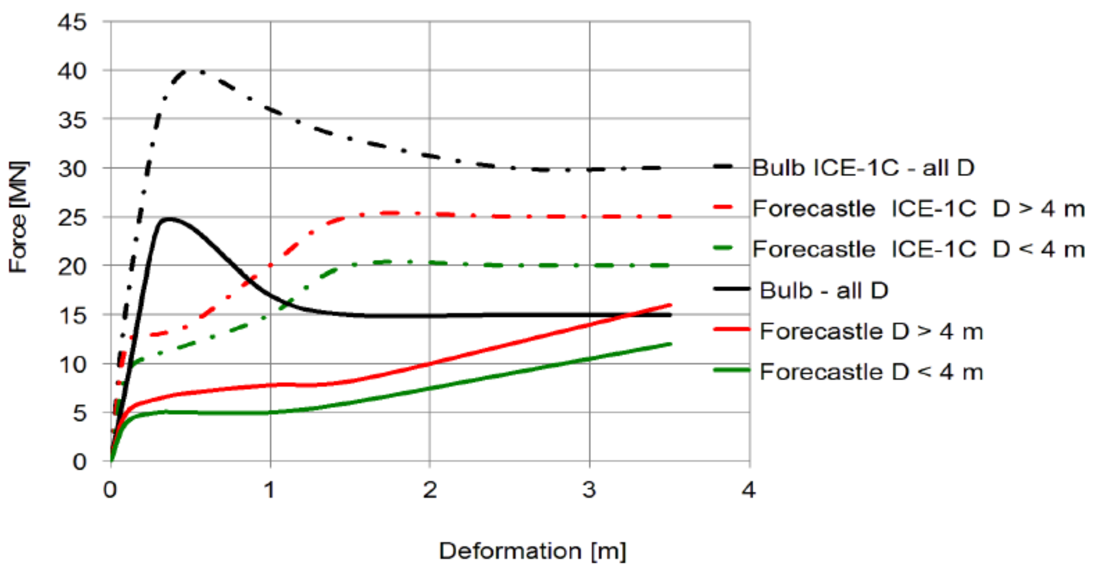



Figure 5.37: Force-deformation curve for the bow impact of supply vessels with a displacement of 5000 to 10000 [tonnes], for standard no reinforced bulbous bow and for reinforced bulbous bows according to class Ice(1C).

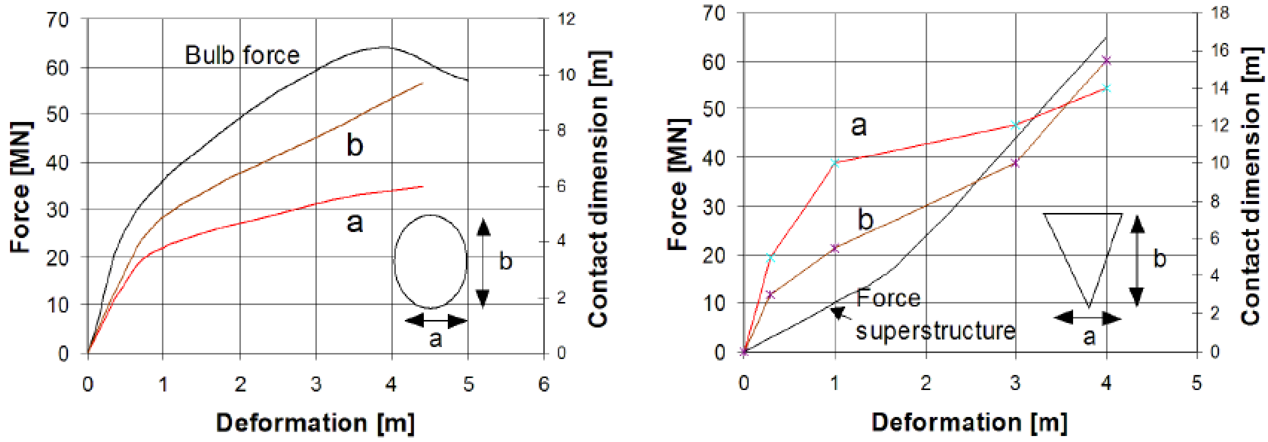



Figure 5.38: Force-deformation curve and contact area for tanker bow impact (~125000 dwt)

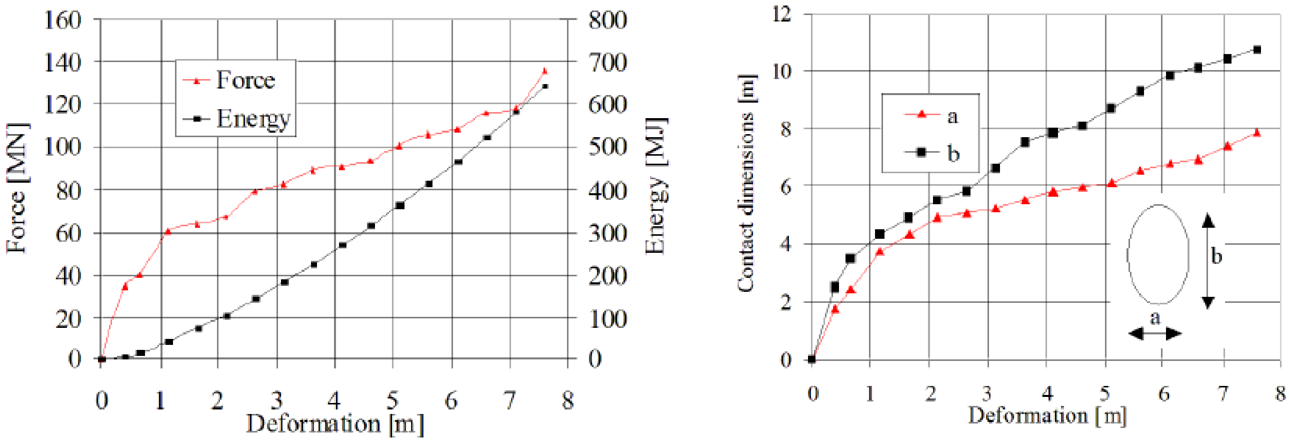



Figure 5.39: Force-deformation curve and contact area for the bulbous bow of a VLCC (~340000 dwt)

## 5.6.8. Loads acting on the ship.

### 5.6.8.1. Introduction.

During drifting impact, the wind, wave and current loads will be acting on the ship too, pushing it forward and contributing to the overturning moment acting on the foundation. During sailing impact these loads will also be present but will be small in comparison with the propulsion load of the ship. The magnitude of these loads used during various simulations is derived in the following sections.

### 5.6.8.2. Wind and current drag force.

When a ship is driven forward by the current then the ship velocity is equal to the current velocity. For the investigations executed during this study the current velocity has been assumed to be equal to 0.48 [m/s]. When in addition also wind is acting on the ship in the same direction as the current, then the velocity of the ship will increase and become larger than the current velocity. However, the ship will never reach a velocity equal to the wind velocity because of the resistance of the water will increase when the ship velocity becomes larger than the current velocity. Therefore, the combined wind and current velocity of the investigated ships has been determined in lit. [2] to vary from 1.08 [m/s to 1.73 [m/s], depending on the ship dimensions.

However, when the ship has been halted by the foundation then the full drag force applied by the wind and current acting on the ship hull will be taken up by the foundation, because in this case the ship velocity is nearly zero and the water resistance will be very small. In this case the wind and current force can be calculated by:

$$F_{wind} = C \cdot \frac{1}{2} \cdot \rho_a \cdot v_a^2 \cdot A_a$$

$$F_{current} = C \cdot \frac{1}{2} \cdot \rho_w \cdot v_c^2 \cdot A_w$$

With: C = The resistance coefficient. For more or less rectangular shapes like the ships, this coefficient is approximately equal to 1.3.

$\rho_a$ = The density of air = 1.225 [kg/m$^3$]

$\rho_w$ = The density of sea water = 1025 [kg/m$^3$]

$v_a$ = The wind velocity in [m/s]

$v_c$ = The current velocity in [m/s]

$A_a$ = The cross-section of the ship perpendicular to the wind in [m$^2$]

$A_w$ = The cross-section of the ship perpendicular to the current in [m$^2$]

During drifting it is assumed that the broad side of the ship is perpendicular to the wind and current. The exact area of the investigated ships is not known but has been estimated from the available ship silhouettes and the water line position. The estimated vales are presented in Table 5.2, together with the wind and current drag force for a wind velocity of 10 [m/s], 5 Beaufort, resp. 25 [m/s], 9 to 10 Beaufort, and for a current velocity of 0.48 [m/s]. For comparison in Table 5.3 the soil failure load as determined in lit. [4] is presented for the investigated foundations. Graphically these results are presented in Figure 5.40. From these results it follows:

1. In general, the area of the ship cross-section in air is larger than the ship cross-section in water. Only for the Kruiplijn coaster this is the other way around.

2. The wind velocity is significantly higher than the current velocity. As the velocity occurs in the drag force equation with a power of 2, it is clear that the effect of the wind force is significant, although the air density is a factor 840 lower than the water density.

3. The results in Table 5.2 and in Figure 5.40 show that for a wind velocity of 10 [m/s], 5 Beaufort, the wind and current load are of the same magnitude. At a wind speed of 25 m/s, 9 to 10 Beaufort, the wind force is considerably higher than the current force.

   For all cases the wind and current load are lower than the soil failure load, hence there is no danger that these forces can lead to the foundation being pushed over by a ship that is pressed against the foundation due to wind and current.

For the dynamic analysis a wind speed of 25 [m/s] will be assumed to be acting at the ship. Furthermore, it will be assumed that the impact takes place at exactly the wind pressure point, so the ship will not rotate away from the foundation. This effect must be investigated in a more elaborate model that also takes the ship motion and dimensions into account.

| Typical dimensions. | | Kruiplijn Coaster | Supply vessel | Chemical & Product tankers | Passenger vessels | Container ship |
|---|---|---|---|---|---|---|
| **Gross Tonnage** | **Unit** | **1554 GT** | **3200 GT** | **10000 GT** | **100000 GT** | **192784 GT** |
| Cross-sectional area above water (estimated) | [m^2] | 176.00 | 1,795.00 | 2,176.00 | 10,962.00 | 11,382.00 |
| Cross-sectional area below water (estimated) | [m^2] | 288.32 | 464.82 | 1,120.50 | 2,008.60 | 4,738.71 |
| | | | | | | |
| Wind velocity | [m/s] | 10.00 | 10.00 | 10.00 | 10.00 | 10.00 |
| Current velocity | [m/s] | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 |
| | | | | | | |
| Wind force | [MN] | 0.01 | 0.14 | 0.17 | 0.87 | 0.91 |
| Current force | [MN] | 0.04 | 0.07 | 0.17 | 0.31 | 0.73 |
| **Total force** | **[MN]** | **0.06** | **0.21** | **0.35** | **1.18** | **1.63** |

Wind velocity 10 [m/s], Current velocity 0.48 [m/s].

| Typical dimensions. | | Kruiplijn Coaster | Supply vessel | Chemical & Product tankers | Passenger vessels | Container ship |
|---|---|---|---|---|---|---|
| **Gross Tonnage** | **Unit** | **1554 GT** | **3200 GT** | **10000 GT** | **100000 GT** | **192784 GT** |
| Cross-sectional area above water (estimated) | [m^2] | 176.00 | 1,795.00 | 2,176.00 | 10,962.00 | 11,382.00 |
| Cross-sectional area below water (estimated) | [m^2] | 288.32 | 464.82 | 1,120.50 | 2,008.60 | 6,070.40 |
| | | | | | | |
| Wind velocity | [m/s] | 25.00 | 25.00 | 25.00 | 25.00 | 25.00 |
| Current velocity | [m/s] | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 |
| | | | | | | |
| Wind force | [MN] | 0.09 | 0.89 | 1.08 | 5.46 | 5.66 |
| Current force | [MN] | 0.04 | 0.07 | 0.17 | 0.31 | 0.93 |
| **Total force** | **[MN]** | **0.13** | **0.96** | **1.25** | **5.76** | **6.60** |

Wind velocity 25 [m/s], Current velocity 0.48 [m/s].

Table 5.2: Wind and current drag force.

| **Soil failure load** | | **Wind farm 1 K07** | **Wind farm 1 C01** | **Wind farm 2 HIGH** | **Wind farm 2 LOW** |
|---|---|---|---|---|---|
| Water depth | [m] | 17.7 | 38.1 | 21.1 | 34.7 |
| Pile penetration | [m] | 23.562 | 31.752 | 29.25 | 28.75 |
| MSL | [m LAT] | 1.72 | 1.72 | 1.72 | 1.72 |
| **Soil failure load at MSL** | **[MN]** | **10.0** | **15.4** | **16.6** | **12.7** |

Table 5.3: Soil failure load.

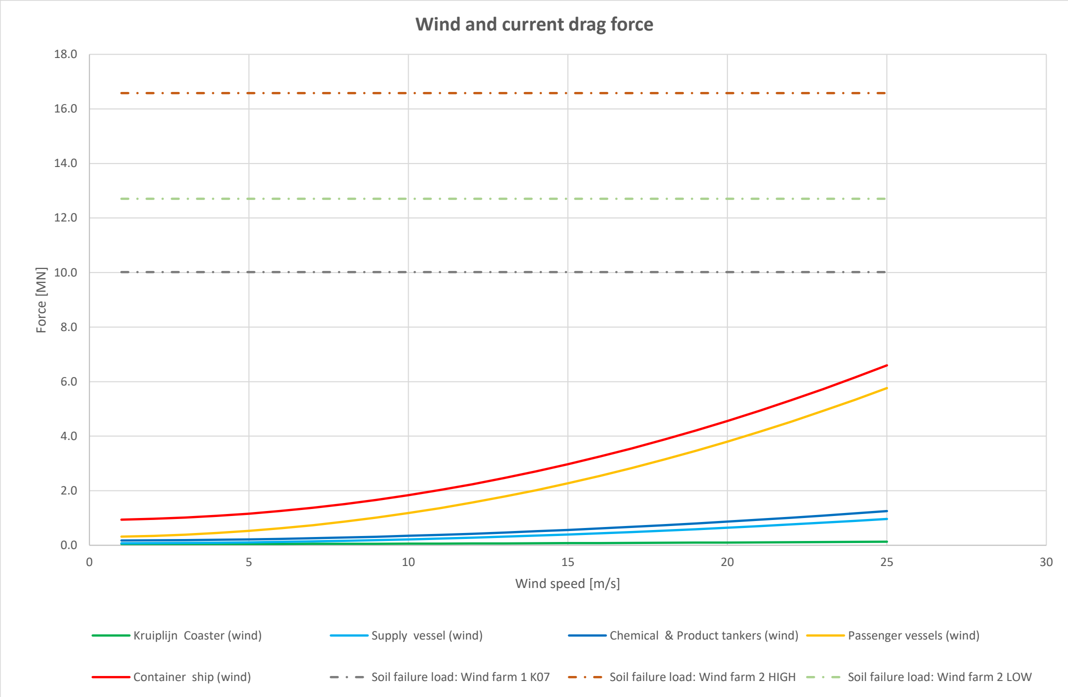



Figure 5.40: Wind and current drag force in comparison with the soil failure load.

### 5.6.8.3. Ship propulsion force.

The propulsion force of the various ships is not documented in the public domain. In most cases only the installed motor power is provided. However, in combination with the maximum nominal ship velocity the ship propulsion force is estimated by:

$$F_{propulsion} = \frac{P_{motor}}{v_{ship}}$$

It must be noted that this is quite conservative as the efficiency of the motor and transmission has been neglected. The ship motor power, nominal velocity and estimated propulsion force are presented numerically in Table 5.4. Comparison with the soil failure load as presented in Table 5.3 shows that the propulsion force is for all ships less than the soil failure load. So, when during impact the ship motor is not turned off there is no danger that the foundation will fail due to the ship propulsion force only. Of course, when the foundation is already damaged by the impact, the ship propulsion force still might lead to failure of the foundation.

For the dynamic analysis the ship propulsion force as presented in Table 5.4 used for the simulations.

| **Typical dimensions.** | **Unit** | **Kruiplijn Coaster** | **Supply vessel** | **Chemical & Product tankers** | **Passenger vessels** | **Container ship** |
|---|---|---|---|---|---|---|
| **Gross Tonnage** | **GT** | **1554 GT** | **3200 GT** | **10000 GT** | **100000 GT** | **192784 GT** |
| Nominal Power | [MW] | 0.749 | 4.64 | 6.39 | 20.16 | 56.25 |
| Nominal speed | [km/h] | 19.44 | 27.00 | 25.20 | 52.20 | 42.20 |
| | [m/s] | 5.40 | 7.50 | 7.00 | 14.50 | 11.72 |
| **Propulsion force** | **[MN]** | **0.139** | **0.619** | **0.913** | **1.390** | **4.799** |

Table 5.4: Ship propulsion force.

## 5.7. Foundation material properties and failure modes.

### 5.7.1. Introduction.

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 5.41. 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. So, the present model is thus not suitable for the simulation of the post-collapse behaviour.

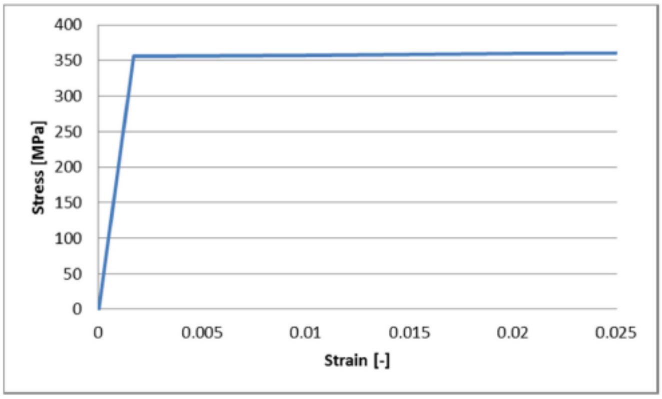



Figure 5.41: Non-linear material curve.

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 5.5. A material factor of 1.2 has been applied to account for material and geometry imperfections.
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.

| Material S355 ML | | |
|---|---|---|
| $t_{min}$ | $t_{max}$ | $\sigma_{yield}$ |
| [mm] | [mm] | [MPa] |
| 0 | 16 | 355 |
| 16 | 40 | 345 |
| 40 | 63 | 335 |
| 63 | 80 | 325 |
| 80 | 100 | 325 |
| 100 | 150 | 320 |

Table 5.5: Material properties for S-355.

For the simulation executed during Part 1 and Part 2 of this study which are aimed at comparing the different failure modes for various windfarms, the yield limit has been selected as the failure criterion. The material selected is according to the specifications for the windfarm under consideration. A material factor of 1.2 has been applied to these data that decreases the yield limit to an ‘allowable’ limit and accounts for material and geometry imperfections.

However, as the foundation pile and tower are thin-walled shells, they are also susceptible to shell buckling. Due to this effect failure of the foundation will occur at lower load levels.

The phenomenon of shell buckling cannot be investigated with beam models. The only way to analyse the possible effect of shell buckling using the beam model is to determine the failure stress of shell buckling as function of the foundation dimensions, e.g., segment length, diameter, and wall thickness. A more accurate analysis can only be performed with a full 3D shell model of the foundation. This will be part of the following phase of this study.

The effect of shell buckling on the failure mode of the foundations will be investigated for the following situations:

1. A drifting ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation. The wind turbine is assumed to be operating and the ship propulsion load is not considered.
2. A sailing ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation, with the ship motor pushing the ship forward. The wind turbine is assumed to be operating and the ship propulsion load is not considered.
3. A sailing ship with impact below the nacelle and a wind load in the direction opposite to the ship motion acting on the foundation, with the ship motor pushing the ship forward. The wind turbine is assumed to be operating and the ship propulsion load is not considered.

These situations have also been investigated with Yield being the failure criterion and thus those 2 sets of results can be compared to each other.

The shell buckling failure stress is determined in Section 5.7.2.

### 5.7.2. The shell buckling failure mode.

The geometry of the analysed foundations, outer diameter and wall thickness, is presented in Figure 5.42. The horizontal lines in the wall thickness graph running up to 250 [mm] are the flange connections. For the determination of the failure stress for shell buckling, each foundation segment between flange connections is regarded as a segment. The flange connections function as stiffeners of the tower and pile wall as they hinder ovalisation and prevent circumferential rotation of the tower and pile wall. Using the shell buckling theory as for example described in 'DIN 18 800 Teil 4' or 'NEN-EN 1993-1-6_2007', the failure stress can be determined for each foundation. The results are presented in Figure 5.43 and Figure 5.44 for Wind farm 1 and 2. For the 2 conceptual design foundations the effect of the buckling stress has not been investigated.

In Figure 5.43 and Figure 5.44 the following information is presented:

1. The yield limit according to NEN-EN10025-3: 2019.
2. The yield limit corrected with a material factor of 1.2, to account for material and geometry imperfections.
3. The shell buckling failure stress.

These results show that a noticeable decrease in failure stress occurs due to shell buckling. This is especially true for the tower sections that generally have a wall thickness less than 50 [mm].

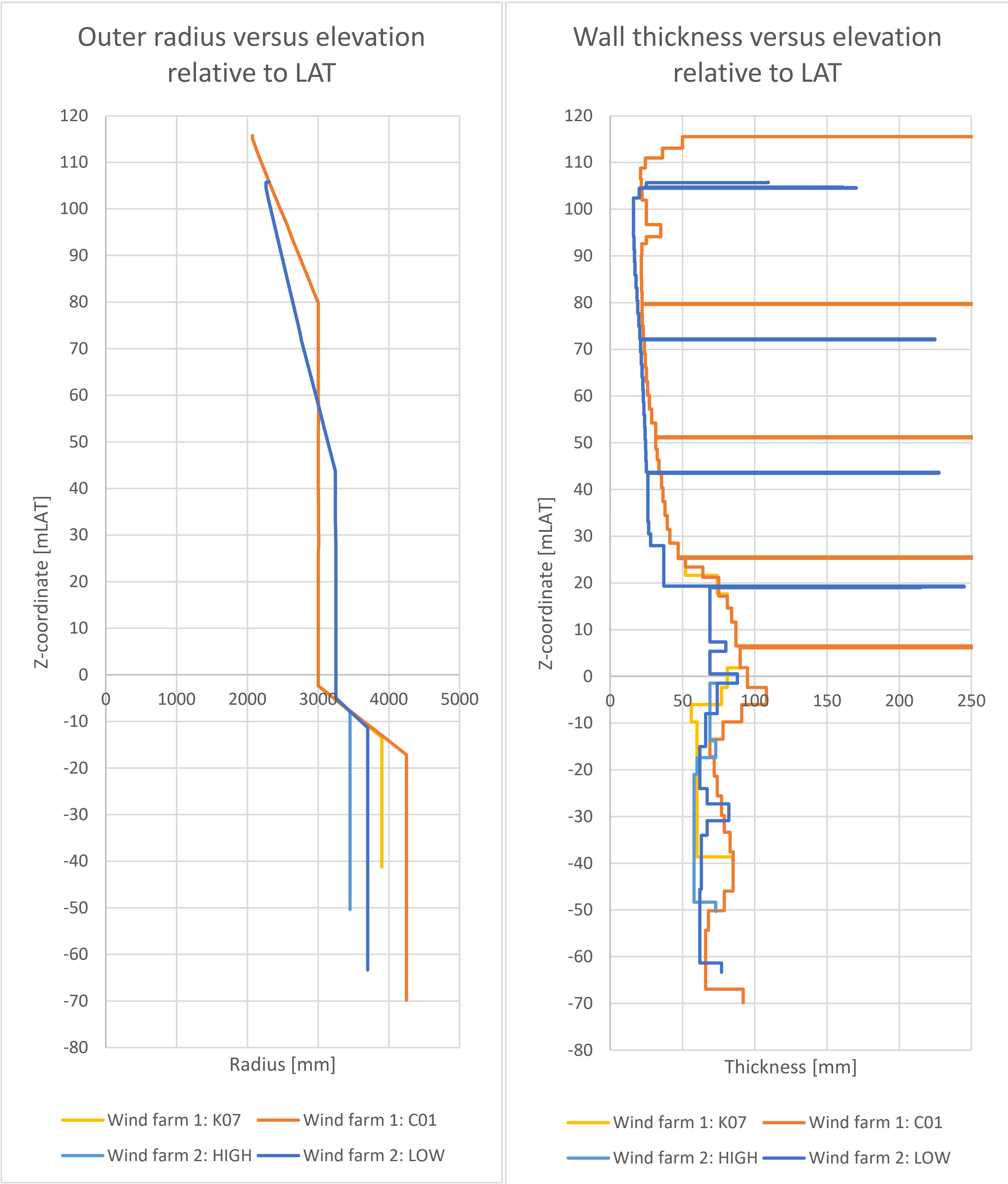



Figure 5.42: Main dimensions of the analysed foundations.

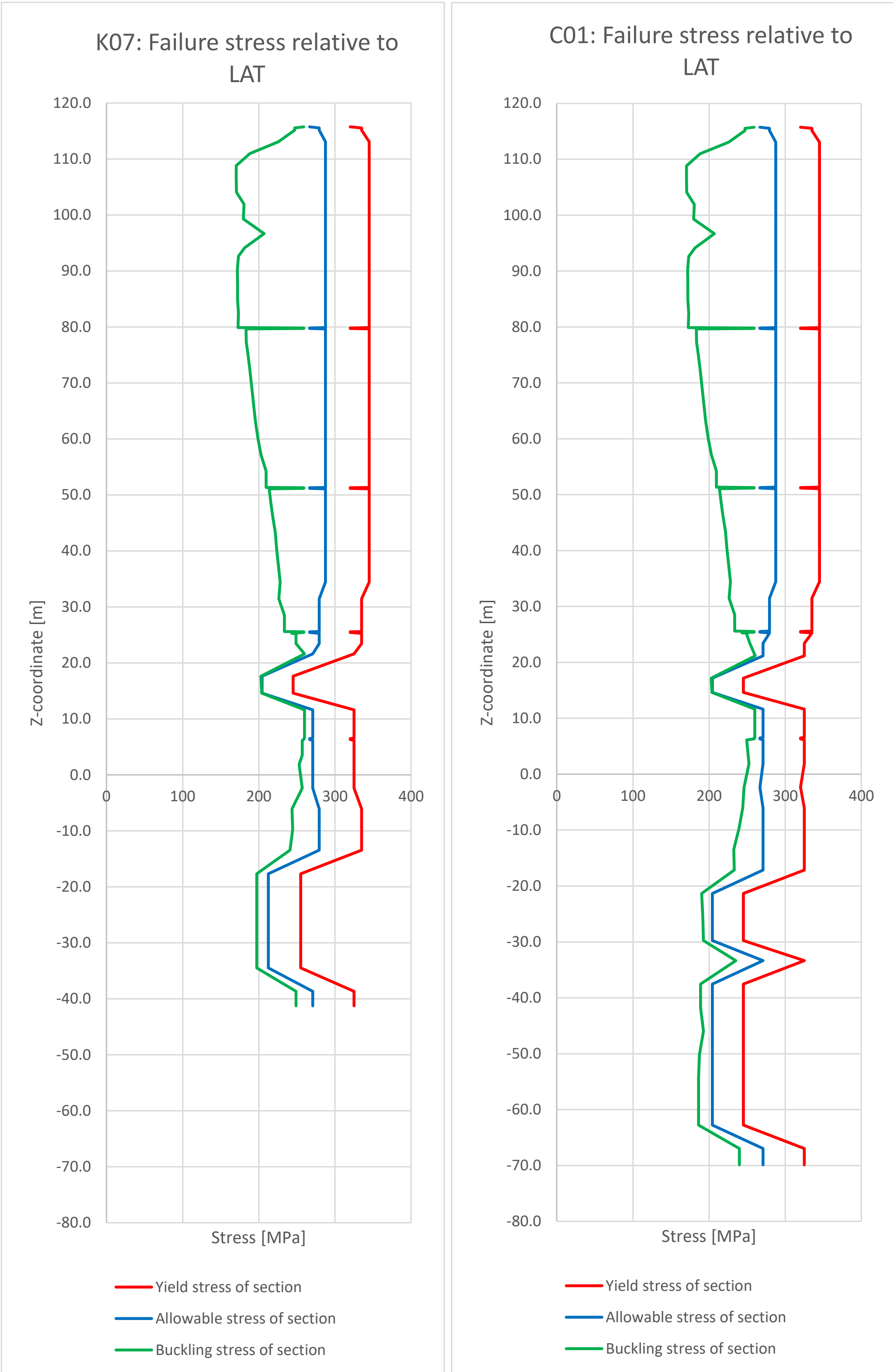



Figure 5.43: Failure stress for the foundations of Windfarm 1.

