BETTER SHIPS, BLUE OCEANS

Further Investigations into the Behaviour of Container Ships in Storms above the Wadden Islands

Summary report

Report No.	**:**	**32558-1-DIR**
Date	**:**	**September 2020**
Version	**:**	**1.2** **Final report**

Further Investigations into the Behaviour of Container Ships in Storms above the Wadden Islands

Summary report

MARIN order No.	:	32558
MARIN Project Manager	:	Bastien Abeil, MSc
Classification	:	Commercial in confidence
Number of pages	:	71
Ordered by	:	Ministerie van Infrastructuur en Waterstaat Directie Maritieme Zaken IBI/F&I/086 Postbox 20906 2500 EX The Hague
Order document	:	Letter of assignment, number 31156553, dated 2020-02-26
Reference	:	MARIN onderzoek MSC Zoe SAP order number 4500295016
Reported by	:	Bastien Abeil, MSc (Model tests), ir. Jos Koning (Study cargo securing), Dr.ir. Riaan van ‘t Veer (Calculations), Levent Kaydihan, PhD (FE analysis container) and Capt. Jan F. Krijt (nautical advisor)
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Version	Date	Version description	MARIN review by	Released by
1.0	July 15, 2020	Draft version	RvtV	BB
1.1	August 26, 2020	Draft Final version		BB
1.2	September 9, 2020	Final version	RvtV/BA	BB

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NEDERLANDSTALIGE SAMENVATTING MET AANBEVELINGEN

Samenvatting

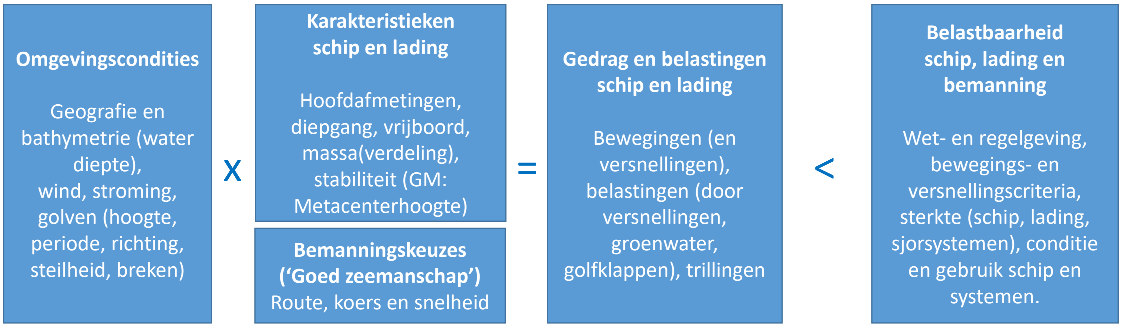
In de avond en nacht van 1 op 2 januari 2019 verloor het Ultra Large Container Ship (ULCS) MSC ZOE 342 containers ten noorden van de Waddeneilanden terwijl het in het verkeersscheidingsstelsel Terschelling-German Bight voer naar Bremerhaven in noordwester stormcondities. Dit resulteerde in grote vervuiling van de zee en Waddeneilanden. De combinatie van hoge (brekende) golven en ondiep water dwars op de vaarroutes resulteert boven de Waddeneilanden in complex gedrag van containerschepen en hun lading, waarbij verschillende fenomenen tegelijkertijd een rol spelen.

Als onderdeel van het onderzoek met de Onderzoeksraad Voor Veiligheid (OVV), concludeerde MARIN[1] dat de volgende fenomenen de meest waarschijnlijke verklaringen voor het verliezen van containers zijn:

1. Extreme (golffrequente) scheepsbewegingen en versnellingen
2. Contact van het schip met de zeebodem
3. Impulsieve krachten van groenwater op de containers
4. Golfklappen tegen de romp van het schip.

Om het verliezen van containers dicht bij dit beschermde natuurgebied (Particularly Sensitive Sea Area, PSSA) in de toekomst te voorkomen, heeft het Ministerie van Infrastructuur en Waterstaat (I&W) MARIN gevraagd ook te onderzoeken hoe containerschepen met andere afmetingen reageren op de condities boven de Waddeneilanden: naast zeer grote containerschepen zoals de MSC ZOE (ULCS, typische lengte 379 m, breedte 59 m), een kortere en smallere ‘Panamax’ (typische lengte 278 m, breedte 32m) en een kleinere container ‘Feeder’ (typische lengte 163 meter, breedte 27 m). Het belang van onderzoek naar kleinere schepen werd bevestigd toen de Feeder ‘Rauma’ op 11 februari 2020 boven de Wadden 7 containers verloor in golven met een significante golfhoogte (Hs) tussen 4.5 en 5.0 m.

Het gedrag van containerschepen in stormcondities is het resultaat van de interactie tussen de omgevingscondities en de karakteristieken van het schip en lading. Het gedrag kan worden beïnvloed door de keuzes van de bemanning als het gaat om de route, koers en snelheid (‘goed zeemanschap’). Een schip met haar lading is veilig wanneer het gedrag en de belastingen onder de belastbaarheid (veilige waarden) van het ontwerp liggen. Schade kan optreden en containers kunnen overboord vallen wanneer de belastingen op het schip en de lading de veilige waarden (belastbaarheid) overschrijden:



In deze stap in het vervolgonderzoek voor het Ministerie van I&W heeft MARIN op basis van modelproeven, berekeningen en literatuuronderzoek voor 3 scheepstypen onderzocht hoe zij zich gedragen in de complexe omstandigheden boven de Wadden in de ondiepe zuidelijke route direct boven de Waddeneilanden en de diepere noordelijke route en wat dit kan betekenen voor het verliezen van containers.

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[1] *Rapporten zijn te vinden op: https://www.onderzoeksraad.nl/en/page/13223/safe-container-transport-north-of-the-wadden-islands.-lessons-learned*

Op basis van de huidige onderzoeksresultaten (en de aannames zoals ze zijn samengevat in de tabel en in secties 6.2 en 6.6) heeft MARIN **voorlopige beperkende golfhoogtes** afgeleid voor deze scheepstypes en routes. Hierbij is, voor de versnellingen en het bodemcontact[2], gekeken naar alle golfrichtingen en voorkomende golfperiodes. De beperkingen in golfhoogtes treden met name op bij golven dwars op de vaarroute of vaarrichting (+/- 20 tot 30 graden) omdat de optredende fenomenen dan meestal het sterkst zijn.

Bij golfhoogten boven deze voorlopige beperkende golfhoogtes kunnen de belastingen op dit soort schepen en hun lading de belastbaarheid (veilige waarden) overschrijden. De bepalende fenomenen per scheepstype en route[3] staan steeds vetgedrukt:

Route	**FEEDER** Aannames: GM=0.8 tot 1.5m 0 tot 8 knopen 9.20 m diepgang Vrijboord 3.0 m	**PANAMAX** Aannames: GM=1.0 tot 2.5m 0 tot 10 knopen 12.20 m diepgang Vrijboord 9.2 m	**ULCS** Aannames: GM=6.0 tot 9.25m 0 tot 10 knopen 12.40 m diepgang Vrijboord 17.9 m
Noordelijke route (37.5m water diepte)	Hs > 7.5 m (versnellingen) Hs > 7.5 m (bodemcontact) **Hs ≈ 3.3 m (groenwater)**	Hs ≈ 6.5 m (versnellingen) Hs > 7.5 m (bodemcontact) **Hs ≈ 5.7 m (groenwater)**	**Hs ≈ 6 m (versnellingen)** Hs > 7.5 m (bodemcontact) Hs ≈ 7.4 m (groenwater)
Zuidelijke route (21.3m water diepte)	Hs > 6.5 m (versnellingen) Hs ≈ 5.5 m (bodemcontact)[4] **Hs ≈ 3.4 m (groenwater)**	Hs ≈ 5.5 m (versnellingen) **Hs ≈ 4.5 m (bodemcontact)** Hs ≈ 4.8 m (groenwater)	Hs ≈ 6 m (versnellingen) **Hs ≈ 4.5 m (bodemcontact)** Hs ≈ 5.9 m (groenwater)

In het algemeen zijn de voorlopige beperkende golfhoogtes in de ondiepe zuidelijke route lager dan in de diepere noordelijke route: het risico op het verliezen van containers in de zuidelijke route is hoger dan in de noordelijke route.

Maar ook voor de noordelijke route heeft MARIN voorlopige beperkende golfhoogtes afgeleid om het verliezen van containers te voorkomen. Deze beperkingen treden op bij dwarsgolven.

Aanbevelingen

Deze **voorlopige beperkende golfhoogtes** voor drie containerscheepstypes zijn belangrijk om het risico op container verlies sterk te verlagen. We bevelen aan om deze golfhoogtes en de verdere bevindingen in dit rapport in acht te nemen bij het besluitvormingsproces rond het gebruik van de routes boven de Waddeneilanden en het advies dat de Kustwacht geeft aan schepen die in dit gebied varen.

Zoals vermeldt, zijn grote slingerbewegingen en groenwater veelal het sterkst bij golven dwars op de vaarroute of vaarrichting. Wanneer dit gedrag zich voordoet, is met lage snelheid ‘met de kop op de golven gaan liggen’ verstandig in het kader van goed zeemanschap.

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[2] *Voor het complexe probleem van groenwater heeft het onderzoek zich tot nu toe moeten beperken tot dwarsgolven.*

[3] *Voor de limiterende golfhoogte wordt bij bodemcontact de golfhoogte gebruikt waarbij de minimum dUKC (dynamic Under Keel Clearance: minimale ruimte onder de kiel in golven) kleiner dan 2 meters is, voor de versnellingen wordt het laagste criterium van de 4 classificatiemaatschappijen gebruikt en voor groenwater de golfhoogte waarbij de relatieve golfbewegingen de laagste container op het dek kunnen raken (limiet=vrijboord+2.5m). In alle gevallen wordt het Most Probable Maximum (MPM: meest waarschijnlijke maximum) in een 3 uurs storm gebruikt.*

[4] *Mogelijk bodemcontact wordt bij de Feeder bij deze golfhoogte alleen voorspeld bij golven vrijwel recht op de kop en bij een snelheid van 8 knopen. Bij een lagere snelheid van 4 knopen (meer realistisch in deze omstandigheden), stijgt de beperkende golfhoogte naar 6.5 m.*

Om de **uiteindelijke beperkende golfhoogtes** te bepalen die nodig zijn om het verlies van containers boven de Wadden te voorkomen, bevelen we een (statistische) risico analyse aan. Zoals aangegeven in de Figuur aan het begin van deze samenvatting, is het daarbij belangrijk de (lange termijn verdeling van) de omgevingscondities (zoals waterdieptes, getijden en golven), de karakteristieken van schip en lading (zoals diepgang, vrijboord en stabiliteit: metacenterhoogte) en het effect van bemanningskeuzes (zoals de koers relatief ten opzichte van de golfrichting) mee te nemen. De aspecten die daarbij worden aanbevolen, zijn opgenomen in dit rapport (sectie 6.6). Voor het bepalen van deze uiteindelijke beperkende golfhoogtes is het belangrijk dat de overheid een noodzakelijk veiligheidsniveau (of toelaatbaar risiconiveau) vaststelt voor het verliezen van containers in de buurt van dit beschermde natuurgebied (Particularly Sensitive Sea Area, PSSA).

We bevelen ook aan om het complexe probleem van groenwater belasting op de containers verder te onderzoeken, speciaal voor de kleinere schepen zoals Feeders met hun relatief lage vrijboord. Groenwater belasting is een beperkende factor voor deze schepen in beide routes. De (statistiek van) complexe niet-lineaire relatieve golfbewegingen, groenwater impacts en reacties van de (stapels) containers vragen verder onderzoek om het risiconiveau en de beperkende golfhoogtes nauwkeuriger te bepalen. Hierbij speelt ook de hoogte van het vrijboord een belangrijke rol. We bevelen aan om, naast dwarsgolven, ook naar situaties met golven (schuin) van voren te kijken. Met lage snelheid ‘met de kop op de golven gaan liggen’ is een logische keuze wanneer grote slingerbewegingen en groenwater optreden in dwarsgolven. Het is echter belangrijk te onderzoeken of er in golven (schuin op) de kop ook groen water tegen de containers aanslaat vanaf de zij of over de boeg.
We raden aan om tijdens dit onderzoek in kopgolven ook verder te kijken naar ‘parametrisch slingeren’[5]. Parametrisch slingeren in kopgolven kan optreden bij bepaalde combinaties van golflengte, golfperiode en eigen slingerperiode van het schip. Het moet worden voorkomen dat de keuze om met de kop op de golven te gaan varen, alsnog resulteert in grote slingerbewegingen en containerverlies. Hoewel een eerste extra set van proeven geen parametrisch slingeren liet zien van het huidige kleine Feeder testmodel, raden we dit extra onderzoek aan om te er zeker van te zijn dat dit probleem zich niet voordoet (of kan worden voorkomen door goede instructies aan bemanningen).
Tot slot bevelen we aan hierbij de reactie van bemanningen op dit soort gebeurtenissen te onderzoeken: hoe reageren zij vanuit goed zeemanschap op situaties waarbij het schip sterk slingert of groenwater op het dek komt?

De resultaten in dit rapport en de voorlopige beperkende golfhoogten zijn een concrete invulling van de onderwerpen die benoemd worden in de IMO Intact Stability code[6]. Zoals Hoofdstuk 5 en achterliggend rapport[7] laat zien, vraagt de bepaling van de **uiteindelijke beperkende golfhoogtes** daarnaast meer transparante en consistente voorschriften[8] van internationale organisaties zoals IMO en de classificatiemaatschappijen:

- De dimensies van containerschepen zijn de afgelopen decennia sterk gegroeid. Er is beperkte ervaring en statistiek om rekening te houden met deze sterke stijging in scheepsgroottes, ontwikkelingen op het vlak van weerroutering, extremere waarden van de stabiliteit (metacenterhoogte GM) van recente scheepsontwerpen en de weersafhankelijke reducties van de versnellingsniveaus die geaccepteerd zijn geraakt de afgelopen 10 jaar. De criteria uit de huidige classificatievoorschriften, die worden gebruikt in de berekeningen van beladingssystemen, kunnen daardoor anders zijn dan de bewegingen en versnellingen die daadwerkelijk acceptabel zijn in de praktijk. Het is daarom noodzakelijk de kennis te verhogen

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[5] *Parametrisch slingeren is één van de belangrijke onderwerpen in de IMO 2nd generation intact stability criteria, maar richt zich niet specifiek op de situatie van hoge (brekende) golven in ondiep water.*

[6] *Zie secties 3.7.5, 5.1.6 en 5.3.6 van Resolution MSC.267(85), 4 December 2008.*

[7] *MARIN Report 32558-5-PaS: ‘Container securing, Overview current practice & regulatory framework’.*

[8] *Zoals SOLAS Chapter VI, de IMO ‘Code of Safe Practice for Cargo Stowage and Securing’ (CSS Code) en de ‘class guidelines’ voor ‘container securing’ van de verschillende classificatiemaatschappijen.*

van de daadwerkelijke belastingen die optreden op containers aan boord van de huidige (zeer grote) containerschepen.

- De grote variaties in de bewegings- en versnellingscriteria tussen de verschillende classificatiebureaus in de berekeningen van de beladingsystemen, zoals aangetoond in Hoofdstuk 5, illustreren deze onzekerheid en het gebrek aan transparantie. Dit heeft effect op de betrouwbaarheid van de ontwerplimieten (veilige waarden waarvoor het schip ontworpen is) en op de beperkende golfhoogtes als gevolg daarvan. Ook is het niet duidelijk hoe de vlaggenstaten controle houden over de standaarden die zij de industrie opleggen op dit vlak.

- Goed zeemanschap is essentieel om de daadwerkelijke belastingen op de lading binnen de ontwerplimieten van de beladingssystemen te houden. Er is op dit moment echter geen verplichting om apparatuur aan boord te hebben die de actuele scheepsbewegingen en versnellingen meet en weergeeft. De bemanning heeft dus niet standaard de informatie om te bepalen of de veilige waarden die zijn gebruikt in de beladingsberekeningen worden overschreden. Ook weet zij vaak niet welke limietwaarden er precies zijn gebruikt in de berekeningen in de beladingscomputer. Het wordt daarom aanbevolen om de bemanningen van containerschepen beter te ondersteunen bij hun beslissingsprocessen aan boord, zodat zij mogelijke problemen tijdens de operatie herkennen en daarop kunnen reageren.

We bevelen de Nederlandse overheid daarom aan hiervoor internationaal aandacht te vragen op basis van de bevindingen in Hoofdstuk 5 en achterliggend rapport.

Tot slot bevelen we aan om het onderzoek naar het risico op containerverlies langs de Nederlandse kust uit te breiden naar andere gebieden op de Noordzee, waar ook de combinatie van ondiep water met hoge golven kan voorkomen in sommige stormcondities.