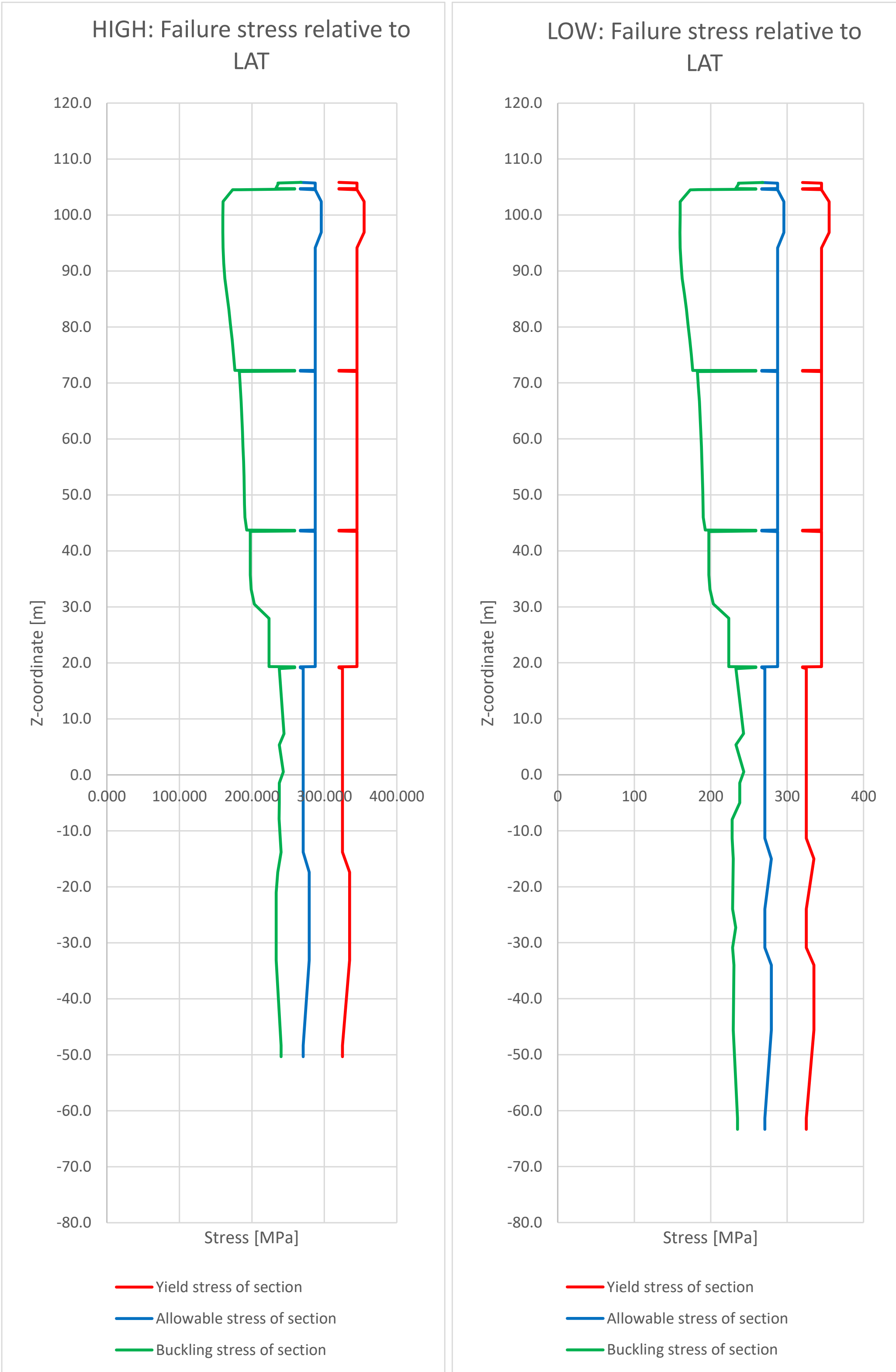



Figure 5.44: Failure stress for the foundations of Windfarm 2.

# 6. Investigated configurations.

## 6.1. Foundations.

To be able to repeat the ship impact simulations as performed in 2005 during the SAFESHIP project, see lit. [2], for the present wind farms, detailed technical information of the wind turbine foundations is required. Therefore the owners, building contractors and turbine manufacturers have been contacted with the request to provide this information. In lit. [23] 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. [24].

It turned out that it is quite difficult to get detailed design information from the windfarm owners, building contractors and turbine manufacturers. 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.

Apart from the 2 conceptual wind turbine foundation designs, sufficient information for the analyses has been provided for the Wind farms 1 and 2 as identified in Section 1. The input data used for the calculations are presented in lit. [5] for the 2 conceptual designs and in Appendix A and B of lit. [6] for Wind farm 1 and 2. The main characteristics of the wind farms are presented in Table 6.1. The outer radius and wall thickness as function of the position along the foundation in [mLAT] are presented in Figure 5.42.

Comparing those wind farms shows:

1. The nominal power and the mass of the rotor and the nacelle are comparable for the 2 real wind farms, but they higher for the 2 conceptual designs. Especially the mass of the turbine of the conceptual designs is considerably higher than for the 2 real wind farms.

2. The hub height for wind farm 1 is c.a. 10 [m] higher than for wind farm 2. This results in a minimum height of the blade tip that is c.a. 8 [m] higher for Windfarm 1. Hence for Windfarm 1 there is less chance for a rotor blade contacting with the superstructure of a ship than for Wind farm 2.
   The hub height of the conceptual designs is again 8 [m] higher than for wind farm 1. No information is available about the rotor diameter and tip height for this turbine.

3. The geometry of the 2 foundations within the same Wind farm is almost the same up to LAT (Z = 0 [mLAT]). Below LAT there is a difference in diameter and wall thickness. The same is valid for the 2 conceptual designs.

4. The major difference between the 2 wind farms is that the foundations of Wind farm 1 consist of a tower, transition piece and pile, whereas the foundations for Windfarm 2 consist of only a tower and pile. Also, the foundations of the conceptual design only consist of a tower and pile.

5. The tower diameter for Wind farm 2 at the straight section is larger than the tower/transition piece diameter at the straight section for Wind farm 1, while for Windfarm 2 the wall thickness is smaller than for Wind farm 1. Furthermore, the tower of Wind farm 2 has a longer conical section with a wall thickness that is smaller than for Wind farm 1. As a result of this, the tower of Wind farm 2 is more susceptible for buckling than the tower of Wind farm 1. At foundation C01 of wind farm 1 the water depth is maximal, resulting in the largest penetration depth, pile diameter and overall wall thickness.

For the 2 conceptual designs the diameter of the tower and of the pile above LAT is considerably higher than for the 2 real wind farms. Below LAT the dimensions are comparable. This difference is required to get a 1st order resonance frequency in the order of 0.17 [Hz, which is above the 1P frequency of the turbines. The wall thickness of the 2 conceptual design foundations is above and below LAT comparable to those for the 2 real wind farms.

6. The position of the main external platform relative to LAT is approximately the same for both real Wind farms and for the conceptual design.

7. The pile diameter at mudline level is for Wind farm 1 larger than for Wind farm 2, and also the wall thickness for Wind farm 1 is in general larger than for Wind farm 2. For the 2 conceptual designs the outer diameters are comparable to those of the real wind farms and the wall thickness of the conceptual designs is approximately the same as for wind farm 2.

8. For Wind farm 1 the Mean Sea Level and the PY-curves for the soil are not available. For this reason the Mean Sea Level for Wind farm 1 has been chosen equal to the Mean Sea Level for Wind farm 2 and the PY curves for Wind farm 2 are also used for Wind farm 1.

| Identification | | | Conceptual designs | | Wind farm 1 | Wind farm 2 |
|---|---|---|---|---|---|---|
| | | | P001 | P002 | | |
| **Turbine** | Rated power | [MW] | 10 | | 8 | 9.5 |
| | Nacelle plus rotor mass | [tonnes] | 644 | | 450.4 | 478.4 |
| | Hub height | [m LAT] | 126 | | 118.025 | 108.85 |
| | Rotor diameter [m] | [m] | -- | | 167 | 164 |
| | Lower position of blade tip | [m LAT] | -- | | 34.525 | 26.85 |
| | | | | | | |
| **Tower** | Top elevation | [m LAT] | 122 | | 115.735 | 105.81 |
| | Bottom elevation | [m LAT] | 17.5 | | 25.415 | 19.15 |
| | Top diameter | [mm] | 4940 | | 4145 | 4530 |
| | Bottom diameter | [mm] | 7000 | | 6000 | 6500 |
| | Maximum wall thickness | [mm] | 59 | | 47 | 37 |
| | Minimum wall thickness | [mm] | 22 | | 20.9 | 16 |
| | Steel quality | | S355 | | S355 | S355 |
| | | | | | | |
| **Transition piece** | Top elevation | [m LAT] | -- | | 25.415 | -- |
| | Bottom elevation | [m LAT] | -- | | 6.314 | -- |
| | Top diameter | [mm] | -- | | 6000 | -- |
| | Bottom diameter | [mm] | -- | | 6000 | -- |
| | Maximum wall thickness | [mm] | -- | | 87 | -- |
| | Minimum wall thickness | [mm] | -- | | 47 | -- |
| | Main platform | [m LAT] | 15 | | 17.848 | 18.5 |
| | Steel quality | | -- | | S355 | -- |
| | | | | | | |
| **Pile** | Top elevation | [m LAT] | 17.5 | 17.5 | 6.314 | 19.15 |
| | Bottom elevation | [m LAT] | -51 | -50 | -41.262 to -69.852 | -50.35 to -63.35 |
| | Top diameter | [mm] | 7000 | 7000 | 6000 | 6500 |
| | Mudline diameter | [mm] | 8000 | 7500 | 7800 / 8500 | 6900 / 7400 |
| | Maximum wall thickness | [mm] | 94 | 82 | 90 / 108 | 88 |
| | Minimum wall thickness | [mm] | 58 | 58 | 56 / 66 | 58 / 62 |
| | Water depth | [m] | 26 | 23 | 17.7 to 38.1 | 21.1 to 34.6 |
| | Pile penetration | [m] | 25 | 27 | 23.562 to 31.752 | 28.75 to 29.25 |
| | Steel quality | | S355 | S355 | S275 / S355 | S275 / S355 |
| **Water level** | MSL | [m LAT] | 1.1 | 1.1 | 1.72 | 1.72 |

Table 6.1: Main characteristics of the wind farms.

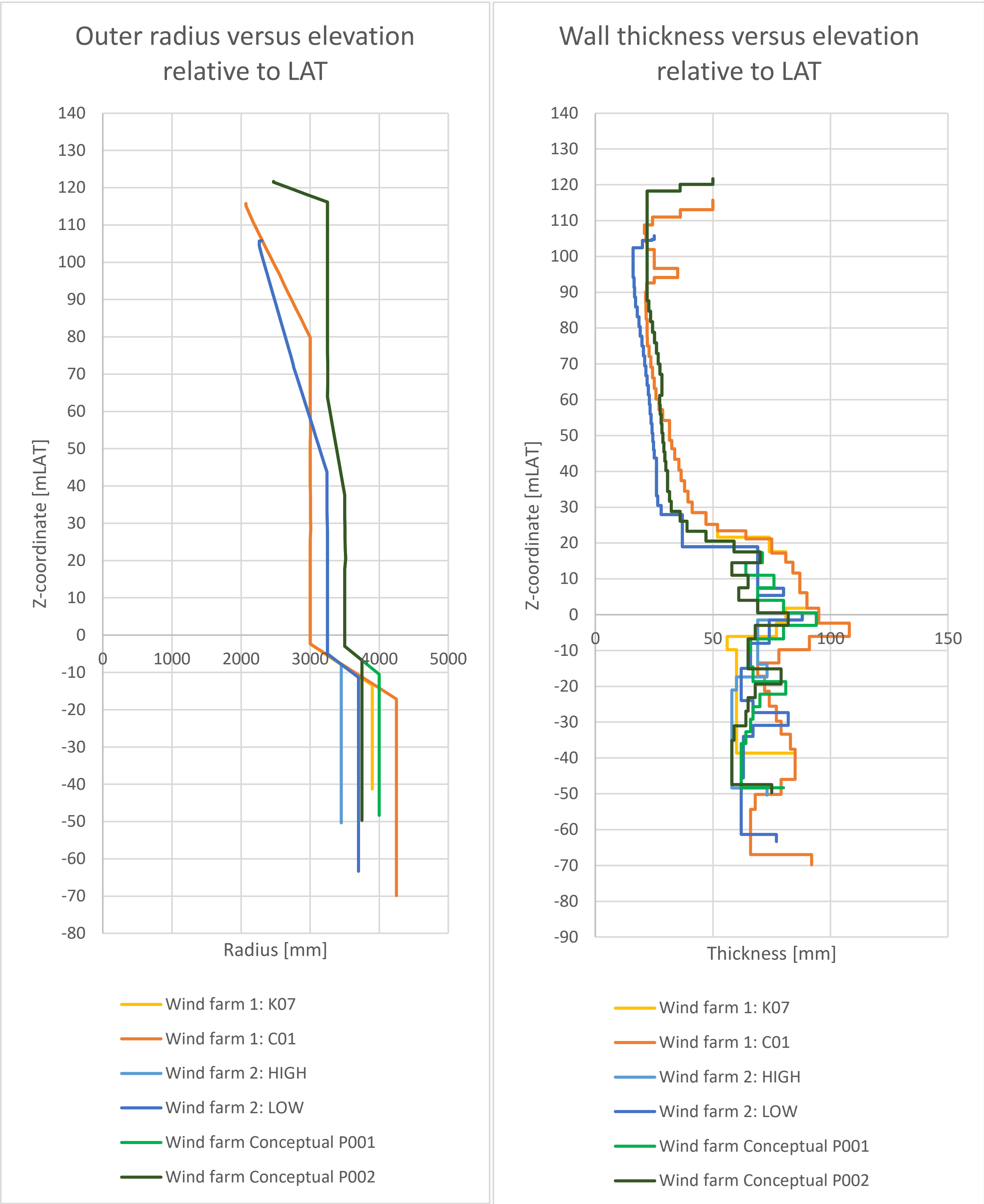



Figure 6.1: Main dimensions of the analysed foundations.

## 6.2. Ships.

In Table 6.2 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 as it is one of the largest ships presently sailing the seas. 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 [MJ] to 192 [MJ], for a drift velocity in the range of 1.1 to 1.7 [m/s].
3. The impact energy when sailing varies from 46 [MJ] to 5000 [MJ], so a ratio of almost 100. The highest value does not occur for the container ship due to its lower sailing velocity, but for a large passenger vessel that is sailing at quite a high velocity. The nominal sailing velocity of a container ship is higher than used in the simulations, but already at this reduced velocity the impact of the sailing container ship has a disastrous effect on the foundation.
4. The location of impact has been estimated from the indicative ship dimensions.

| **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 6.2: Review of ship properties for the ships used in the investigation.

# 7. Evaluation of other parameters affecting the ship impact behaviour of the foundations.

## 7.1. Introduction.

In Section 5 it has been explained which aspects influencing the behaviour of ship and wind turbine foundation, in the case a drifting or sailing ship collides with the foundation, have been taken into account. The model used is a beam model for the foundation and a point mass model for the ship. With this model the effect of various parameters can be investigated, but the model has its limitations and therefore not the effect of all relevant parameters can be investigated. In this Section these parameters will be discussed briefly.

## 7.2. Evaluation of other parameters affecting the ship impact behaviour.

### 7.2.1. The gyroscopic effect of the rotating rotor.

The mass moments of inertia of the rotor blades and the nacelle have been considered in the analysis of the impact behaviour of the turbine. What has not been considered is the gyroscopic effect of the rotating blades in case of an operating turbine. This gyroscopic effect tends the keep the rotation axis of the rotor pointing in the same direction when an external moment tends to change to the position of this axis. As such, the gyroscopic effect will resist the motion of the nacelle under the external moments introduced by the ship impact. The correcting moment is a function of the rotational speed with which the position of the rotor axis changes and thus acts like a damper. This leads to an additional moment acting on the connection nacelle-tower and the top part of the tower.

At the moment of impact, the nacelle will be stationary and not rotating around its vertical axis, so the yaw angle will be constant, and the rotor blades will be turned into the wind. So, at the moment of impact the effect of the gyroscopic moment will be small. This means that for the present investigations in lit. [3], [4] and this document the gyroscopic effect is not important. However, for the analysis of the post-impact behaviour of the foundation the gyroscopic moment in case of an operating turbine will affect, dampen, the motion of the turbine and lead to an additional load on the nacelle-tower connection and the top of the tower. To study this effect more detailed operation of the turbine manufacturers is required. It is therefore advisable to seek cooperation of the turbine manufacturers to analyse the possible effects of a ship impact on the connection nacelle-tower.

### 7.2.2. The damping of an offshore wind turbine.

Damping is generally defined as dissipation of the system energy to environment (normally in terms of heat). It is widely accepted that damping is a critical factor that can limit the amplitude of the dynamic response which would improve the fatigue life of the structure. Offshore wind turbines are subjected to a combination of damping originated from various sources. According to literature, see lit. [25], there are five main sources of damping in offshore wind turbines:

- Aerodynamic damping.
- Hydrodynamic damping.
- Structural damping.
- Supplemental damping provided by mechanical dissipating devices.
- Foundation (or soil) damping.

The total damping in the system can be obtained as the sum of the damping from different sources, see Figure 7.1. Offshore wind turbines are lightly damped structures, and their total damping varies in a wide range. For the turbines in the parked condition, the damping ratio (ξ) as a percentage of critical damping, may be in a range of 1–3% and for the ones in operational condition, in a range of 7–10%. The various damping sources will be discussed briefly below, see lit. [25].

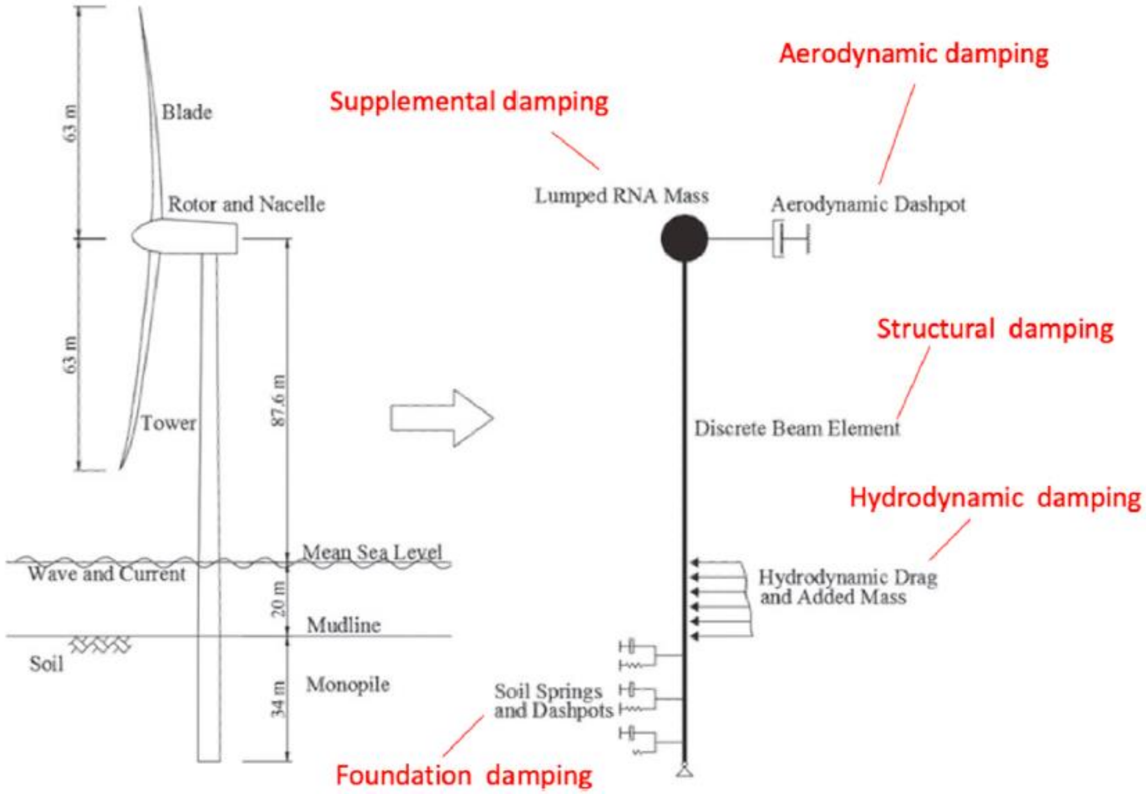



Figure 7.1: Different sources of damping.

1. **Aerodynamic damping**

   The main source of aerodynamic damping is the interaction of wind turbine and forcing air acting on the structure. In operational condition, the aerodynamic damping highly contributes to the overall damping of the OWT. But during the rotor-stop condition, the aerodynamic damping is almost negligible. Researchers have reported aerodynamic damping within a range of 4%–8% in the for-aft (FA) direction and 0.08%–1.43% in side-side (SS) direction. These values are highly dependent on factors like the wind speed, the rotation speed, the pitch angle of blades and the yaw angle of the rotor.

2. **Hydrodynamic damping.**

   There are two main sources for hydrodynamic damping: water wave radiation and damping due to hydrodynamic drag. The hydrodynamic drag is proportional to the structure velocity and is almost negligible due to low velocity. The wave radiation is a function of relative velocity and has a larger influence. The values that have been reported for hydrodynamic damping of offshore wind turbines vary widely in a range between 0.07% and 0.23%, the radiation damping is estimated to be of the order 0.11 to 0.22% and an upper limit of drag damping is 0.15%. In most cases the conclusion is that the values of hydrodynamic damping are considerably lower compared to the other damping sources.

3. **Structural damping.**

   Structural damping is the dissipation of energy along the structure when it vibrates. It originates from internal friction of the structure material which transforms energy to heat. The damping values as defined in standards for steel structures are typically used for structural damping of offshore wind turbines. For example some sources, see lit. [25], report structural damping for offshore wind turbines to be 0.19% which is implemented in Eurocode EN 1991, 2005, while Germanischer Lloyd recommends steel damping values between 0.2 and 0.3%. Others suggest values from 0.15% to 1.5% can be expected, where the lower values are usually considered for pure material damping and higher values are for structures with additional damping sources like joints.

4. **Supplemental damping.**

   As fatigue is an important parameter in the design of offshore wind turbines, it is necessary to reduce the dynamic responses of the structure. One way is the application of structural control techniques usually used in skyscrapers and bridges. Tuned mass dampers are usually used in offshore wind turbines to reduce loads and the amplitude of vibrations. Tower oscillation dampers (tuned mass dampers) are systems integrated to offshore wind turbines to reduce the amplitude of vibrations. These systems usually introduce a high amount of damping to offshore wind turbines, that can be in the range of 1.36%.

5. **Foundation (or soil) damping.**

   During operating conditions, the foundation (or soil) damping is considered to have the second largest contribution to the overall offshore wind damping, after aerodynamic damping, but when the turbine is idle or when the side-side behaviour is considered, the aerodynamic damping is almost negligible and foundation damping is the most prominent. Foundation damping consists of the energy loss through radiation of elastic waves and soil material damping. The sources of foundation damping for a monopile can be summarized as follows:

   - Radiation damping
   - Pore-water dissipation (seepage) damping
   - Soil material damping

   Radiation damping (also known as geometrical or external damping) is the result of the energy dissipation which occurs due to elastic waves spreading across the soil volume surrounding the monopile. This type of damping is frequency dependant and is important where loadings occur at high frequencies (>1 Hz). It is generally believed that radiation damping is negligible for offshore wind turbines when the loading frequency of wind and wave loadings is typically below 1 Hz.

   Damping due to the seepage of pore water between soil particles (equalisation of excess pore pressures) is regarded as viscous and is proportional to the velocity and frequency but independent of soil strain level. To understand the importance of seepage damping, one should consider the drainage conditions around a monopile. In fine grained soils with low permeability (e.g., clays), soils will behave in an (almost) undrained manner with zero volumetric strain, where there is insufficient time for excess pore-water pressures to dissipate between load cycles and thus there will be no viscous damping. In coarse-grained soils with medium to high permeability (e.g., sands or silty sands), the soil surrounding a monopile may behave in a drained, partially drained or fully undrained manner, depending on the rate of loading, drainage length and drainage properties of the soil. To date there is no widely accepted model which can accurately capture both the stress-strain and drainage response of monopiles.

Soil material damping (also known as internal damping) is the dissipation of energy within the soil mass due to friction, sliding between particles and structural rearrangement. The mechanisms which contribute to soil material damping are friction between the soil particles, strain rate effects and non-linear soil behaviour. One of the complexities of soil material damping is the relationship with pore water pressures through the changes in effective stress within the soil. While the pore water seepage can lead to viscous damping, changes in excess pore water pressure result in changes in the soils effective stress which affects the material damping. Soil material damping for monopiles is thought to be generally insensitive to frequency or rate of loading, but highly dependent on the soil strain.

The soil material damping is often modelled with the Takeda hysteresis model or the kinematic hysteresis model as discussed in Section 5.4.2 and as such is already included in the simulation models used in this study.

As indicated above, accurate information about the damping values for specific offshore wind turbines are not available. The soil damping has already been included in the applied models and the aerodynamic damping is negligible when the turbine is in a standstill condition. When the turbine is operating aerodynamic damping can be within a range of 4%–8% in the for-aft direction and 0.08%–1.43% in side-side direction. Overall, the damping is estimated to be in a range of 1–3% for a wind turbine in a standstill condition and in a range of 7–10% the operational condition.

The aerodynamic damping and the hydrodynamic damping, have a viscous nature, meaning that they are a function of the relative speed between the air or water and the foundation and the turbine. For the ship impact situation this means that at the moment of the ship impact damping does not play a significant role. Only after the impact when the turbine and foundation are starting to vibrate because of the impact, damping plays a role. This means that damping is only relevant during the post impact behaviour of the foundation and as such not relevant for the present investigations. Therefore, the effect of damping is not further investigated in this study.

### 7.2.3. Dynamic behaviour of the rotor blades.

The dynamic behaviour of the rotor blades during the impact of a ship against a wind turbine has not been investigated in detail yet and was also not part of this study. Even in standstill conditions it is expected that the rotor blades start vibrating when the turbine suddenly starts to move under the accelerations induced by the ship impact. To study this phenomenon detailed knowledge of the structure of the blades is required, which is proprietary information of the wind turbine manufacturers. As such this kind of study should be carried out by or in close cooperation with the wind turbine manufacturers.

### 7.2.4. Connection between nacelle and tower top.

The connection between the nacelle and the tower top is also a possible critical location. The yaw bearing is in general not designed to take up large acceleration loads that occur during ship impact. Failure of this connection due to ship impact is thus possible and might ultimately lead to the nacelle with the rotor breaking away from the tower top. Just as for the blade structure, the turbine-tower connection is proprietary information of the wind turbine manufacturers and as such also this kind of study should be carried out by or in close cooperation with the wind turbine manufacturers.

### 7.2.5. Local denting of the foundation at the impact point.

For this study a beam model has been used for the wind turbine foundation. With this model it is not possible to investigate the local deformations that will occur of the monopile at the contact location between the foundation and the ship. These local deformations are highly dependent on the impact characteristics such as the impact velocity, but also on the ship geometry. During a drifting impact when the ship most likely hits the foundation with its sideboard the height of the contact area is, especially for larger ships, significantly larger than when a sailing ship hits the foundation with its bow or bulb. Furthermore, also the ship structure and the actual location of the impact against the ship hull plays an important role in the development of the local deformation of the monopile. When the impact is located directly at a bulkhead it is quite likely that significant local denting of the monopile can occur, whereas when the impact is in the middle between 2 bulkheads this is less so.

When local denting occurs, this affects the stability of the foundation directly at the impact point and can lead to an overall failure of the foundation at the impact point, resulting in the foundation falling towards the ship. Even the beam model already indicated this possible outcome for the impact between the sailing passenger vessel and the wind turbine foundation.

The effect of local denting on the failure mode of the wind turbine foundation can only be investigated in detail when a full 3D FE model of the foundation and the ship hull is taken into account for the simulation.

### 7.2.6. Contact between ship and secondary structural components.

At the most likely impact location between a ship and the wind turbine foundation, e.g., at, just above or just below sea level secondary structures are connected to the monopile foundation. For the present wind farms these secondary structures generally are, see Figure 7.2:

1. The main platform, mostly located at LAT+15m to LAT+20m.
2. The access ladder and rest platform, running from LAT up to the main platform.
3. The boat landing, running from LAT-3m up to LAT+10m.

The main platform extends around the whole foundation, whereas the other components are only located at 1 side of the foundation which is located at the lee side of the foundation, so mostly at the East side. This means that a drifting ship driven by the predominantly western winds will most likely not hit these secondary components directly. Of course, when during the impact the ship rotates around of the foundation it might scrape along these components and this can lead to local failure to the ship hull or the monopile wall.

Larger ships, e.g., large tankers, passenger vessels and container ships are likely to also hit the main platform, which can lead to severe damage to the ship upper structure, but considering the large height above sea level it will not lead to the sinking of the ship. As such, a detailed study of the impact between a ship and the secondary components is less urgent.

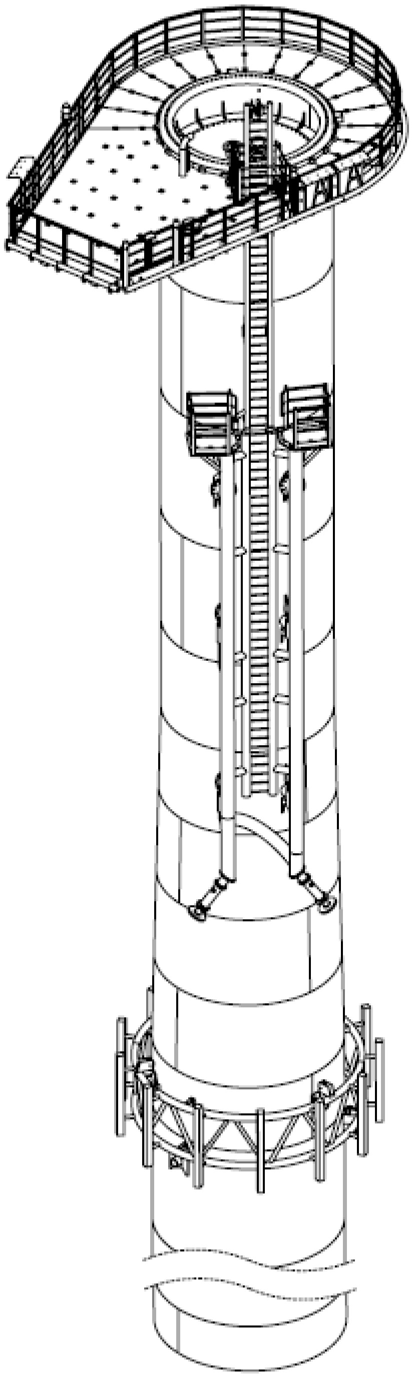


Figure 7.2: Secondary steel structures connected to a monopile foundation.

# 8. Analysis of the collision between a ship and the conceptual design wind turbine foundations.

## 8.1. Introduction.

During the 1st part of the study no data of real existing wind farms were available due to NDA considerations. However, from one party the properties of a conceptual design for 2 wind farm foundations were received. These conceptual designs are based on soil properties and water depths characteristic for the Dutch part of the North Sea. These designs therefore have been used to get insight in the possible behaviour of wind turbine foundations when collide by a ship. A summary of these results is presented in this Section. More detailed results are presented in lit. [5].

## 8.2. Soil failure.

To determine the soil failure, it has been assumed that the yield limit of the steel of the foundation is infinitely high, so that no plastic deformation of the foundation occurs. This means that the foundation behaves elastically. Furthermore, a lateral load is applied on the foundation and this load acts at MSL. This load is gradually increased linearly until soil failure occurs and the foundation is pushed over. Also, the gravity load is acting on the foundation and the turbine and when the foundation is pushed over significantly, this gravity load will assist in soil collapse.

In Figure 8.1 the failure force of the soil is shown as function of the displacement at the load application point at LAT, together with the displacement at seabed and at the pile tip. The graphs show that the load gradually increases and then reaches a maximum when soil failure occurs. From that moment on the force to turn over the foundation decreases until the soil fully collapses, and the gravity load is sufficient to flatten the foundation.

From the results 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 8.1. 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 over the foundation is equal to 1357 [MJ] for foundation P001 and 1244 [MJ] for foundation 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 8.1: Soil failure data.

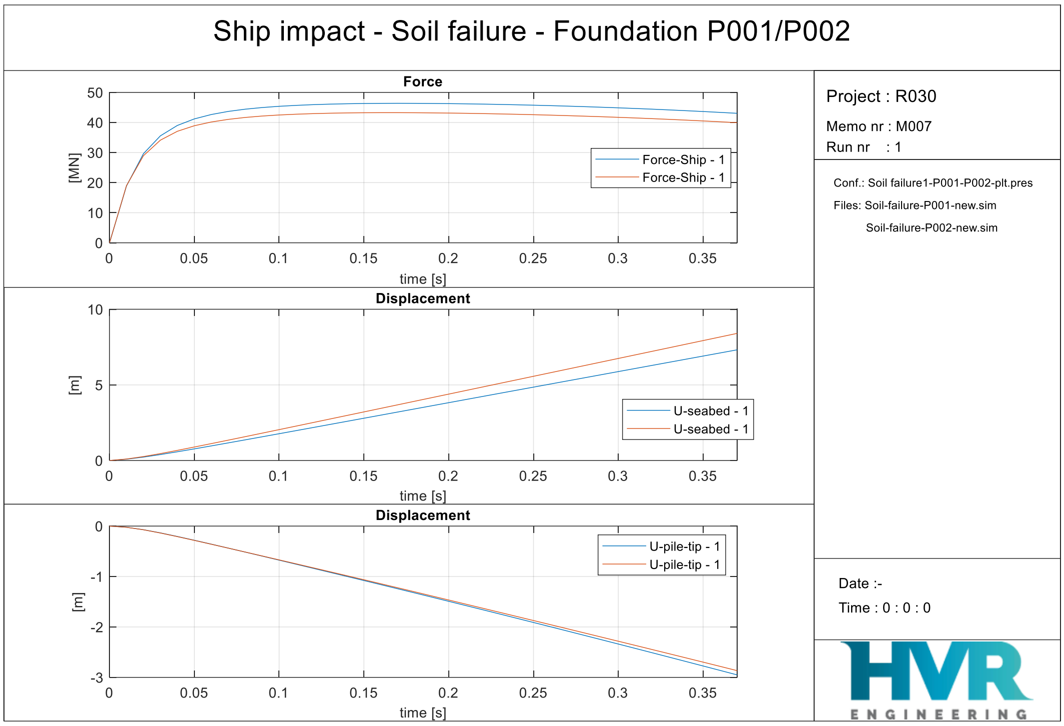



Figure 8.1: Soil failure

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

## 8.3. Initial collision investigations.

The initial collision investigations have been carried out for the following conditions:

1. The soil properties for foundation P001.
2. 'Full reversible' soil model, see Section 5.4.3. This means that it is assumed that when rebound occurs, the force follows the same curve backwards as during the impact, so no energy is dissipated by the soil.
3. Nominal impact force as function of the ship deformation. This impact force has been scaled from the data presented in the DNVGL-RP-C204 standard, see lit. [22], using the ship displacement as scaling parameter.
4. Nominal drifting and sailing velocity as presented in Table 6.2.
5. No wind, wave, current or turbine loads acting on the foundation.
6. No wind, wave or current loads acting on the ship and no propulsion load for the sailing ship.
7. Failure criterion: The Yield limit.

A summary of the main results is presented in Table 8.2. Regarding the possible failure modes of the wind turbine foundation, the following modes have been identified:

1. **No pile or tower failure, just elastic foundation deformation.**

   This occurs for the following ships and conditions.

   - Kruiplijn coaster, drifting
   - Kruiplijn coaster, sailing.
   - Supply vessel, drifting.

   So only for the smaller ships no permanent global damage of the foundation occurs. Of course, still a local dent could occur at the impact point, but this cannot be simulated by the present model.

2. **Tower failure.**

   This occurs for the following ships and conditions.

   - Supply vessel, sailing.
   - Chemical tanker, drifting.

   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. This is mainly caused by the fact that no energy is dissipated by the soil.

| **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 8.2: Summary of main results of the initial simulations.

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

   This occurs for the following ships and conditions.

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

   Failure in the tower occurs because the inertia of the nacelle prevents it from following the displacement of the foundation at the impact point, 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 fracture of the tower wall will occur.

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

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.**

   This occurs for the following ships and conditions.

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

   This happens for the larger ships, which have a kinetic energy that cannot be taken up by the soil and leading to collapse of the soil, with the ships overrunning the foundations. Due to the failure in the tower, the turbine tends to move towards the ship, but the ship overrunning the foundation tends to move the turbine in the direction of motion of the ship. It depends on the ultimate velocity of the turbine whether it drops down on to the ship or moves away from the ship. For the investigated configurations it is most likely that the nacelle will move away from the ship.

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 cannot 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 a cone transition is susceptible to this. Of course, the stiffening flanges present at the cone transition have not been included in this analysis as the model could not yet cope with these flanges, but nevertheless it can be concluded that a cone transition in a tower is susceptible to failure.
3. For the investigated foundations failure below the impact point 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 cannot 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.

## 8.4. Parameter variations.

### 8.4.1. The soil properties.

All initial simulations as presented in Section 8.3 have been carried out with soil P001 and the corresponding foundation. In this Section the results of the behaviour of the soil P002 and its corresponding foundation are presented when the following ships collide with this foundation:

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

Comparison of the results of the collision of these ships with the foundations P001 and P002 shows:

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

   This 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 to the eigenfrequencies. Hence the strength and dynamic properties of these two foundations are comparable and therefor the reaction to ship impact can be expected to be comparable too.

2. In Figure 6.1 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, with P001 having a larger wall thickness. 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.

### 8.4.2. The rebound properties of the soil.

All simulations in Section 8.3 have been carried out with the assumption that when rebound occurs, the force follows the same curve backwards as during the impact so that no energy is dissipated by the soil. 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. 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, see Section 5.4.3. Do instead of the ‘Full reversible’ soil model the ‘Non reversible’ soil model has now been used.

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 numerical results are summarised in Table 8.3. Comparison of the results for both soil models shows:

1. Supply vessel, sailing.

   This ship has been selected for this analysis 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.

Using the 'Non reversible' soil model instead of the 'Full reversible' soil model now leads to the following results:

a. Up to the moment of failure of the foundation with the 'Full reversible' soil model, the results are identical. Only after the ship has been stopped and rebound occurs, the results are different.

b. For the foundation with the 'Full reversible' soil model failure occurs in the tower above the impact point as the nacelle can't follow the rebound motion of the foundation, whereas with 'Non reversible' soil model no failure in the tower occurs and the foundation starts oscillating in its 1st eigenmode. This is due to the fact that with the 'Non reversible' soil model most energy is dissipated by the soil and only a small part is returned to the foundation and the ship. As a results, the rebound velocity of the ship is now only -0.84 [m/s] instead of -1.28 [m/s] with the 'Full reversible' soil model.

| **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 8.3: Summary of results for different soil rebound properties.

2. Chemical tanker, drifting.

This ship has been selected for this analysis 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 as was the case for the Supply vessel.

The numerical results are summarised in Table 8.3. Comparison of the results for both soil models shows:

a. Up to the moment of failure of the foundation with the 'Full reversible' soil model, 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] with the 'Full reversible' soil model.

c. The maximum displacements for the nacelle, the impact point, at seabed level and for the pile tip are the same as with the 'Full reversible' soil model. However, the deformations at seabed level and of the pile tip, so the pile displacement inside the soil remains almost constant after impact, instead of bouncing back to a virtually 0 displacement.

d. The foundation above seabed does not fail with the 'Non reversible' soil model 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, with the 'Non reversible' soil model, the foundation thus does not fail, but remains oscillating after impact.

3. Container ship, drifting.

   The drifting container ship has been selected for this analysis because with the 'Full reversible' soil model 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 numerical results are summarised in Table 8.3. Comparison of the results for both soil models shows:

   a. With both soil models 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 with the 'Non reversible' soil model larger than with the 'Full reversible' soil model. However, this is mainly due to the fact that this numerical instability occurs 0.64 [sec] later with the 'Non reversible' soil model.

   d. The maximum accelerations acting at the nacelle are approximately the same for both investigated soil models.

   e. The displacement of the foundation part inside the soil behaves with the 'Non reversible' soil model differently from the situation with the 'Full reversible' soil model. The pile tip does not rebound back to zero, but more or less keeps its maximal displacement. This is probably more realistic than the behaviour than with the 'Full reversible' soil model.

   f. For both soil models, the ship will keep on moving forward and eventually the foundation inside the soil will break and the ship will drift over the foundation.

4. Container ship, sailing.

   The sailing container ship has been selected for this analysis because with the 'Full reversible' soil model failure occurs due to the sheer mass of the container ship in combination with the high impact velocity.

   The numerical results are summarised in Table 8.3. Comparison of the results for both soil models shows:

   a. In this case the difference in the results of the foundation between the two soil models 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 with the 'Non reversible' soil model not bounce back due to the relaxation of the soil as is the case with the 'Full reversible' soil model, but keeps on displacing further, caused by the forward motion of the ship. At a certain moment when the pile is behaving fully plastic, 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. For both soil models, the ship will keep on moving forward and eventually the foundation inside the soil will break and the ship will sail over the foundation.

The main conclusion of this analysis with the 2 soil models 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, as is the case with the 'Full reversible' soil model, 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.

### 8.4.3. The impact force.

For the simulations in Section 8.3 the impact force as function of the displacement has been scaled from the data presented in the DNVGL-RP-C204 standard, see lit. [22]. 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 at 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 numerical results are summarised in Table 8.4. From these results it follows:

1. Chemical tanker, drifting.
    a. When the ship is weaker, the deceleration of the ship takes slightly longer, e.g. 1.4 [sec] versus 1.21 [sec] for the original ship strength.
    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 ship strength. This force is still lower than the force at which complete ship hull 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 ship strength. 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 8.4: Summary of results for different impact force curves.

2. Passenger vessel, drifting.

   a. The failure mode is the same as for the original ship strength. The nacelle cannot 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 in ship strength 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 hull fully collapses.

   c. Overall, the behaviour of foundation with reduced ship strength is the same as for the situation with the original ship strength, only the whole process lasts a little longer due to the weakness of the ship.

3. Container vessel, drifting.

   a. The failure mode is almost the same as for original ship strength. 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 in ship strength 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 hull fully collapses.

   c. Overall, the behaviour of foundation with reduced ship strength is the same as for the situation with the original ship strength, only the whole process lasts a little longer due to the 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 occurs at all. 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 at the impact point and this will also have an effect on the global failure mode.

### 8.4.4. 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 other 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 $\sqrt{2}$, so reduction of the impact energy with a factor 2.
2. Passenger vessel, drifting, reduction factor of the impact velocity with a factor $\sqrt{2}$, so reduction of the impact energy with a factor 2.

The numerical results are summarised in Table 8.5. From these results it follows:

1. Chemical tanker, drifting.
    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 2$^{nd}$ impact with the ship occurs during the rebound.

        Due to this, the nacelle is now able to follow the 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 1$^{st}$ resonance mode.
2. Passenger vessel, drifting.
    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 8.5: 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 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.

## 8.5. Summary.

The investigations in Section 8.4 together with the initial results in Section 8.3 leads to following identified global failure modes for the conceptual design wind turbine foundations.

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 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.

   This failure mode only occurs with the 'Full reversible' soil model, when after impact all energy stored inside the soil is returned to the foundation and the ship.

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 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 can occur 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 on 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 inside the soil. This might of course lead to damage to the bottom of the ship.

When both of the above-mentioned failure modes do occur nearly at the same moment, this 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.

## 8.6. 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 be 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 6.1 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 do occur that are up to and above the yield limit, see for example Figure 8.2. 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.

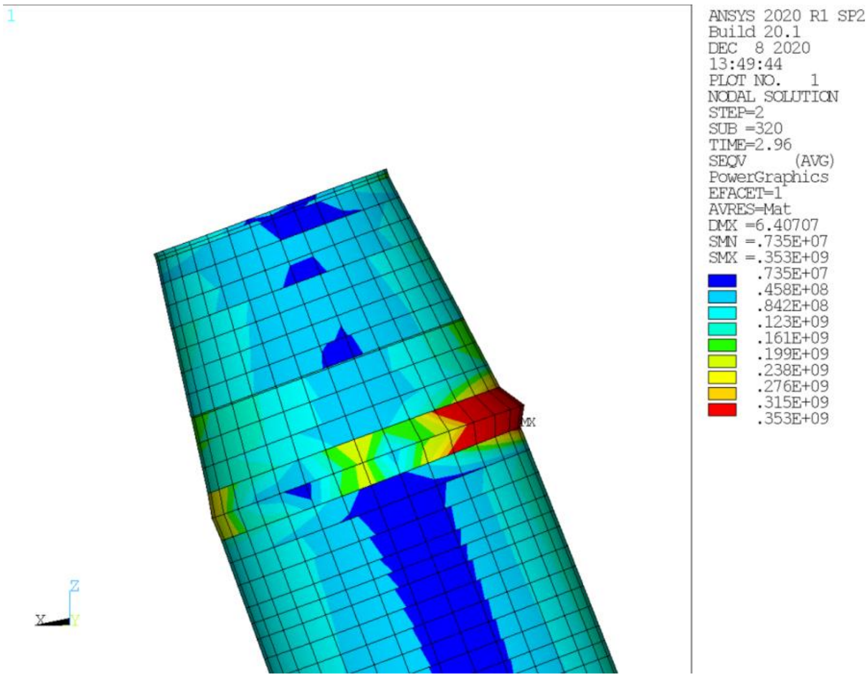



Figure 8.2: Tower top cone connecting tower with nacelle – results for drifting Chemical tanker.

# 9. Analysis of the collision between a ship and the wind turbine foundations of 2 existing wind farms.

## 9.1. Introduction.

During the 2nd part of the study, the investigations executed for the conceptual wind turbine foundations as presented in the previous Section, have been repeated for the foundations of 2 existing wind farms for which sufficient information has been received. A summary of these results is presented in this Section. More detailed results are presented in lit. [6].

## 9.2. Soil failure.

To determine the soil failure, it has been assumed that the yield limit of the steel of the foundation is infinitely high, so that no plastic deformation of the foundation occurs. This means that the foundation behaves elastically. Furthermore, a lateral load is applied on the foundation and this load acts at MSL. This load is gradually increased linearly until soil failure occurs and the foundation is pushed over. Also, the gravity load is acting on the foundation and the turbine and when the foundation is pushed over significantly, this gravity load will assist in soil collapse.

In Figure 9.1 the failure force of the soil is shown as function of the displacement at the load application point at MSL, together with the displacement at seabed and at the pile tip. For all foundations the MSL is equal to 1.72 [m]. The graphs show that the load gradually increases and then reaches a maximum when soil failure occurs. From that moment on the force to turn over the foundation decreases until the soil fully collapses, and the gravity load is sufficient to flatten the foundation.

The numerical results are presented in Table 9.1. From these results it follows:

1. The soil properties for the foundations K07 and HIGH are the same and also the soil properties for the foundations C01 and LOW are the same. There is a difference in soil conditions between K07/HIGH and C01/LOW.
2. The soil failure load is in the range from 10.0 [MN] to 16.6 [MN], while the required energy to fully overturn the foundation varies from 165.6 [MJ] to 382.5 [MJ]
3. Comparing K07 and HIGH shows that the increase in pile penetration with c.a. 5.7 [m] has a larger effect than the increase in water depth with 3.4 [m]. The soil failure load increases from 10.0 [MN] to 16.6 [MN] and the failure energy increases from 165.6 [MJ] to 382.5 [MJ].
4. Comparing LOW and C01 shows also that the increase in pile penetration with c.a. 3.0 [m] has a larger effect than the increase in water depth with 3.4 [m]. The soil failure load increases from 12.7 [MN] to 15.4 [MN] and the failure energy increases from 298.0 [MJ] to 381.5 [MJ].
5. Comparing K07 and C02 shows that for the different soil properties the increase in penetration depth has a larger effect than the increase in water depth. The soil failure load increases from 10.0 [MN] to 15.4 [MN] and the failure energy increases from 165.6 [MJ] to 381.5 [MJ].
6. Comparing HIGH and LOW shows that for almost the same penetration depth the increase in water depth results in a decrease of the soil failure load from 16.6 [MN] to 12.7 [MN] and a decrease in failure energy from 382.5 [MJ] to 298[MJ].

Finally, it must be noted that in Part 1, see Section 8 and lit. [5], a soil failure load of 46.4 [MN] for location P001 and 43.3 [MN] for location P002 has been found. The corresponding turn-over energies were respectively

1357 [MJ] and 1244 [MJ]. These values are thus for the conceptual foundation designs considerably higher than for the actual wind farms investigated in this Section. As the penetration depths of the conceptual design foundations are comparable to the penetration depths of the foundations of wind farm 1 and 2, it can be concluded that the soil strength used for the conceptual designs is significantly higher than the soil strength for the actual wind farms!

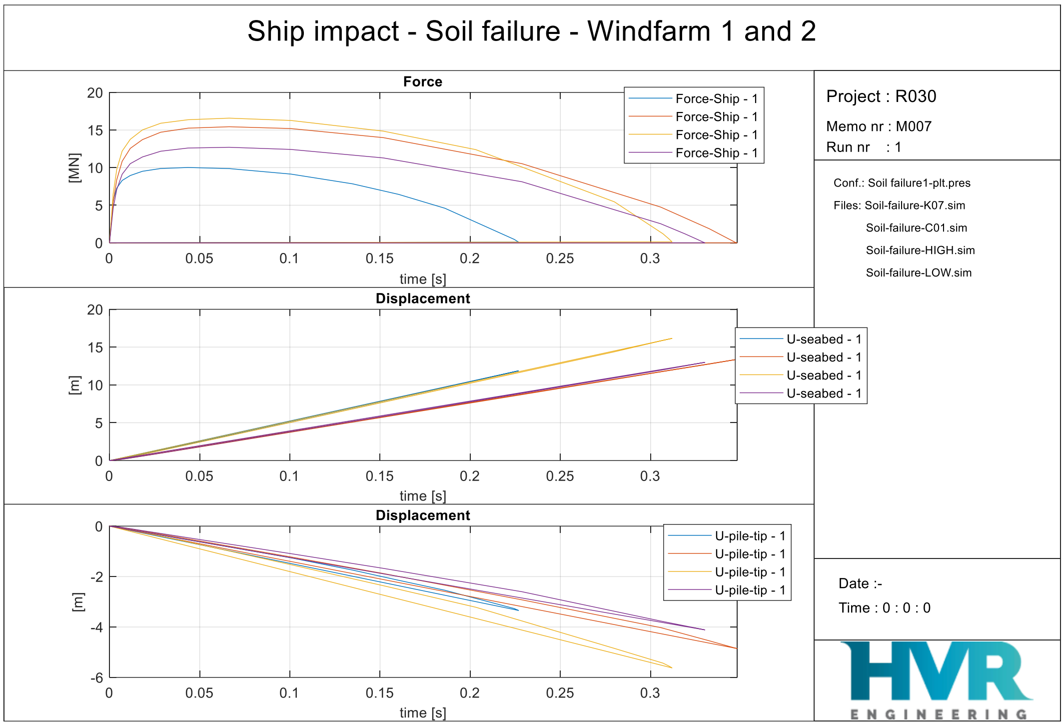



Figure 9.1: Soil failure

(Blue line = C01, Red line = K07, Yellow line = HIGH, Purple line = LOW).

| Soil failure load | | Wind farm 1 | Wind farm 1 | Wind farm 2 | Wind farm 2 |
|---|---|---|---|---|---|
| | | **K07** | **C01** | **HIGH** | **LOW** |
| Water depth | [m] | 17.7 | 38.1 | 21.1 | 34.7 |
| Pile penetration | [m] | 23.562 | 31.752 | 29.25 | 28.75 |
| MSL | [m LAT] | 1.72 | 1.72 | 1.72 | 1.72 |
| **Soil failure load at MSL** | **[MN]** | **10.0** | **15.4** | **16.6** | **12.7** |
| **Energy dissipation capacity** | **[MJ]** | **165.6** | **381.5** | **382.5** | **298.0** |

Table 9.1: Soil failure load.

Based on the energy required to fully push over the foundations, see Table 9.1, and the kinetic energy of the investigated ships, see Table 6.2, it can be determined whether ultimately the investigated foundations will be able to stop the ship. This is presented in Table 9.2. It follows that foundation K07 is not able to stop the drifting container ship and that apart from this all drifting ships can be stopped by the investigated foundations. Of course, it must be kept in mind that this conclusion can change when the actual drift velocity is higher than assumed in Table 6.2 of this report.

For the sailing ships it follows that foundation K07 is only able to stop the sailing Kruiplijn coaster, whereas the other foundations are able to also stop the sailing Supply vessel. The sailing Chemical tanker, Passenger vessel and Container ship cannot be stopped by the foundation and these ships will sail over the foundation.

| Drifting ship | Stopping power foundation | | | |
|---|---|---|---|---|
| | Wind farm 1 | Wind farm 1 | Wind farm 2 | Wind farm 2 |
| | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | Yes | Yes | Yes | Yes |
| Supply vessel | Yes | Yes | Yes | Yes |
| Chemical tanker | Yes | Yes | Yes | Yes |
| Passenger vessel | Yes | Yes | Yes | Yes |
| Container ship | No | Yes | Yes | Yes |

| Sailing ship | Stopping power foundation | | | |
|---|---|---|---|---|
| | Wind farm 1 | Wind farm 1 | Wind farm 2 | Wind farm 2 |
| | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | Yes | Yes | Yes | Yes |
| Supply vessel | No | Yes | Yes | Yes |
| Chemical tanker | No | No | No | No |
| Passenger vessel | No | No | No | No |
| Container ship | No | No | No | No |

Table 9.2: Stopping capacity of the investigated foundations.
(Yes = the foundation can stop the ship; No = the foundation is run over by the ship)

## 9.3. Initial collision investigations.

The initial collision investigations for the 2 real wind farms have been carried out for the following conditions:

1. 'Full reversible' soil model and 'Non reversible' soil mode, see Section 5.4.3.
2. Nominal impact force as function of the ship deformation. This impact force has been scaled from the data presented in the DNVGL-RP-C204 standard, see lit. [22], using the ship displacement as scaling parameter.
3. Nominal drifting and sailing velocity as presented in Table 6.2.
4. No wind, wave, current or turbine loads acting on the foundation.
5. No wind, wave or current loads acting on the ship and no propulsion load for the sailing ship.
6. Failure criterion: The Yield limit, with a safety factor of 1.2.
7. Reduced impact force with a certain arbitrary factor in order to get a lower failure limit and a more gradual slope at 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.
8. Reduced impact velocity with a factor $\sqrt{2}$, so reduction of the impact energy with a factor 2.

The executed simulations are presented in Table 9.3 and will be discussed in Section 9.3.1 and 9.3.2. More detailed information is provided in lit. [6].

| Nr. | Executed simulations: Drifting |
|---|---|
| 1 | Kruiplijn coaster - 1 - Drifting. |
| | 'Full reversible' soil model |
| 2 | Kruiplijn coaster - 2 - Drifting. |
| | 'Non reversible' soil model |
| 11 | Supply vessel - 1 - Drifting. |
| | 'Full reversible' soil model |
| 12 | Supply vessel - 2 - Drifting. |
| | 'Non reversible' soil model |
| 21 | Chemical tanker - 1 - Drifting, High impact force. |
| | 'Full reversible' soil model |
| 22 | Chemical tanker - 2 - Drifting, Low impact force. |
| | 'Full reversible' soil model |
| 23 | Chemical tanker - 3 - Drifting, High impact force. |
| | 'Non reversible' soil model |
| 24 | Chemical tanker - 4 - Drifting, High impact force, reduced impact velocity |
| | 'Full reversible' soil model |
| | Impact velocity decreased with √2, so impact energy reduced with 50%. |
| 31 | Passenger vessel - 1 - Drifting, High velocity, High impact force. |
| | 'Full reversible' soil model |
| 32 | Passenger vessel - 2 - Drifting, Low velocity, High impact force. |
| | 'Full reversible' soil model |
| 33 | Passenger vessel - 3 - Drifting, High velocity, Low impact force. |
| | 'Full reversible' soil model |
| 34 | Passenger vessel - 4 - Drifting, High velocity, High impact force. |
| | 'Non reversible' soil model |
| 41 | Container ship - 1 - Drifting, High impact force. |
| | 'Full reversible' soil model |
| 42 | Container ship - 2 - Drifting, Low impact force. |
| | 'Full reversible' soil model |
| 43 | Container ship - 3 - Drifting, High impact force. |
| | 'Non reversible' soil model |

| Nr. | Executed simulations: Sailing |
|---|---|
| 1 | Kruiplijn coaster - 1 - Sailing. |
| | 'Full reversible' soil model |
| 2 | Kruiplijn coaster - 2 - Sailing. |
| | 'Non reversible' soil model |
| 11 | Supply vessel - 1 - Sailing. |
| | 'Full reversible' soil model |
| 12 | Supply vessel - 2 - Sailing. |
| | 'Non reversible' soil model |
| 21 | Chemical tanker - 1 - Sailing, Nominal velocity |
| | 'Full reversible' soil model |
| 22 | Chemical tanker - 2 - Sailing, Low velocity. |
| | 'Full reversible' soil model |
| | Impact velocity reduced to 2 [m/s]. |
| 23 | Chemical tanker - 3 - Sailing, Low velocity. |
| | 'Non reversible' soil model |
| | Impact velocity reduced to 2 [m/s]. |
| 31 | Passenger vessel - 1 - Sailing. |
| | 'Full reversible' soil model |
| 32 | Passenger vessel - 2 - Sailing. |
| | 'Non reversible' soil model |
| 41 | Container ship - 1 - Sailing |
| | 'Full reversible' soil model |
| 42 | Container ship - 2 - Sailing. |
| | 'Non reversible' soil model |

Table 9.3: Executed simulations.

### 9.3.1. Drifting impact.

Drifting impact is characterised by:

1. A fairly low impact velocity, in the range from 1.1 [m/s] to 1.7 [m/s], and therefore a limited amount of kinetic energy, ranging from 3.8 [MJ] to 192 [MJ], that must be dissipated up on impact. Of course, these values depend on the ship size and type.

2. Broad side impact with a large contact height between ship and pile, resulting in a lack of crumple zones to absorb and dissipate the force of an impact.

3. A stiff ship behaviour, resulting in a fast rise in impact force and with a high maximum impact force, ranging from 10 [MN] to 75 [MN], depending on the ship size and type.

   The effect of the different foundations on the maximum impact force is limited, see Table 9.4.