Wageningen, September 2020
MARITIME RESEARCH INSTITUTE NETHERLANDS

Dr.ir. B. Buchner
Algemeen Directeur

1 INTRODUCTION

1.1 Backgrounds

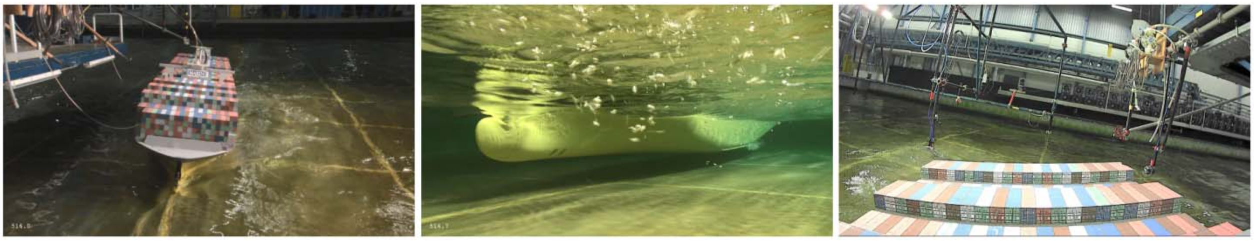
In the evening and night of January 1 to 2 of 2019, the Ultra Large Container Ship (ULCS[9]) MSC ZOE lost 342 containers north of the Wadden Islands while sailing along the Terschelling-German Bight Traffic Separation Scheme (TSS) to Bremerhaven in north-westerly storm conditions. This resulted in large-scale pollution of the sea and Wadden Islands.


Source: Kustwacht

Source: www.nioz.nl

The MSC Zoe after the accident (left) and one of the containers lost by the MSC Zoe (right) on the beach of Terschelling

Following this accident, the Dutch Safety Board (Onderzoeksraad voor Veiligheid, OVV) started the investigation ‘Lost Containers’ (‘Verloren Containers’), which aimed at determining the consequences of the accident for sea transportation safety along the Dutch coast. As independent research organisation, MARIN assisted the OVV with a model test campaign using environmental conditions as encountered by the MSC Zoe on January 1 and 2, 2019 above the Dutch Wadden Islands, which were determined by Deltares. For these tests a scale model of a typical ULCS was tested at the scale of 1 to 63.2. These tests are reported in MARIN Report 31847-1-SHIPS ‘Behaviour of an Ultra Large Container Ship in shallow water’ and are published by the OVV[10] as part of their extensive investigations.



Different views of the tested model of an Ultra Large Container Ship (from MARIN Report 31847-1-SHIPS).

Based on these model tests, it was concluded that the most probable explanations for the loss of containers for the tested Ultra Large Container Ships (ULCS) in the investigated harsh weather conditions are:

1. Extreme (wave-frequency) ship motions and accelerations
2. Ship contact with the sea bottom
3. Lifting forces and impulsive loading on containers due to green water
4. Slamming-induced impulsive loading on the hull.

It should be noted that these phenomena cannot be separated and can be experienced by the ship in combination. Based on these test results and calculations, the OVV issued an intermediate warning regarding the TSS Terschelling-German Bight on October 31, 2019: “Based on preliminary results of

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[9] *Category of container ships able to transport 10,000 containers or more*

[10] *Reports can be found at: https://www.onderzoeksraad.nl/en/page/13223/safe-container-transport-north-of-the-wadden-islands.-lessons-learned*

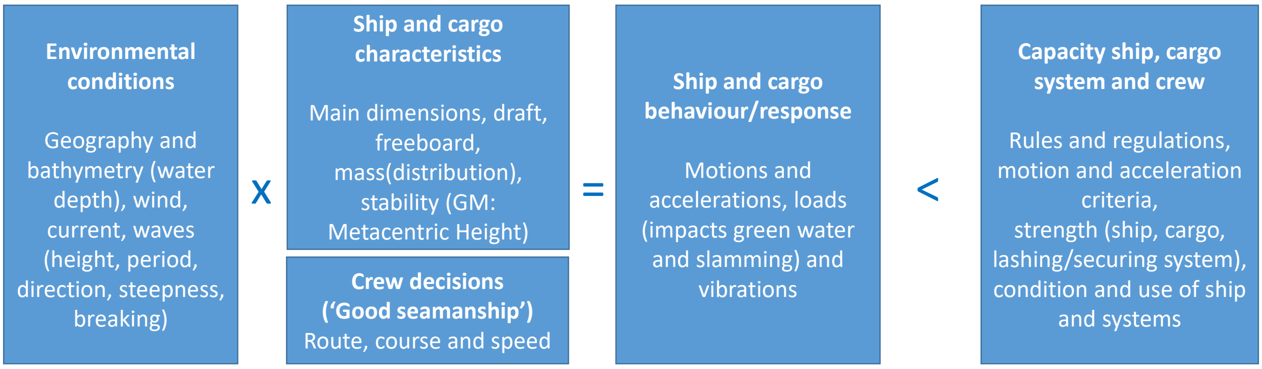
model calculations and scale model testing, it appears that certain wind and wave conditions as well as tidal conditions can result in large heave and roll motions, which affect the safe distance between the ship and the seabed. For ships with dimensions similar to those of the MSC Zoe, there is a risk of contact or near contact with the seabed”. Following this intermediate warning, the Dutch Ministry of Infrastructure and Water Management requested MARIN to investigate the behaviour of a wider range of container ships sailing north of the Dutch Wadden Islands, and advise the Ministry in the process of policy-making related to the access to shipping routes in the area.

1.2 Objectives

The Ministry of Infrastructure and Water Management has the objective to prevent loss of containers above the Wadden Islands in the future. This may require changes in policy, procedures, regulation and legislation, both nationally and internationally. MARIN was asked to support the Ministry in its substantiated decision-making based on factual information with its maritime expertise, calculation tools and facilities.

As shown above, the previous model tests gave indispensable insight in the mechanisms that can lead to the loss of containers above the Wadden Islands. However, the tests were only performed for one single ULCS-sized ship, in weather conditions representative from those encountered by the MSC Zoe on January 1 and 2, 2019. To assist the Ministry in fulfilling its objectives, a broader look on ship sizes, environmental conditions and their mutual relationship was required.

As shown schematically in the figure below, ship behaviour in storm conditions is a result of the interaction between the environmental conditions and the characteristics of the ship with its cargo. The ship response can be influenced by the decisions of the crew with respect to route, course and speed (‘Good seamanship’). A ship and its cargo are safe when their behaviour and loads are below the capacity (safe values) of the design. Damage can occur and containers can be lost when the loads on the ship and cargo exceeds the (structural) capacity of the cargo and/or its securing equipment.



So the main question of the present investigation was:

Which combinations of environmental conditions (that occur above the Wadden Islands) and ship types (that sail above the Wadden Islands) result in such ship behaviour/response that the containers and their securing equipment (lashings) might fail, so that they are lost in the sea?

The present report describes the first step in the further investigation of this question. In this analysis we are focussing on the effect of the four (coupled) mechanisms in the ship behaviour/response for three ship types: ultra large container ships (ULCS) with lengths of up to 400 metres, like the MSC ZOE, a shorter and narrower Panamax, nearly 300 metres long, and a smaller container feeder with a length of 160 metres. The importance of testing smaller ships was underscored when the feeder ‘Rauma’ lost 7 containers on February 11th 2020 in a significant wave height of approximately 4.5 to 5m.

The feeder 'Rauma' lost 7 containers on February 11th 2020 (Source: Netherlands Coast Guard).

1.3 Reports

In order to meet these objectives MARIN has performed desk studies, calculations and model tests. They are reported in separate reports:

- Scale model tests in a wave basin to estimate the seaworthiness of three classes of container ships (delivered in Report 32558-2-OB).
- Seakeeping calculations to extend the study including parameters partially or not covered by the model tests, such as loading conditions, wave heading (delivered in Report 32558-3-SEA).
- Finite element calculations of green water loading to determine the maximum allowable loads on a 40 feet Container (delivered in Report 32558-4-PaS)
- Analysis of the present status of cargo securing requirements and criteria to determine applicable criteria for the ship sizes considered in the study (delivered in Report 32558-5-PaS).

This report provides a summary of the findings of the complete study and provides the derivation of preliminary limiting wave heights for the three containerships investigated (ULCS, Panamax and Feeder) in the southern (Terschelling-German Bight TTS) and northern sailing route (East-Friesland TSS) along the Dutch Wadden Islands. For details reference is made to the reports above.

1.4 Assumptions

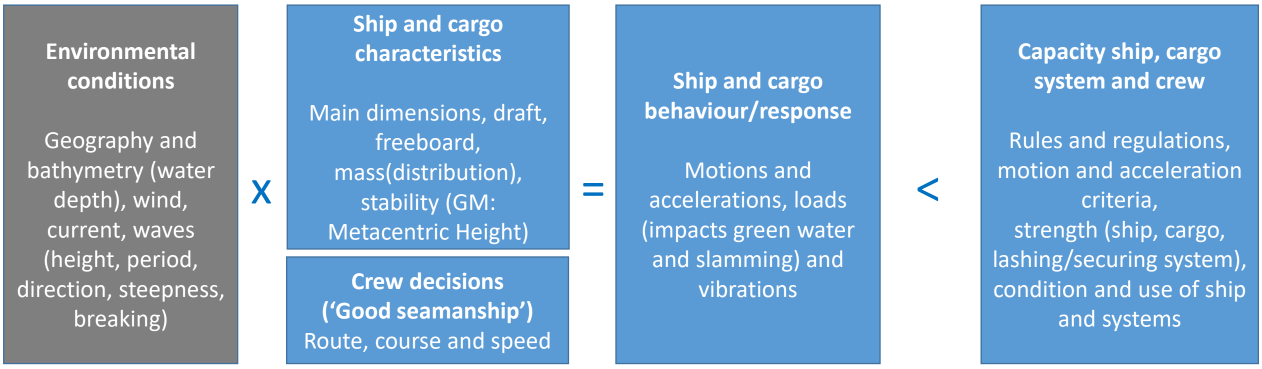
It should be noted that the investigations are carried out under the following assumptions:

1. The present study focusses on the behaviour of the ships in realistic (short-crested) wave conditions and shallow water. In MARIN Report 31847-1-SHIPS 'Behaviour of an Ultra Large Container Ship in shallow water' it was shown that the effects of tidal current and wind were relatively small.
2. The influence of the ship flexural response on local accelerations was not taken into account: the ship was assumed to be of infinite rigidity.
3. The dynamic and structural behaviour of the container stacks with their lashings was not investigated in detail. It is also assumed that all systems are in good order and used properly.
4. All seakeeping calculations are performed using a linear seakeeping model in combination with a stochastic linearization procedure for roll damping verified and if necessary calibrated to the model test findings.

2 ENVIRONMENTAL CONDITIONS ABOVE THE DUTCH WADDEN ISLANDS

2.1 Environmental conditions

This Chapter summarizes the specific environmental conditions above the Wadden Islands and their contribution to the risk of losing containers close to this Particularly Sensitive Sea Area (grey block):



Environmental conditions
Geography and bathymetry (water depth), wind, current, waves (height, period, direction, steepness, breaking)

x

Ship and cargo characteristics
Main dimensions, draft, freeboard, mass(distribution), stability (GM: Metacentric Height)

Crew decisions (‘Good seamanship’)
Route, course and speed

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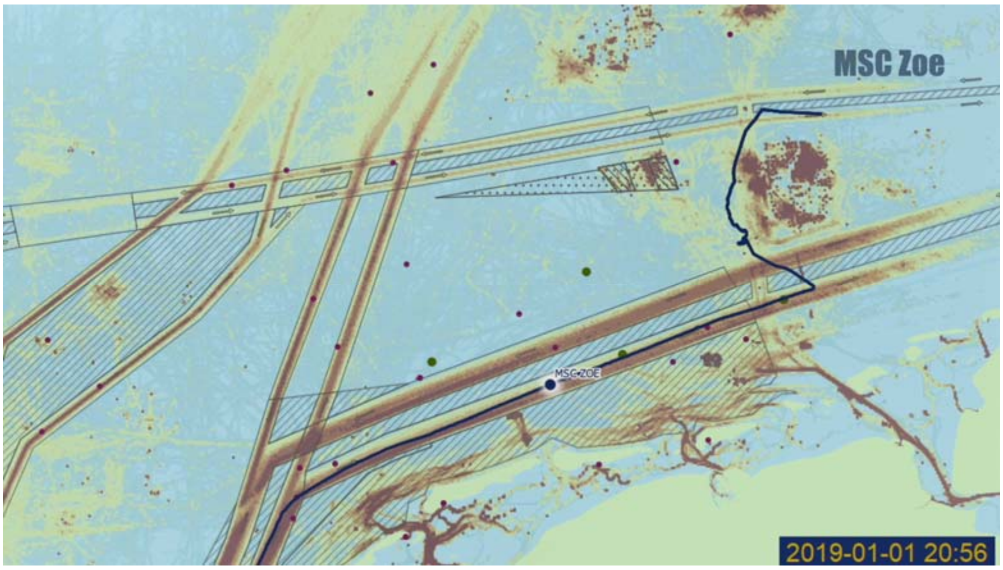
Ship and cargo behaviour/response
Motions and accelerations, loads (impacts green water and slamming) and vibrations

<

Capacity ship, cargo system and crew
Rules and regulations, motion and acceleration criteria, strength (ship, cargo, lashing/securing system), condition and use of ship and systems

2.2 Routes and water depths

The Figure below shows the track of the MSC ZOE on January 1 and 2 of 2019, following the southern (Terschelling-German Bight TTS) route until container damage was notified in the early morning.



AIS track of the MSC ZOE on January 1 and 2 of 2019

The present study considers both the southern (Terschelling-German Bight TTS) and northern sailing route (East-Friesland TSS) along the Wadden Islands, as depicted in the Figure below. The compass direction of the southern route is about 70^0 or 250^0. The northern route has a direction 80^0 or 260^0 depending on the direction of sailing. The ship heading is thus only slightly different between the two routes, so that, given a particular storm direction, the relative ship heading can be considered equal on both routes. At several locations the water depth on the route is given (chart datum LAT, Lowest Astronomical Tide)[11].

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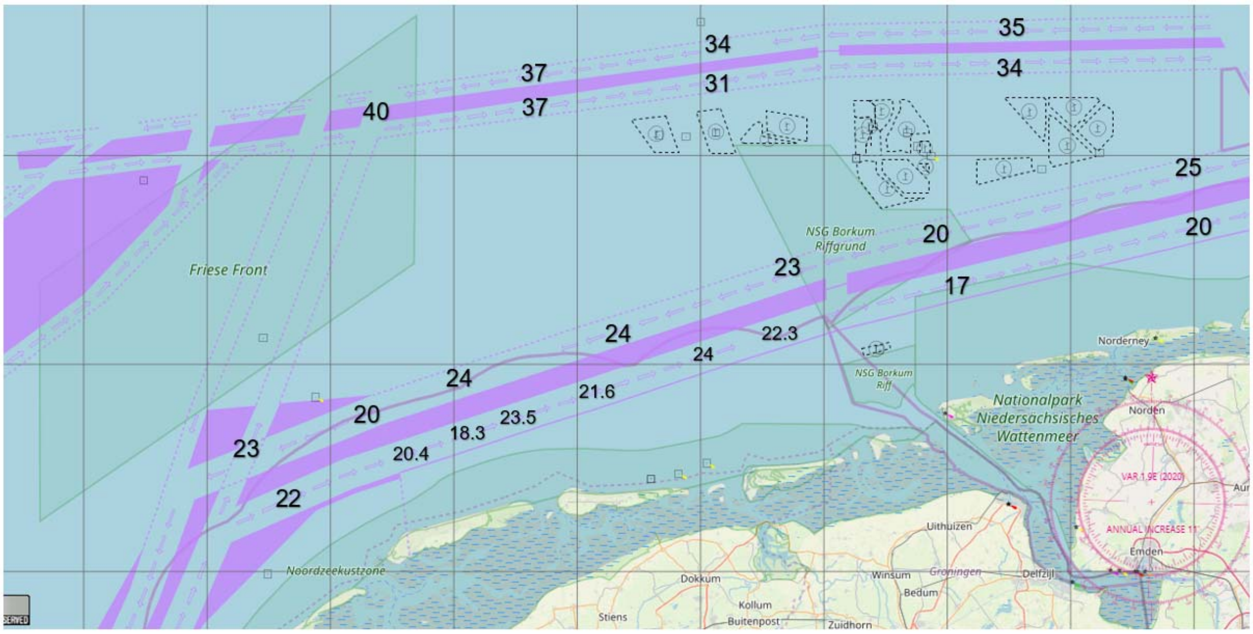
[11] *Data is taken from an electronic chart (Navionics) and verified with ‘Atlas Nederland, NL 1, 2019, published by NV charts. Local depth changes due to wrecks are not included in our summary.*



Area of interest with traffic routes.

The water depth on the sailing route varies over time, mainly due to the tidal water movements. The bathymetry along the routes varies as well. The northern sailing route is almost twice as deep as the southern route.

Following MARIN Report 31847-1-SHIPS, that focused on the conditions on January 1 and 2 of 2019, the present calculations and model tests were performed for three water depths:

- 21.3 m, the minimum water depth on the southern sailing route during the MSC ZOE accident.
- 26.6 m, the maximum water depth on the southern sailing route during the MSC ZOE accident.
- 37.5 m, considered representative for the water depth on the northern route.

It should be noted, however, that at other locations along the route (for instance in the German part of the southern route) and in other tidal conditions even lower water depths can occur. This requires further investigation as part of a (statistical) risk analysis that takes into account the long term distribution of environmental conditions (bathymetry, tides, wind and waves) and ship types sailing in the area.

2.3 Metocean conditions

The sea area above the Dutch Wadden Islands is characterised by a low water depth. In north-westerly storm conditions the sea state can build up over a relatively long period of time and due to the long fetch this can develop into high sea state conditions with long(er) wave periods. This in combination with the limited water depth results in complex, non-linear wave behaviour that manifest itself in sea state with steep, sometimes breaking, crests and long flat troughs. Such specific conditions have a clear effect on the seakeeping behaviour of ships sailing in this area.