4. Impact due to drifting is occurring with the ship hitting the foundation directly below the rotor, so the ship is moving with the wind.

| Ship | Impact force [MN] | |
|---|---|---|
| | Drifting | |
| | Wind farm 1 | Wind farm 2 |
| Kruiplijn coaster | 11 | 10 |
| Supply vessel | 29 | 27 |
| Chemical & Product tankers | 43 | 39 |
| Passenger vessels | 66 | 59 |
| Container ship | 81 | 67 |

Table 9.4: Maximum impact force in [MN] as function of ship type, wind farm and impact condition during Drifting.

The main results can now be summarised as follows:

1. **Foundation failure, see Table 9.5.**

   a. As a result of the Drifting impact characteristics, the foundation behaviour is mostly governed by the high initial accelerations induced by the impact and the stiff ship behaviour, resulting in possible failure of the tower above the ship.

   b. Tower failure mostly occurs higher up in the foundation, closer to the turbine, see Table 9.5. It can be caused by the inertia of the turbine in combination with the linear acceleration, but also by the rotational inertia of the turbine in combination with the rotational acceleration. In the latter case the tower failure mostly occurs close below the top flange.

   The exact failure location of course depends on the dynamic behaviour and strength of the structure and is therefore depending on the foundation design.

   From Table 9.5 it follows that especially foundation K07 of Wind farm 1 is susceptible for failure close to the tower top, which is caused by the rotational inertia of the turbine in combination with the rotational acceleration. Foundation C01 of Wind farm 1 is less susceptible because this location is positioned at a larger water depth and is slightly more flexible. However also foundation C01 is quite heavily loaded at the failure location of foundation K07. A small increase in impact velocity can therefore also lead to failure at this same location for foundation C01.

For the foundations HIGH and LOW of wind farm 2 the tower failure is mostly governed by the linear acceleration loads acting on the foundation. These failures occur further downwards.

c. The direction of motion of the turbine at the moment of tower failure, see Table 9.5, is mostly directed towards the ship. This means that when full collapse of the tower occurs, the turbine will drop down onto the ship.

   In some cases, especially for the foundations of Wind farm 2 and then more specifically for foundation LOW the turbine moves away from the ship at the moment of tower failure. This occurs when the deceleration of the foundation after the impact due to rebound is that large that bending moment due to the turbine inertia becomes too high.

d. When no collapse of the foundation or the soil occurs, the ship is ultimately stopped by the foundation and especially for the larger ships, e.g., the Chemical tanker and the Passenger vessel, there can be a considerable permanent inclination of the foundation. Also, the tower will be bended at the location where the tower failure occurs. This most likely means that further operation of the turbine will not be possible anymore.

e. A lower impact velocity or a less stiff/weaker ship hull is advantageous, but the differences are not clearly visible in the main results. For some foundations it results in no failure, but not for all foundations.

<table>
<tr><th rowspan="2">Ship</th><th rowspan="2">Simulation run</th><th colspan="6">Tower failure location [mLAT] during Drifting</th></tr>
<tr><th colspan="3">Wind farm 1</th><th colspan="3">Wind farm 2</th></tr>
<tr><th>Foundation</th><th></th><th>K07</th><th colspan="2">C01</th><th>HIGH</th><th colspan="2">LOW</th></tr>
<tr><td>Kruiplijn coaster</td><td>1</td><td>--</td><td colspan="2">--</td><td>--</td><td colspan="2">--</td></tr>
<tr><td></td><td>2</td><td>--</td><td colspan="2">--</td><td>--</td><td colspan="2">--</td></tr>
<tr><td></td><td></td><td></td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td>Supply vessel</td><td>1</td><td>107.9</td><td colspan="2">--</td><td>90.9</td><td colspan="2">85.9</td></tr>
<tr><td></td><td>2</td><td>107.9</td><td colspan="2">--</td><td>91.4</td><td colspan="2">--</td></tr>
<tr><td></td><td></td><td></td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td>Chemical & Product tankers</td><td>1</td><td>107.9</td><td colspan="2">--</td><td>30.9</td><td colspan="2">30.5</td></tr>
<tr><td></td><td>2</td><td>--</td><td colspan="2">--</td><td>88.6</td><td colspan="2">30.7</td></tr>
<tr><td></td><td>3</td><td>106.4</td><td colspan="2">--</td><td>30.7</td><td colspan="2">30.9</td></tr>
<tr><td></td><td>4</td><td>107.6</td><td colspan="2">--</td><td>--</td><td colspan="2">--</td></tr>
<tr><td></td><td></td><td></td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td>Passenger vessels</td><td>1</td><td>88.6</td><td>108.3</td><td>72.5</td><td>30.9</td><td>86.4</td><td>30.9</td></tr>
<tr><td></td><td>2</td><td>107.4</td><td colspan="2">--</td><td>30.9</td><td colspan="2">--</td></tr>
<tr><td></td><td>3</td><td>88.6</td><td>107.9</td><td>60.7</td><td>89.6</td><td>86.4</td><td>30.9</td></tr>
<tr><td></td><td>4</td><td>88.6</td><td>108.8</td><td>74.5</td><td>30.9</td><td>86.4</td><td>30.9</td></tr>
<tr><td></td><td></td><td></td><td colspan="2"></td><td></td><td colspan="2"></td></tr>
<tr><td>Container ship</td><td>1</td><td>108.1</td><td colspan="2">--</td><td>80.9</td><td colspan="2">--</td></tr>
<tr><td></td><td>2</td><td>108.1</td><td colspan="2">--</td><td>--</td><td colspan="2">--</td></tr>
<tr><td></td><td>3</td><td>108.1</td><td colspan="2">--</td><td>--</td><td colspan="2">--</td></tr>
</table>

| Ship | Simulation run | Direction of tower failure during Drifting | | | |
|---|---|---|---|---|---|
| | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | -- | -- | -- | -- |
| | 2 | -- | -- | -- | -- |
| | | | | | |
| Supply vessel | 1 | Towards ship | -- | Towards ship | Away from ship |
| | 2 | Towards ship | -- | Towards ship | |
| | | | | | |
| Chemical & Product tankers | 1 | Towards ship | -- | Away from ship | Away from ship |
| | 2 | -- | -- | Towards ship | Away from ship |
| | 3 | Towards ship | -- | Away from ship | Away from ship |
| | 4 | Towards ship | -- | -- | -- |
| | | | | | |
| Passenger vessels | 1 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Towards ship | -- | Away from ship | -- |
| | 3 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 4 | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | |
| Container ship | 1 | Towards ship | -- | Towards ship | -- |
| | 2 | Towards ship | -- | -- | -- |
| | 3 | Towards ship | -- | -- | -- |

Table 9.5: Tower failure behaviour, Drifting.

**2. Foundation collapse, see Table 9.6.**

Foundation collapse either occurs due to tower collapse, with the turbine falling down or due to soil collapse when the ship is pushing the foundation over. A combination of the two can also occur.

Tower collapse cannot be accurately modelled with the present simulation program. It is assumed that when the simulation becomes numerically instable this indicates tower collapse.

The results in Table 9.6 show:

a. The foundations for Wind farm 2 are more susceptible for tower collapse for the Supply vessel and the Chemical tanker than the foundations of Wind farm 1. For the Passenger vessel, drifting at a higher velocity, the foundations of Wind farm 1 seem to be more susceptible. For the Container ship in most cases no tower collapse occurs.

b. For foundation K07 the simulations do not clearly show whether soil failure occurs or not. Based on energy considerations only, foundation K07 should be able to stop the drifting Passenger vessel and thus no soil failure is expected, but the foundation will be left at a considerable inclination after the impact. The other foundations with a penetration depth in the range of 28 [m] to 32 [m] are also able to stop the Passenger vessel.

c. When being impacted by a drifting large Container ship, for all foundations soil failure does occur. The Container ship pushes the foundation over and drifts over it. In this case it is of course quite possible that the hull of the ship will be penetrated and sinking of the ship occurs.

d. When tower collapse occurs, then either the turbine will drop down onto the ship or the turbine will drop away from the ship, depending on the governing failure mode of the foundation and the dynamics of the impact.

e. A lower impact velocity or a less stiff/weaker ship hull is advantageous, but the differences are not clearly visible in the main results. For some foundations it results in prevents collapse, but not for all foundations.

**3. Failure at or below the impact area between ship and foundation.**

No failure has been found at or below the impact area between ship and foundation. Of course, directly at the impact area local plastic deformation is likely to occur, but the simulations do no indicate that these will significantly contribute to the failure of the foundations. The part of the foundation above the impact area is much more sensitive to failure due to the effect of the acceleration acting on the foundation and the inertia of the turbine.

It must be noted that for the conceptual foundation designs as presented in Section 8, foundation failure inside the soil was found for the drifting Passenger vessel and the drifting Container ship. The fact that it does not occur for the 2 real wind farms 1 and 2 might be due to the fact that the soil strength assumed for the conceptual foundation designs is considerably higher than the soil strength of the 2 existing wind farms, see Section 9.2. For the wind farms 1 and 2 therefore soil collapse does occur before failure of the foundation pile.

A more detailed full 3D analysis incorporating shell models of the ship hull and the foundation is required to gain more insight in this.

**4. Ship behaviour.**

The behaviour of the various analysed ships can be summarised as follows, see Table 9.5 and Table 9.6.

| Ship | Simulation run | Tower collapse during Drifting | | | |
|---|---|---|---|---|---|
| | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | No | No | No | No |
| | 2 | No | No | No | No |
| | | | | | |
| Supply vessel | 1 | No | No | Yes | Yes |
| | 2 | No | No | No | No |
| | | | | | |
| Chemical & Product tankers | 1 | No | No | Yes | Yes |
| | 2 | No | No | Yes | No |
| | 3 | No | No | Yes | No |
| | 4 | No | No | No | No |
| | | | | | |
| Passenger vessels | 1 | Yes | Yes | No | No |
| | 2 | No | No | No | No |
| | 3 | Yes | No | Yes | No |
| | 4 | Yes | Yes | No | No |
| | | | | | |
| Container ship | 1 | No | No | Yes | No |
| | 2 | No | No | No | No |
| | 3 | No | No | No | No |

| Ship | Simulation run | Soil collapse during Drifting | | | |
|---|---|---|---|---|---|
| | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | No | No | No | No |
| | 2 | No | No | No | No |
| | | | | | |
| Supply vessel | 1 | No | No | No | No |
| | 2 | No | No | No | No |
| | | | | | |
| Chemical & Product tankers | 1 | No | No | No | No |
| | 2 | No | No | No | No |
| | 3 | No | No | No | No |
| | 4 | No | No | No | No |
| | | | | | |
| Passenger vessels | 1 | Ultimately yes | No | No | No |
| | 2 | Yes | No | No | No |
| | 3 | Ultimately yes | No | No | No |
| | 4 | Ultimately yes | No | No | No |
| | | | | | |
| Container ship | 1 | Yes | Yes | Ultimately yes | Yes |
| | 2 | Yes | Yes | Yes | yes |
| | 3 | Yes | Yes | Yes | Yes |

| Ship | Simulation run | Nacelle motion after impact, Drifting | | | |
|---|---|---|---|---|---|
| | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | |
| Supply vessel | 1 | Oscillating | Oscillating | Towards ship | Away from ship |
| | 2 | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | |
| Chemical & Product tankers | 1 | Oscilating | Oscilating | Away from ship | Away from ship |
| | 2 | Oscillating | Oscillating | Towards ship | Oscillating |
| | 3 | Oscillating | Oscillating | Away from ship | Oscillating |
| | 4 | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | |
| Passenger vessels | 1 | Towards ship | Towards ship | Oscillating | Oscillating |
| | 2 | Away from ship | Oscillating | Oscillating | Oscillating |
| | 3 | Towards ship | Oscillating | Towards ship | Oscillating |
| | 4 | Towards ship | Towards ship | Oscillating | Oscillating |
| | | | | | |
| Container ship | 1 | Away from ship | Away from ship | Towards ship | Away from ship |
| | 2 | Away from ship | Away from ship | Away from ship | Away from ship |
| | 3 | Away from ship | Away from ship | Away from ship | Away from ship |

Table 9.6: Collapse behaviour, Drifting.

a. Kruiplijn coaster.

The drifting Kruiplijn coaster is stopped by the foundations without collapse of the tower or the soil. Also, it is not likely that this will lead to sinking of the ship.

Local deformation of the foundation at the impact point is likely. Whether this will prevent further operation of the turbine cannot be determined and needs a full 3D analysis that takes into account the ship and the foundation using a 3D shell model.

These results are comparable with those for the conceptual foundation design investigated in Section 8.

b. Supply vessel.

The drifting supply vessel is stopped by the foundations but leads to plastic deformation of the tower wall higher up in the tower, close to the turbine. This happens for both Wind farms. For Wind farm 2 it even leads to collapse of the tower. Whether the turbine drops onto the ship or away from the ship depends on the dynamics of the foundation.

Collapse of the soil does not occur, but depending on the actual soil behaviour there can be a small remaining inclination of the foundation.

Most likely further operation of the turbine is afterwards not possible anymore.

This is not in agreement with the results for the conceptual foundation designs investigated Section 8. For those conceptual designs no failure resp. collapse of the foundation did occur for the supply vessel.

c. Chemical tanker.

The Chemical tanker is stopped by the foundations. Soil failure does not occur, but after the impact the foundation remains standing having a considerable inclination.

For almost all foundations tower failure does occur. For Wind farm 1 this occurs close to the tower top due to the rotational accelerations acting on the turbine, with the turbine moving towards the ship. However, no collapse of the tower does occur.

For Wind farm 2 this occurs lower down the tower due to the linear accelerations acting on the turbine and in 50% of the cases also collapse of the tower does occur. When this happens, in most cases this causes the turbine to move away from the ship.

Most likely further operation of the turbine is afterwards not possible anymore.

A lower impact velocity has a positive effect and can prevent collapse, the effect of a less stiff/weaker ship hull is also advantageous, but not for all foundations.

These results are comparable with the results for the conceptual foundation design investigated in Section 8.

d. Passenger vessel.

Based on energy consideration, foundation K07 is able to stop the Passenger vessel, but this cannot be actually simulated with the present model. When the foundation is left standing, it will have a significant permanent inclination after the impact. This is due to the fact that the penetration depth of the foundation is with 23.5 [m] fairly small. The other foundations with a penetration depth in the range of 28 [m] to 32 [m] are able to stop the Passenger vessel, leaving the foundations standing, having a considerable inclination.

For almost all foundations tower failure does occur. In most cases this occurs lower down the foundation due to the linear accelerations acting on the turbine. However sometimes it also happens closer to the tower top due to the rotational accelerations acting on the turbine. Also, it happens that failure at both locations occurs at almost the same time. This is especially the case for the more flexible foundations at large water depth.

Due to the tower failure, the turbine moves towards the ship in most cases.

A lower impact velocity or a less stiff/weaker ship hull is advantageous, but the differences are not clearly visible in the main results.

For Foundation K07 the tower failure results in a collapse of the tower in most situations. For the other foundations collapse of the tower mainly occurs for a stiff ship construction and nominal drift velocity.

Most likely further operation of the turbine is afterwards not possible anymore.

These results are partly in agreement with the results for the conceptual foundation designs investigated in Section 8.

e. Container ship.

The Container ship pushes over all foundations and drifts over it. In this case it is of course quite possible that the hull of the ship will be penetrated and sinking of the ship occurs. Based on energy considerations only, the foundations should be able to stop the drifting Container ship, but due to the dynamics of the impact and the overhanging mass of the nacelle adding to the overturning moment still soil failure does occur.

Sometimes also tower failure occurs, e.g., for foundation K07, but for the other foundations this in most cases does not happen. Collapse of the tower mostly does not occur.

A lower impact velocity or a less stiff/weaker ship hull does not have much effect. The mass of the ship is simply too large.

These results are in agreement with the results for the conceptual foundation design investigated in Section 8.

5. Turbine accelerations.

The minimum (negative) and maximum (positive) values of the accelerations acting on the turbine due to the ship impact are presented in Table 9.7. It shows that for the Kruiplijn coaster, the Supply vessel and the Chemical tanker the absolute accelerations are in general maximal 10 [m/s$^2$]. For the Passenger vessel drifting at a higher speed and for the large Container ship the maximum absolute acceleration increase to 19 [m/s$^2$].

These values are in the same range as found for the conceptual foundation designs investigated in Section 8.

| Ship | Simulation run | Nacelle acceleration during impact, Drifting | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | K07 | | C01 | | HIGH | | LOW | |
| | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | -4.37 | 4.89 | -5.09 | 4.71 | -2.94 | 3.53 | -4.67 | 4.07 |
| | 2 | -3.19 | 4.97 | -3.04 | 4.26 | -2.23 | 3.54 | -2.44 | 4.07 |
| | | | | | | | | | |
| Supply vessel | 1 | -6.35 | 7.77 | -8.09 | 6.37 | -7.04 | 8.56 | -10.88 | 6.77 |
| | 2 | -5.09 | 6.68 | -6.61 | 6.15 | -5.64 | 9.64 | -5.28 | 6.82 |
| | | | | | | | | | |
| Chemical & Product tankers | 1 | -7.92 | 8.66 | -8.59 | 10.30 | -7.30 | 9.80 | -5.86 | 10.26 |
| | 2 | -5.02 | 7.36 | -7.57 | 8.23 | -8.77 | 7.66 | -5.60 | 7.65 |
| | 3 | -7.92 | 10.68 | -8.59 | 9.61 | -6.53 | 9.97 | -7.57 | 9.94 |
| | 4 | -6.01 | 7.47 | -6.71 | 8.38 | -6.28 | 6.39 | -7.66 | 7.11 |
| | | | | | | | | | |
| Passenger vessels | 1 | -15.62 | 19.00 | -17.00 | 16.13 | -12.57 | 15.93 | -9.51 | 12.35 |
| | 2 | -10.69 | 12.52 | -10.66 | 13.60 | -6.32 | 9.59 | -6.24 | 9.52 |
| | 3 | -8.09 | 9.84 | -8.03 | 8.53 | -5.52 | 10.01 | -8.53 | 11.46 |
| | 4 | -15.62 | 18.93 | -15.51 | 16.13 | -12.57 | 15.59 | -9.51 | 12.51 |
| | | | | | | | | | |
| Container ship | 1 | -13.60 | 18.40 | -13.19 | 19.25 | -10.70 | 14.31 | -10.85 | 13.16 |
| | 2 | -7.90 | 10.50 | -7.91 | 10.35 | -4.86 | 8.33 | -4.59 | 9.42 |
| | 3 | -13.60 | 18.30 | -13.19 | 15.21 | -10.70 | 14.02 | -10.62 | 13.16 |
| **Overall extremes** | | **-15.62** | **19.00** | **-17.00** | **19.25** | **-12.57** | **15.93** | **-10.88** | **13.16** |

Table 9.7: Turbine accelerations, Drifting.

### 9.3.2. Sailing impact.

Sailing impact is characterised by:

1. A high impact velocity, in the range from 5.4 [m/s] to 14.5 [m/s], and therefore a considerable amount of kinetic energy, ranging from 46 [MJ] to 4937 [MJ], that must be dissipated up on impact. Of course, depending on the ship size and type.

   It has been assumed that ship propulsion is stopped at or just for impact, so the ship does not keep pushing on during the impact.

2. Bow impact with a small contact height between ship and pile that, depending on the actual construction, can act as a crumple zone to absorb and dissipate the force of an impact.

3. A more deformable ship behaviour, resulting in a gradual rise in impact force and with a medium to high maximum impact force, ranging from 16 [MN] to 55 [MN], depending on the ship size and type. E.g., the passenger vessel impacting at a high speed of 14.5 [m/s] reaches a maximum impact force of 127 [MN].

   The effect of the different foundations on the maximum impact force is limited, see Table 9.8.

| Ship | Impact force [MN] | |
|---|---|---|
| | Sailing | |
| | Wind farm 1 | Wind farm 2 |
| Kruiplijn coaster | 16 | 16 |
| Supply vessel | 35 | 33 |
| Chemical & Product tankers | 55 | 53 |
| Passenger vessels | 129 | 124 |
| Container ship | 40 | 39 |

Table 9.8: Maximum impact force in [MN] as function of ship type, wind farm and impact condition during Sailing.

4. Impact due to sailing is occurring with the ship hitting the foundation directly below the rotor, so the ship is moving with the wind.

The main results can now be summarised as follows:

1. **Foundation failure, see Table 9.9.**

    a. As a result of the Sailing impact characteristics, the foundation behaviour is mostly governed by the high initial accelerations induced by the high ship velocity that is not sufficiently absorbed by the bow of the ship, resulting in possible failure of the tower above the ship or at the point of impact.

    b. Tower failure mostly occurs in the lower half of the foundation, closer to the impact point, see Table 9.9. It is mostly caused by the inertia of the turbine in combination with the linear acceleration. At high impact speed, e.g., the Passenger vessel at 14.5 [m/s], failure can occur directly at the impact point. This is especially the case for foundations in small water depths that react more stiffly than foundations in large water depths. The exact failure location of course depends on the dynamic behaviour and strength of the structure and is therefore depending on the foundation design.

    c. In most cases the turbine moves towards the ship when failure of the tower occurs, see Table 9.10. However sometimes, e.g., for the Kruiplijn coaster and the Chemical tanker at Low speed, the failure of the tower occurs when the foundation is decelerating after the impact when the ship has already been stopped. The inertia of the turbine then results in a too large bending moment leading to the turbine breaking away from the ship. Especially the foundations of Wind farm 2 are susceptible to this.

        For the Kruiplijn coaster this only occurs for the ‘Full reversible’ soil model when the full energy stored into the soil is returned to the foundation and the ship. For the ‘Non reversible’ soil model no tower failure occurs. So, in these cases the actual soil behaviour is of importance.

    d. The foundations are only able to stop a sailing ship at nominal speed completely for the Kruiplijn coaster and, apart from foundation K07, also for the Supply vessel. Also, when the sailing velocity is reduced, e.g. to 2 [m/s] for the chemical tanker, the foundations are able to stop the ship.

        After the impact the foundations that are able to stop the ship will have a significant permanent inclination.

    e. Depending on the actual soil behaviour, continued operation of the turbine after being impact by the Kruiplijn coaster might be possible.

2. **Foundation collapse, see Table 9.10.**

    Foundation collapse either occurs due to tower collapse, with the turbine falling down onto the ship or due to soil collapse when the ship is pushing the foundation over. A combination of the two phenomena is quite likely for the larger ships.

    Tower collapse cannot be accurately modelled with the present simulation program. It is assumed that when the simulation becomes numerically instable this indicates tower collapse.

| Ship | Simulation run | Tower failure location [mLAT] during Sailing | | | |
|---|---|---|---|---|---|
| | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | -- | 37.9 | 30.7 | 31.2 |
| | 2 | -- | -- | -- | -- |
| | | | | | |
| Supply vessel | 1 | 60.7 | 60.7 | 31.2 | 31.4 |
| | 2 | 60.7 | 60.7 | 31.2 | 31.4 |
| | | | | | |
| Chemical & Product tankers | 1 | 29.5 | 28.5 | 31.4 | 30.9 |
| | 2 | -- | -- | 30.9 | 30.9 |
| | 3 | -- | -- | 30.9 | 30.9 |
| | | | | | |
| Passenger vessels | 1 | -1.2 | 12.3 | -2.0 | 28.5 |
| | 2 | -1.2 | 12.3 | -2.0 | 28.5 |
| | | | | | |
| Container ship | 1 | 29.0 60.7 | 60.9 | 30.9 | 30.9 |
| | 2 | 29.0 60.7 | 60.9 | 30.9 | 30.9 |

| Ship | Simulation run | Direction of tower failure during Sailing | | | |
|---|---|---|---|---|---|
| | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | -- | Away from ship | Away from ship | Away from ship |
| | 2 | -- | -- | -- | -- |
| | | | | | |
| Supply vessel | 1 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | |
| Chemical & Product tankers | 1 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | -- | -- | Away from ship | Away from ship |
| | 3 | -- | -- | Away from ship | Away from ship |
| | | | | | |
| Passenger vessels | 1 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | |
| Container ship | 1 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Towards ship | Towards ship | Towards ship | Towards ship |

Table 9.9: Tower failure behaviour, Sailing.

The results in Table 9.10 show:

a. Apart from the sailing impact by a Kruiplijn coaster and by a Chemical tanker sailing at Low speed always collapse of the tower at the failure point occurs. For Wind farm 2 collapse does also occur for the sailing Chemical tanker at Low speed.

b. In most cases when collapse occurs the turbine will drop down onto the ship. Only in case of the Chemical tanker sailing at Low speed collapse occurs when the ship has almost been stopped and the turbine will drop away from the ship. This of course can also happen for other ships that are sailing at a speed that can just be absorbed by the foundation without soil collapse.

c. It is possible that the foundation will ultimately be able to stop a sailing Supply vessel at nominal speed or a large ship, e.g., a Chemical tanker, sailing at low speed. But otherwise collapse of the soil will always occur and the ship will sail over the foundation. In most cases also collapse of the tower occurs and the turbine will drop towards the ship.

   For the Passenger vessel sailing at High Speed, failure will occur either at the impact point, especially for the stiffer foundations in low water depth, or closely above the impact point. The Passenger vessel will sail over the foundation, and it is quite likely that the ship hull will be penetrated by the part of the foundation that remains inside the soil. This likely might lead to the sinking of the ship.

d. For the large Container ship the tower will collapse at c.a. 30 [m] above the impact point. The kinetic energy of this ship is that large that it is quite possible that it will sail over the foundation and that the hull will be penetrated by the part of the foundation that remains inside the soil. This might lead to the sinking of the ship.

3. **Failure at or below the impact area between ship and foundation.**

   As indicated above, this occurs for the Passenger vessel impacting at high nominal speed against the foundations that are located in shallow water. These foundations behave stiff. For more flexible foundations in deeper water the failure point shifts to positions above the impact point.

   This of course can also happen for other larger ships that are impacting at a high speed.

   Failure of the foundation below the impact point or inside the soil has not been observed.

   It must be noted that for the conceptual foundation designs as presented in Section 8, foundation failure inside the soil was found for the sailing Container ship. The fact that it does not occur for the 2 real wind farms 1 and 2 might be due to the fact that the soil strength assumed for the conceptual foundation designs is considerably higher than the soil strength of the 2 existing wind farms, see Section 9.2. For the wind farms 1 and 2 therefore soil collapse does occur before failure of the foundation pile.

   A more detailed full 3D analysis incorporating shell models of the ship hull and the foundation will give more insight in this.

4. **Ship behaviour.**

   The behaviour of the various analysed ships can be summarised as follows, see Table 9.9 and Table 9.10.

   a. Kruiplijn coaster.

      The sailing Kruiplijn coaster is stopped by the foundations without soil failure. Whether failure or collapse of the tower occurs depends on the actual elastic behaviour of the soil and the foundation. When much energy is returned to the foundation and the ship, then the deceleration of the foundation might lead to collapse of the tower due to the inertia of the turbine. The turbine will then move away from the ship.

      These results are comparable with those for the conceptual foundation design investigated in Section 8.

   b. Supply vessel.

      The sailing Supply vessel might ultimately be stopped by the foundations without soil collapse, except for foundation K07. But in all cases collapse of the tower will occur with the turbine dropping down towards the ship.

      This is not in agreement with the results for the conceptual foundation design investigated Section 8. For those conceptual designs the foundation behaved stiffer and tower failure occurred after the ship was stopped by the elastic energy being returned to the ship and the foundation. As a result, the turbine moved away from the ship when collapse occurred.

| Ship | Simulation run | Tower collapse during Sailing | | | |
|---|---|---|---|---|---|
| | | Wind farm 1 | | Wind farm 2 | |
| **Foundation** | | **K07** | **C01** | **HIGH** | **LOW** |
| Kruiplijn coaster | 1 | No | No | No | Yes |
| | 2 | No | No | No | No |
| | | | | | |
| Supply vessel | 1 | Yes | Yes | Yes | Yes |
| | 2 | Yes | Yes | Yes | Yes |
| | | | | | |
| Chemical & Product tankers | 1 | Yes | Yes | Yes | Yes |
| | 2 | No | No | Yes | Yes |
| | 3 | No | No | Yes | Yes |
| | 4 | | | | |
| | | | | | |
| Passenger vessels | 1 | Yes | Yes | Yes | Yes |
| | 2 | Yes | Yes | Yes | Yes |
| | | | | | |
| Container ship | 1 | Yes | Yes | Yes | Yes |
| | 2 | Yes | Yes | Yes | Yes |

| Ship | Simulation run | Soil collapse during Sailing | | | |
|---|---|---|---|---|---|
| | | Wind farm 1 | | Wind farm 2 | |
| **Foundation** | | **K07** | **C01** | **HIGH** | **LOW** |
| Kruiplijn coaster | 1 | No | No | No | No |
| | 2 | No | No | No | No |
| | | | | | |
| Supply vessel | 1 | Probably not | Probably not | Probably not | Probably not |
| | 2 | Probably not | Probably not | Probably not | Probably not |
| | | | | | |
| Chemical & Product tankers | 1 | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 2 | No | No | No | No |
| | 3 | No | No | No | No |
| | | | | | |
| Passenger vessels | 1 | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 2 | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | |
| Container ship | 1 | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 2 | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |

| Ship | Simulation run | Nacelle motion after impact, Sailing | | | |
|---|---|---|---|---|---|
| | | Wind farm 1 | | Wind farm 2 | |
| **Foundation** | | **K07** | **C01** | **HIGH** | **LOW** |
| Kruiplijn coaster | 1 | Oscillating | Oscilating | Oscilating | Away from ship |
| | 2 | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | |
| Supply vessel | 1 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | |
| Chemical & Product tankers | 1 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Oscillating | Oscillating | Away from ship | Away from ship |
| | 3 | Oscillating | Oscillating | Away from ship | Away from ship |
| | | | | | |
| Passenger vessels | 1 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | |
| Container ship | 1 | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Towards ship | Towards ship | Towards ship | Towards ship |

Table 9.10: Collapse behaviour, Sailing.

c. Chemical tanker.

The Chemical tanker sailing at nominal speed results in failure of the tower and collapse of the soil. The turbine will drop down onto the ship and the ship will ultimately sail over the foundation. There will be danger that the hull is penetrated, and the ship might sink.

When the Chemical tanker sails at Low speed it can be stopped by the foundation without soil failure. In that case the elastic rebound of the soil and the foundation might lead to tower failure with the turbine moving away from the ship.

These results are not fully comparable with the results for the conceptual foundation design investigated in Section 8. No failure of the foundation inside the soil has been observed for the Wind farms 1 and 2.

d. Passenger vessel.

   For the Passenger vessel sailing at High Speed, failure will occur either at the impact point, especially for the stiffer foundations in low water depth, or closely above the impact point for the more flexible foundation in deeper water.

   The Passenger vessel will sail over the ship, and it is quite likely that the ship hull will be penetrated by the part of the foundation that remains inside the soil. This likely might lead to the sinking of the ship.

   These results are not fully comparable with the results for the conceptual foundation design investigated in Section 8. No failure of the foundation inside the soil has been observed for Wind farm 1 and Wind farm 2 and for these wind farms the turbine will most likely drop down onto the ship.

e. Container ship.

   The mass of the Container ship sailing at nominal speed is way too large for the foundations. The Container ship pushes over all foundations and sails over it. In all cases also collapse of the tower occurs, with the turbine dropping down onto the ship.

   These results are not fully comparable with the results for the conceptual foundation design investigated in Section 8. No failure of the foundation inside the soil has been observed for Wind farm 1 and 2 and it is more likely that the turbine will drop down onto the ship.

5. Turbine accelerations.

   The minimum (negative) and maximum (positive) values of the accelerations acting on the turbine due to the ship impact are presented in Table 9.11. It shows that for the Kruiplijn coaster, the Supply vessel and the Chemical tanker the absolute accelerations are in general maximal 10 [$m/s^2$] (with 2 exceptions). For the Passenger vessel sailing at a higher speed and for the large Container ship the maximum absolute acceleration increase to 18 [$m/s^2$].

   These values are in the same range as found for the conceptual foundation design investigated in Section 8.

| Ship | Simulation run | Nacelle acceleration during impact, Sailing | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Wind farm 1 | | | | Wind farm 2 | | | |
| **Foundation** | | K07 | | C01 | | HIGH | | LOW | |
| | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | -9.40 | 6.49 | -6.66 | 6.74 | -7.35 | 4.38 | -6.58 | 5.54 |
| | 2 | -4.79 | 6.51 | -4.30 | 6.71 | -4.91 | 4.40 | -6.41 | 5.58 |
| | | | | | | | | | |
| Supply vessel | 1 | -6.33 | 9.15 | -5.84 | 9.74 | -4.91 | 7.45 | -5.12 | 8.46 |
| | 2 | -7.42 | 12.98 | -5.11 | 9.24 | -4.34 | 8.55 | -5.79 | 7.64 |
| | | | | | | | | | |
| Chemical & Product tankers | 1 | -4.95 | 12.35 | -3.72 | 13.12 | -8.12 | 8.76 | -8.10 | 7.92 |
| | 2 | -4.04 | 7.30 | -5.94 | 7.74 | -5.37 | 5.43 | -6.60 | 6.85 |
| | 3 | -4.23 | 6.64 | -5.74 | 7.40 | -6.13 | 5.30 | -6.29 | 7.37 |
| | | | | | | | | | |
| Passenger vessels | 1 | -12.51 | 15.21 | -5.76 | 17.97 | -4.25 | 14.72 | -9.49 | 16.00 |
| | 2 | -14.42 | 12.46 | -5.76 | 17.36 | -4.51 | 14.98 | -9.68 | 16.48 |
| | | | | | | | | | |
| Container ship | 1 | -3.67 | 11.92 | -7.21 | 8.31 | -4.35 | 7.76 | -5.54 | 8.13 |
| | 2 | -2.66 | 10.83 | -7.06 | 9.87 | -4.26 | 8.02 | -5.63 | 8.22 |
| **Overall extremes** | | **-14.42** | **15.21** | **-7.21** | **17.97** | **-8.12** | **14.98** | **-9.68** | **16.48** |

Table 9.11: Turbine accelerations, Sailing.

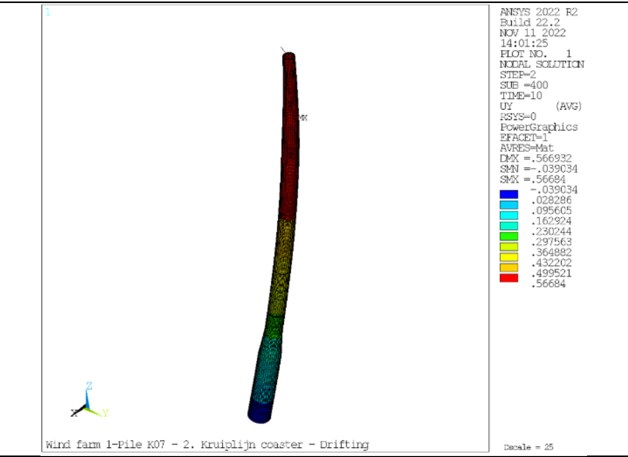
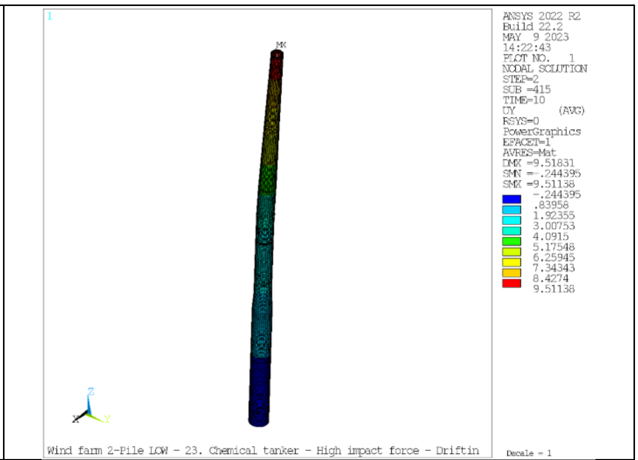
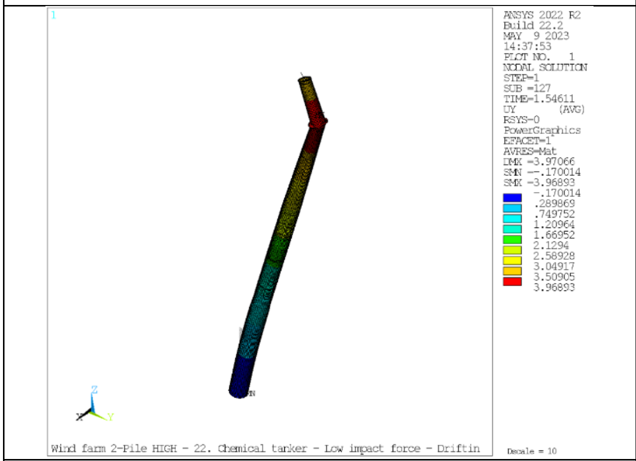
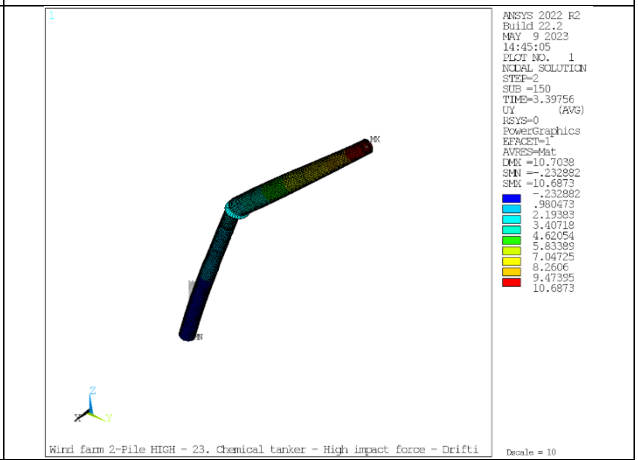
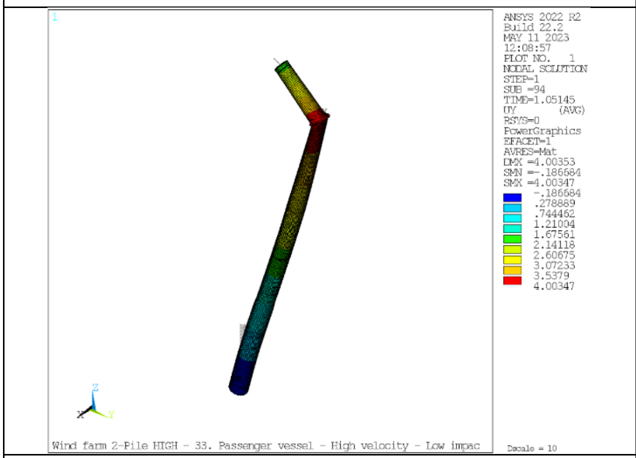
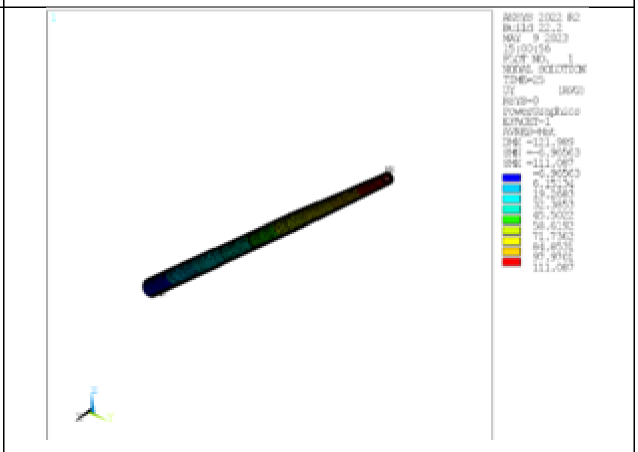
### 9.3.3. Summary of failure modes.

Based on the results presented in this Section, the following main failure modes can be identified.

1. No pile or tower failure, just elastic foundation deformation, the foundation remains standing and oscillates in its 1st eigenmode, see Table 9.12, mode 1.
2. Tower failure (plastic deformation) but no tower collapse, see Table 9.12, mode 2.
3. Tower failure/collapse, turbine moving towards the ship, see Table 9.12, mode 3.
4. Tower failure/collapse, turbine moving away from the ship, see Table 9.12, mode 4.
5. Soil collapse, turbine moving towards the ship, see Table 9.12, mode 5.

   Due to the collapse of the soil, the foundation moves away from the ship, while due to the failure of the tower the nacelle tends to move towards the ship. Which of the 2 counteracting motions becomes dominant cannot be simulated by the present model and depends on the velocity with which each failure develops. It is thus not possible to predict whether the tower failure will result in the turbine dropping down on the ship or that the soil failure will ultimately lead to the turbine moving away from the ship.
6. Soil collapse, turbine moving away from the ship, see Table 9.12, mode 6.
7. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving towards the ship, see Table 9.12, mode 7.

8. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving away the ship, see Table 9.12, mode 8.

| | |
|---|---|
|  |  |
| 1. No pile or tower failure. | 2. Tower failure (plastic deformation) but no tower collapse. |
|  |  |
| 3. Tower failure/collapse, turbine moving towards the ship. | 4. Tower failure/collapse, turbine moving away from the ship. |
|  |  |
| 5. Soil collapse, turbine moving towards the ship. | 6. Soil collapse, turbine moving away from the ship. |

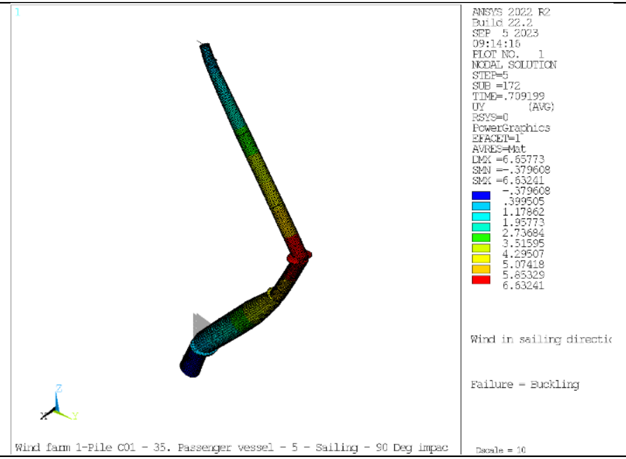
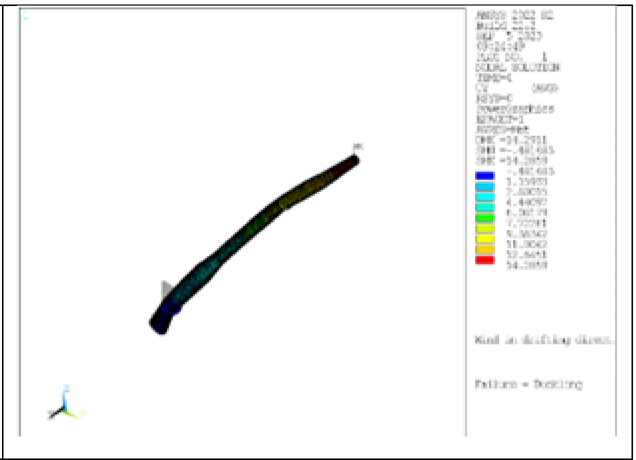
|  |  |
|---|---|
| 7. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving towards the ship. | 8. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving away the ship. |

Table 9.12: Graphical presentation of detected failure modes.

In Table 9.13 and Table 9.14 it is shown for which foundations each failure mode is applicable. Comparison of these results with the results presented in Section 8 for the conceptual foundation designs clearly shows quite significant differences. For the conceptual design the soil support is much larger, leading to a much larger soil failure load and a combination of pile failure inside the soil and soil failure. For the foundations of the Wind farms 1 and 2 only soil failure occurs, there is no pile failure inside the soil. Also, the behaviour of the tower of the conceptual design is in general stiffer. It seems that the actual foundations of wind farm 1 and 2 are more optimized with respect to strength and stiffness than the conceptual design, in order to minimize costs.

Regarding the survivability of the foundation of the turbine under ship impact, it follows that the foundations of Wind farm 1 and 2 are only able to survive drifting and sailing impact for ships up to c.a. 3000 tonnes displacement.

| Drifting | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Soil model | Load | Velocity | Failure mode | | | |
| | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Full reversible | High load | Nominal velocity | 1 | 1 | 1 | 1 |
| | 2 | Non reversible | High load | Nominal velocity | 1 | 1 | 1 | 1 |
| | | | | | | | | |
| Supply vessel | 1 | Full reversible | High load | Nominal velocity | 2 | 1 | 3 | 4 |
| | 2 | Non reversible | High load | Nominal velocity | 2 | 1 | 2 | 2 |
| | | | | | | | | |
| Chemical & Product tankers | 1 | Full reversible | High load | Nominal velocity | 2 | 1 | 4 | 4 |
| | 2 | Full reversible | Low load | Nominal velocity | 1 | 1 | 3 | 2 |
| | 3 | Non reversible | High load | Nominal velocity | 2 | 1 | 4 | 2 |
| | 4 | Full reversible | High load | Low velocity | 2 | 1 | 1 | 1 |
| | | | | | | | | |
| Passenger vessels | 1 | Full reversible | High load | Nominal velocity | 3 | 3 | 2 | 2 |
| | 2 | Full reversible | High load | Low velocity | 2 | 1 | 2 | 1 |
| | 3 | Full reversible | Low load | Nominal velocity | 3 | 2 | 3 | 2 |
| | 4 | Non reversible | High load | Nominal velocity | 3 | 3 | 2 | 2 |
| | | | | | | | | |
| Container ship | 1 | Full reversible | High load | Nominal velocity | 6 | 6 | 5 | 6 |
| | 2 | Full reversible | Low load | Nominal velocity | 6 | 6 | 6 | 6 |
| | 3 | Non reversible | High load | Nominal velocity | 6 | 6 | 6 | 6 |

Table 9.13: Summary of detected failure modes during Drifting.

| Sailing | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Soil model | Load | Velocity | Failure mode | | | |
| | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Full reversible | High load | Nominal velocity | 1 | 2 | 2 | 4 |
| | 2 | Non reversible | High load | Nominal velocity | 1 | 1 | 1 | 1 |
| | | | | | | | | |
| Supply vessel | 1 | Full reversible | High load | Nominal velocity | 3 | 3 | 3 | 3 |
| | 2 | Non reversible | High load | Nominal velocity | 3 | 3 | 3 | 3 |
| | | | | | | | | |
| Chemical & Product tankers | 1 | Full reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |
| | 2 | Full reversible | High load | Low velocity | 1 | 1 | 4 | 4 |
| | 3 | Non reversible | High load | Low velocity | 1 | 1 | 4 | 4 |
| | | | | | | | | |
| Passenger vessels | 1 | Full reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |
| | 2 | Non reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |
| | | | | | | | | |
| Container ship | 1 | Full reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |
| | 2 | Non reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |

Table 9.14: Summary of detected failure modes during Sailing.

## 9.4. Parameter variations.

### 9.4.1. The direction of impact of the ship relative to the rotor.

In the previous Sections it has been assumed that the ship is drifting or sailing with the wind and is impacting with the foundation directly below the rotor. For drifting impact this is a reasonable assumption as the rotor of the turbine is always directed towards the wind and a drifting ship is pushed with the wind. However, for sailing impact the impact direction is fully independent of the wind/wave direction. Therefore, in this Section it is investigated what will happen when the sailing ship hits the foundation at the side opposite of the rotor directly below the nacelle and at an angle perpendicular to the rotor axis, see also Section 5.6.6.

For each ship and turbine, the following simulations have been carried out:

1. Run 1: Sailing impact directly below the rotor of the turbine, so in line parallel with the rotor axis. See Figure 5.19 and Figure 9.2, impact in the positive Y-direction.

2. Run 2: Sailing impact at an angle of 90° of the rotor axis. See Figure 5.19 and Figure 9.3, impact in the positive X-direction.

3. Run 3: Sailing impact directly below the nacelle of the turbine, so in line parallel with the rotor axis, but in the opposite direction as for run 1. See Figure 5.19 Figure 9.4, impact in the negative Y-direction.

Figure 9.2: Impact directly below the rotor of the turbine in the positive Y-direction.


Figure 9.3: Impact at an angle of 90° of the rotor axis in the positive X-direction.


Figure 9.4: Impact directly below the nacelle of the turbine impact in the negative Y-direction.

The observed failure modes for the foundations according to the identified modes presented Section 9.3.3 are for the directional runs presented in Table 9.15. It follows that the foundations of Wind farm 1 and 2 are only able to survive the sailing impact for the Kruiplijn coaster, so ships up to c.a. 3000 tonnes displacement. For all other ship foundations failure or soil collapse will occur for the sailing ships, with the turbine moving towards the ship. Whether the turbine will actually drop down on to the ship in case of soil failure, mode 5, depends on the interaction between the push-over behaviour and the failure of the tower causing the turbine to move towards the ship. This cannot be predicted with the present model.

It follows from Table 9.15 that the failure mode is mostly independent of the direction of impact between ship and foundation. Only when the impact conditions are such that the foundation failure is close to the edge between 2 failure modes the direction of impact can have an effect on the foundation behaviour. This is for example the case for foundation C01 in case of the impact by a sailing Supply vessel. When the Supply vessel hits the foundation directly below the rotor tower failure and collapse occurs but when it hits below the nacelle still tower failure does occur, but no tower collapse and turbine will not drop down after the impact.

Looking more closely to the underlying results on which the detected failure modes are based, see Table 9.16 to Table 9.20, shows that although the failure mode does not change, there are still smaller differences in foundation behaviour as function of the impact direction. For example, the location height of the tower failure varies as function of the impact direction. This is due to the moments of inertia of the nacelle and the rotor that are not the same in each direction. It follows that the moment of tower failure/collapse after the start of the impact differs slightly and that the location of the tower failure can shift upwards or downwards along the foundation.

| Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | | | | | | | | | | |
| Supply vessel | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 5 | 2 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

Table 9.15: Summary of detected failure modes during sailing with directional impact.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower failure location [mLAT] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 60.4 | 60.2 | 30.9 | 31.5 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | 60.2 | 60.2 | 30.5 | 31.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 59.7 | 28.5 | 31.4 | 31.5 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -1.2 | 12.3 | -1.6 | 28.0 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | -1.2 | 12.3 | -1.5 | 28.0 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -1.2 | -0.7 | -1.6 | 28.0 |
| | | | | | | | | | | |
| Container ship | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 29.0 | 60.2 | 30.5 | 30.5 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | 28.5 | 60.2 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |

Table 9.16: Tower failure behaviour, Failure location, directional impact.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Direction of tower failure | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

Table 9.17: Tower failure behaviour, Failure direction, directional impact.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Yes | No | Yes | Yes |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Container ship | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |

Table 9.18: Tower failure behaviour, Tower collapse, directional impact.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Soil collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Ultimately yes | No | Probably not | Probably not |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Container ship | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |

Table 9.19: Soil failure behaviour, Soil collapse, directional impact.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle motion after impact | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | | | | | | |
| Supply vessel | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Oscillating | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

Table 9.20: Turbine motion after impact, directional impact.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -4.79 | 6.51 | -4.30 | 6.71 | -4.91 | 4.40 | -6.41 | 5.58 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | -3.62 | 5.67 | -4.07 | 4.84 | -4.18 | 4.08 | -5.98 | 5.57 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -3.93 | 7.21 | -4.83 | 5.40 | -4.55 | 4.40 | -6.04 | 6.18 |
| | | | | | | | | | | | | | | |
| Supply vessel | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -7.42 | 12.98 | -5.11 | 9.24 | -4.34 | 8.55 | -5.79 | 7.64 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | -3.94 | 8.04 | -6.34 | 11.69 | -5.87 | 7.22 | -3.61 | 7.89 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -3.56 | 9.37 | -5.15 | 11.38 | -3.14 | 7.51 | -10.45 | 8.53 |
| | | | | | | | | | | | | | | |
| Chemical & Product tankers | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -4.56 | 12.28 | -3.72 | 12.94 | -7.13 | 9.38 | -7.88 | 8.03 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | -3.92 | 11.54 | -2.38 | 11.10 | -10.52 | 10.60 | -10.50 | 7.83 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -4.17 | 11.96 | -9.97 | 9.76 | -7.49 | 9.09 | -8.18 | 8.38 |
| | | | | | | | | | | | | | | |
| Passenger vessels | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -14.42 | 12.46 | -5.76 | 17.36 | -4.51 | 14.98 | -9.68 | 16.48 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | -15.65 | 14.46 | -11.44 | 16.29 | -4.38 | 15.94 | -10.30 | 17.37 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -15.61 | 13.16 | -4.33 | 12.13 | -3.86 | 15.41 | -9.58 | 15.57 |
| | | | | | | | | | | | | | | |
| Container ship | 1 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -2.66 | 10.83 | -7.06 | 9.87 | -4.26 | 8.02 | -5.63 | 8.22 |
| | 2 | Sailing | 0 Deg; Side | No wind | Non reversible | High load / Nominal speed | -3.60 | 12.15 | -1.94 | 11.37 | -6.94 | 10.33 | -7.23 | 7.59 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -8.84 | 9.95 | -6.30 | 9.23 | -2.45 | 8.05 | -5.41 | 9.81 |
| **Overall extremes** | | | | | | | **-15.65** | **14.46** | **-11.44** | **17.36** | **-10.52** | **15.94** | **-10.50** | **17.37** |

Table 9.21: Turbine accelerations for all ships and foundations, directional impact.

### 9.4.2. The effect of the wind loading on the foundation.

In the previous Sections the wind loading has not been taken into account. This wind load of course adds an extra load to the foundation and therefore can affect the failure mode of the foundation. When the motion of the ship is in the same direction as the wind load, which is quite likely in case of a drifting ship, then the wind load will contribute to the overturning motion of the foundation. On the other hand, when the ship is sailing against the wind when impacting with the foundation and considering that collapse of the foundation towards the ship is most likely, then the wind load will magnify the effect of the impact and might lead to collapse of the foundation at lower ship velocities.

The effect of the wind load has been investigated for the following situations:

1. Run 1: A drifting ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation. The wind turbine is assumed to be operating, meaning that the forces acting on the turbine add to the wind forces acting on the foundation.
2. Run 2: A sailing ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation. The wind turbine is assumed to be operating, meaning that the forces acting on the turbine add to the wind forces acting on the foundation.
3. Run 3: A sailing ship with impact below the nacelle and a wind load in the direction opposite to the ship motion acting on the foundation. The wind turbine is assumed to be operating, meaning that the forces acting on the turbine add to the wind forces acting on the foundation.

The loads on the foundation due to the turbine operation and the wind, wave and current loads are determined in Section 5.5.

The observed failure modes for the foundations according to the identified modes presented Section 9.3.3 are shown in Table 9.22 for the reference situation without wind load and in Table 9.23 the failure modes for each foundation are shown in case the wind load is present. The data on which these results are based are presented in Table 9.24 to Table 9.28. It must be noted that although the failure mode for various configurations might be the same, the actual point of failure in [mLAT] or the exact moment of collapse might be different.

Comparison of the results in Table 9.22 and Table 9.23 and analysis of the results shows:

1. Kruiplijn coaster.
    a. For the drifting or sailing Kruiplijn coaster no tower failure does occur when no wind load is present.
    b. When the wind load is present and the turbine is operating still no tower failure occurs for the drifting Kruiplijn coaster.
    c. When the wind load is present, the turbine is operating and the ship is sailing with the wind soil failure mode 6, with the turbine moving away from the ship, occurs for foundation K07 of Windfarm 1. The additional wind load in combination with the impact load causes failure of the soil due to the low penetration depth for foundation K07.
    d. When the wind load is present, the turbine is operating and the ship is sailing with the wind, tower failure mode 4, with the turbine moving away from the ship, occurs for foundation LOW of Windfarm 2. The additional wind load in combination with the effects of the impact is sufficient to cause failure of the tower.
    e. When sailing against the wind no foundation or soil failure does occur for the Kruiplijn coaster.

| Drifting / Sailing - Reference | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 2 | 1 | 2 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 5 | 2 | 3 | 3 |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 2 | 1 | 4 | 2 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 5 | 3 | 2 | 2 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 6 | 6 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

Table 9.22: Summary of detected failure modes during drifting/sailing without wind load (reference).

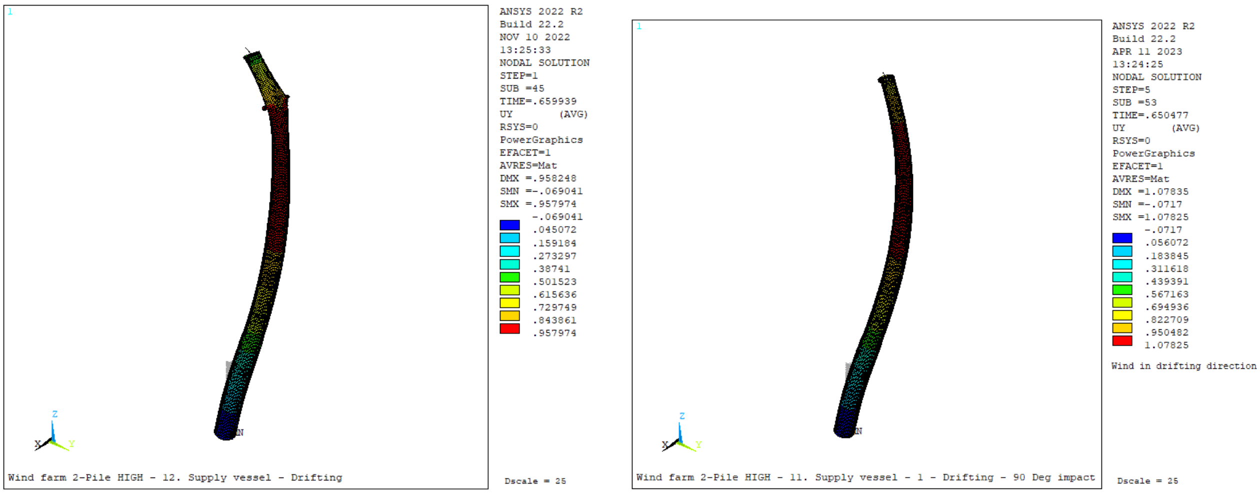
| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 1 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 6 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

Table 9.23: Summary of detected failure modes during drifting/sailing with wind load.

2. Supply vessel.
    a. During drifting impact a difference in the foundation behaviour due to the wind load acting on the foundation with operating turbine is found for foundation HIGH of Windfarm 2. Without wind and the

drifting ship impacting below the rotor, the tower fails at 91.4 [mLAT], with the turbine moving towards the ship. No collapse of the tower does occur and after impact the foundation remains standing and keeps on oscillating.
When the wind load **is** present and the ship is drifting with the wind and impacting below the rotor **no** tower failure does occur.