To assure that realistic waves conditions are used for the present calculations and tests, the wave conditions (significant wave height, peak period, spectrum shape) were obtained from hindcast data of the ERA5 database[12] for the L9 offshore platform[13].

The wave scatter diagram for the winter period (all wave directions) is shown in the Figure below. It can be seen that the most recurring conditions are (significant) wave heights of 1 to 3 m in combination with

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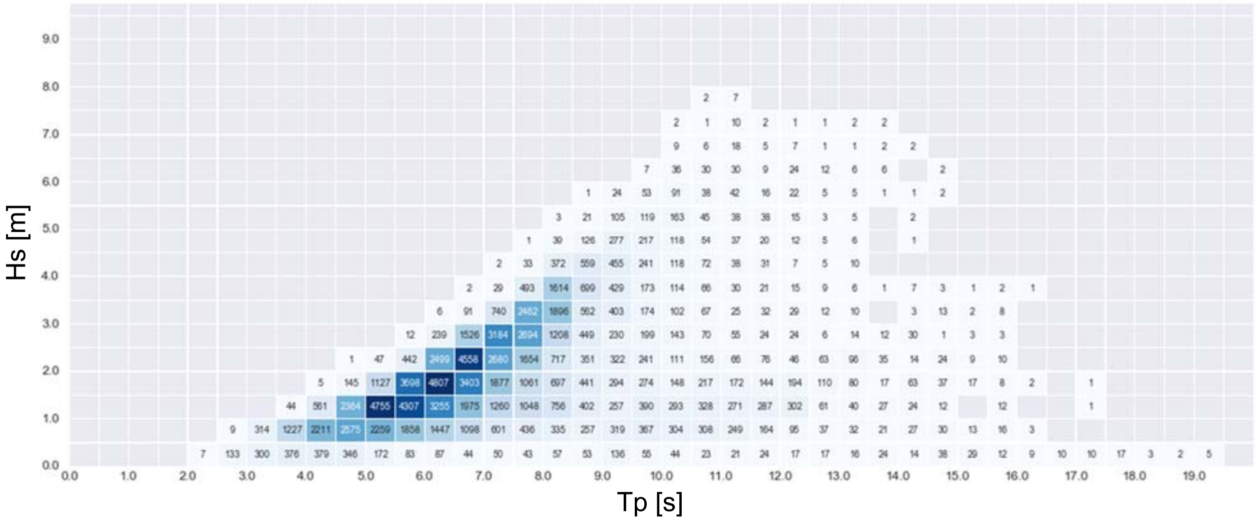
[12] *https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5*

[13] *Located 20 NM north of Vlieland, coordinates [53.61383°N / 4.960895°E.]*

peak periods of 5 to 7.5 s. The highest storm conditions had a significant wave height of 8 m with peak period 11 s.



Wave scatter diagram from 40-year ERA5 hindcast data for platform L9 – Dec. till Feb.

From the scatter diagram the significant wave height cumulative probability distribution is calculated from which the long-term return period sea state height can be derived. These are listed in the Table below, together with the associated most probable wave peak period of the wave spectrum. The peak enhancement factor (gamma) is based on the wave analysis carried out by Deltares for the specific conditions occurring during the MSC ZOE accident. Apart from the most probable wave period, the scatter diagrams is used to derive the 95% occurring wave period range conditional on a certain wave height.

The results derived from the ERA5 database were used to assure the correct wave period and wave height ranges for the present study. For a (most realistic) risk assessment the combination of water depth and sea state conditions is needed, in combination with statistical probabilities of the wave enhancement factor for which now industry practise is applied. As well, the non-linearity of the sea states requires more attention. For such a detailed metocean study the involvement of Deltares is recommended.

Return period (year)	Hs (m) (approx.)	Tp (s) (most probable)	Gamma (estimated)
1.0	6.5	11.5	1.5
2.0	7.0	12.0	1.5
5.0	7.25	12.25	1.5
10.0	7.5	12.5	1.5

Hs level (m)	95% range Tp occurring (s) S to W to N wave direction
> 7	10.3 to 14.3
6 to 7	9.7 to 14.2
5 to 6	8.8 to 13.4
4 to 5	8.0 to 12.0
3 to 4	7.1 to 11.5

Metocean summary table, return periods and most probable wave period ranges

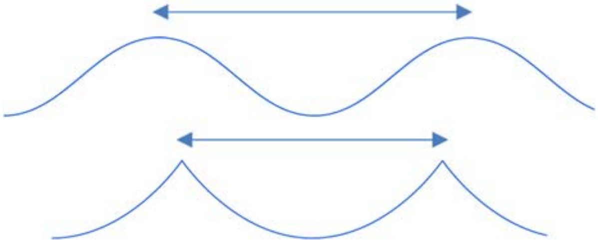
2.4 Characterization of shallow water waves

Water waves are gravity waves that may be determined by their height (vertical distance between a crest and a trough), length (distance between two crests) or wave period (time between the passing of two crests) and direction of propagation.

At sea the waves have an irregular character. This character is usually described by a wave spectrum, which specifies the distribution of waves of different amplitudes and periods. This spectrum is determined by a significant height (Hs), a peak period (Tp) and a shape. The type of spectrum (e.g. Bretschneider), possibly completed by a peak enhancement factor define the spectral shape. For the present investigation MARIN was provided spectral information of the different wave conditions and a wave calibration phase was carried out so that the spectrum derived from the measured wave train matched the specifications.

Deep water waves, found in water deeper than approximately half of the wave length, may be described as of sinusoidal shape, with the wave crests equally distant from the undisturbed free surface as the wave troughs. Their speed, or celerity, is related to the wave period: waves of small length (or short waves) travel slower than longer waves.

Shallow water waves, found in areas of depth lower than half the wave length, are waves that experience the influence of the sea bottom. Low waves on shallow water do have a sinusoidal shape like in deep water but the wave orbital trajectory and wave velocities are different. With increasing wave height the non-linearity increases more rapidly than in deep water leading to pronounced different wave shapes than deep water waves: they feature narrower, higher crests and flatter, less pronounced troughs. This means that the wave crests are more likely to break than deep water waves. For the same wave period, the length of a shallow water wave is smaller than that of a deep water wave. These features are illustrated in the Figure below. In addition, shallow water waves travel slower than deep water waves.



Deep water wave (above) and shallow water wave (below) with definition of wave length

In these conditions also wave breaking occurs, resulting in wave crests falling forward at high velocity. These dangerous shallow water waves are well-known to crews sailing regularly in the area. The pictures below visualize steep wave breaking phenomena above the Wadden Islands.

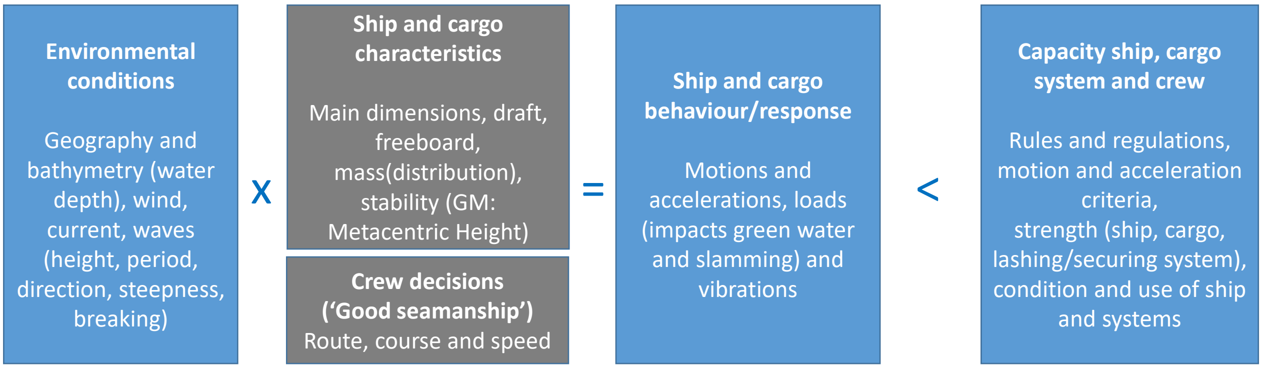
Example of wave breaking at the L09 Platform (source: Flying Focus)

Example of wave breaking above Borkum (source: Flying Focus)

3 SELECTION OF CONTAINERSHIPS SAILING IN THE AREA

3.1 Ship and cargo characteristics

This Chapter summarizes the typical characteristics of containerships sailing above the Wadden Islands, selected for the present investigations (grey block):



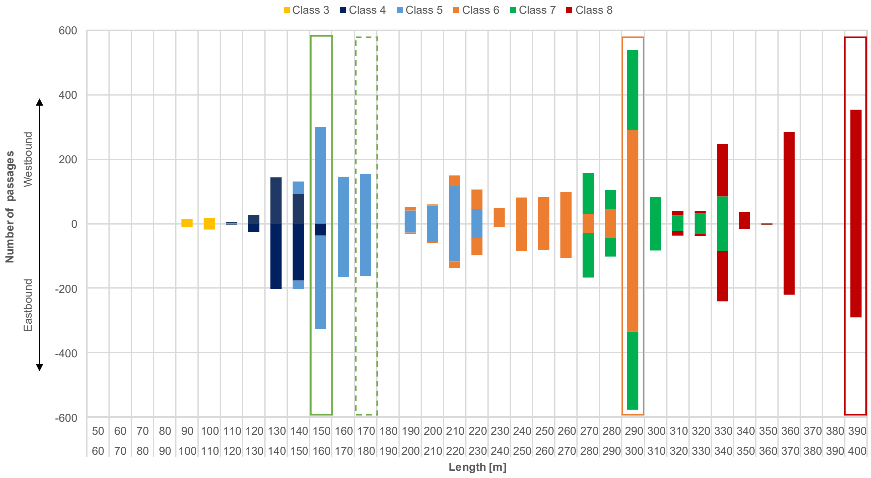
More details can be found in Report 32558-2-OB.

3.2 Results of network analysis

An important prerequisite for the study was to identify the range in size and loading condition of the container ships that sail in the area above the Wadden islands. This was done using the following source of information:

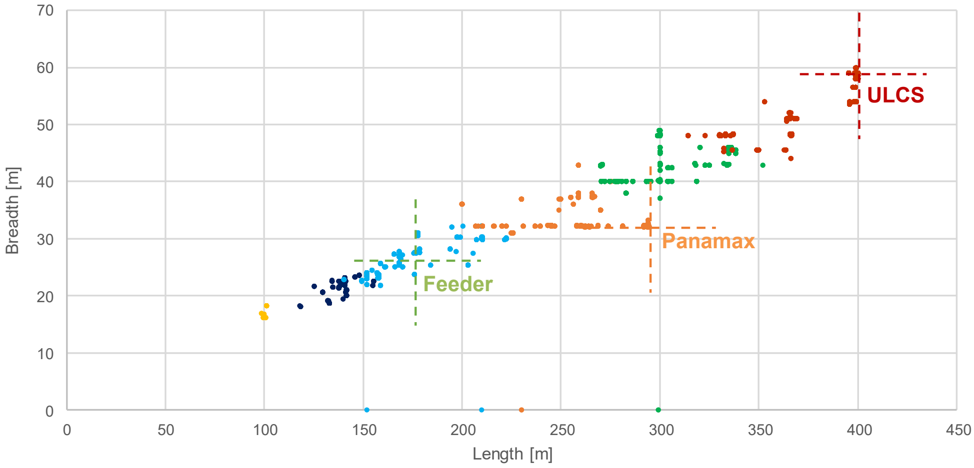
- Network analysis on the Terschelling-German Bight TSS (southern route) and East Friesland-German Bight TSS (northern route) for the period 2018-2019, filtered on container vessels.
- Database of ship models of MARIN, filtered on container vessels.
- Database of sailed scenarios at the MARIN bridge simulator.

The network analysis gave insight in the size of container ships passing on the southern and northern routes, as shown in the Figure below. In the Figure three main size clusters stand out: feeder ships of length 130 to 180 m, intermediate ships of length 260 to 300 m and Ultra Large Container Ships (or Post-Panamax container ships) of size 330 to 400 m. For each category the peak length is highlighted by a plain, coloured rectangle.



Number of passages of container ships on the Terschelling-German Bight TSS, by length from network analysis, period 2018-2019. Length is length over all (LOA).

Further exploration of the network analysis, together with the database of scale models, shows that for the first and the last of the above mentioned clusters of ship sizes, the breadth increase linearly with the length. In the second cluster fall a large part of Panamax ships with a breadth of 32.2 m, which is limited by the width of the Panama canal. Hence the trend line for this category is seen to be dominantly horizontal.



Ship breadth versus length from network analysis, with selected particulars for the three ships

From this analysis it was concluded that the traffic of container ships along the two routes above the Wadden islands may be represented by the following three ships:

- Feeder ship of length over all 160-170 m and breadth 27 m
- Panamax ship of length over all 290-300 m and breadth 32.2 m
- Ultra Large Container Ship of length over all 390-400 m and breadth 59 m

The different categories of ships are illustrated in the Figure below.

ULCS “BARZAN” Panamax “ORCA I” Feeder ship “WES JANINE”

Three ship categories as commonly found above the Dutch Wadden Islands, source: www.marinetraffic.com, www.porttechnology.org

Based on a review of publically available data and MARIN’s own data bases (see Report 32558-2-OB) the following weight and stability data were selected for the present investigations:

Feeder	
Description	**Magnitude**
LPP (m)	163.0
B (m)	27.0
T (m) (TA=Tm=TF)	9.20
Displacement (ton)	29500
C_B (-)	0.710
LCB (m) and LCG (m) from AP	78.20
Freeboard at bow bulwark (m)	8.0
Freeboard mid ship (m)	3.0
Bilge keel height (m)	0.40
Bilge keel length (m)	48.8

Panamax	
Description	**Magnitude**
LPP (m)	278.0
B (m)	32.20
T (m) (TA=Tm=TF)	12.20
Displacement (ton)	70324
C_B (-)	0.63
LCB (m) and LCG (m) from AP	134.791
Freeboard at bow bulwark (m)	14.80
Freeboard at mid ship (m)	9.20
Bilge keel height (m)	0.40
Bilge keel length (m)	77.5

ULCS	
Description	**Magnitude**
LPP (m)	379.40
B (m)	59.00
T (m) (TA=TF)	12.40
C_B (-)	0.66
LCB (m) from AP	190.77
DISPLACEMENT (ton)	188449
Bilge keel height (m)	0.40
Bilge keel length (m)	102.8

Three vessel sizes – principal dimensions

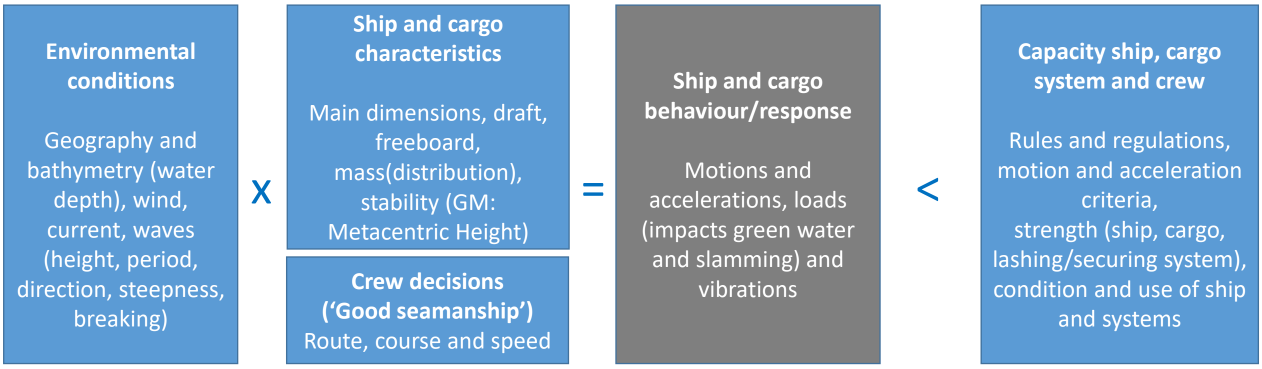
The three models used for the present model testing are shown below:

Vessels tested at MARIN: ULCS, Panamax and Feeder

4 SEAKEEPING BEHAVIOUR IN SHALLOW WATER

4.1 Ship and cargo behaviour/response

This Chapter summarizes the typical behaviour of containerships and cargo in the conditions above the Wadden Islands, which may lead to the loss of containers (grey block):



Environmental conditions

Geography and bathymetry (water depth), wind, current, waves (height, period, direction, steepness, breaking)

x

Ship and cargo characteristics

Main dimensions, draft, freeboard, mass(distribution), stability (GM: Metacentric Height)

Crew decisions (‘Good seamanship’)

Route, course and speed

=

Ship and cargo behaviour/response

Motions and accelerations, loads (impacts green water and slamming) and vibrations

<

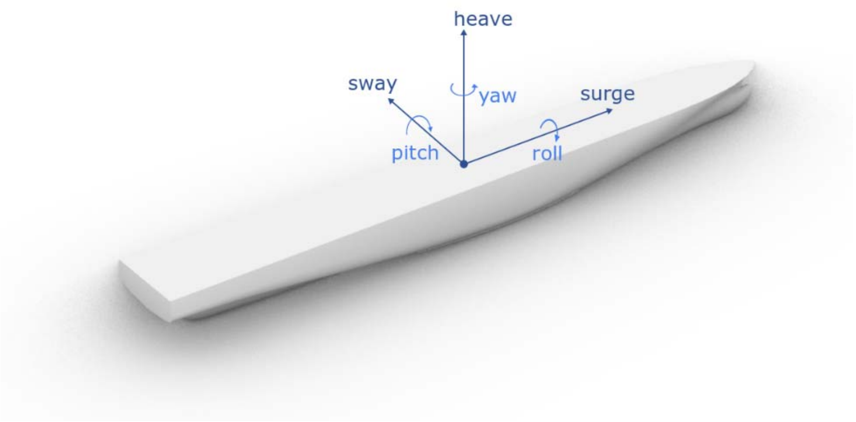
Capacity ship, cargo system and crew

Rules and regulations, motion and acceleration criteria, strength (ship, cargo, lashing/securing system), condition and use of ship and systems

More details can be found in Report 32558-2-OB and Report 32558-3-SEA.

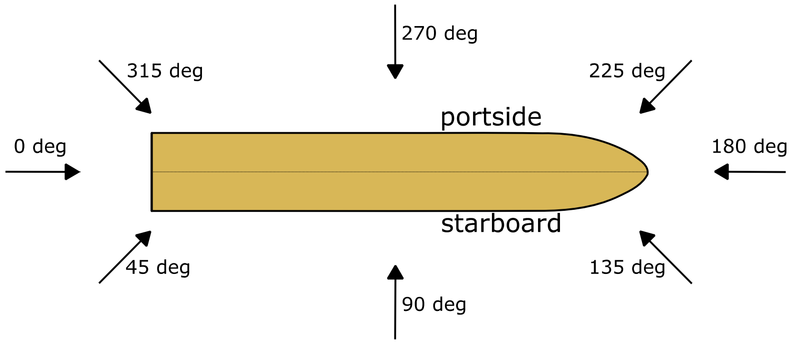
4.2 Short introduction in ship seakeeping

A ship in waves moves in six degrees of freedom (6-DOF):



Ship motions in six degrees of freedom

And the wave directions are defined as follows:



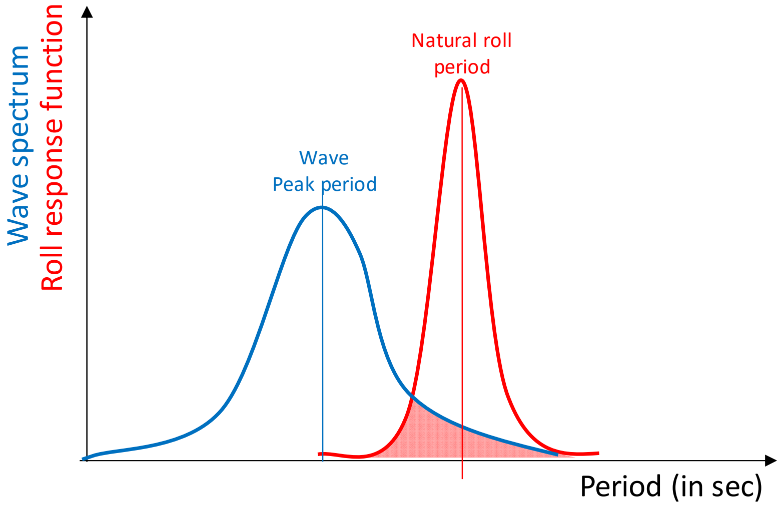
Wave heading convention

Traditionally, the motions of the ship are described by the extended version of Newton’s second law showing that they will be the result of a balance between excitation forces coming from the waves and the inertial forces, damping forces and restoring forces:

$$\underbrace{\boxed{M \times \ddot{x}}}_{\text{Mass x Acceleration}} + \underbrace{\boxed{B \times \dot{x}}}_{\text{Damping x Velocity}} + \underbrace{\boxed{C \times x}}_{\text{Stiffness (or stability) x Motion}} = \underbrace{\boxed{F}}_{\text{Wave forces (wave height en period)}}$$

Equation of motion in one degree of freedom

As a result, a ship behaves like a mass-spring-damper system. Such system always have a natural period. For the roll motion it is the period the ship rolls naturally after it is excited by an external force. At this period, the ship reacts strongly on the waves, at other wave periods the response is less. We express this by means of a response function, as shown in a simplified way in the Figure below (red). The response function (or Response Amplitude Operator, RAO) defines the relation between the input wave and the output motion response. The shaded area below the wave spectrum and response function determines the reaction of the ship in a certain sea condition.



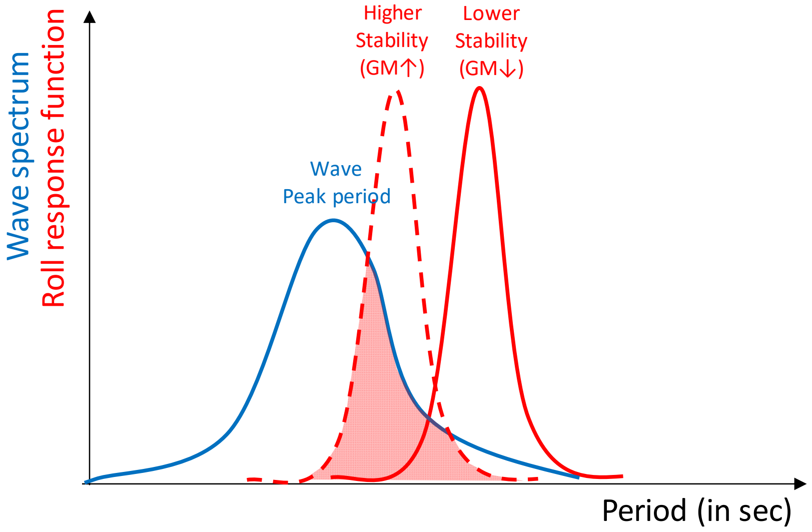
The shaded area below the wave spectrum (blue) and response function (red) determines the reaction of the ship on the wave spectrum

The natural roll period of a ship (T_φ) is strongly dependent on the transverse stability and ~~transverse~~ mass distribution of the ship. The initial stability of a ship is defined by its metacentric height (GM). The stability of a ship increases with the GM value (meaning, it requires a larger external moment to list the ship to a certain roll angle). The transverse mass distribution is described by the radius of gyration along the x-axis, often expressed by the k_{xx}. The natural roll period can then be determined as follows (when the kxx is corrected for the added mass due to oscillations):

$$T_\varphi = 2\pi \sqrt{\frac{k_{xx}^2}{g\ GM}}$$

So, with a larger stability (larger GM), the natural period becomes shorter. Depending on the wave period in the area, this will result in a different roll motion response of the ship, as explained in the figure below.

For all three containerships, the natural roll period for the low GM case is well outside the occurring wave periods in the area of concern, and to be specific, those low GM ships have a *longer* natural roll period. This implies a uniform trend for all (studied) containerships: with increasing GM the ship roll motions will increase.



The effect of a shorter natural period of a ship with the higher initial stability (GM value) on the motion response in the same seastate.

4.3 Summary of previous findings

In MARIN Report 31847-1-SHIPS ‘Behaviour of an Ultra Large Container Ship in shallow water’, published by the OVV[14], it was found that the following four phenomena together may lead to the loss of containers above the Wadden Islands in shallow water and high (breaking) waves for Ultra Large Container Ships (ULCS) such as the MSC ZOE:

1. Extreme (wave-frequency) ship motions and accelerations

60 metre-wide (ULCS) containerships like the MSC ZOE are very stable with relatively short natural periods. When a force is applied to them they want to return to their upright equilibrium position quickly. This results in a short natural period at which the ship starts to roll as it is brought into motion by an external force. For the present generation of ultra large containerships this natural period can be between 15 and 20 seconds, which comes close to the wave periods that occur above the Wadden Islands during north-westerly storms. As a result, roll resonance can occur, causing heeling angles of up to 16 degrees. So, although they are stable, these large containerships can roll strongly. This causes large accelerations and forces being applied to the containers that can exceed safe design values. The transverse accelerations are in beam seas very similar from bow to stern. It is to mention that the shallow water conditions above the Wadden shorten the wave length and increase the wave slope: conditions that increase roll motions compared to less steep deep water waves.

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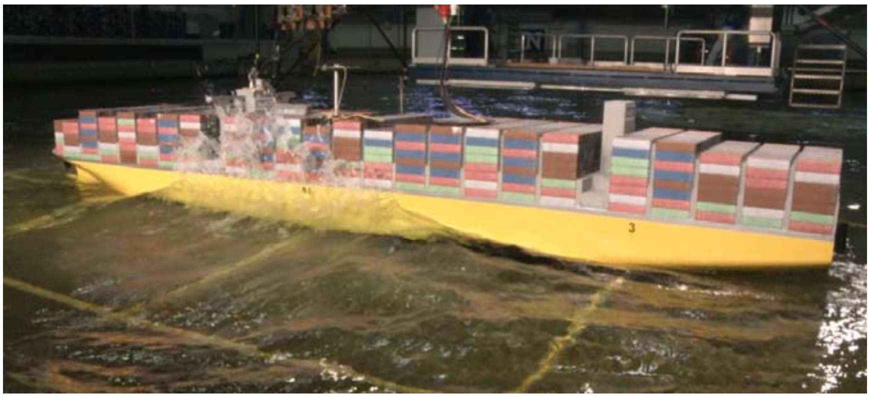
[14] *Reports can be found at: https://www.onderzoeksraad.nl/en/page/13223/safe-container-transport-north-of-the-wadden-islands.-lessons-learned*

2. Ship contact with the sea bottom

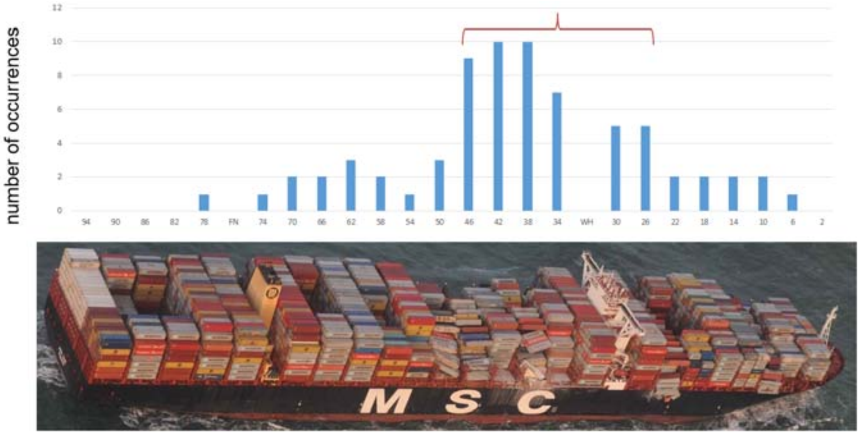
In beam waves, the ULCS does not only roll from side to side, but also heaves up and down many vertical metres. With a large draft of around 12 metres in a water depth of only 21 metres, there is very limited under keel clearance between the ship and the seabed: less than 10 metres. As a result of the combined rolling and heaving, a wide ship with a large draft can touch the seabed. When this happens, shocks and vibrations can occur in the ship, containers and lashings. The lashings can fail as a result.

3. Impulsive green water loading against the containers

In the very shallow water above the Wadden Islands, breaking waves can hit the side of the ship, resulting in a large upward jet of water reaching the containers, which are 20 to 40 metres above the surface of the sea. We call this ‘green water’, as it is massive sea water, not just white foam in the wind. This massive green water hits the bottom and the side of the containers. These can become damaged as a result, but complete stacks of containers can also be pushed over like dominos. Breaking waves can hit the side of the ship, resulting in a large upward jet of water, up to the containers 20 to 40 metres above sea. This can damage containers or push over container stacks like dominos.

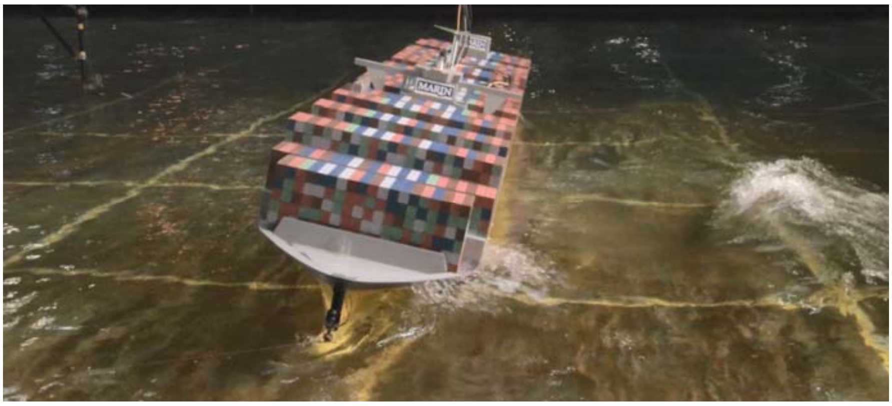


If we compare the locations on the ship where green water impacts are observed with the damaged rows of containers on the ship (MSC ZOE), we see a clear correlation. It is therefore probable that green water impacts played a role in the loss of the containers.



4. Slamming induced impulsive loading on the hull.

Finally: the hull of the ship was also hit by breaking waves. This can result in (high-frequency) vibrations throughout the ship, damaging containers and lashings. The container tiers are not connected to each other apart from the lowest rows on deck. Hull vibrations thus lead to very complex cargo behaviour that is well outside the scope of the present investigations, but such dynamics are envisioned to increase the local structural loads considerably.



4.4 Present model test scope of work

These four phenomena can also be critical for other ship types. As presented in the previous chapter, MARIN has advised the Ministry of Infrastructure and Water Management to conduct further investigations of three ships types: beside the ultra large containerships of almost 400 metres like the MSC ZOE, also a shorter and narrower Panamax, nearly 300 metres and a smaller container feeder with a length of 160 metres.

Further the instrumentation of the ship models has been extended with the measurement of relative wave motions along the ship and the green water impacts on the containers. The scope of work is summarized below, further details can be found in Report 32558-2-OB:

- Three ships sizes covering the range of container ships sailing in the area.
- Rigid wooden hull models. Instrumentation of each model for motion measurements, accelerations, relative wave motions and green-water loading impacts. In the previous series, green water was not measured specifically. In total 22 impact panels were used: partially vertical (under the containers) and partially horizontal (side of the containers). The size of the force

panels was 5x5cm model scale, 3.16x3.16m full-scale (area of 10m^2 full scale).The location of a number of the aluminium force panels on the ULCS is shown in the Figure below:

- A range of water depths from 21 m (Terschelling-German Bight TSS) to 37,5m (East Friesland TSS, also referred to as northerly deep water route).
- A range of wave heights and periods typical for the area north of Dutch Wadden Islands.
- A range of typical GM (stability) values.
- Different wave directions (beam, bow quartering, stern quartering). In the previous series only beam waves were tested.
- Different vessel speeds. Because of the limited length of the basin, the testing will be a combination of long term zero speeds tests (3 hours) for enough statistical data and forward speed runs.

The present model tests give insight in the importance of each mechanism based on the combination of ship size, water depth and environmental condition. This is the first objective of the tests.

The second objective of the tests is to provide validation and tuning data for the calculations, so that a wider range of ships and conditions (such as stability data) can be investigated numerically.

4.5 Summary of the present results for an ULCS, Panamax and Feeder

Detailed results of the model tests can be found in Report 32558-2-OB. Below a short review is given of the most important results for the ULCS, Panamax and Feeder, with the focus on the three most important phenomena determined in the previous phase:

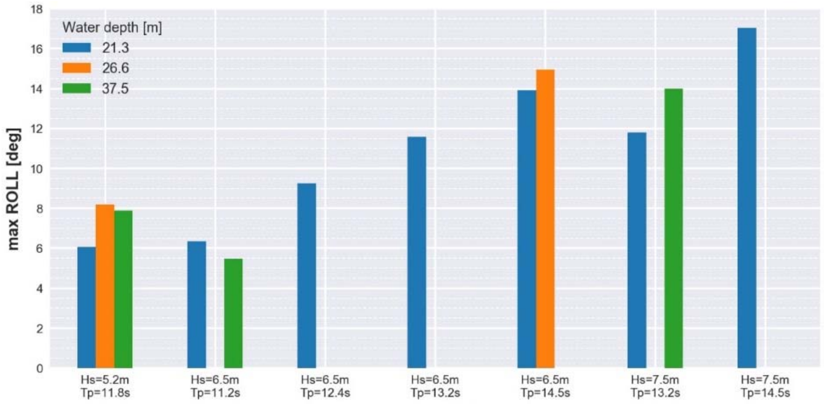
1. Extreme (wave-frequency) ship motions and accelerations
2. Contact with the seabed
3. Impulsive green water loading against the containers

The 4th mechanism, slamming induced impulsive loading on the hull, could not be quantified with the present model tests. The estimate of the vibrations and accelerations resulting from wave slamming is an extremely complex task as it requires a correct modelling (numerically or in the basin) of the flexural response of the vessel, including both natural periods and damping. In the case of model tests, this can be done for the natural periods using scale models consisting of several segments (connected with each other by an aluminium beam with suitable properties). This was outside the scope of work of the present model tests. Although it is assumed that the three phenomena above are dominant in the loss of containers above the Wadden Islands, this issue should not be forgotten in future investigations.

4.5.1 Extreme (wave-frequency) ship motions and accelerations

<u>Ultra Large Container Ship (ULCS)</u>
Considering a loading condition with a GM of 9 m the vessel exhibits a natural roll period of 17.2 s at a water depth of 21.3 m. Such period is relatively close to the range of wave periods that are encountered in the North Sea.