In Figure 9.5 the deformation of the foundation is shown for the 2 situations. It follows that without wind the compression stress at the impact side of the foundation becomes too high and plastic deformation of the tower occurs. When the wind is present at that location a tensile stress is acting in the tower due to the wind load which is bending the tower away from the ship. The compression stress due to the ship impact adds to the tensile stress already present and results in a total compression stress that is lower than when no wind is present so that failure of the tower does not occur.




No wind — With wind

Figure 9.5: Foundation behaviour for Windfarm 2, Foundations HIGH, ship sailing with the wind and impact below the rotor.

b. During sailing impact for foundation C01 of Windfarm 1 a different failure mode is found for the sailing ship impacting below the nacelle and sailing against the wind. When no wind is present tower failure mode 2 occurs, with the turbine moving towards the ship, but no tower collapse occurs, see Figure 9.6. When the wind is present and is acting against the ship motion in the same direction as the motion of the turbine due to the tower collapse, the failure mode shifts to 3 and the tower collapses and moves towards the ship, see Figure 9.6. In this case the compression stress that occurs at the tower failure side adds to the compression stress caused by the wind load and leads to collapse of the tower.

c. For the combinations of ship motion and foundation the behaviour without and with wind is comparable for the Supply vessel.

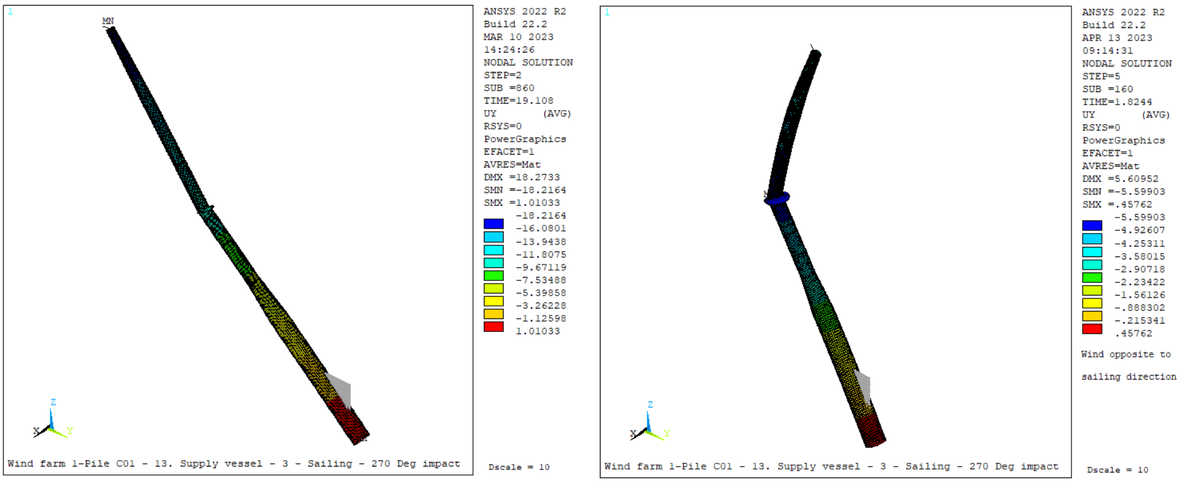
3. Chemical tanker.

For the Chemical tanker differences in foundation behaviour without and with wind are found for the drifting ship. For the sailing ship the behaviour without and with wind is the same, soil failure mode 5 occurs with the turbine moving towards the ship due to tower collapse.

The detected differences for the drifting Chemical tanker are:

a. Foundation K07 of Windfarm 1, drifting ship.

For both situations, without and with wind, tower failure does occur at 106.4 [mLAT] with the turbine bending towards the ship. However, no tower collapse does occur for both conditions.
For the situation without wind no soil collapse does occur either and the ship is finally stopped by the foundation. So, failure mode 2 is applicable.



No wind With wind

Figure 9.6: Foundation behaviour for Windfarm 1, Foundations C01, ship sailing against the wind and impact below the nacelle.

With wind however, soil collapse does occur because the combination of the wind load and the impact force is too large for the soil to support due to the low penetration depth of the pile for foundation K07. Hence in this case failure mode 6 is applicable.

b. Foundation LOW of Windfarm 2, drifting ship.

For both situations, without and with wind, tower failure does occur at 30.5 [mLAT] with the turbine moving away from the ship.
For the situation without wind no tower collapse does occur, the ship is stopped by the foundation and the turbine keeps on vibrating after the impact. So, failure mode 2 is applicable.
With wind however, collapse of the tower does occur because the combination of the wind load and the bending load caused by the overhanging turbine is too much for the tower and collapse of the tower does occur, with the turbine moving away from the ship. Hence in this case failure mode 4 is applicable.

4. Passenger vessel.

For the Passenger vessel also differences in foundation behaviour without and with wind are found for the drifting ship. For the sailing ship the behaviour without and with wind is the same, soil failure mode 5 occurs with the turbine moving towards the ship due to tower collapse.

The detected differences for the drifting Passenger vessel are:

a. Foundation C01 of Windfarm 1, drifting ship.

For the situation without wind tower failure does occur in first instance close to the tower top at 108.8 [mLAT] and in second instance at 74.5 [mLAT]. The latter failure is more severe and ultimately

tower collapse does occur at this location, with the turbine moving towards the ship. Soil failure is not expected based on energy considerations and hence failure mode 3 is applicable.
With wind tower failure occurs also close to the tower top at 115.7 [mLAT], but the failure lower down does not occur because the tensile stress caused by the wind load partly compensates the compression stress developing due to the ship impact and thus no overload of the tower does occur lower down. Soil failure does not occur, so the failure mode 2, with the tower bended towards the ship but no tower collapse.

b. Foundation HIGH of Windfarm 2, drifting ship.

   For both situations, without and with wind, tower failure does occur at c.a. 30.5 [mLAT] with the turbine moving towards the ship, but no tower collapse does occur.
   For the situation without wind the ship the ship is stopped by the foundation and the foundation keeps on oscillating. Hence failure mode 2 is applicable.
   For the situation with wind the deformation of the tower changes direction and shifts from bending towards the ship to bending away from the ship. Next tower failure occurs with the turbine moving away from the ship. Ultimately the ship will be stopped by the foundation and thus failure mode 4 is applicable.

c. Foundation LOW of Windfarm 2, drifting ship.

   For the situation without wind tower failure does occur at c.a. 30.9 [mLAT] and at 86.4 [mLAT], with the turbine moving towards the ship, but no tower collapse does occur. In the end the ship is stopped by the foundation and the foundation keeps on oscillating. Hence failure mode 2 is applicable.
   For the situation with wind tower failure only occurs at 31.1 [mLAT], with the turbine moving towards the ship, but no tower collapse occurs. Then, when the impact progresses the deformation of the tower changes direction and shifts from bending towards the ship to bending away from the ship and then finally tower collapse does occur with the turbine moving away from the ship. Ultimately the ship will be stopped by the foundation and thus failure mode 4 is applicable.

5. Container ship.

   For the Container ship no differences in foundation behaviour are found for the conditions without and with wind, not for the drifting ship and not for the sailing ship. In case of the drifting ship failure mode 6 occurs, with the turbine being pushed away from the ship due to soil collapse and for the sailing ship failure mode 5 occurs with the turbine being pushed away from the ship due to soil collapse but moving towards the ship due to tower collapse.

The main conclusion from the results presented above is that the presence of the wind load acting on an operating turbine during the impact between a ship and a wind turbine foundation can have an effect on the failure mode. This occurs mostly during drifting of a ship or for a smaller sailing ship such as a Kruiplijn coaster or a Supply vessel. The effect is that failure resp. collapse of the tower occurs somewhat earlier or later than when no wind is present. Also, when due to the impact the foundation is loaded up to the limit but just no failure or collapse does occur yet, then the additional wind load can just lead to failure or collapse of the foundation. In these situations sometimes also the failure location in [mLAT] shifts upwards or downwards. On the other hand, when without wind failure or collapse does occur then an advantageous wind load can just prevent this failure or collapse.

For larger sailing ships the impact behaviour is so dominant that the presence of wind does hardly or not at all have much effect on the failure behaviour.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower failure location [mLAT] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 107.9 | -- | 91.4 | -- |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 60.4 | 60.2 | 30.9 | 31.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 59.7 | 28.5 | 31.4 | 31.5 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 106.4 | -- | 30.7 | 30.9 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 88.6 | 108.8 | 30.9 | 86.4 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -1.2 | 12.3 | -1.6 | 28.0 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -1.2 | -0.7 | -1.6 | 28.0 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 108.1 | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | 29.0 | 60.2 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |

Without wind.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower failure location [mLAT] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 115.7 | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 60.2 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 107.2 | -- | 30.5 | 30.5 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 106.4 | 115.7 | 30.5 | 31.1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -0.7 | 12.8 | -2.7 | 30.0 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -0.7 | 11.8 | -2.7 | 30.0 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | 30.5 | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 28.5 | 60.2 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 60.2 | 30.5 | 30.5 |

With wind.

Table 9.24: Tower failure behaviour, Failure location.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Direction of tower failure | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | -- | Towards ship | -- |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | -- | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

Without wind.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Direction of tower failure | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | Away from ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | -- | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | Away from ship | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

With wind.

Table 9.25: Tower failure behaviour, Failure direction.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| **Foundation** | | | | | | | **K07** | **C01** | **HIGH** | **LOW** |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Yes | No | Yes | Yes |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | Yes | No |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |

Without wind.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| **Foundation** | | | | | | | **K07** | **C01** | **HIGH** | **LOW** |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | Yes | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |

With wind.

Table 9.26: Tower failure behaviour, Tower collapse.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Soil collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Ultimately yes | No | Probably not | Probably not |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Ultimately yes | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |

Without wind.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Soil collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | No | No |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | No | Probably not |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | No | Probably not | Probably not |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Ultimately yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |

With wind.

Table 9.27: Soil failure behaviour, Soil collapse.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle motion after impact | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| **Foundation** | | | | | | | **K07** | **C01** | **HIGH** | **LOW** |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Oscillating | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Away from ship | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Away from ship | Away from ship | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

Without wind.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle motion after impact | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| **Foundation** | | | | | | | **K07** | **C01** | **HIGH** | **LOW** |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Oscillating | Oscillating | Away from ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Oscillating | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Oscillating | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Away from ship | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

With wind.

Table 9.28: Turbine motion after impact.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -3.19 | 4.97 | -3.04 | 4.26 | -2.23 | 3.54 | -2.44 | 4.07 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -4.79 | 6.51 | -4.30 | 6.71 | -4.91 | 4.40 | -6.41 | 5.58 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -3.93 | 7.21 | -4.83 | 5.40 | -4.55 | 4.40 | -6.04 | 6.18 |
| | | | | | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -5.09 | 6.68 | -6.61 | 6.15 | -5.64 | 9.64 | -5.28 | 6.82 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -7.42 | 12.98 | -5.11 | 9.24 | -4.34 | 8.55 | -5.79 | 7.64 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -3.56 | 9.37 | -5.15 | 11.38 | -3.14 | 7.51 | -10.45 | 8.53 |
| | | | | | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -7.92 | 10.68 | -8.59 | 9.61 | -6.53 | 9.97 | -7.57 | 9.94 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -4.56 | 12.28 | -3.72 | 12.94 | -7.13 | 9.38 | -7.88 | 8.03 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -4.17 | 11.96 | -9.97 | 9.76 | -7.49 | 9.09 | -8.18 | 8.38 |
| | | | | | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -15.62 | 18.93 | -15.51 | 16.13 | -12.57 | 15.59 | -9.51 | 12.51 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -14.42 | 12.46 | -5.76 | 17.36 | -4.51 | 14.98 | -9.68 | 16.48 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -15.61 | 13.16 | -4.33 | 12.13 | -3.86 | 15.41 | -9.58 | 15.57 |
| | | | | | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -13.60 | 18.30 | -13.19 | 15.21 | -10.70 | 14.02 | -10.62 | 13.16 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -2.66 | 10.83 | -7.06 | 9.87 | -4.26 | 8.02 | -5.63 | 8.22 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -8.84 | 9.95 | -6.30 | 9.23 | -2.45 | 8.05 | -5.41 | 9.81 |
| **Overall extremes** | | | | | | | **-15.62** | **18.93** | **-15.51** | **17.36** | **-12.57** | **15.59** | **-10.62** | **16.48** |

Without wind.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -2.13 | 4.81 | -2.36 | 3.50 | -2.55 | 3.76 | -2.80 | 3.68 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.36 | 9.76 | -5.44 | 5.55 | -4.81 | 5.03 | -7.84 | 6.77 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -4.75 | 4.09 | -4.89 | 4.04 | -5.11 | 3.53 | -5.18 | 4.54 |
| | | | | | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.06 | 7.98 | -4.22 | 6.42 | -4.71 | 5.26 | -4.88 | 6.60 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 12.69 | -0.86 | 8.83 | -4.21 | 9.18 | -3.24 | 10.19 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -3.36 | 7.96 | -1.47 | 7.87 | -5.59 | 7.91 | -5.73 | 7.51 |
| | | | | | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.67 | 10.28 | -7.98 | 9.92 | -7.79 | 7.89 | -5.91 | 9.03 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.07 | 10.99 | -1.77 | 10.03 | -6.25 | 9.87 | -4.21 | 9.97 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -1.86 | 6.86 | -10.42 | 8.68 | -6.79 | 8.12 | -5.19 | 6.92 |
| | | | | | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -14.66 | 22.47 | -12.17 | 15.97 | -10.47 | 13.25 | -8.38 | 12.47 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -12.35 | 15.78 | -8.44 | 15.10 | -3.64 | 14.10 | -10.87 | 15.27 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -15.45 | 15.84 | -6.50 | 20.22 | -8.69 | 12.42 | -8.77 | 12.18 |
| | | | | | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -11.31 | 13.50 | -11.02 | 14.95 | -9.47 | 9.73 | -7.47 | 10.33 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.15 | 11.50 | -2.83 | 11.02 | -6.21 | 9.54 | -2.68 | 9.81 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -10.28 | 9.30 | -5.76 | 9.11 | -6.25 | 8.61 | -3.94 | 6.84 |
| **Overall extremes** | | | | | | | **-15.45** | **22.47** | **-12.17** | **20.22** | **-10.47** | **14.10** | **-10.87** | **15.27** |

With wind.

Table 9.29: Turbine accelerations for all ships and foundations, without and with wind load.

### 9.4.3. The effect of the loads acting on a ship.

In the previous Sections it has been assumed that the motor of the ship is shut down just before impact, so during impact the ship does not keep on pushing against the foundation. However, when the motor is not shut down in time, the motor propulsion force will keep on pushing the ship against the foundation during and after the impact. Also, in case of a drifting ship, the load of the wind and the current acting on the ship will keep on pushing the ship against the foundation during and after the impact. In both cases this force will have an effect on the behaviour of the foundation during and after impact.

The effect of the ship propulsion load by either wind and current or the ship motor has been investigated for the following situations:

4. Run 4: A drifting ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation, with the wind/current load pushing the ship forward. The wind turbine is assumed to be operating.
5. Run 5: A sailing ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation, with the ship motor pushing the ship forward. The wind turbine is assumed to be operating.
6. Run 6: A sailing ship with impact below the nacelle and a wind load in the direction opposite to the ship motion acting on the foundation, with the ship motor pushing the ship forward. The wind turbine is assumed to be operating.

The magnitude of the Wind and current drag forces and the propulsion load acting on the ship have been derived in Section 5.6.8.

The observed failure modes for the foundations according to the identified modes presented Section 9.3.3 are shown in Table 9.23 for the reference situation with wind load acting on the foundation and the operating wind turbine, but without a load acting on the ship. In Table 9.30 the failure modes are shown when in addition to the wind load acting on the foundation and the turbine also the ship propulsion load due wind/current or the ship motor is present. The data on which the results presented in Table 9.30 are based are presented in Table 9.31 to Table 9.35. It must be noted that although the failure mode for various configurations might be the same, the actual point of failure in [mLAT] or the exact moment of collapse might be different.

Comparison of the results in Table 9.23 and Table 9.30 and analysis of the results shows:

1. Kruiplijn coaster.

   For the drifting or sailing Kruiplijn coaster there is no difference in behaviour during impact when the propulsion load due to wind/current or the ship motor is present or not.

2. Supply vessel.

   For the drifting or sailing Supply vessel there is no difference in behaviour during impact when the propulsion load due to wind/current or the ship motor is present or not.

3. Chemical tanker.

   For the drifting or sailing Chemical tanker there is no difference in behaviour during impact when the propulsion load due to wind/current or the ship motor is present or not.

| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 1 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 6 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

With wind, no propulsion load.

| Drifting / Sailing | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Soil model | Load / Speed | Wind load | Failure mode | | | |
| | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | 1 | 1 | 1 | 1 |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | 6 | 1 | 1 | 4 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | 1 | 1 | 1 | 1 |
| | | | | | | | | | |
| Supply vessel | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | 2 | 1 | 1 | 1 |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | 5 | 3 | 3 | 3 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | 5 | 3 | 3 | 3 |
| | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | 6 | 1 | 4 | 4 |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | 5 | 5 | 5 | 5 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | 5 | 5 | 5 | 5 |
| | | | | | | | | | |
| Passenger vessels | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | 5 | 6 | 6 | 6 |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | 5 | 5 | 5 | 5 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | 5 | 5 | 5 | 5 |
| | | | | | | | | | |
| Container ship | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | 6 | 6 | 6 | 6 |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | 5 | 5 | 5 | 5 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | 5 | 5 | 5 | 5 |

with wind and with propulsion load.

Table 9.30: Summary of detected failure modes during drifting/sailing with wind load and with propulsion force.

4. Passenger vessel.

   For the Passenger vessel differences in foundation behaviour without and with propulsion force are found for the drifting ship. For the sailing ship the behaviour without and with propulsion force is the same, soil failure mode 5 occurs with the turbine moving towards the ship due to tower collapse.

   The detected differences for the drifting Passenger vessel are:

   a. Foundation C01 of Windfarm 1, drifting ship.

      For the situation without propulsion load failure does occur in first instance close to the tower top at 115.7 [mLAT]. However, no tower collapse or soil collapse does occur and the foundation keeps on oscillating after impact, so failure mode 2 is applicable.
      With propulsion load the foundation behaviour is identical, but in the end the foundation is being pushed over by the ship, so the failure mode shifts from 2 to 6.

   b. Foundation HIGH of Windfarm 2, drifting ship.

      For the situation without propulsion load tower failure does occur at c.a. 30.5 [mLAT] with the turbine moving towards the ship, but no tower collapse does occur. The deformation of the tower then changes direction and shifts from bending towards the ship to bending away from the ship. Next tower

failure occurs with the turbine moving away from the ship. Ultimately the ship will be stopped by the foundation and thus failure mode 4 is applicable.
With propulsion load the behaviour of the foundation is essentially the same, but now the foundation is pushed over by the ship and soil failure does occur. The failure mode thus shifts from mode 4 to mode 6.

c. Foundation LOW of Windfarm 2, drifting ship.

For the situation without propulsion load tower failure does occur at 31.1 [mLAT], with the turbine moving towards the ship, but no tower collapse occurs. Then, when the impact progresses the deformation of the tower changes direction and shifts from bending towards the ship to bending away from the ship and then finally tower collapse does occur with the turbine moving away from the ship. Ultimately the ship will be stopped by the foundation and thus failure mode 4 is applicable.
With propulsion load the behaviour of the foundation is essentially the same, but now the foundation is pushed over by the ship and soil failure does occur. The failure mode thus shifts from mode 4 to mode 6.

5. Container ship.

For the drifting or sailing Chemical tanker there is no difference in behaviour during impact when the propulsion load due to wind/current or the ship motor is present or not.

The main conclusion from the results presented above is that the presence of the propulsion load due to wind/current or the ship motor acting on the ship during the impact between a ship and a wind turbine foundation only has a noticeable effect when without these loads the soil was on the verge of collapse. The additional propulsion force can then be sufficient to push-over the foundation. The effect of the propulsion load on the actual impact behaviour of the steel structure is negligible.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower failure location [mLAT] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 115.7 | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 60.2 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 107.2 | -- | 30.5 | 30.5 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 106.4 | 115.7 | 30.5 | 31.1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -0.7 | 12.8 | -2.7 | 30.0 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -0.7 | 11.8 | -2.7 | 30.0 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | 30.5 | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 28.5 | 60.2 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 60.2 | 30.5 | 30.5 |

With wind load.

| Ship | Simulation run | Ship motion | Soil model | Load / Speed | Wind load | Tower failure location [mLAT] | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | -- | -- | -- | -- |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | -- | -- | -- | 30.5 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | -- | -- | -- | -- |
| | | | | | | | | | |
| Supply vessel | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | 115.7 | -- | -- | -- |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | 60.2 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | 107.2 | -- | 30.5 | 30.5 |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | 28.5 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | |
| Passenger vessels | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | 106.4 | 115.7 | 30.5 | 31.1 |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | -0.7 | 12.8 | -2.7 | 30.0 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | -0.7 | 11.8 | -2.7 | 30.0 |
| | | | | | | | | | |
| Container ship | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | -- | -- | 30.5 | -- |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | 28.5 | 60.2 | 30.5 | 30.5 |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | 28.5 | 60.2 | 30.5 | 30.5 |

With wind load and propulsion load.

Table 9.31: Tower failure behaviour, Failure location, wind load and propulsion load.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Direction of tower failure | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | Away from ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | -- | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | Away from ship | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

With wind load.

| Ship | Simulation run | Ship motion | Soil model | Load / Speed | Wind load | Direction of tower failure | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | -- | -- | -- | -- |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | -- | -- | -- | Away from ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | -- | -- | -- | -- |
| | | | | | | | | | |
| Supply vessel | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Towards ship | -- | -- | -- |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Towards ship | -- | Away from ship | Away from ship |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | |
| Passenger vessels | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | |
| Container ship | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | -- | -- | Away from ship | -- |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Towards ship | Towards ship | Towards ship | Towards ship |

With wind load and propulsion load.

Table 9.32: Tower failure behaviour, Failure direction, wind load and propulsion load.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | Yes | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |

With wind load.

| Ship | Simulation run | Ship motion | Soil model | Load / Speed | Wind load | Tower collapse | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | No | No | No | No |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | No | No | No | Yes |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | No | No | No | No |
| | | | | | | | | | |
| Supply vessel | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | No | No | No | No |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Yes | Yes | Yes | Yes |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Yes | Yes | Yes | Yes |
| | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | No | No | Yes | Yes |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Yes | Yes | Yes | Yes |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Yes | Yes | Yes | Yes |
| | | | | | | | | | |
| Passenger vessels | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Yes | No | Yes | Yes |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Yes | Yes | Yes | Yes |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Yes | Yes | Yes | Yes |
| | | | | | | | | | |
| Container ship | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | -- | -- | Yes | No |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Yes | Yes | Yes | Yes |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Yes | Yes | Yes | Yes |

With wind load and propulsion load.

Table 9.33: Tower failure behaviour, Tower collapse, wind load and propulsion load.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Soil collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | No | No |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | No | Probably not |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | No | Probably not | Probably not |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Ultimately yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |

With wind load.

| Ship | Simulation run | Ship motion | Soil model | Load / Speed | Wind load | Soil collapse | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | No | No | No | No |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Yes | No | No | No |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | No | No | No | No |
| | | | | | | | | | |
| Supply vessel | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | No | No | No | No |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Ultimately yes | Probably not | Probably not | Probably not |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Ultimately yes | Probably not | Probably not | Probably not |
| | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Yes | No | No | Probably not |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | |
| Passenger vessels | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Ultimately yes | Yes | Yes | Yes |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | |
| Container ship | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Yes | Yes | Ultimately yes | Yes |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |

With wind load and propulsion load.

Table 9.34: Soil failure behaviour, Soil collapse, wind load and propulsion load.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle motion after impact | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Oscillating | Oscillating | Away from ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Oscillating | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Oscillating | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Away from ship | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

With wind load.

| Ship | Simulation run | Ship motion | Soil model | Load / Speed | Wind load | Nacelle motion after impact | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Away from ship | Oscillating | Oscillating | Away from ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | | | | | |
| Supply vessel | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Away from ship | Oscillating | Away from ship | Away from ship |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | |
| Passenger vessels | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Towards ship | Away from ship | Away from ship | Away from ship |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | |
| Container ship | 1 | Drifting, with wind load | Non reversible | High load / Nominal speed | With wind | Away from ship | Away from ship | Away from ship | Away from ship |
| | 2 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | With wind | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing, with propulsion load | Non reversible | High load / Nominal speed | Against wind | Towards ship | Towards ship | Towards ship | Towards ship |

With wind load and propulsion load.

Table 9.35: Turbine motion after impact, wind load and propulsion load.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -3.19 | 4.97 | -3.04 | 4.26 | -2.23 | 3.54 | -2.44 | 4.07 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -4.79 | 6.51 | -4.30 | 6.71 | -4.91 | 4.40 | -6.41 | 5.58 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -3.93 | 7.21 | -4.83 | 5.40 | -4.55 | 4.40 | -6.04 | 6.18 |
| | | | | | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -5.09 | 6.68 | -6.61 | 6.15 | -5.64 | 9.64 | -5.28 | 6.82 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -7.42 | 12.98 | -5.11 | 9.24 | -4.34 | 8.55 | -5.79 | 7.64 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -3.56 | 9.37 | -5.15 | 11.38 | -3.14 | 7.51 | -10.45 | 8.53 |
| | | | | | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -7.92 | 10.68 | -8.59 | 9.61 | -6.53 | 9.97 | -7.57 | 9.94 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -4.56 | 12.28 | -3.72 | 12.94 | -7.13 | 9.38 | -7.88 | 8.03 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -4.17 | 11.96 | -9.97 | 9.76 | -7.49 | 9.09 | -8.18 | 8.38 |
| | | | | | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -15.62 | 18.93 | -15.51 | 16.13 | -12.57 | 15.59 | -9.51 | 12.51 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -14.42 | 12.46 | -5.76 | 17.36 | -4.51 | 14.98 | -9.68 | 16.48 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -15.61 | 13.16 | -4.33 | 12.13 | -3.86 | 15.41 | -9.58 | 15.57 |
| | | | | | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -13.60 | 18.30 | -13.19 | 15.21 | -10.70 | 14.02 | -10.62 | 13.16 |
| | 2 | Sailing | 90 Deg; Below rotor | No wind | Non reversible | High load / Nominal speed | -2.66 | 10.83 | -7.06 | 9.87 | -4.26 | 8.02 | -5.63 | 8.22 |
| | 3 | Sailing | 270 Deg; Below nacelle | No wind | Non reversible | High load / Nominal speed | -8.84 | 9.95 | -6.30 | 9.23 | -2.45 | 8.05 | -5.41 | 9.81 |
| **Overall extremes** | | | | | | | **-15.62** | **18.93** | **-15.51** | **17.36** | **-12.57** | **15.59** | **-10.62** | **16.48** |

Without wind.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -2.13 | 4.81 | -2.36 | 3.50 | -2.55 | 3.76 | -2.80 | 3.68 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.36 | 9.76 | -5.44 | 5.55 | -4.81 | 5.03 | -7.84 | 6.77 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -4.75 | 4.09 | -4.89 | 4.04 | -5.11 | 3.53 | -5.18 | 4.54 |
| | | | | | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.06 | 7.98 | -4.22 | 6.42 | -4.71 | 5.26 | -4.88 | 6.60 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 12.69 | -0.86 | 8.83 | -4.21 | 9.18 | -3.24 | 10.19 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -3.36 | 7.96 | -1.47 | 7.87 | -5.59 | 7.91 | -5.73 | 7.51 |
| | | | | | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.67 | 10.28 | -7.98 | 9.92 | -7.79 | 7.89 | -5.91 | 9.03 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.07 | 10.99 | -1.77 | 10.03 | -6.25 | 9.87 | -4.21 | 9.97 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -1.86 | 6.86 | -10.42 | 8.68 | -6.79 | 8.12 | -5.19 | 6.92 |
| | | | | | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -14.66 | 22.47 | -12.17 | 15.97 | -10.47 | 13.25 | -8.38 | 12.47 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -12.35 | 15.78 | -8.44 | 15.10 | -3.64 | 14.10 | -10.87 | 15.27 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -15.45 | 15.84 | -6.50 | 20.22 | -8.69 | 12.42 | -8.77 | 12.18 |
| | | | | | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -11.31 | 13.50 | -11.02 | 14.95 | -9.47 | 9.73 | -7.47 | 10.33 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.15 | 11.50 | -2.83 | 11.02 | -6.21 | 9.54 | -2.68 | 9.81 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -10.28 | 9.30 | -5.76 | 9.11 | -6.25 | 8.61 | -3.94 | 6.84 |
| **Overall extremes** | | | | | | | **-15.45** | **22.47** | **-12.17** | **20.22** | **-10.47** | **14.10** | **-10.87** | **15.27** |

With wind.

Table 9.36: Turbine accelerations.

### 9.4.4. The effect of shell buckling as failure criterion.

In the previous Sections the failure criterion of the foundation has been assumed to be the Yield stress corrected with a safety factor of 1.2. However, as the foundation pile and tower are thin-walled shells, they are also susceptible to shell buckling. Due to this effect failure of the foundation will occur at lower load levels.