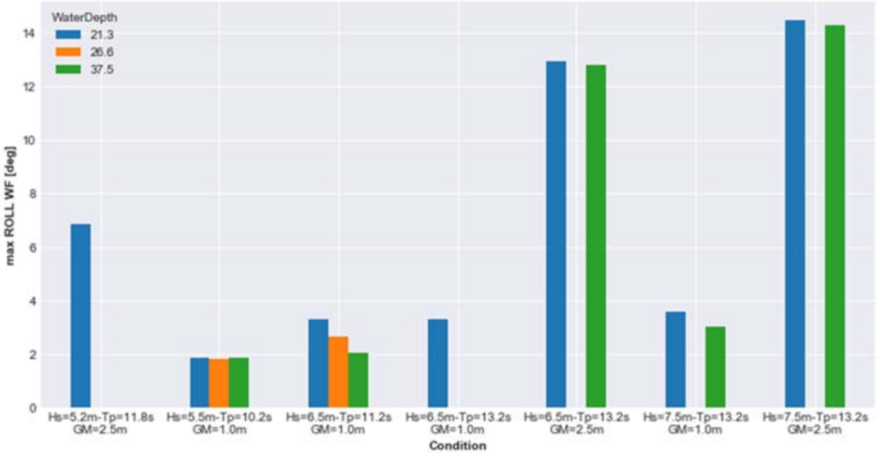
In beam waves of significant height 6.5 m the ship exhibits a rolling behaviour with (maximum) amplitudes up to 16 deg. When the wave height is increased to 7.5 m the amplitudes reach 17 degrees, see the figure below:



Largest amplitudes of roll (Vs = 0 kn)

Motion-induced transverse accelerations on deck reach a maximum amplitude of 3.9 m/s^2 in 6.5 m high beam waves. At the top of tier “8”[15] the transverse accelerations reach 4.6 m/s^2. Vertical accelerations up to 3.6 m/s2 were measured at the ship side in 6.5 m high beam waves.

<u>Panamax</u>
A scale representation of a Panamax ship was tested with GM values of 1.0 m and 2.5 m. Under these conditions the natural roll period was 29.0 and 18.4 s, respectively. This indicates that under the higher GM condition the ship may be sensitive to direct roll excitation from oblique or side waves.
The roll response of the ship in beam waves of significant height 5.5 to 7.5 m was such that maximum amplitudes of 7.5 to 15 deg were observed. Such motion was observed under a loading condition with GM = 2.5 m, see the Figure below:



Largest amplitudes of roll (Vs = 0 kn)

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[15] *Note that our tier numbering in the report is not aligned with the tier numbering seen in the ship cargo stowage plans (where tier 80 is usually the first container tier on deck). Our tier 1 is the lowest container on deck, and e.g. tier 8 refers to the 8th container vertically above deck.*

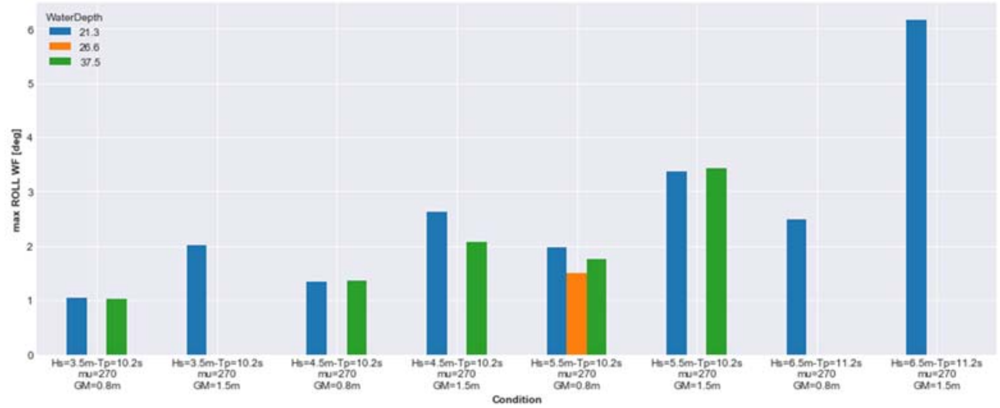
At the lower GM (1 m) the direct roll response is negligible, however some roll response as the result of second order wave excitation (wave groups) may be expected. This was left outside the scope of the present tests and calculations.

The largest transverse accelerations on deck were found to be 3.5 m/s^2 in 6.5 m high waves. The vertical accelerations are found to be largest at the container bays located far forward: 5 m/s^2 in 6.5 m high beam waves.

<u>Feeder</u>

A scale representation of a feeder ship was tested with GM values of 0.8 m and 1.3 m. Under these conditions the natural roll period, depending on the water depth, was 26 to 28 s and 18 to 20 s, respectively.

Because the tested conditions featured lower peak periods (shorter waves), the feeder ship showed a relatively limited roll behaviour; maximum amplitudes of 7 deg. It is expected that the behaviour will worsen when the ship is exposed to longer waves or sails with forward speed in stern-quartering waves. The roll motions are shown in the Figure below:



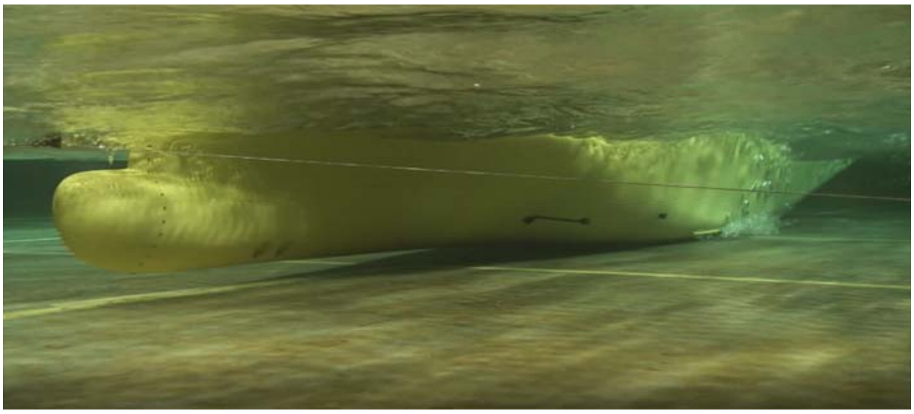
Largest amplitudes of roll (Vs = 0 kn)

The transverse acceleration at deck locations peaks at 2.5 m/s^2 in 5.5 m high waves and 3.7 m/s^2 in 6.5 m high waves. Those at the highest tier (Tier “4”) reach 2.7 m/s^2 in 5.5 m high waves and 4.1 m/s^2 in 6.5 m high waves. Vertical accelerations on deck peak at 2.2 m/s^2 in 3.5 m high waves, up to 3.8 m/s2 in 5.5 m high waves and 4.3 m/s2 in 6.5 m high waves.

4.5.2 Contact with the seabed

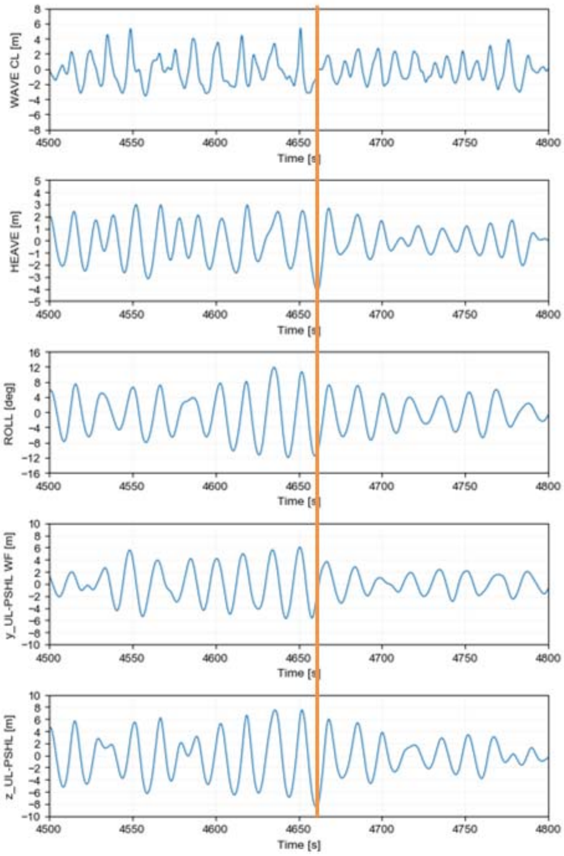
<u>Ultra Large Container Ship (ULCS)</u>

Underwater observations show that in most tested conditions the model hull comes repeatedly in the vicinity of the basin floor, as shown in the Figure below. At zero speed, in beam waves, the combined action of heave and roll leads the windward side of the ship to experience large vertical motions, much larger than what is observed at the ship bow or at the stern, or on the leeward side of the ship.



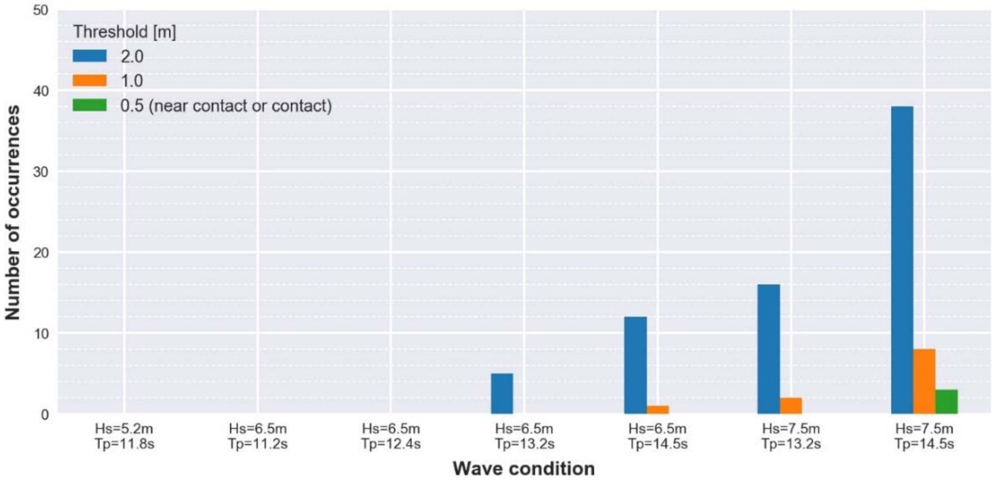
The model comes to a near contact with the basin floor, Hs = 6.5 m, Tp = 14.5 s, beam waves, zero speed

The area of the hull located amidships and slightly inward of the bilge keels is considered to be most exposed area to bottom contact (see Figure below, PSHL). The surge in occurrences noted for a same wave height but increasing peak period periods highlights the role of the roll motion in the behaviour.



Time traces of incident wave, heave, roll and transverse and vertical motion of the bilge area portside (Hs = 6.5 m, Tp = 14.5 s, wave direction=270 deg, Vs = 0 kn)

An analysis of the vertical motions of the ship port side during the tests at zero speed shows that in 6.5 m high waves, the bilge area comes regularly within 2 m of the basin floor, and a few times within 1 m. In such wave condition no actual contact with the basin floor were observed. The frequency of occurrence increases in 7.5 m high waves, one contact with the basin floor was noted in the condition with a peak period of 14.5 s.

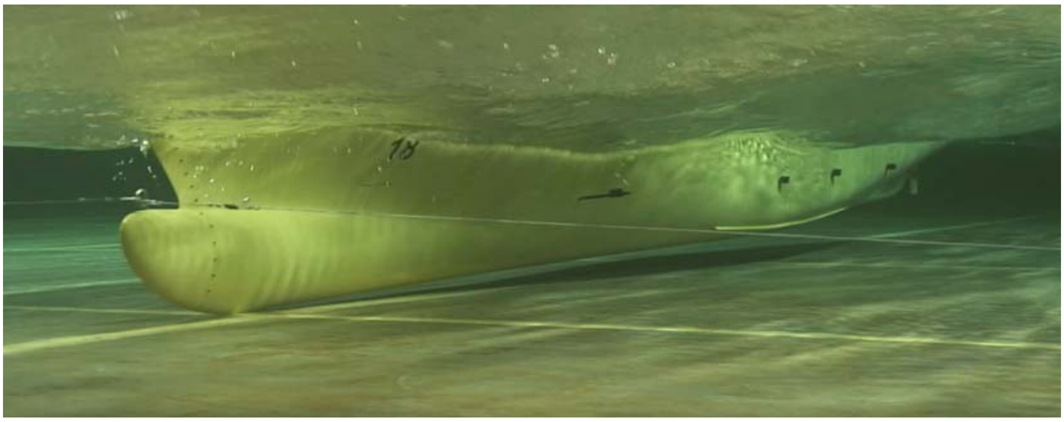


Number of occurrences of location PSHL coming within a given distance to or make a contact with the sea bed during a three-hour storm condition, Vs = 0 kn, beam waves

The tests at forward speed[16] confirm the findings of those at zero speed. In addition, tests performed at other headings (slightly bow-quartering and stern-quartering seas) show a lower risk of contact with the bottom.

It is concluded that, because of large heave and roll amplitudes in combination with a large ship breadth, the vertical motions at the ship side are such that a contact with the seabed may be envisaged in beam waves of 6.5 m height.

Panamax
Video observations and an analysis of the vertical motion of reference points spread over the vessel indicate that the bulb is most likely to come to a near contact or contact with the sea bed. While in 5.2 and 5.5 m high waves the bulb does not come in the vicinity of the floor, contact was observed once at zero speed in beam waves with significant height of 6.5 m and higher combined with a peak period of 13.2 s, for both GM values.



The model bulb hits the basin floor (time on video 11968 s)
(Hs = 6.5 m, Tp = 13.2 s, beam waves, zero speed)

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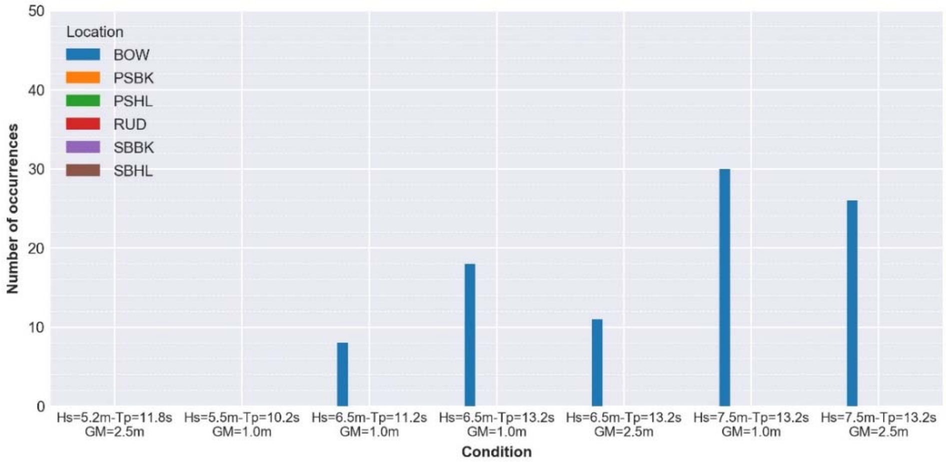
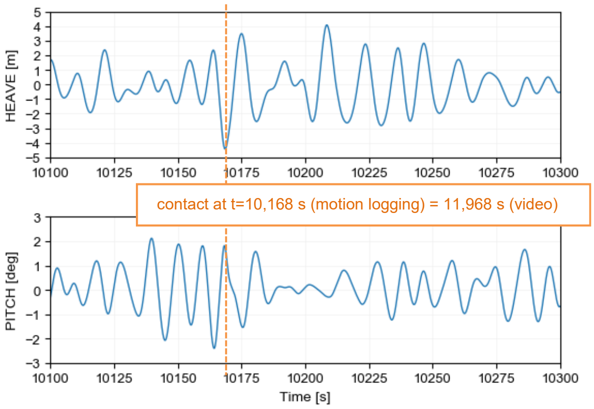
[16] *See MARIN Report 32558-2-OB*

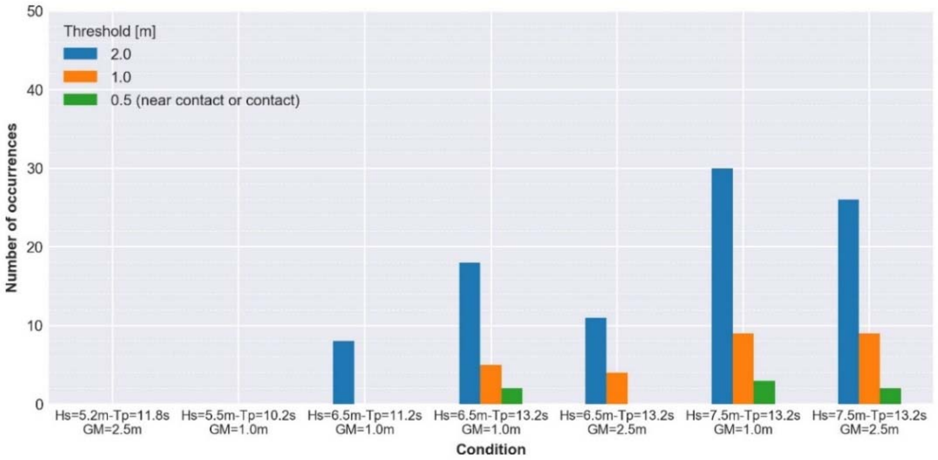


Number of occurrences of reference locations on ship coming within 2 m of the sea bed (Vs = 0 kn, beam waves)

The contact with the bottom occurred as the ship model experienced a large downward motion of the bow. This motion was the result of a large downward heave amplitude (-4.4 m) combined with a mild pitch amplitude (1.8 deg). Although the pitch amplitude was limited, the large arm length between the ship Centre of Gravity (CoG) and bow yielded an amplified effect of pitch on the vertical motion at the bow, in the order of 2.7 m vertical motion at the bow per degree pitch.



Time trace of heave and pitch (Hs = 6.5 m, Tp = 13.2 s, beam waves, zero speed)

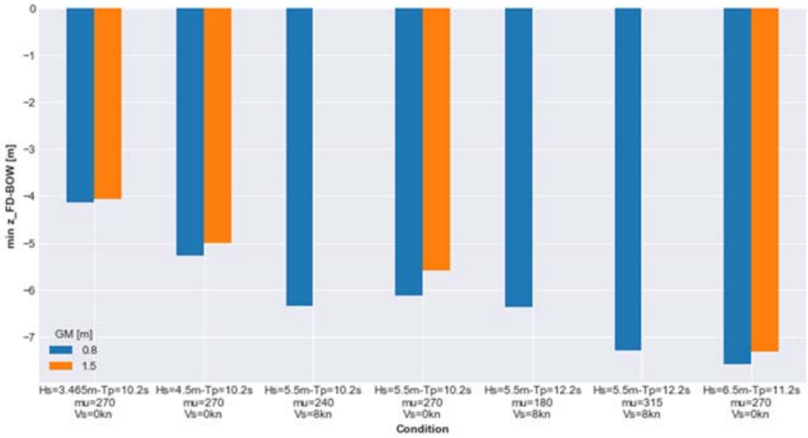


Number of occurrences of the underside of the bulb coming within X m of the sea bed (Vs = 0 kn, beam waves)

In summary: contact of the Panamax hull with the seabed were observed in beam waves of significant height 6.5 m and above. The contact was witnessed to occur at the bow, under the foot of the bulb. Such contacts happened after a combination of a large downwards heave motion and a mild pitch motion.

Feeder

With a draught of 9.2 m the Under Keel Clearance (UKC) of the Feeder in the tested conditions is at least 12.1 m. During the tests the largest vertical motions are seen at the bow. Nevertheless, the bow does not come at less than 4.5 m of the basin floor in the tested conditions. Therefore it may be concluded that the probability of contact with the sea bed bottom in the tested wave conditions is negligible.



Largest negative amplitude of vertical motion at the bow

Contact of the hull with the seabed was not observed in the tested conditions. In the worst condition tested (6.5 m high wave) the underwater keel clearance remained at least 4.5 m.

4.5.3 Impulsive green water loading against the containers

Shallow, beam waves reflect strongly against the side of the ship, particularly when steep crests with high horizontal velocity are (close to) breaking. These waves cannot penetrate the ship and can hardly propagate underneath in the restricted clearance, therefore they run upwards against the ship side.

This results in a ‘water jet’ of substantial velocity that may reach the main deck, where the containers are located. This ‘green water’ can hit the underside of the lowest tier, as well as the side of the containers higher up. The resulting upward-lifting forces and impulsive loading can damage both containers and their lashings. When one container is damaged or its lashing is failing, a complete stack can collapse. Green water impacts on higher containers can also push dynamically the side of the stack sideways. This can result in a contact with the container stack further inside, causing ‘domino’-like failure mechanisms.

The transversal and vertical wave loads presented in the tables below are determined for the whole side panel (32 m^2) or underside panel (30 m^2) of side containers, scaled from the measurements made at the force panels (5 cm wide at model scale). It should be noted that the underside of the side container on the feeder was considered to be only half-exposed, hence an area of 15 m2 was taken.

ULCS

The vertical loads experienced by the side container on the lowest tier are very sensitive to both wave height and water depth. As witnessed during previous projects a very large increase in load is found in very shallow condition (21.3 m water depth). The largest loads are noted mostly at the bow, with lower peaks at the aft.

	Water depth	
Hs	21.3 m	37.5 m
[m]	[kN]	[kN]
6.5	6234	896
7.5	22670	2256

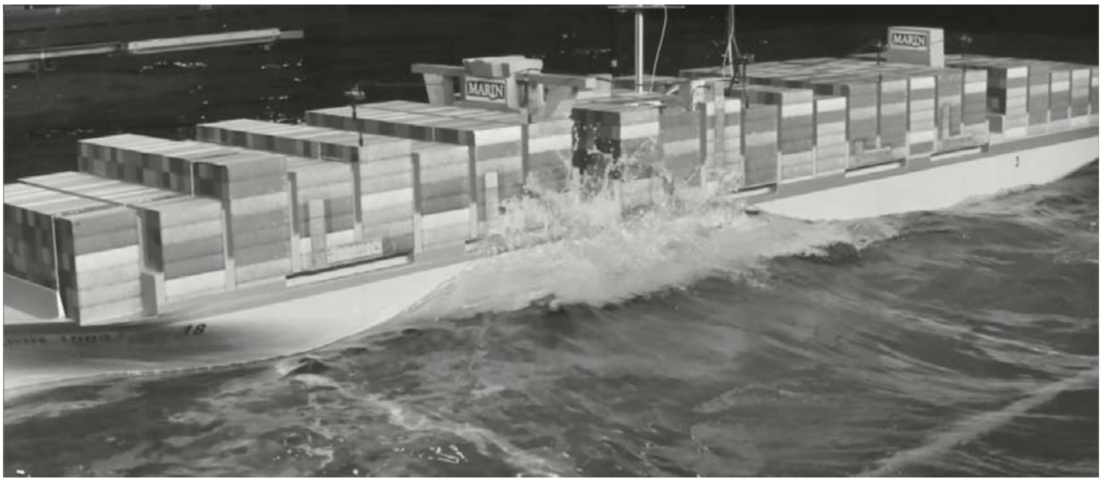
Maximum vertical wave load applied on the underside panel of the side container

The overall magnitude of the transverse loads on the side panels is a step lower than the vertical loads. The largest loads were found amidships. A comparison of the loads determined at different heights shows that the loads are concentrated on the lowest two tiers.

	Water depth	
Hs	21.3 m	37.5 m
[m]	[kN]	[kN]
6.5	2825	503
7.5	3790	2797

Maximum transversal wave load applied on the side panel of the side container

As the area of the side and underside panels of containers is 32 and 30 m^2 (see page above), we have to divide the forces above by 32 (side) or 30 (underside) to come to the average peak pressure in kPa (kN/m^2).



Green water loading on the ship side
(Hs = 6.5 m, Tp = 14.5 s, Vs = 0 kn)

Panamax

The vertical loads experienced by the side container on the lowest tier are very sensitive to both wave height and water depth. As witnessed during previous projects a very large increase in load is found in very shallow condition (21.3 m water depth). Very large loads were noted over the whole ship length, the largest magnitudes were found at the aft ship.

	Water depth		
Hs	21.3 m	26.6 m	37.5 m
[m]	[kN]	[kN]	[kN]
5.2 – 5.5	5358	2516	555
6.5	22366	1327	530
7.5	10004	-	1707

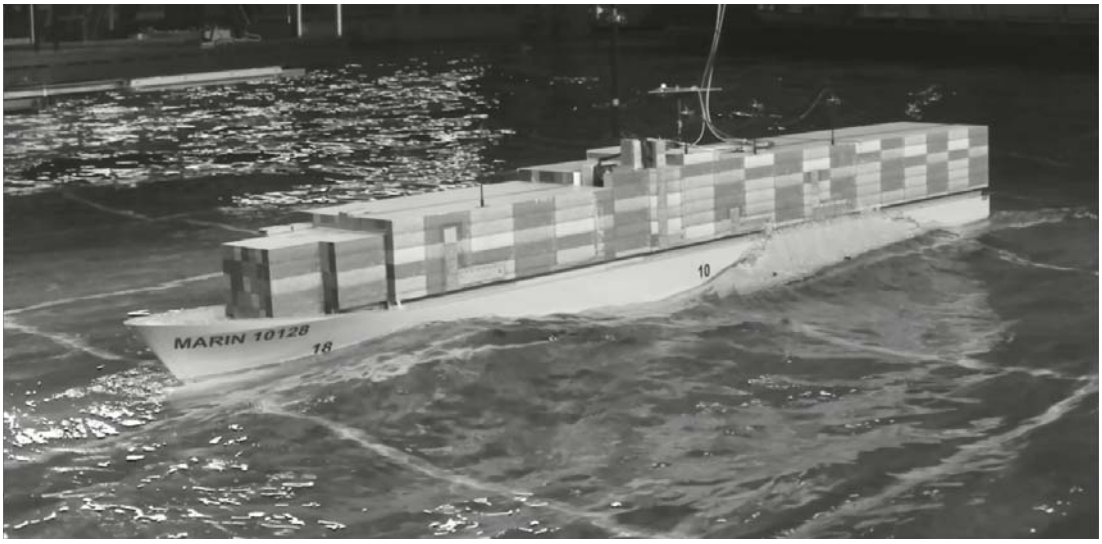
Maximum vertical wave load applied on the underside of the side container

The same remark applies to the transverse loads, although their overall magnitude is a step lower than the vertical loads. The largest loads were found amidships. A comparison of the loads measured at different heights shows that the loads are concentrated on the lowest two tiers.

	Water depth		
Hs	21.3 m	26.6 m	37.5 m
[m]	[kN]	[kN]	[kN]
5.2 – 5.5	797	-	0
6.5	4311	442	359
7.5	11620	-	347

Maximum transversal wave load applied on the side panel of the side container

As the area of the side and underside panels of containers is 32 and 30 m^2, we have to divide the forces above by 32 (side) or 30 (underside) to come to the average peak pressure in kPa (kN/m^2).



Green water loading on the Panamax side
(Hs = 5.2 m, Tp = 11.8 s, Vs = 0 kn)

Feeder

Except in the tested head wave conditions, significant green water impacts were reported for all tested conditions. The largest peak values were obtained during the tests at zero speed in beam waves.
Only when the significant wave height is reduced to 3.5 m, both the magnitude and the area affected by green water are reduced. Although there is an effect of the water depth, green water occurs in both water depths.

	Water depth	
Hs	21.3 m	37.5 m
[m]	[kN]	[kN]
3.5	2477	385
4.5	9475	7688
5.5	10985	8614
6.5	10677	-

Maximum vertical wave load applied on the underside of the side container

	Water depth	
Hs	21.3 m	37.5 m
[m]	[kN]	[kN]
3.5	0	0
4.5	4058	1372
5.5	4962	26806
6.5	8540	-

Maximum transversal wave load applied on the side panel of the side container

As the exposed area of the side and underside panels of containers is 32 and 15 m^2, we have to divide the forces above by 32 (side) or 15 (underside) to come to the average peak pressure in kPa (kN/m^2).

Green water loading on the Feeder
(Hs = 4.5 m, Tp = 10.2 s, Vs = 0 kn)

4.6 Preliminary investigations into parametric rolling

To prevent large roll motions and green water for ships sailing in beam waves in north-westerly storm conditions above the Wadden Islands, the recommendation to change heading with the bow into the waves at slow speed seems logical. However, in head waves parametric rolling[17] might occur for unfavorable combinations of wave length, wave period and natural roll period. It should be prevented that the decision to head into the waves, results in large motions due to parametric rolling.

A short additional test campaign was therefore dedicated to assess the sensitivity of the Feeder to parametric roll, see Report 32558-2-OB. The tests considered two specific conditions: the ship in head waves without forward speed and the ship sailing at low speed into the waves. Wave heights and periods as well as the water depth applied during the tests were selected based on well-known combinations that might be sensitive to parametric rolling. During the tests no clear signs of parametric roll were witnessed. Nevertheless, it may not be concluded from the limited test results with one model that Feeders are not subject to parametric roll at all. This phenomenon is related to the shape of the bow and stern, which may vary from one ship to another. Further the present small model size of the Feeder did not allow the full range of loading conditions, while parametric roll is sensitive to loading condition. Therefore, this set of tests should be seen as a first step regarding the investigation of

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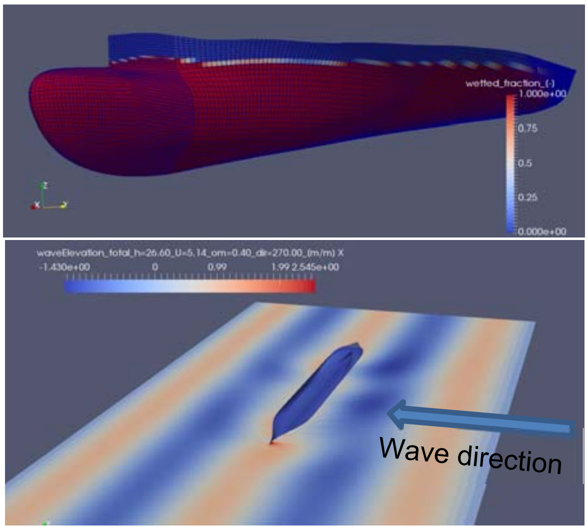
[17] *Parametric rolling is also considered in the IMO 2nd generation intact stability criteria*

parametric roll, to be followed by a more detailed analysis including numerical simulations as well as model tests with a larger model.

4.7 Seakeeping calculations

To extend the model test results to a wider range of wave conditions and directions, also numerical seakeeping calculations were carried out. These calculations were performed with the MARIN FATIMA program. FATIMA is an exact forward speed seakeeping program that accounts for the shallow water dispersion relationship. The theory is based on the 3D Rankine source panel distribution on the hull and free surface. There is a coupling between the steady wave pattern around the ship and the seakeeping hydrodynamics when the ship is at forward speed. This is a rather unique feature, not present in most other seakeeping codes. It increases the accuracy of results at forward speed considerable. The viscous roll damping due to the presence of the bilge keel is accounted for based on the state-of-art calculations using the PRECAL code. This code allows for the calculation of the roll damping in forced oscillations in calm water. The obtained damping from the bilge keel in such calculation can be directly compared to the damping obtained in a roll decay tests. The calm water damping is than used through stochastic linearization in combination with local relative velocities at the bilge keel in FATIMA. Tuning to the model tests assured a consistent and approved roll damping level in irregular waves.

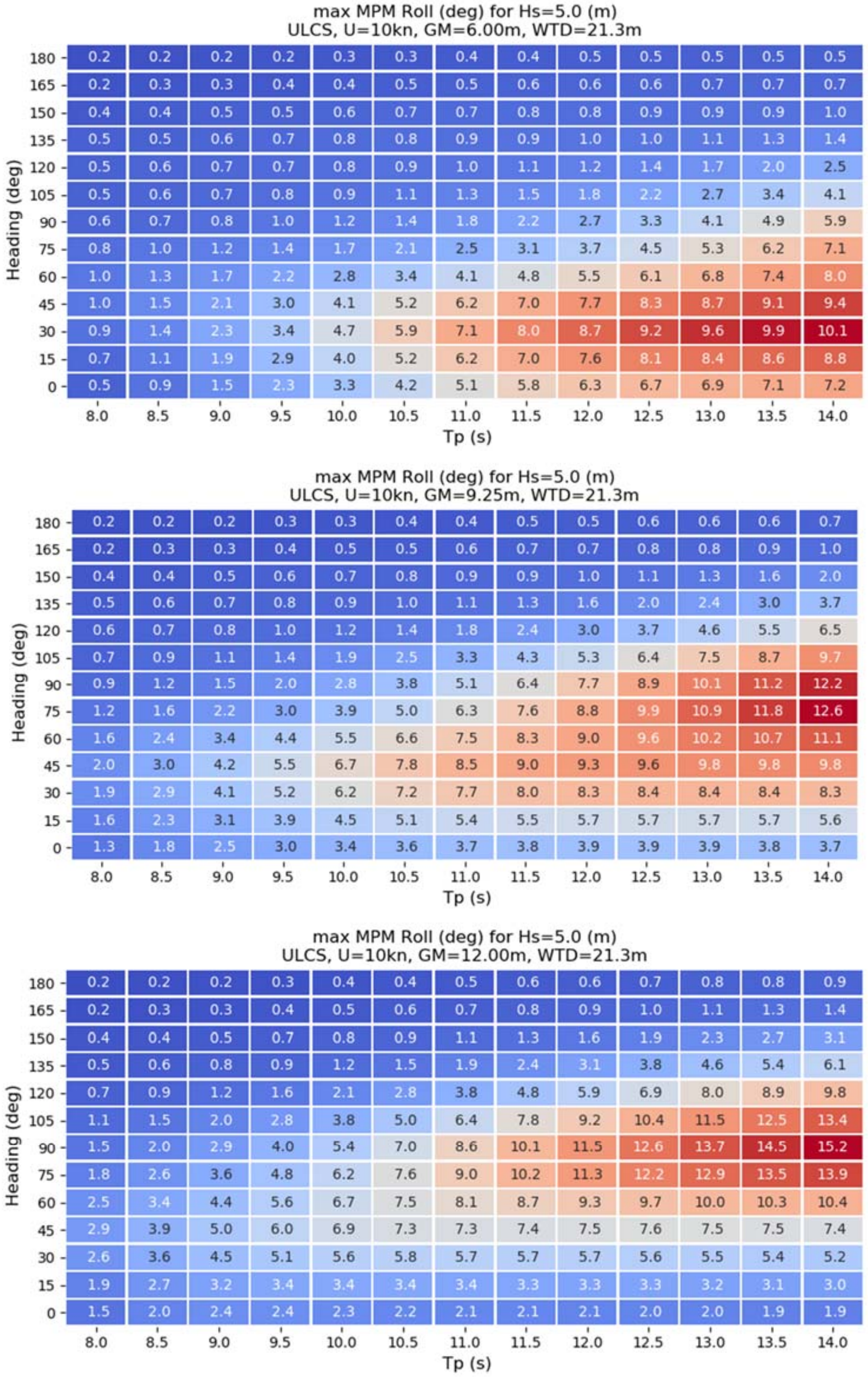
In the Figure below the hull mesh of the ULCS as used in FATIMA is shown with the curved waterline that represent the calm water wave profile along the ship length. The Figure also shows the wave amplitude due to the incident and diffracted wave at one particular wave frequency at 10 knots forward speed in beam wave condition. Close to the vessel the wave pattern due to forward speed is still visible, as this is the base flow around the vessel in all wave calculations in FATIMA.