The phenomenon of shell buckling cannot be investigated accurately with beam models. The only way to analyse the possible effect of shell buckling using the beam model is to determine the failure stress of shell buckling as function of the foundation dimensions, e.g., segment length, diameter, and wall thickness. A more accurate analysis can only be performed with a full 3D shell model of the foundation, which will be part of the following phase of this study.

The effect of shell buckling on the failure mode of the foundations has been investigated for the following situations:

1. Run 4: A drifting ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation. The wind turbine is assumed to be operating and the ship propulsion load is not considered.
2. Run 5: A sailing ship with impact below the rotor and a wind load in the direction of the ship motion acting on the foundation, with the ship motor pushing the ship forward. The wind turbine is assumed to be operating and the ship propulsion load is not considered.

3. Run 6: A sailing ship with impact below the nacelle and a wind load in the direction opposite to the ship motion acting on the foundation, with the ship motor pushing the ship forward. The wind turbine is assumed to be operating and the ship propulsion load is not considered.

The shell buckling failure criterion for the foundation has been derived in Section 5.7.

The observed failure modes for the foundations according to the identified modes presented Section 9.3.3 are shown in Table 9.23 for the reference situation with wind load acting on the foundation and the operating wind turbine, using the Yield limit as failure criterion. In Table 9.37 the failure modes are shown when the shell buckling failure stress is used as failure criterion. The data on which the results presented in Table 9.37 are based are presented in Table 9.38 to Table 9.42. It must be noted that although the failure mode for various configurations might be the same, the actual point of failure in [mLAT] or the exact moment of collapse might be different.

Comparison of the results in Table 9.23 and Table 9.37 and analysis of the results shows:

1. Kruiplijn coaster.

   For the drifting Kruiplijn coaster there is no difference in failure mode during impact due to the changed failure criterion. However, for the sailing impact differences do occur for the following foundations and simulations:

   a. Foundation K07 of Windfarm 1, ship sailing with the wind.

      When yield is the failure criterion, no tower failure occurs and in the end the foundation is run over by the ship. When shell buckling is the criterion then tower failure occurs at 60.2 [mLAT], with the turbine moving towards the ship. As now part of the impact energy is dissipated by the tower failure no soil collapse does occur and the foundation remains standing and oscillating. So no tower collapse occurs. As a result of this the failure mode changes from 6 to 2.

   b. Foundation C01 of Windfarm 1, ship sailing with the wind.

      When yield is the failure criterion, no tower failure or soil failure occurs and in the end the foundation remains standing and oscillating.
      When shell buckling is the failure criterion tower failure occurs at 60.2 [mLAT], with the turbine moving away from the ship. The failure mode thus changes from 1 to 4.

   c. Foundation HIGH of Windfarm 2, ship sailing with the wind.

      When yield is the failure criterion, no tower failure or soil failure occurs and in the end the foundation remains standing and oscillating.
      When shell buckling is the failure criterion tower failure occurs at 85.9 [mLAT], with the turbine moving away from the ship. The failure mode thus changes from 1 to 4.

   d. Foundation HIGH of Windfarm 2, ship sailing against the wind.

      When yield is the failure criterion, no tower failure or soil failure occurs and in the end the foundation remains standing and oscillating.
      When shell buckling is the failure criterion tower failure now occurs at 88.6 [mLAT], with the turbine again moving away from the ship. The failure mode thus also changes from 1 to 4.

| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 1 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 6 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

With wind, yield failure criterion.

| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 4 | 4 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 4 | 3 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 2 | 3 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 3 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 7 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 8 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

With wind, shell buckling failure criterion.

Table 9.37: Summary of detected failure modes during drifting/sailing with wind load and using Yield or shell buckling as failure criterion.

e. Foundation LOW of Windfarm 2, ship sailing against the wind.

   When yield is the failure criterion, no tower failure or soil failure occurs and in the end the foundation remains standing and oscillating. When shell buckling is the failure criterion tower failure occurs at 30.5 [mLAT], with the turbine again towards the ship and finally tower failure does occur with the turbine still moving towards the ship. The failure mode thus changes from 1 to 3.

2. Supply vessel.

   For the sailing Supply vessel there is no difference in failure mode during impact due to the changed failure criterion. However, for the drifting Supply vessel differences in failure behaviour do occur for foundation C01 of Windfarm 1 and for the foundations HIGH and LOW of Windfarm 2. The following differences do occur:

   a. Foundation C01 of Windfarm 1, drifting ship.

      When yield is the failure criterion, no tower failure or soil failure occurs and in the end the foundation remains standing and oscillating.
      When shell buckling is the failure criterion tower failure occurs at 115.7 [mLAT], with the turbine

moving towards the ship. No tower failure or soil collapse does occur and the foundation remains standing, with the turbine oscillating. The failure mode thus changes from 1 to 2.

b. Foundation HIGH of Windfarm 2, drifting ship.

When yield is the failure criterion, no tower failure or soil failure occurs and in the end the foundation remains standing and oscillating.
When shell buckling is the failure criterion tower failure occurs at 85.9 [mLAT], with the turbine moving towards the ship and finally tower collapse does occur. The failure mode thus changes from 1 to 3.

c. Foundation LOW of Windfarm 2, drifting ship.

When yield is the failure criterion, no tower failure or soil failure occurs and in the end the foundation remains standing and oscillating.
When shell buckling is the failure criterion tower failure initially occurs at 101.7 [mLAT], with the turbine again moving away from the ship, but not tower collapse occurs at this location. The failure mode thus also changes from 1 to 4.

3. Chemical tanker.

For the sailing Chemical tanker there is no difference in failure mode during impact due to the changed failure criterion. However, for the drifting Chemical tanker differences in failure behaviour do occur for foundations K07 and C01 of Windfarm 1 and for foundation HIGH of Windfarm 2. The following differences do occur:

a. Foundation K07 of Windfarm 1, drifting ship.

When yield is the failure criterion, tower failure does occur at 107.2 [mLAT], with the turbine moving towards the ship. However, no tower collapse does occur and in the end the foundation is run over by the ship and the turbine is moving away from the ship, so the failure mode is 6.
When shell buckling is the failure criterion tower failure occurs at 87.5 [mLAT], with the turbine moving towards the ship and finally at this location tower collapse occurs. Ultimately also soil failure will occur. The failure mode thus changes from 6 to 5.

b. Foundation C01 of Windfarm 1, drifting ship.

When yield is the failure criterion, no tower failure or soil failure occurs and in the end the foundation remains standing and oscillating. The failure mode is thus equal to 1.
When shell buckling is the failure criterion tower failure occurs at 108.3 [mLAT], with the turbine moving towards the ship. No tower failure or soil collapse does occur and the foundation remains standing, with the turbine oscillating. The failure mode thus changes from 1 to 2.

c. Foundation HIGH of Windfarm 2, drifting ship.

When yield is the failure criterion, tower failure does occur at 30.5 [mLAT], with the turbine moving away from the ship. Finally at this location tower collapse occurs with the turbine still moving away from the ship. The failure mode is thus equal to 4.
When shell buckling is the failure criterion tower failure occurs at 65.8 [mLAT], with the turbine moving towards the ship and quickly hereafter tower collapse does occur with the turbine still moving towards the ship. The failure mode thus changes from 4 to 3.

d. Foundation LOW of Windfarm 2, drifting ship.

When yield is the failure criterion, tower failure does occur at 30.5 [mLAT], with the turbine moving away from the ship. Finally at this location tower collapse occurs with the turbine still moving away from the ship. The failure mode is thus equal to 4.
When shell buckling is the failure criterion tower failure occurs at 83.2 [mLAT], with the turbine moving towards the ship, but no tower collapse occurs. Later, when the tower springs back the turbine starts moving away from the ship and then at 83.2 [mLAT] tower failure occurs with the turbine moving away from the ship. The failure mode thus remains 4, but the behaviour is different from the behaviour when yield was the failure criterion.

4. Passenger vessel.

For the sailing Passenger vessel there is no difference in failure mode during impact due to the changed failure criterion. However, for the drifting Passenger vessel differences in failure behaviour do occur for all four foundations. The following differences do occur:

The detected differences for the drifting Passenger vessel are:

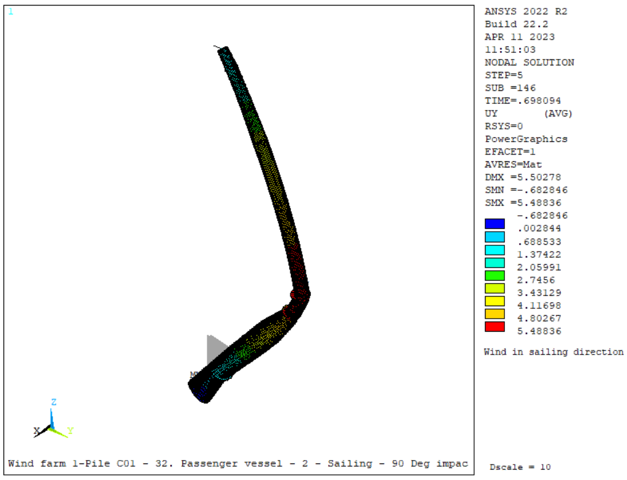
a. Foundation C01 of Windfarm 1, drifting ship.

When yield is the failure criterion failure does occur in first instance close to the tower top at 115.7 [mLAT], with the turbine moving towards the ship. However, no tower collapse or soil collapse does occur and the foundation keeps on oscillating after impact, so failure mode 2 is applicable.
When shell buckling is the failure criterion initially tower failure does occur at 108.8 [mLAT], with the turbine moving away from the ship. Then, later, also tower failure occurs at 60.1 [mLAT] with the turbine moving towards the ship. At this location also tower collapse occurs with the turbine moving towards the ship. So the failure mode changes to 3.

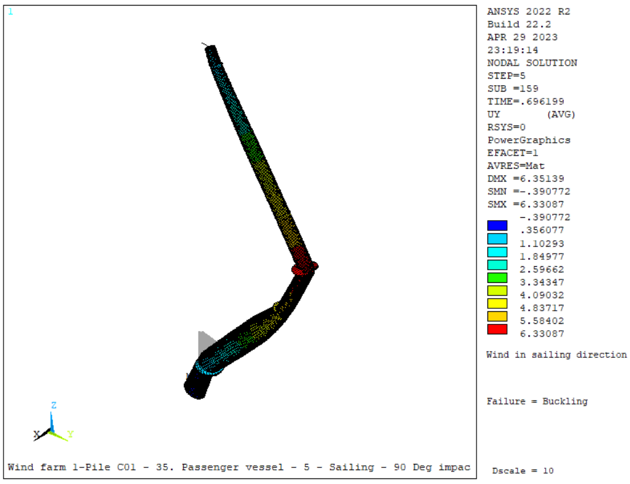
b. Foundation C01 of Windfarm 1, sailing ship, with the wind.

The failure mode for foundation C01 with the ship sailing with the wind is comparable for the simulation with yield as failure criterion or shell buckling as failure criterion. However, there exists one significant difference as explained below.

When yield is the failure criterion, tower failure occurs at 12.8 [mLAT] with the turbine moving towards the ship. Also tower collapse does occur and the foundation is run over by the ship, with the turbine moving towards the ship. Inside the soil the onset of foundation failure is visible, but not dominant yet. Hence, the failure mode is identified as 5.
When shell buckling is the failure criterion, tower does occur at the impact point, at -0.68 [mLAT] and at 28.5 [mLAT]. At this latter location also tower collapse occurs. The foundation is finally also run over by the ship with the turbine moving towards the ship, but while this happens also the foundation failure inside the soil becomes significant, see Figure 9.7. For this reason, the failure mode is now identified as 7. This mode occurs because due to the shell bucking the foundation pile becomes the weakest element instead of the soil. This mode 7 with failure of the foundation pile inside the soil was also observed for the conceptual foundation designs discussed in Section 8 where the soil resistance was much higher and the foundation pile also was the weakest element.




With wind, yield as criterion




With wind, shell buckling as criterion

Figure 9.7: Foundation behaviour for Windfarm 1, Foundations C01, ship sailing with the wind and impact below the rotor.

c. Foundation HIGH of Windfarm 2, drifting ship.

   When yield is the failure criterion failure tower failure does occur at c.a. 30.5 [mLAT] with the turbine moving towards the ship, but no tower collapse does occur. The deformation of the tower then changes direction and shifts from bending towards the ship to bending away from the ship. Next tower failure occurs with the turbine moving away from the ship. Ultimately the ship will be stopped by the foundation and thus failure mode 4 is applicable.
   When shell buckling is the failure criterion the foundation behaviour is basically the same, but tower failure occurs earlier in the process and the deformation at the moment of tower collapse with the turbine moving towards the ship is larger than when the yield limit is the failure criterion. Hence it is expected that the failure mode shifts to 3.

d. Foundation LOW of Windfarm 2, drifting ship.

   When yield is the failure criterion failure, the foundation LOW behaves in the same manner as foundation HIGH, with the failure mode being 4.
   When shell buckling is the failure criterion, initially tower failure, but no collapse, does occur at 102.4 [mLAT] with the turbine moving away from the ship. Somewhat later tower failure occurs at 75 [mLAT] with the turbine moving towards the ship. At that location also tower collapse occurs. The failure mode thus shifts also to 3.

5. Container ship.

   For the sailing Container ship there is no difference in failure mode during impact due to the changed failure criterion. However, for the drifting Container ship in this case differences in failure behaviour do occur for all the foundations of Windfarm 1. The following differences do occur:

   a. Foundation K07 of Windfarm 1, drifting ship.

      When yield is the failure criterion, no tower failure does occur for foundation K07. However, the foundation is run over by the ship and soil collapse does occur with the turbine moving away from the ship. So, the failure mode is 6.
      When shell buckling is the failure criterion tower failure and collapse does occur at 106.6 [mLAT], with

the turbine moving towards the ship. Ultimately the foundation will also be run over by the ship. The failure mode is therefore identified as being 5.

b. Foundation C01 of Windfarm 1, drifting ship.

When yield is the failure criterion, foundation C01 behaves the same as foundation K07, no tower failure does occur, the foundation is run over by the ship and soil collapse does occur with the turbine moving away from the ship. So, the failure mode is 6.
When shell buckling is the failure criterion, 3.4 [sec] after impact foundation failure occurs inside the soil at -51.55 [mLAT], while at the same time soil collapse does occur. Somewhat later on also tower failure occurs at 60.2 [mLAT] with the turbine moving away from the ship. The failure mode is in this case equal to 8.

The main conclusion from the results presented above is that the shift of the failure stress from yield to shell buckling, which means a considerable decrease in failure stress, results for a number of cases to an upward shift of the failure location of the foundation. Also, the moment of failure mostly occurs at a slightly earlier moment in the process and at lower acceleration levels of the turbine. This mostly occurs for the smaller ships which do not lead to a complete run over of the foundation. Also, for these smaller ships the failure mode sometimes shifts to a more severe mode and even when this is not the case the actual behaviour during the impact might be slightly different. This shift of the failure location to a higher position is caused by the fact that the upper part of the foundation, e.g., the tower segments, are more susceptible to shell buckling due to the fact that these segments have a small wall thickness which is less than 50 mm.

For the larger ships which result in a run over of the foundation there are sometimes also changes in the failure location and the actual behaviour of the foundation, but the overall results do not change. It must however be noted that for foundation C01 foundation failure inside the soil does occur for the Passenger vessel sailing with the wind and for the Container ship drifting with the wind. For these situations the reduced strength of the pile due to shell buckling results in the pile becoming the weakest element instead of the soil. This does not happen when the yield limit is the failure criterion.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower failure location [mLAT] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 115.7 | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 60.2 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 107.2 | -- | 30.5 | 30.5 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 106.4 | 115.7 | 30.5 | 31.1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -0.7 | 12.8 | -2.7 | 30.0 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -0.7 | 11.8 | -2.7 | 30.0 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | 30.5 | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 28.5 | 60.2 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 60.2 | 30.5 | 30.5 |

With wind, yield failure criterion.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower failure location [mLAT] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 60.2 | 60.2 | 85.9 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -- | -- | 88.6 | 30.5 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 115.7 | 115.7 | 85.9 | 101.7 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 60.2 | 60.2 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 60.2 | 60.2 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 87.5 | 108.3 | 65.8 | 83.2 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 28.5 | 30.5 | 30.5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 108.8 | 108.8 | 30.5 | 102.4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -0.7 | 28.5 / -0.68 | -2.7 | 28.0 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -0.7 | 28.5 | -2.7 | 28.0 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 106.6 | -51.6 | 85.9 | 85.9 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 28.5 | 60.2 | 30.5 | 30.5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 28.5 | 60.2 | 30.5 | 30.5 |

With wind, shell buckling failure criterion.

Table 9.38: Tower failure behaviour, Failure location.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Direction of tower failure | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | Away from ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | -- | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | Away from ship | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

With wind, yield failure criterion.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Direction of tower failure | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | -- | -- |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Away from ship | Away from ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -- | -- | Away from ship | Towards ship |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Away from ship | Towards ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | y from ship, inside | Towards ship | Towards ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

With wind, shell buckling failure criterion.

Table 9.39: Tower failure behaviour, Failure direction.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -- | -- | Yes | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |

With wind, yield failure criterion.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Tower collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | No | No | Yes | Yes |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Yes | Yes | Yes | Yes |

With wind, shell buckling failure criterion.

Table 9.40: Tower failure behaviour, Tower collapse.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Soil collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| **Foundation** | | | | | | | **K07** | **C01** | **HIGH** | **LOW** |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | No | No |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | No | No | Probably not |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | No | Probably not | Probably not |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Yes | Yes | Ultimately yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |

With wind, yield failure criterion.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Soil collapse | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| **Foundation** | | | | | | | **K07** | **C01** | **HIGH** | **LOW** |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | No | No | No | No |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | No | No | Probably not |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Probably not | Probably not | Probably not |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Yes | Ultimately yes | Yes |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Ultimately yes | Ultimately yes | Ultimately yes | Ultimately yes |

With wind, shell buckling failure criterion.

Table 9.41: Soil failure behaviour, Soil collapse.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle motion after impact | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Oscillating | Oscillating | Away from ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Oscillating | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Oscillating | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Away from ship | Away from ship | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

With wind, yield failure criterion.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle motion after impact | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Oscillating | Oscillating |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Oscillating | Away from ship | Away from ship | Away from ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Away from ship | Towards ship |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Oscillating | Oscillating | Towards ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Oscillating | Towards ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Away from ship | Away from ship | Away from ship |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | Towards ship | Towards ship | Towards ship | Towards ship |

With wind, shell buckling failure criterion.

Table 9.42: Turbine motion after impact.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -2.13 | 4.81 | -2.36 | 3.50 | -2.55 | 3.76 | -2.80 | 3.68 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.36 | 9.76 | -5.44 | 5.55 | -4.81 | 5.03 | -7.84 | 6.77 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -4.75 | 4.09 | -4.89 | 4.04 | -5.11 | 3.53 | -5.18 | 4.54 |
| | | | | | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.06 | 7.98 | -4.22 | 6.42 | -4.71 | 5.26 | -4.88 | 6.60 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 12.69 | -0.86 | 8.83 | -4.21 | 9.18 | -3.24 | 10.19 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -3.36 | 7.96 | -1.47 | 7.87 | -5.59 | 7.91 | -5.73 | 7.51 |
| | | | | | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.67 | 10.28 | -7.98 | 9.92 | -7.79 | 7.89 | -5.91 | 9.03 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.07 | 10.99 | -1.77 | 10.03 | -6.25 | 9.87 | -4.21 | 9.97 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -1.86 | 6.86 | -10.42 | 8.68 | -6.79 | 8.12 | -5.19 | 6.92 |
| | | | | | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -14.66 | 22.47 | -12.17 | 15.97 | -10.47 | 13.25 | -8.38 | 12.47 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -12.35 | 15.78 | -8.44 | 15.10 | -3.64 | 14.10 | -10.87 | 15.27 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -15.45 | 15.84 | -6.50 | 20.22 | -8.69 | 12.42 | -8.77 | 12.18 |
| | | | | | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -11.31 | 13.50 | -11.02 | 14.95 | -9.47 | 9.73 | -7.47 | 10.33 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.15 | 11.50 | -2.83 | 11.02 | -6.21 | 9.54 | -2.68 | 9.81 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -10.28 | 9.30 | -5.76 | 9.11 | -6.25 | 8.61 | -3.94 | 6.84 |
| **Overall extremes** | | | | | | | **-15.45** | **22.47** | **-12.17** | **20.22** | **-10.47** | **14.10** | **-10.87** | **15.27** |

With wind, yield failure criterion.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -2.19 | 4.79 | -2.36 | 3.50 | -2.56 | 3.75 | -2.80 | 3.68 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -2.21 | 5.88 | -4.34 | 5.47 | -4.18 | 4.96 | -2.92 | 6.08 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -4.67 | 4.09 | -4.89 | 4.04 | -6.02 | 3.51 | -4.04 | 3.97 |
| | | | | | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.90 | 6.40 | -4.54 | 5.67 | -5.60 | 4.96 | -3.66 | 5.44 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -1.77 | 7.33 | -1.08 | 6.21 | -4.52 | 7.14 | -1.48 | 6.57 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -3.13 | 5.52 | -2.68 | 4.75 | -4.15 | 4.91 | -5.12 | 4.20 |
| | | | | | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.67 | 7.13 | -6.94 | 9.30 | -4.84 | 7.09 | -4.44 | 7.65 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 8.61 | -2.10 | 6.53 | -3.34 | 6.15 | -3.37 | 6.46 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -6.90 | 6.70 | -4.71 | 5.22 | -4.82 | 4.38 | -5.67 | 4.06 |
| | | | | | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -13.01 | 13.14 | -12.15 | 12.16 | -11.03 | 10.25 | -10.26 | 11.03 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -13.35 | 14.78 | -7.82 | 11.42 | -10.07 | 11.51 | -7.26 | 10.20 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -16.48 | 7.77 | -10.77 | 7.96 | -4.63 | 5.94 | -7.21 | 6.64 |
| | | | | | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -11.31 | 17.22 | -11.02 | 16.43 | -9.46 | 10.71 | -9.40 | 9.51 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.59 | 8.90 | -2.60 | 7.17 | -2.99 | 5.70 | -2.83 | 6.06 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -7.70 | 5.64 | -3.87 | 4.94 | -5.64 | 4.54 | -6.95 | 4.27 |
| **Overall extremes** | | | | | | | **-16.48** | **17.22** | **-12.15** | **16.43** | **-11.03** | **11.51** | **-10.26** | **11.03** |

With wind, shell buckling failure criterion.

Table 9.43: Turbine accelerations for all ships and foundations, with wind load.

## 9.5. 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 be in the range from -19 to +19 [m/s$^2$] as an upper limit. These values are somewhat higher than found during the Safeship analysis in 2005, see lit. [2].

Evaluation of the effect of these accelerations on the connection between nacelle and tower must be carried out by the turbine manufacturers.

# 10. Conclusions.

## 10.1. Conclusions for the conceptual wind farm foundation designs.

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 P001 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. Comparison of these results for the conceptual foundation designs with those for the wind farms 1 and 2, that have actually been build, shows that the stopping power of the conceptual foundation designs is caused by the fact that the soil resistance used for the conceptual designs is significantly higher than for the wind farms 1 and 2. It thus seams that for the conceptual foundation designs very favourable soil conditions have been used.

3. Failure in the tower is mostly governed by the acceleration loads acting on the foundation. When these accelerations are too high, the nacelle cannot 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.

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

5. The conceptual foundation designs include a cone transition close to the tower top. This is especially disadvantageous because it is very near the tower top where the nacelle is connected to the top flange of the tower. As such, this cone transition is affected by both lateral acceleration loads and rotational accelerations loads induced by the turbine at the moment of impact.

6. Failure below the impact point for the conceptual foundation designs always occurs inside the seabed. This failure mode is mostly governed by the sheer impact load caused by the impact velocity and energy. Accelerations have not much effect at this failure mode.

7. For the investigated foundations, pure soil failure does not occur due to its high strength. 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.

8. Local deformation of the foundation at the impact point cannot 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.

9. Comparison of the behaviour of the two conceptual design foundations P001 and P002 when being impacted by 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 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.

10. 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 especially happens when it is assumed that upon rebound the soil force follows the same path backwards as during impact, so no energy is dissipated inside the soil.

    When it is assumed that the rebound of the soil goes along a line with the same slope as for zero displacement, then energy is dissipated by the deformation of the soil and 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.

    For the large ships, e.g., large passenger vessels or container 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.

11. For the large ships the force-displacement curves for broadside impact simulating the plastic deformation of the ship have been scaled from the data presented in the DNVGL-RP-C204 standard, see lit. [22]. 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 and weaker 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 and more weaker 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.

12. 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.

13. 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, see lit. [2].

14. Since the soil properties used for the conceptual design foundations are very conservative in comparison with the real soil properties that are valid for the 2 analysed wind farms 1 and 2 that have actually been build, the observed failure modes of the conceptual design foundations are not fully representative. Therefore, the failure modes of the conceptual design foundations are not elaborated on in this Section.

## 10.2. Conclusions for the wind farms 1 and 2.

1. For the actually build wind farms 1 and 2 investigated in this report the soil failure load is in the range of 10.0 [MN] to 16.6 [MN] ], while the total energy that can be dissipated by the soil is in the range of 165.6 [MJ] to 382.5 [MJ]. For the conceptual foundation designs investigated in Part 1 of this study the soil failure load was in the range from 43.3 [MN] to 46.4 [MN] and the dissipated energy was in the range from 1244 [MJ] to 1357 [MJ], so considerably higher. . It thus seams that for the conceptual foundation designs very favourable soil conditions have been used.
2. Drifting impact is characterised by:
    a. A fairly low impact velocity, in the range from 1.1 [m/s] to 1.7 [m/s].
    b. Broad side impact with a large contact height between ship and pile, resulting in a lack of crumple zones to absorb and dissipate the force of an impact.
    c. A stiff ship behaviour, resulting in a fast rise in impact force and with a high maximum impact force.
3. Sailing impact is characterised by:
    a. A high impact velocity, in the range from 5.4 [m/s] to 14.5 [m/s].
    b. Bow impact with a small contact height between ship and pile that, depending on the actual construction, can act as a crumple zone to absorb and dissipate the force of an impact.
    c. A more deformable ship behaviour, resulting in a gradual rise in impact force and with a medium to high maximum impact force.
4. For Drifting impact, the main results are as follows:
    a. The foundation behaviour is mostly governed by the high initial accelerations induced by the impact and the stiff ship behaviour, resulting in possible failure of the tower above the ship.
    b. Tower failure mostly occurs higher up in the foundation, closer to the turbine. It can be caused by the inertia of the turbine in combination with the linear acceleration, e.g., for Wind farm 2, but also by the rotational inertia of the turbine in combination with the rotational acceleration, e.g. for Wind farm 1. In the latter case the tower failure mostly occurs close below the top flange.
    c. The direction of motion of the turbine at the moment of tower failure resp. tower collapse is mostly directed towards the ship. This means that when full collapse of the tower occurs, the turbine will drop down onto the ship.

       In some cases, especially for the foundations of Wind farm 2, the turbine moves away from the ship at the moment of tower failure. This does occur when the deceleration of the foundation after the impact due to rebound is that large that bending moment due to the turbine inertia becomes too high.

d. When no collapse of the foundation or the soil occurs, the ship is ultimately stopped by the foundation and especially for the larger ships, e.g., the Chemical tanker and the Passenger vessel, there can be a considerable permanent inclination of the foundation after the impact. Also, the tower will be bended at the location where the tower failure occurs. This most likely means that further operation of the turbine will not be possible anymore.

e. Foundation collapse either occurs due to tower collapse, with the turbine falling down or due to soil collapse when the ship is pushing the foundation over. A combination of the two can also occur.

f. The foundations for Wind farm 2 are more susceptible for tower collapse for the Supply vessel and the Chemical tanker than the foundations of Wind farm 1. For the Passenger vessel, drifting at a higher velocity, the foundations of Wind farm 1 seem to be more susceptible. For the Container ship in most cases no tower collapse occurs.

g. Soil failure occurs for foundation K07 when being impacted by a drifting Passenger vessel. This foundation has a small penetration depth. The other foundations with a larger penetration depth can stop the Passenger vessel.

h. When being impacted by a drifting large Container ship, for all foundations soil failure does occur. The Container ship pushes the foundation over and drifts over it. In this case it is of course quite possible that the hull of the ship will be penetrated and sinking of the ship occurs.

i. A lower impact velocity or a less stiff/weaker ship hull is advantageous, but the differences are not clearly visible in the main results. For some foundations it prevents collapse, but not for all foundations.

j. No failure has been found at or below the impact area between ship and foundation. Of course, directly at the impact area local plastic deformation is likely to occur, but the simulations do not indicate that these will significantly contribute to the failure of the foundations. The part of the foundation above the impact area is much more sensitive to failure due to the effect of the acceleration acting on the foundation and the inertia of the turbine.

   A more detailed full 3D analysis incorporating shell models of the ship hull and the foundation is required to gain more insight in this.