Hull mesh and calm water wave profile (above) and free surface elevation around the vessel due to diffracted and incident waves (below) for 10 knots forward speed (21.3 m water depth).

The numerical model in FATIMA was tuned and validated against model tests for each ship as good as possible (see Report 32558-3-SEA). For those (GM) conditions in which no model tests were performed the same calibration on the roll damping was applied. An example result is given below for the roll motion Most Probable Maximum (MPM in 3 hours) for the ULCS with 3 GM values in a Hs of 5 metres. The strong influence of GM and wave heading is very clear in this Figure.

All calculations were performed in short-crested sea states using a cos(2s) model with s=12, which aligns to the wave spreading used in the model tests. This wave spreading was calculated by Deltares for the accidental sea state of the MSC ZOE. The short-crestedness explains the small roll motions noticeable in head seas. In general, short-crestedness somewhat lowers the roll response in beam seas. The figures below shows as well that a low-GM ULCS will roll more in stern quartering seas (when the wave encounter frequency is lower and more near the roll natural period) than in beam seas condition.



Heading (deg) \ Tp (s)	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0
180	0.2	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.5
165	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.6	0.7	0.7	0.7
150	0.4	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.8	0.9	0.9	0.9	1.0
135	0.5	0.5	0.6	0.7	0.8	0.8	0.9	0.9	1.0	1.0	1.1	1.3	1.4
120	0.5	0.6	0.7	0.7	0.8	0.9	1.0	1.1	1.2	1.4	1.7	2.0	2.5
105	0.5	0.6	0.7	0.8	0.9	1.1	1.3	1.5	1.8	2.2	2.7	3.4	4.1
90	0.6	0.7	0.8	1.0	1.2	1.4	1.8	2.2	2.7	3.3	4.1	4.9	5.9
75	0.8	1.0	1.2	1.4	1.7	2.1	2.5	3.1	3.7	4.5	5.3	6.2	7.1
60	1.0	1.3	1.7	2.2	2.8	3.4	4.1	4.8	5.5	6.1	6.8	7.4	8.0
45	1.0	1.5	2.1	3.0	4.1	5.2	6.2	7.0	7.7	8.3	8.7	9.1	9.4
30	0.9	1.4	2.3	3.4	4.7	5.9	7.1	8.0	8.7	9.2	9.6	9.9	10.1
15	0.7	1.1	1.9	2.9	4.0	5.2	6.2	7.0	7.6	8.1	8.4	8.6	8.8
0	0.5	0.9	1.5	2.3	3.3	4.2	5.1	5.8	6.3	6.7	6.9	7.1	7.2

Heading (deg) \ Tp (s)	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0
180	0.2	0.2	0.2	0.3	0.3	0.4	0.4	0.5	0.5	0.6	0.6	0.6	0.7
165	0.2	0.3	0.3	0.4	0.5	0.5	0.6	0.7	0.7	0.8	0.8	0.9	1.0
150	0.4	0.4	0.5	0.6	0.7	0.8	0.9	0.9	1.0	1.1	1.3	1.6	2.0
135	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.6	2.0	2.4	3.0	3.7
120	0.6	0.7	0.8	1.0	1.2	1.4	1.8	2.4	3.0	3.7	4.6	5.5	6.5
105	0.7	0.9	1.1	1.4	1.9	2.5	3.3	4.3	5.3	6.4	7.5	8.7	9.7
90	0.9	1.2	1.5	2.0	2.8	3.8	5.1	6.4	7.7	8.9	10.1	11.2	12.2
75	1.2	1.6	2.2	3.0	3.9	5.0	6.3	7.6	8.8	9.9	10.9	11.8	12.6
60	1.6	2.4	3.4	4.4	5.5	6.6	7.5	8.3	9.0	9.6	10.2	10.7	11.1
45	2.0	3.0	4.2	5.5	6.7	7.8	8.5	9.0	9.3	9.6	9.8	9.8	9.8
30	1.9	2.9	4.1	5.2	6.2	7.2	7.7	8.0	8.3	8.4	8.4	8.4	8.3
15	1.6	2.3	3.1	3.9	4.5	5.1	5.4	5.5	5.7	5.7	5.7	5.7	5.6
0	1.3	1.8	2.5	3.0	3.4	3.6	3.7	3.8	3.9	3.9	3.9	3.8	3.7

Heading (deg) \ Tp (s)	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0
180	0.2	0.2	0.2	0.3	0.4	0.4	0.5	0.6	0.6	0.7	0.8	0.8	0.9
165	0.2	0.3	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.4
150	0.4	0.4	0.5	0.7	0.8	0.9	1.1	1.3	1.6	1.9	2.3	2.7	3.1
135	0.5	0.6	0.8	0.9	1.2	1.5	1.9	2.4	3.1	3.8	4.6	5.4	6.1
120	0.7	0.9	1.2	1.6	2.1	2.8	3.8	4.8	5.9	6.9	8.0	8.9	9.8
105	1.1	1.5	2.0	2.8	3.8	5.0	6.4	7.8	9.2	10.4	11.5	12.5	13.4
90	1.5	2.0	2.9	4.0	5.4	7.0	8.6	10.1	11.5	12.6	13.7	14.5	15.2
75	1.8	2.6	3.6	4.8	6.2	7.6	9.0	10.2	11.3	12.2	12.9	13.5	13.9
60	2.5	3.4	4.4	5.6	6.7	7.5	8.1	8.7	9.3	9.7	10.0	10.3	10.4
45	2.9	3.9	5.0	6.0	6.9	7.3	7.3	7.4	7.5	7.6	7.5	7.5	7.4
30	2.6	3.6	4.5	5.1	5.6	5.8	5.7	5.7	5.7	5.6	5.5	5.4	5.2
15	1.9	2.7	3.2	3.4	3.4	3.4	3.4	3.3	3.3	3.3	3.2	3.1	3.0
0	1.5	2.0	2.4	2.4	2.3	2.2	2.1	2.1	2.1	2.0	2.0	1.9	1.9

Roll MPM as function of wave period and heading for 3 GM conditions (Hs=5m).

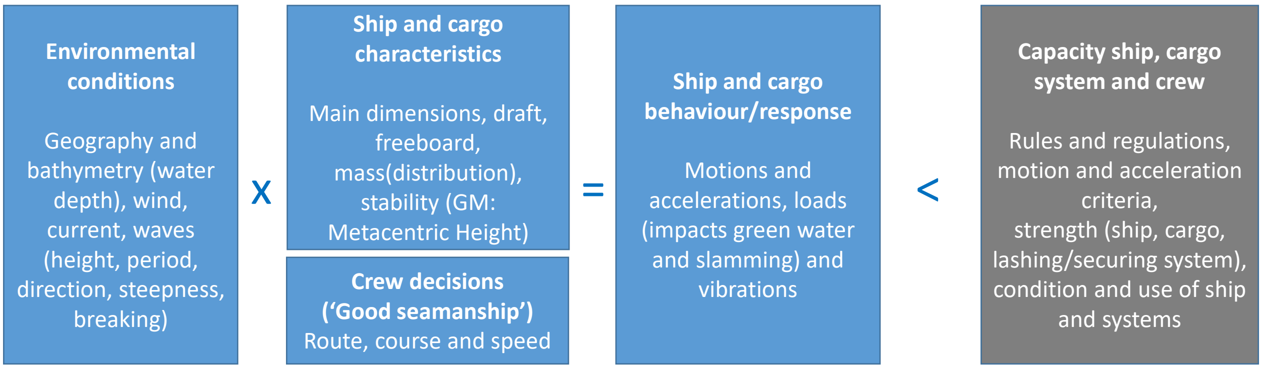
In table below the observations on the global motions of the three containerships are summarised:

Item	**FEEDER**	**PANAMAX**	**ULCS**
Descriptive	Large heave motions Acceptable roll motions Large pitch motions	Large heave motions Very large roll motions Modest pitch motions	Large heave motions Very large roll motions Small pitch motions
Effect of GM	Heave and pitch motion extremes are unaffected by GM Roll motion extremes strongly depend on GM		
Effect of ship speed	Almost absent	Only some effect on roll which varies with GM	Only some effect on roll which varies with GM
Going from southern to northern route	Heave identical Roll reduces by 30% Pitch reduces by 10%	Heave nearly identical Roll reduces by about 15% Pitch nearly identical	Heave increase of 20% Roll nearly identical Pitch nearly identical
Heave response southern route (8 or 10 knots)	MPM 4.5 m at Hs=5m, beam seas	MPM 4.0 m at Hs=5m, Beam seas	MPM 3.3 m at Hs=5m, Beam seas
Roll response southern route (8 or 10 knots)	GM-1: MPM 3.7 deg, GM-2: MPM 6.3 deg, GM-3: MPM 11.2 deg, at Hs=5m	GM-1: MPM 7.5 deg, GM-2: MPM 17.0 deg, GM-3: MPM 23.0 deg, at Hs=5m	GM-1: MPM 10.1 deg GM-2: MPM 12.6 deg GM-3: MPM 15.2 deg at Hs=5m
Pitch response southern route (8 or 10 knots)	MPM 5.6 deg at Hs=5m, max in head seas	MPM 2.6 deg at Hs=5m, max in bow quartering seas	MPM 1.6 deg at Hs=5m, Max in bow quartering seas

5 PRESENT STATUS OF CARGO SECURING REQUIREMENTS AND CRITERIA

5.1 Capacity of the ship, cargo system and crew

This Chapter summarizes the present status of international rules and regulations describing the capacity of containerships and their cargoes to withstand the behaviour of containerships at sea (grey block):



Environmental conditions

Geography and bathymetry (water depth), wind, current, waves (height, period, direction, steepness, breaking)

X

Ship and cargo characteristics

Main dimensions, draft, freeboard, mass(distribution), stability (GM: Metacentric Height)

Crew decisions (‘Good seamanship’)

Route, course and speed

=

Ship and cargo behaviour/response

Motions and accelerations, loads (impacts green water and slamming) and vibrations

<

Capacity ship, cargo system and crew

Rules and regulations, motion and acceleration criteria, strength (ship, cargo, lashing/securing system), condition and use of ship and systems

More details can be found in Report 32558-5-PaS.

5.2 Scope of evaluation

The capacity of the cargo and its securing system was be studied based on the outline of present rules, guidelines and criteria, in particular SOLAS Chapter VI and the IMO ‘Code of Safe Practice for Cargo Stowage and Securing’ (CSS Code)[1]. These codes provide the IMO framework for safe stowage of cargoes and acceleration levels for generic (non-standardised) cargo depending for instance of the ship’s size and stability (GM value). In MARIN Report 32558-5-PaS ‘Container securing, Overview current practice & regulatory framework’ a review is made of:

- The cargo securing principles, the equipment and typical safe operating ratings and the common practice in container transport operation.
- The regulatory framework that defines container transport operations and where the responsibility lies for generic transport safety.
- How class societies implemented rules and class notations for cargo securing when they were authorized by flag state administrations to do the appraisal of SOLAS mandatory Cargo Securing Manuals.
- The role of the ship’s crew to handle the vessel carefully and avoid extreme motions and loads that can occur in adverse weather.
- The effect of ship dimensions on cargo securing loads and the sensitivity of various size ships to uncertainties in the loading process and vessel handling.

5.3 Evolution of vessel size versus their regulatory frame work

Container vessel dimensions have increased substantially over past few decades. The evolution of maximum container capacity over time is illustrated in the Figure below.

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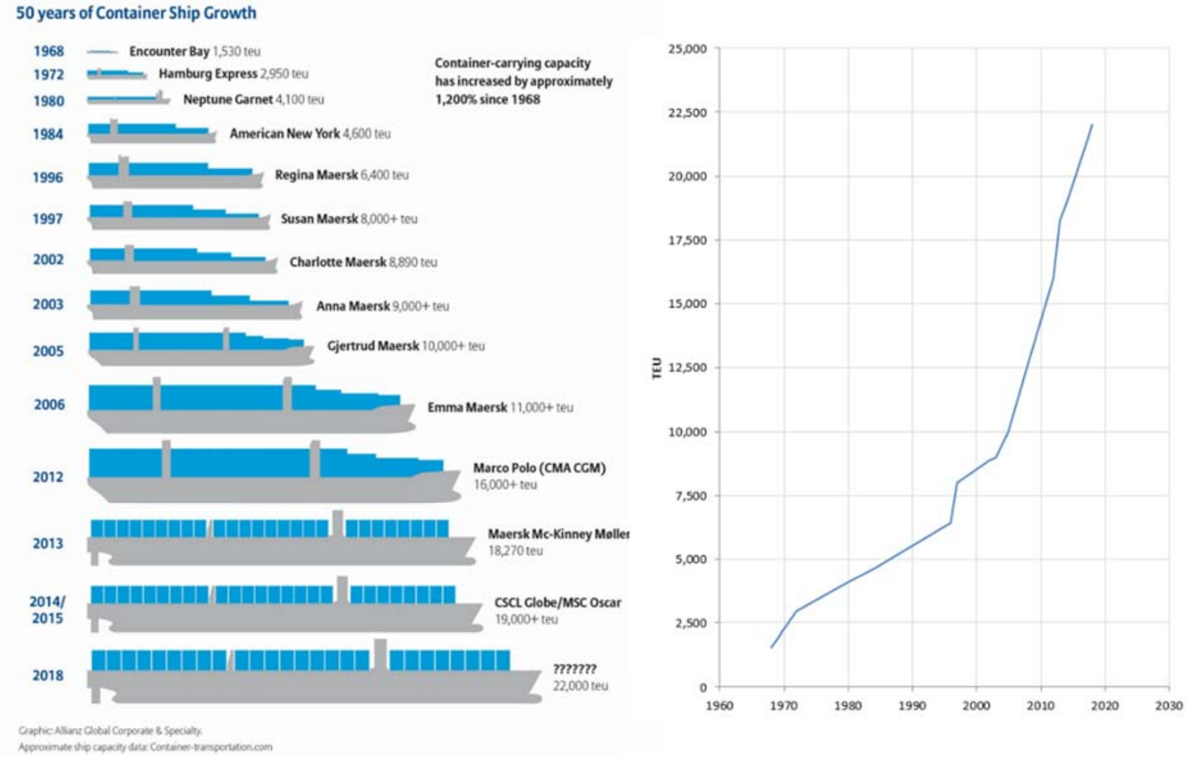
[1] IMO Res. A714 (17) 1991



Evolution of container ships (from: worldshipping.org)

Design and outfitting of container lashing arrangements was originally done by ship owners and designers in cooperation with yard, lashing gear manufacturers and class in the new build process. Some Class Societies offered class notations for the validation of container lashing arrangements and their operation since the early seventies.

Statutory requirements on loading procedures date back to the SOLAS adaptation of a mandatory CSM in 1991, the guidelines for its preparation via the CSS code and the statistics used for that purpose based on ships and shipping in the 1980's.

Loading capacity started to increase steeply since 2000. Since that time, there have been marginal statutory changes on container securing arrangements. Guidelines for the preparation of CSM were modified in 2010. Mandatory container weight verification was adapted in 2014.

Large changes however did occur in the class society rules when they were delegated the approval of CSM's on behalf of flag state authorities. The rules are maintained by the class societies themselves and can be/are regularly updated. Specific class notations and rules for container ship lashing arrangements were drawn up and extended for the latest generation of vessels in the period of 2010 – 2015 along with entrance of the first ULCS ships.

5.4 Design accelerations for the three ship types under investigation

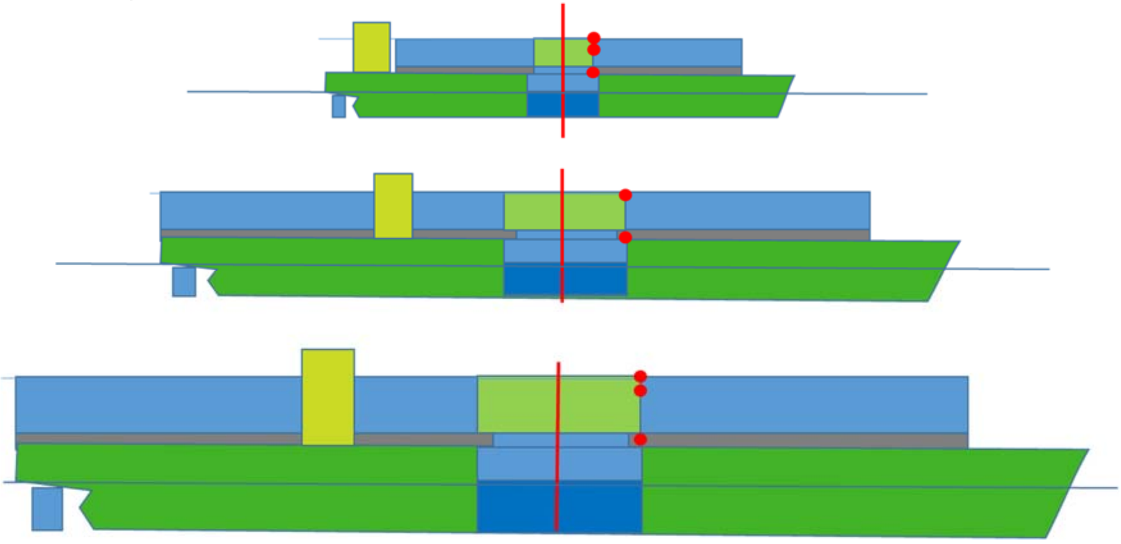
For the three ship sizes under consideration in the present investigations, MARIN has reviewed the differences between the acceleration levels according to class rules.