5. For Sailing impact the main results are as follows:

   a. The foundation behaviour is mostly governed by the high initial accelerations induced by the high ship velocity that is not sufficiently absorbed by the bow of the ship, resulting in possible failure of the tower above the ship or at the point of impact.

   b. Tower failure mostly occurs in the lower half of the foundation, closer to the impact point. It is mostly caused by the inertia of the turbine in combination with the linear acceleration. At high impact speed, e.g., the Passenger vessel at 14.5 [m/s], failure can occur directly at the impact point.

   c. In most cases the turbine moves towards the ship when failure or collapse of the tower occurs. However sometimes, e.g., for the Kruiplijn coaster and the Chemical tanker at Low speed, the failure of the tower occurs when the foundation is decelerating after the impact when the ship has already been stopped. The inertia of the turbine then results in a too large bending moment leading to the turbine breaking away from the ship. Especially the foundations of Wind farm 2 are susceptible to this.

d. The foundations are only able to stop a sailing ship at nominal speed completely for the Kruiplijn coaster and, apart from foundation K07, also for the Supply vessel. Also, when the sailing velocity is reduced, e.g., to 2 [m/s] for the chemical tanker, the foundations are able to stop the ship.

   After the impact the foundations will have a significant permanent inclination.

e. Depending on the actual soil behaviour, continued operation of the turbine after being impacted by the Kruiplijn coaster might be possible.

f. Apart from the sailing impact by a Kruiplijn coaster and by a Chemical tanker sailing at Low speed always collapse of the tower occurs. For Wind farm 2 collapse does also occur for the sailing Chemical tanker at Low speed.

g. It is possible that the foundation will ultimately be able to stop a sailing Supply vessel at nominal speed or a large ship, e.g., a Chemical tanker, sailing at low speed. But otherwise collapse of the soil will always occur and the ship will sail over the foundation. In most cases also collapse of the tower occurs and the turbine will drop onto the ship.

h. For the Passenger vessel sailing at High Speed, failure will occur either at the impact point, especially for the stiffer foundations in low water depth, or closely above the impact point. The Passenger vessel will sail over the foundation, and it is quite likely that the ship hull will be penetrated by the part of the foundation that remains inside the soil. This likely might lead to the sinking of the ship.

i. For the large Container ship the tower will collapse at c.a. 30 [m] above the impact point. The kinetic energy of this ship is that large that it is quite possible that it will sail over the foundation and that the hull will be penetrated by the part of the foundation that remains inside the soil. This might lead to the sinking of the ship.

6. 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 -19 to +19 [$m/s^2$] as an upper limit. These values are somewhat higher than found during the Safeship analysis in 2005, see lit. [2].

   Evaluation of the effect of these accelerations on the connection between nacelle and tower must be carried out by the turbine manufacturers.

7. Soil modelling.

   a. Evaluation of the soil models used for the design of wind farms shows that the py-approach is still the preferred method for the design of monopile foundations for windfarms. This method has also been applied for the wind farms 1 and 2 under investigation in this report and will therefore also be used for the ship impact analysis.

   b. For the modelling of the soil a distinction can be made between gapping and non-gapping soils. For gapping soils, e.g., cohesive soils, a gap occurs between the soil and the pile wall at the rear of the laterally loaded pile. Under repeated cyclic loading the gap grows wider at the ground surface and becomes deeper during cycling. For non-cohesive soils, e.g., sand and loamy sand, in general no gapping does occur. It is assumed that when a gap occurs, the sand immediately fills up the gap and when the pile springs back immediately the soil at the rear side of the pile is mobilised, as explained for the kinematic hysteresis model discussed above.

   c. The soil in the Dutch part of the North Sea consists mainly of non-cohesive soils that are non-gapping. Also, the loading due to ship impact is mostly unidirectional so the effect of occurring gaps is less relevant. For this reason, the kinematic hysteresis soil model that is most appropriate for non-gapping soils is used for the description of the soil behaviour during the parameter variations as presented in Section 9.4.

   d. The kinematic hysteresis model is identical to the 'Non-reversible' soil model that has also been used in Sections 8.4.2 and 9.4.

8. Directional impact.

   a. Evaluation of the direction of impact of a ship with a wind turbine foundation, e.g., below the rotor, below the nacelle or from the side, shows that the failure mode is mostly independent of the direction of impact between ship and foundation. Only when the impact conditions are such that the foundation failure is close to the edge between 2 failure modes the direction of impact can have an effect on the foundation behaviour. E.g., for foundation C01 in case of the impact by a sailing Kruiplijn coaster tower failure and collapse does occur when the ship hits the foundation directly below the rotor at 60.2 [mLAT], but no tower collapse occurs when the ship hits the foundation below the nacelle. In the latter case still tower failure occurs at 28.5 [mLAT] but the tower does not collapse, and the turbine does not drop down.

   b. Apart from this the direction of impact influences the actual behaviour of the foundation such as for example the time interval between the start of the impact and actual moment of foundation failure or the location, in [mLAT], where the tower failure does occur as indicated above for foundation C01 in case of the impact by a sailing Kruiplijn coaster.

9. External loads acting on the foundation and the operating turbine.

   a. Evaluation of the effect of the wind, wave, current and turbine loads acting on the foundations shows that the presence of the wind load acting on an operating turbine during the impact between a ship and a wind turbine foundation can have an effect on the failure mode. This occurs mostly during drifting of a ship or for a smaller sailing ship such as a Kruiplijn coaster or a Supply vessel. The effect is that failure resp. collapse of the tower occurs somewhat earlier or later than when no wind is present. Also, when due to the impact the foundation is loaded up to the limit but just no failure or collapse does occur yet, then the additional wind load can just lead to failure or collapse of the foundation. In these situations sometimes also the failure location in [mLAT] shifts upwards or downwards.

On the other hand, when without wind failure or collapse does occur then an advantageous wind load can just prevent this failure or collapse.

b. For larger sailing ships the impact behaviour is so dominant that the presence of wind does hardly or not at all have much effect on the failure behaviour.

10. The effect loads acting on a ship.

    a. Evaluation of the effect of loads acting on a ship during the impact, e.g., wind/current loads or the motor propulsion load, shows that the presence of the these loads during the impact between a ship and a wind turbine foundation only have a noticeable effect when without these loads the soil was on the verge of collapse. The additional loads pushing or driving the ship forward can then be sufficient to push-over the foundation. The effect of the wind/current loads or the motor propulsion load on the actual impact behaviour of the steel structure is negligible.

11. Shell buckling failure criterion.

    a. When the failure criterion of the foundation is shifted from the Yield limit to shell buckling, then the strength of the foundation deceases considerably. The analyses show that this results for a number of situations to an upward shift of the failure location of the foundation. Also, the moment of failure mostly occurs at a slightly earlier moment in the process and at lower acceleration levels of the turbine. This mostly occurs for the smaller ships which do not lead to a complete run over of the foundation. Also for these smaller ships the failure mode sometimes shifts to a more severe mode and even when this is not the case the actual behaviour during the impact might be slightly different. This shift of the failure location to a higher position is caused by the fact that the upper part of the foundation, e.g. the tower segments, are more susceptible to shell buckling due to the fact that these segments have a small wall thickness which is less than 50 mm.

    b. For the larger ships which result in a run over of the foundation there are sometimes also changes in the failure location and the actual behaviour of the foundation, but the overall results do not change. It must however be noted that for foundation C01 foundation failure inside the soil does occur for the Passenger vessel sailing with the wind and for the Container ship drifting with the wind because due to the reduction in strength the foundation pile becomes critical instead of the soil. This does not happen when the yield limit is the failure criterion.

## 10.3. 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, see Table 9.12, mode 1.

2. Tower failure (plastic deformation) but no tower collapse, see Table 9.12, mode 2.

3. Tower failure/collapse, turbine moving towards the ship, see Table 9.12, mode 3.

4. Tower failure/collapse, turbine moving away from the ship, see Table 9.12, mode 4.

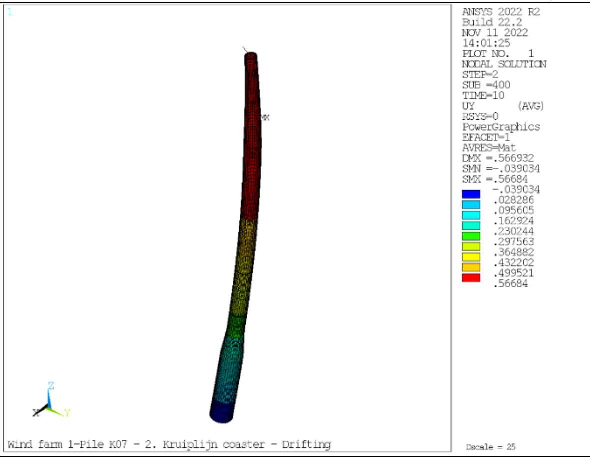
5. Soil collapse, turbine moving towards the ship, see Table 9.12, mode 5.

   Due to the collapse of the soil, the foundation moves away from the ship, while due to the failure of the tower the nacelle tends to move towards the ship. Which of the 2 counteracting motions becomes dominant cannot be simulated by the present model and depends on the velocity with which each failure develops. It is thus not possible to predict whether the tower failure will result in the turbine dropping down on the ship or that the soil failure will ultimately lead to the turbine moving away from the ship.

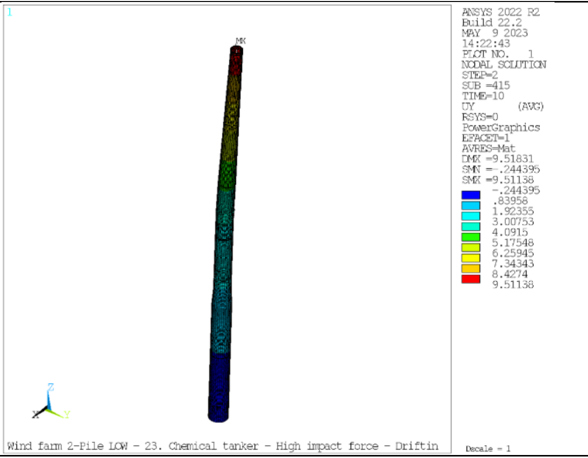
6. Soil collapse, turbine moving away from the ship, see Table 9.12, mode 6.

7. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving towards the ship, see Table 9.12, mode 7.

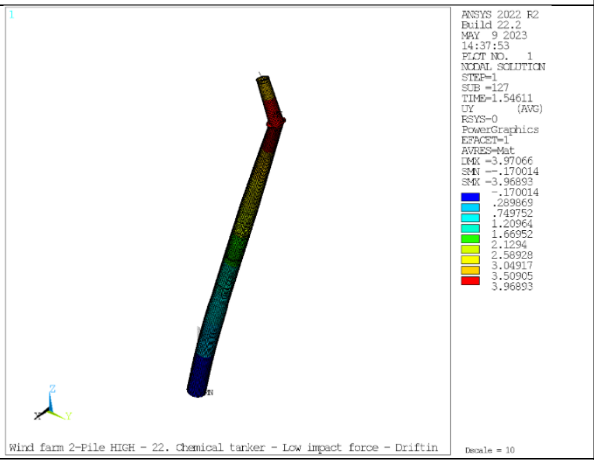
8. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving away the ship, see Table 9.12, mode 8.



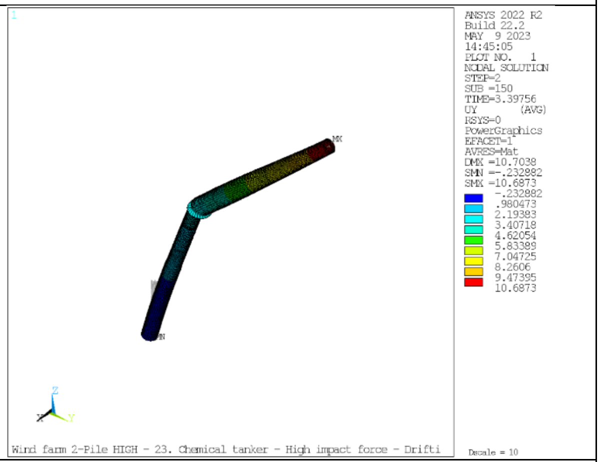

1. No pile or tower failure.




2. Tower failure (plastic deformation) but no tower collapse.




3. Tower failure/collapse, turbine moving towards the ship.




4. Tower failure/collapse, turbine moving away from the ship.

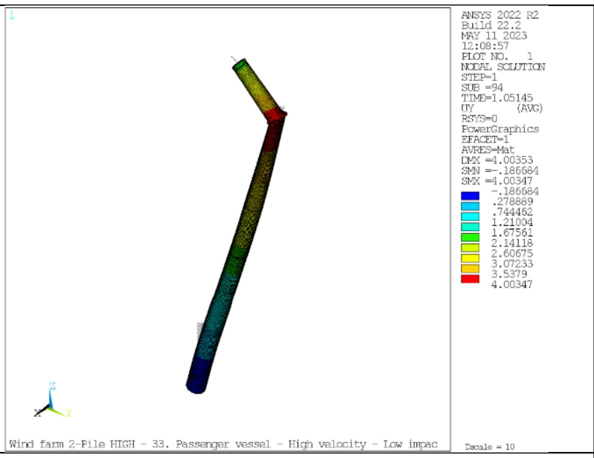
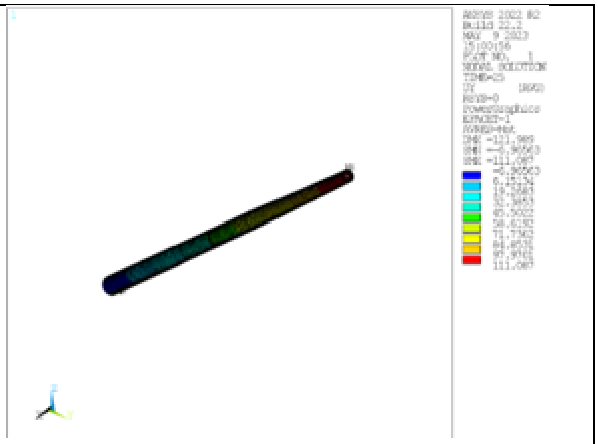
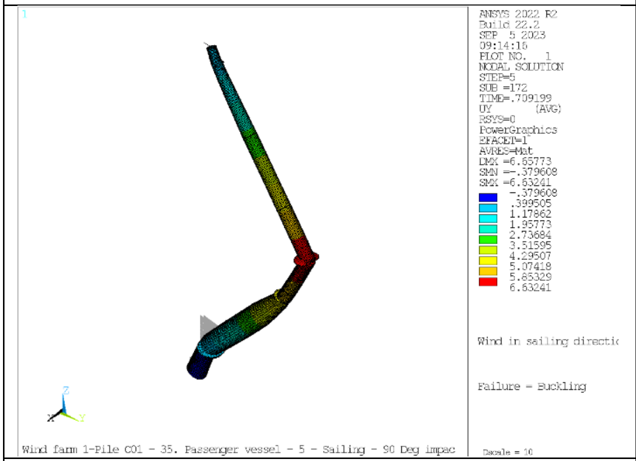
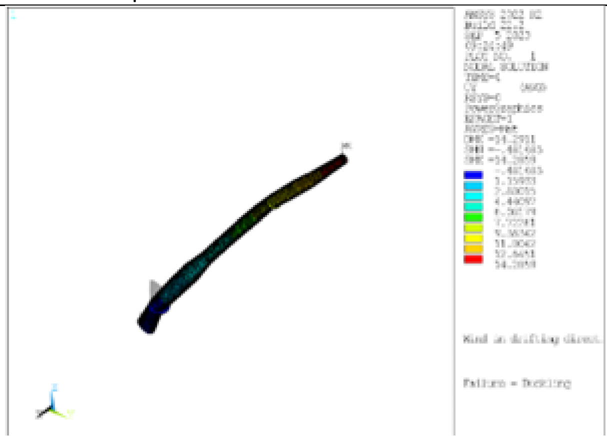
<table>
<tr>
<td>
</td>
<td></td>
</tr>
<tr>
<td>5. Soil collapse, turbine moving towards the ship.</td>
<td>6. Soil collapse, turbine moving away from the ship.</td>
</tr>
<tr>
<td>
</td>
<td></td>
</tr>
<tr>
<td>7. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving towards the ship.</td>
<td>8. Pile failure inside the soil, tower failure due to the inertia of the nacelle, turbine moving away the ship.</td>
</tr>
</table>

Table 10.1: Graphical presentation of detected failure modes.

In Table 10.2 and Table 10.3 it is shown for which foundations each failure mode is applicable in case of the original investigations as presented in Section 9. Comparison of these results with the results presented for the conceptual foundation designs in Section 8 clearly shows quite significant differences. For the conceptual designs the soil support is much larger, leading to a much larger soil failure load and a combination of pile failure inside the soil in combination with soil failure. For the foundations of the Wind farms 1 and 2 only soil failure occurs, there is no pile failure inside the soil. Also, the behaviour of tower of the conceptual designs is in general stiffer.

Regarding the survivability of the foundation of the turbine under ship impact, it follows that the foundations of Wind farm 1 and 2 are only able to survive drifting and sailing impact for ships up to c.a. 3000 tonnes displacement.

| Drifting | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Soil model | Load | Velocity | Failure mode | | | |
| | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Full reversible | High load | Nominal velocity | 1 | 1 | 1 | 1 |
| | 2 | Non reversible | High load | Nominal velocity | 1 | 1 | 1 | 1 |
| | | | | | | | | |
| Supply vessel | 1 | Full reversible | High load | Nominal velocity | 2 | 1 | 3 | 4 |
| | 2 | Non reversible | High load | Nominal velocity | 2 | 1 | 2 | 2 |
| | | | | | | | | |
| Chemical & Product tankers | 1 | Full reversible | High load | Nominal velocity | 2 | 1 | 4 | 4 |
| | 2 | Full reversible | Low load | Nominal velocity | 1 | 1 | 3 | 2 |
| | 3 | Non reversible | High load | Nominal velocity | 2 | 1 | 4 | 2 |
| | 4 | Full reversible | High load | Low velocity | 2 | 1 | 1 | 1 |
| | | | | | | | | |
| Passenger vessels | 1 | Full reversible | High load | Nominal velocity | 3 | 3 | 2 | 2 |
| | 2 | Full reversible | High load | Low velocity | 2 | 1 | 2 | 1 |
| | 3 | Full reversible | Low load | Nominal velocity | 3 | 2 | 3 | 2 |
| | 4 | Non reversible | High load | Nominal velocity | 3 | 3 | 2 | 2 |
| | | | | | | | | |
| Container ship | 1 | Full reversible | High load | Nominal velocity | 6 | 6 | 5 | 6 |
| | 2 | Full reversible | Low load | Nominal velocity | 6 | 6 | 6 | 6 |
| | 3 | Non reversible | High load | Nominal velocity | 6 | 6 | 6 | 6 |

Table 10.2: Summary of detected failure modes during Drifting.

| Sailing | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Soil model | Load | Velocity | Failure mode | | | |
| | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Full reversible | High load | Nominal velocity | 1 | 2 | 2 | 4 |
| | 2 | Non reversible | High load | Nominal velocity | 1 | 1 | 1 | 1 |
| | | | | | | | | |
| Supply vessel | 1 | Full reversible | High load | Nominal velocity | 3 | 3 | 3 | 3 |
| | 2 | Non reversible | High load | Nominal velocity | 3 | 3 | 3 | 3 |
| | | | | | | | | |
| Chemical & Product tankers | 1 | Full reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |
| | 2 | Full reversible | High load | Low velocity | 1 | 1 | 4 | 4 |
| | 3 | Non reversible | High load | Low velocity | 1 | 1 | 4 | 4 |
| | | | | | | | | |
| Passenger vessels | 1 | Full reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |
| | 2 | Non reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |
| | | | | | | | | |
| Container ship | 1 | Full reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |
| | 2 | Non reversible | High load | Nominal velocity | 5 | 5 | 5 | 5 |

Table 10.3: Summary of detected failure modes during Sailing.

Because the effect of the impact direction and the loads acting on the ship due wind, wave and current or the ship motor only has a limited effect on the foundation behaviour under impact, the results with the wind load and the yield or shell buckling failure criterion are most appropriate to judge the behaviour of the investigated foundations under impact.

A review of the identified failure modes occurring for the various ships and foundations is presented in Table 10.4. From these results it follows that the foundations of Wind farm 1 and 2 are only able to survive drifting impact for ships up to c.a. 3000 tonnes displacement, such as the investigated Kruiplijn coaster, when buckling is the dominant failure criterion. When yield is the dominant failure criterion, also impact by drifting ships up to c.a. 7000 tonnes, e.g. the Supply vessel, can be survived by the foundation without tower collapse.
Sailing impact by these ships in most cases leads to foundation failure, with the danger of the turbine dropping down on the ship.

For the larger ships, e.g., Chemical tankers, Passenger vessels and Container ships catastrophic failure of the foundations does almost always occur, with the danger of the turbine dropping down on the ship.

Finally, in Table 10.5 the maximum accelerations for the turbine are presented. These are relevant for the strength verification of the connection between nacelle and tower top. It follows that for the Kruiplijn coaster, the Supply vessel and the Chemical tanker the absolute accelerations are in general maximal +/-10 [m/s$^2$]. For the Passenger vessel and for the large Container ship the maximum absolute acceleration increases to +/-20 [m/s$^2$].

| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 1 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 1 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 4 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 6 | 6 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

With wind, yield failure criterion.

| Drifting / Sailing | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Failure mode | | | |
| | | | | | | | Wind farm 1 | | Wind farm 2 | |
| Foundation | | | | | | | K07 | C01 | HIGH | LOW |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 1 | 1 | 1 | 1 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 4 | 4 | 4 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 1 | 1 | 4 | 3 |
| | | | | | | | | | | |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 2 | 2 | 3 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | | | | | | | | | | |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 2 | 3 | 4 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 3 | 3 | 3 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 7 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | | | | | | | | | | |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 8 | 6 | 6 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | 5 | 5 | 5 | 5 |

With wind, shell buckling failure criterion.

Table 10.4: Summary of detected failure modes during drifting/sailing with wind load and using Yield or shell buckling as failure criterion.

| Ship | Simulation run | Ship motion | Impact direction | Wind load | Soil model | Load / Speed | Nacelle acceleration during impact | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Wind farm 1 | | | | Wind farm 2 | | | |
| Foundation | | | | | | | K07 | | C01 | | HIGH | | LOW | |
| | | | | | | | Min | Max | Min | Max | Min | Max | Min | Max |
| Kruiplijn coaster | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -2.19 | 4.81 | -2.36 | 3.50 | -2.56 | 3.76 | -2.80 | 3.68 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.36 | 9.76 | -5.44 | 5.55 | -4.81 | 5.03 | -7.84 | 6.77 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -4.75 | 4.09 | -4.89 | 4.04 | -6.02 | 3.53 | -5.18 | 4.54 |
| Supply vessel | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -4.06 | 7.98 | -4.54 | 6.42 | -5.60 | 5.26 | -4.88 | 6.60 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 12.69 | -1.08 | 8.83 | -4.52 | 9.18 | -3.24 | 10.19 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -3.36 | 7.96 | -2.68 | 7.87 | -5.59 | 7.91 | -5.73 | 7.51 |
| Chemical & Product tankers | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.67 | 10.28 | -7.98 | 9.92 | -7.79 | 7.89 | -5.91 | 9.03 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -3.12 | 10.99 | -2.10 | 10.03 | -6.25 | 9.87 | -4.21 | 9.97 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -6.90 | 6.86 | -10.42 | 8.68 | -6.79 | 8.12 | -5.67 | 6.92 |
| Passenger vessels | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -14.66 | 22.47 | -12.17 | 15.97 | -11.03 | 13.25 | -10.26 | 12.47 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -13.35 | 15.78 | -8.44 | 15.10 | -10.07 | 14.10 | -10.87 | 15.27 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -16.48 | 15.84 | -10.77 | 20.22 | -8.69 | 12.42 | -8.77 | 12.18 |
| Container ship | 1 | Drifting | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -11.31 | 17.22 | -11.02 | 16.43 | -9.47 | 10.71 | -9.40 | 10.33 |
| | 2 | Sailing | 90 Deg; Below rotor | With wind | Non reversible | High load / Nominal speed | -6.59 | 11.50 | -2.83 | 11.02 | -6.21 | 9.54 | -2.83 | 9.81 |
| | 3 | Sailing | 270 Deg; Below nacelle | Against wind | Non reversible | High load / Nominal speed | -10.28 | 9.30 | -5.76 | 9.11 | -6.25 | 8.61 | -6.95 | 6.84 |
| **Overall extremes** | | | | | | | **-16.48** | **22.47** | **-12.17** | **20.22** | **-11.03** | **14.10** | **-10.87** | **15.27** |

Table 10.5: Overall extremes for the turbine accelerations.

# 11. Literature.


[1] Duursma, A.M., et. al. : "WIND OP ZEE 2030: Gevolgen voor de scheepvaartveiligheid en mogelijke mitigerende maatregelen; Kwalitatieve en kwantitatieve analyse.", MARIN, report. 31132-3-MSCN-rev. 1.0, d.d. 13 mei 2019.

[2] van Rooij, J.H.A., e.a. : "SAFESHIP Reduction of Ship Collision Risks for Offshore Wind Farms NNE5/2001/521 - Evaluation of the practical applicability and design aspects of potential risk reducing technical measures for Offshore Wind Turbines and High Voltage Transformer Stations" Deliverable number 2, Hessels & van Rooij Engineering B.V., d.d. 25th of January 2005.

[3] Orlando, M. : "Ship impact against wind turbines – A literature review." , HVR Engineering, doc. 081.R030.M002 d.d. 11 December 2019

[4] van Rooij, J.H.A. : "Review of the status of the ship impact simulation programs.", HVR Engineering, doc. 081.R030.M003 d.d. 11 December 2019

[5] van Rooij, J.H.A. : "Investigation of ship impact against wind turbine foundations in the Dutch part of the North Sea.", HVR Engineering, doc. 081.R030.M006-Rev.3, d.d. 25 January 2024

[6] van Rooij, J.H.A. : "Investigation of ship impact against wind turbine foundations in the Dutch part of the North Sea – Part 2.", HVR Engineering, doc. 081.R030.M007-Rev.3, d.d. 25 January 2024

[7] van Rooij, J.H.A. : "Investigation of ship impact against wind turbine foundations in the Dutch part of the North Sea – Part 3.", HVR Engineering, doc. 081.R030.M008-Rev.4, d.d. 25 January 2024

[8] van Rooij, J.H.A. : "3D FEM analysis to determine the effects of a ship collision against a wind turbine monopile foundation.", HVR Engineering, doc. 081.R030.M010-Rev.5, d.d. 10 January 2024

[9] DNV (2019). : "Offshore standard DNV-OS-J101: Design of offshore wind turbine structures general - LRFD method". Technical report DNV-OS-J101", July 2019, Det Norske Veritas.

[10] API (2010) : "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design.", API 2010, RP2A-WSD", 21st edn, American Petroleum Institute.

[11] Wolf, T. K. et. al. : "Assessment of p-y Curves from Numerical Methods for a Non- Slender Monopile in Cohesionless Soil.", 2013, Department of Civil Engineering, Aalborg University, Denmark, ISSN 1901-7278, DCE Technical Memorandum No. 024

[12] : "Laterally Loaded Piles, Theory Manual.", 2022 Rocscience Inc.

[13] Lovera, A. et al. : "Pile response to multi-directional lateral loading using P–y curves approach." 2021, Géotechnique 71, No. 4, p. 288–298.
.

[14] Zdravkovic, L., et. al. : "Finite element modelling of laterally loaded piles in stiff glacial clay till at Cowden.",
2019, Géotechnique, https://doi.org/10.1680/jgeot.18, PISA.005.

[15] Taborda, D. M. G., et. al. : "Finite element modelling of laterally loaded piles in a dense marine sand at Dunkirk.",
2019, Géotechnique, https://doi.org/10.1680/jgeot.1, PISA.006.

[16] Ondrej , : "Pile lateral support based on PY-curves.",
CSI Knowledge base, October 18, 2022.

[17] Takeda T., el. al. : "Reinforced concrete response to simulated earthquakes.",
Journal of the Structural Division, Proc. of the American Society of Civil Engineers, December 1970.

[18] Pranjoto, S., et. al. : "Gapping effects on the lateral stiffness of piles in cohesive soil.",
2003, Pacific Conference on Earthquake Engineering, Paper number 096.

[19]. SWL : "Hornsea offshore wind farm project one – environmental statement volume 5 annex 5.1.2 –wave modelling.",
Technical Report, 2013, SMart Wind Limited London, UK

[20] Levy, N. H., et. al. : "Effect of recent load history on laterally loaded piles in normally consolidated clay.,
2007, Int. J. Geomech. 7, No. 4, 277–286.

[21] Hesham El Naggar, M., et. al.: "Dynamic analysis for laterally loaded piles and dynamic p–y curves'.
2000, NRC Canada.

[22] -- : "Structural design against accidental loads.",
DNV-RP-C204 Recommended Practice, Edition September 2019,

[23] van Rooij, J.H.A. : "Korte project omschrijving t.b.v. informatie Windpark operators/eigenaren.",
HVR Engineering, doc. 081.R030.M001 d.d. 11 December 2019
(description in both Dutch and English)

[24] van Rooij, J.H.A. : "Table of contents summary for transfer of information in the frame of the ship impact analysis against Wind turbine foundations.",
HVR Engineering, doc. 081.R030.M004 d.d. 28 September 2019

[25] Malekjafarian, A., et. al. : "Foundation damping for monopile supported offshore wind turbines: A review.",
Marine Structures 77 (2021).