The shape parameters are mainly width, length, displacement and draught. Initial stability or GM is another important parameter for wave induced motions and accelerations. GM is a function of shape parameters in combination with the loading condition (location of Centre of Gravity and tank fillings).
Class societies were asked to provide design responses for the tested ship designs with corresponding loading conditions. No reductions factors were applied to the listed formulas, the calculations were done for unrestricted conditions. Output parameters were the estimated roll motion period, the maximum roll

motion angle, and transverse accelerations at three test points for the three ships as indicated in the Table and Figure below.

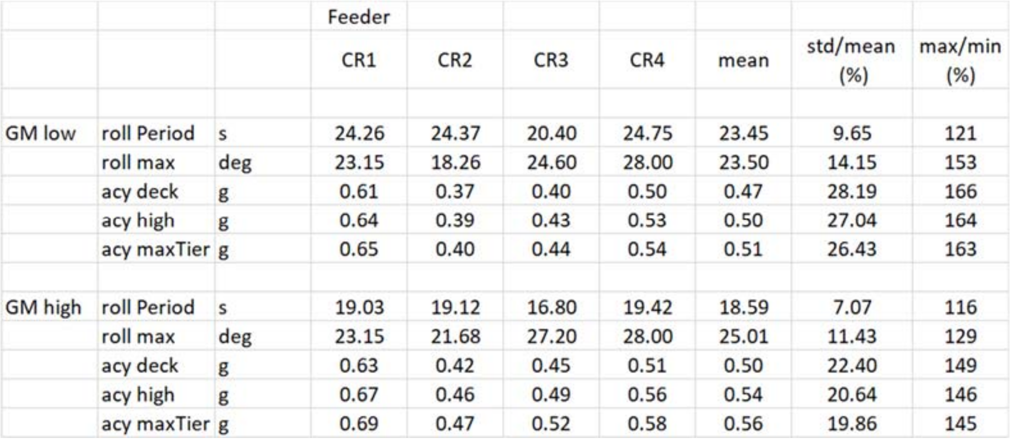
			feeder	Panamax	ULCS
Test Point 1	rel APP	m	81.8	139.5	190.3
(midship, max width, deck level)	rel CL	m	12.3	14.9	28.1
	rel BL	m	16.6	22.0	31.4
Test Point 2	rel APP	m	81.8		190.3
(midship, max width, high tier)	rel CL	m	12.3		28.1
	rel BL	m	25.2		51.7
Test Point 3	rel APP	m	81.8	139.5	190.3
(midship, max width, top tier)	rel CL	m	12.3	14.9	28.1
	rel BL	m	29.6	42.1	57.9

Acceleration test point locations

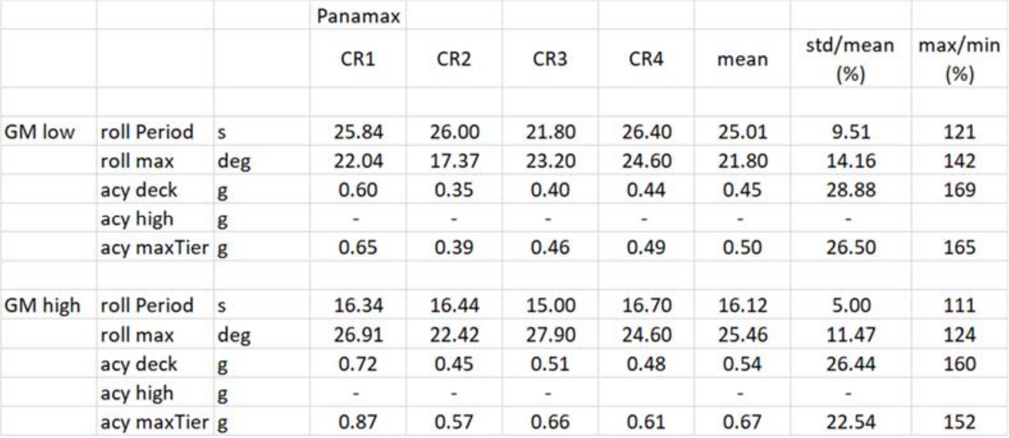


Ship types and acceleration output test points

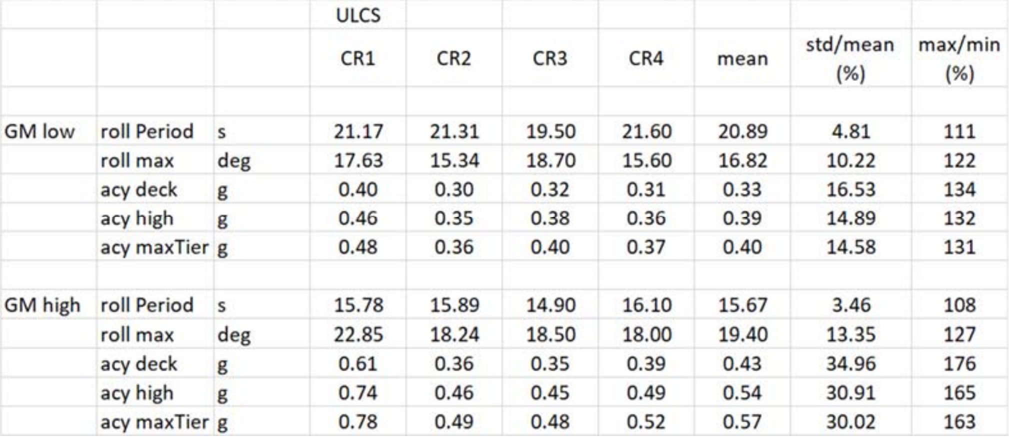
Four class societies submitted calculated results for the listed conditions. The results are represented in Tables below. The results are referred to the rule sets of four class registers labelled as CR1 to CR4. They are not linked back to underlying class organisations since it was the objective to evaluate rule consistency and not compare individual rule results.



			Feeder						
			CR1	CR2	CR3	CR4	mean	std/mean (%)	max/min (%)
GM low	roll Period	s	24.26	24.37	20.40	24.75	23.45	9.65	121
	roll max	deg	23.15	18.26	24.60	28.00	23.50	14.15	153
	acy deck	g	0.61	0.37	0.40	0.50	0.47	28.19	166
	acy high	g	0.64	0.39	0.43	0.53	0.50	27.04	164
	acy maxTier	g	0.65	0.40	0.44	0.54	0.51	26.43	163
GM high	roll Period	s	19.03	19.12	16.80	19.42	18.59	7.07	116
	roll max	deg	23.15	21.68	27.20	28.00	25.01	11.43	129
	acy deck	g	0.63	0.42	0.45	0.51	0.50	22.40	149
	acy high	g	0.67	0.46	0.49	0.56	0.54	20.64	146
	acy maxTier	g	0.69	0.47	0.52	0.58	0.56	19.86	145



			Panamax						
			CR1	CR2	CR3	CR4	mean	std/mean (%)	max/min (%)
GM low	roll Period	s	25.84	26.00	21.80	26.40	25.01	9.51	121
	roll max	deg	22.04	17.37	23.20	24.60	21.80	14.16	142
	acy deck	g	0.60	0.35	0.40	0.44	0.45	28.88	169
	acy high	g	-	-	-	-	-	-	
	acy maxTier	g	0.65	0.39	0.46	0.49	0.50	26.50	165
GM high	roll Period	s	16.34	16.44	15.00	16.70	16.12	5.00	111
	roll max	deg	26.91	22.42	27.90	24.60	25.46	11.47	124
	acy deck	g	0.72	0.45	0.51	0.48	0.54	26.44	160
	acy high	g	-	-	-		-	-	
	acy maxTier	g	0.87	0.57	0.66	0.61	0.67	22.54	152



			ULCS						
			CR1	CR2	CR3	CR4	mean	std/mean (%)	max/min (%)
GM low	roll Period	s	21.17	21.31	19.50	21.60	20.89	4.81	111
	roll max	deg	17.63	15.34	18.70	15.60	16.82	10.22	122
	acy deck	g	0.40	0.30	0.32	0.31	0.33	16.53	134
	acy high	g	0.46	0.35	0.38	0.36	0.39	14.89	132
	acy maxTier	g	0.48	0.36	0.40	0.37	0.40	14.58	131
GM high	roll Period	s	15.78	15.89	14.90	16.10	15.67	3.46	108
	roll max	deg	22.85	18.24	18.50	18.00	19.40	13.35	127
	acy deck	g	0.61	0.36	0.35	0.39	0.43	34.96	176
	acy high	g	0.74	0.46	0.45	0.49	0.54	30.91	165
	acy maxTier	g	0.78	0.49	0.48	0.52	0.57	30.02	163

Class rule response values Feeder vessel, Panamax vessel and ULCS.

We observe the following:

- There are differences in design accelerations and motion amplitudes for the different ship types and stability (GM) in particular. Design accelerations decrease somewhat with size.
- Ship crews should thus be aware of, and account for different max allowable criteria on different sized ships and loading conditions.
- The bigger Panamax and ULCS vessels show highest effects of GM variations.
- One class register out of the four that were evaluated uses higher design motions and accelerations.
- The large variations between class rule values for extreme accelerations and motions in lashing design calculation, illustrate the differences and uncertainties in various extreme motion prediction load case models.

5.5 Review of the current practice of container cargo securing

Report 32558-5-PaS offers a review of the current practice in container cargo securing, the rules around it, the loads on it, and the estimation processes for these loads. The following observations are made:

On Safety and minimal standards

- There are different views on acceptable limits for cargo loss. The probability to lose a specific container is extremely low, but the probability that any containers are lost in an area where severe weather can occur is high because of constant ship traffic and high transport volumes.

- Statutory requirements as laid out in the SOLAS convention, Chapter VI, Rules 2 and Rule 5, put the responsibility for a non-commercially biased approval of cargo stowage and securing procedures with the flag state. This role has been delegated to the shipping industry with the authorisation of class societies to approve stowage and securing arrangements on behalf of flag states.
    - The rule defining, inspection and enforcing role of classification societies has many favourable aspects. The rules are clear. They can be readily maintained and updated based on new experience. And in particular the inclusion of cargo securing and gear in class notation makes it part of the annual class surveys which means that gear condition is checked regularly by independent surveyors. Since class notation is, essential for insurance this makes gear condition and maintenance a primary factor, as it should be.
    - The fidelity of the probability of exceedance of the design points in the rules however is not transparent and cannot be easily verified.
    - It is unclear how flag state authorities maintain control over the standards that are imposed on the industry in their name.

On container securing in particular

- Specialised container ships have flag state approved securing arrangements that are specified to fixed maximum allowable loads.
- Container deck cargo planning is done such that maximum ‘expected’ securing loads per voyage stay below the fixed maximum allowed ratings of containers and lashing gear. Any safety margins thus should be accounted for in the estimation of the securing loads per voyage.
- Maximum expected securing loads are obtained by combining documented cargo weights with extreme motions and wind and wave loads using empirical models. The background of these models is not transparent. There is uncertainty in the design load cases against which safe working limits of equipment are validated that come on top of uncertainty in cargo weights and sea state.
    - Limited experience and statistics are available to account for the steep rise in ship dimensions, developments with weather-routed navigation, extreme GM ranges of recent ship designs, and weather dependent reductions on acceleration levels that have become commonly accepted over the past 10 years. Rule values used in lashing calculations may be different from motions that are considered acceptable in practice.
    - Good seamanship is essential to keep actual loads on cargo inside the limitations of the securing arrangements. There is uncertainty in this role since crew don’t know the true acceleration levels and they also don’t know the rule design values that were used in lashing calculations and which vary with the ships loading condition (GM).
    - Important aspects of loading mechanisms for containers on large ships are not included in design considerations at all. These are in particular:
        - stack dynamic interaction loads
        - impulsive and vibration accelerations from hull girder flexibility

5.6 Recommendations

It is recommended to increase knowledge about extent and probabilistic of loads acting on containers on board modern ultra large container ships

From a practical point of view, there should be more focus on options for the crew to recognise developing problems during operations. There is at present no mandatory equipment on board to measure actual ship motions and accelerations. Ship crews thus do not have means to relate actual vessel response to design points that are used in the lashing calculations. Design points, which often are not even available to these crews since they stay ‘inside’ the lashing computer.

It is recommended that flag states put more emphasis on their governing role on minimal safety standards on behalf of ship crews and third party coastal communities that suffer consequences in case of incidents.

The following actions are highlighted to improve the fidelity of the current practice:

- Demonstrate the fidelity of the empirical models and loadcases that are used for motion and acceleration load predictions against a reliable data set of true in-service data. This could be done by acquiring, and providing uniform access to, a dataset of on-board measured data on motions and accelerations as function of ship dimensions, GM, speed and weather. It should be encouraged to validate the design models against such a data set.

- Investigate and account for the additional securing loads by dynamic row interactions between multi row container stacks due to short period accelerations from hull girder flexibility under impulsive or vibration loads.

- Improve the crew awareness of the margins between actual motion levels and the motion limits used for the lashing calculations with the cargo as stowed. For this, it should be encouraged or required to introduce on-board tools to measure the instantaneous accelerations and compare these with the design accelerations and motions that were used for the cargo securing calculations.

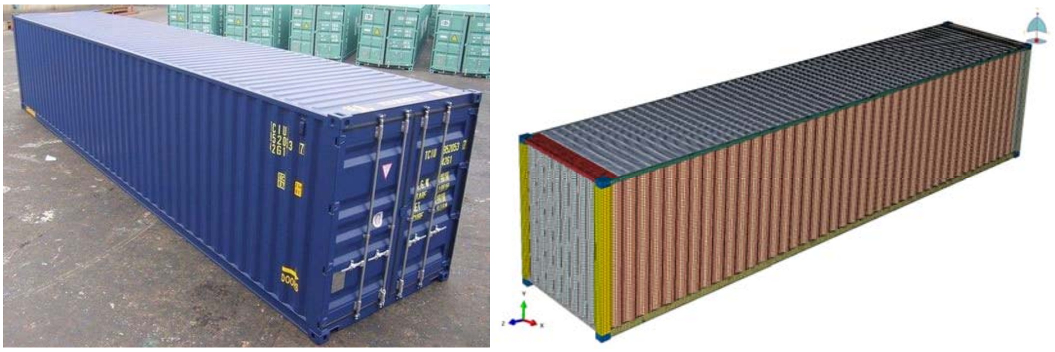
Both above items exceed the jurisdiction of a single flag state. It is thus recommended to pursue above actions via a project that aims to recommend such to IMO. Such project would require support from flag states, class societies, ship owners/operators, gear/equipment manufacturers, and independent research groups.

5.7 Finite element calculations of green water loading

To determine the capacity of present day containers against green water loading on container side surfaces, finite element calculations were carried out. Details can be found in Report 32558-4-PaS.

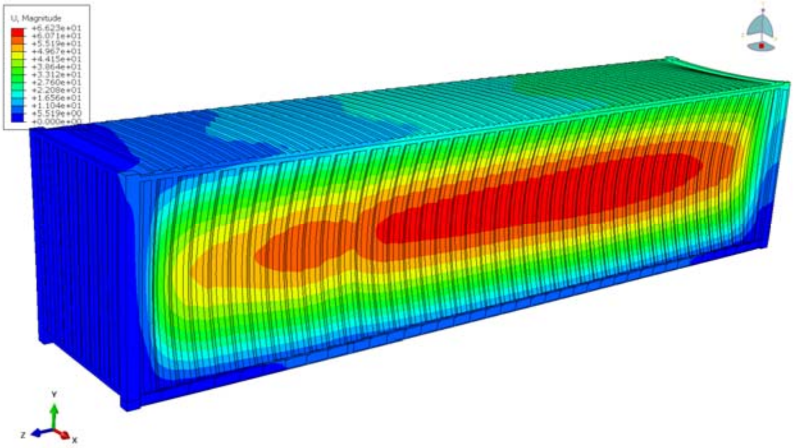
Container loss occurred by the green water loading

The aim of the present study was to find the failure limits of a 40 foot shipping container structure against green water loading from the sides. Amongst the failure modes, yielding and buckling failures are chosen as important modes for the nature of the loading and are analysed for the side panel and front panel. For vertical posts, stacking loading is to be analysed. For this purpose, a numerical finite element model is developed by using a 40 foot structural drawing that was designed according to ISO standards of 1496-1 and 668.



Standard 40 feet ISO container (left) and the modelling with a finite element mesh (right).

For the present initial study the green water pressure is assumed as uniform over the front or side panel surface. Therefore unit uniform pressure is applied in analyses to calculate its order for both yielding and buckling analyses.



Displacement results at the limit state with 9.07 kPa – mm

For side and front plating, the pressure values that just yields to yielding stress limit of the material are found. Buckling load values which the structural component loses its stability are also calculated. As a summary of all performed analyses, limiting pressure and buckling load values can be seen in the Table below.

	Pressure at yielding limit	Pressure at the buckling limit
Side panel analysis	9.07 kPa	10.99 kPa
Front panel analysis	21.26 kPa	22.71 kPa

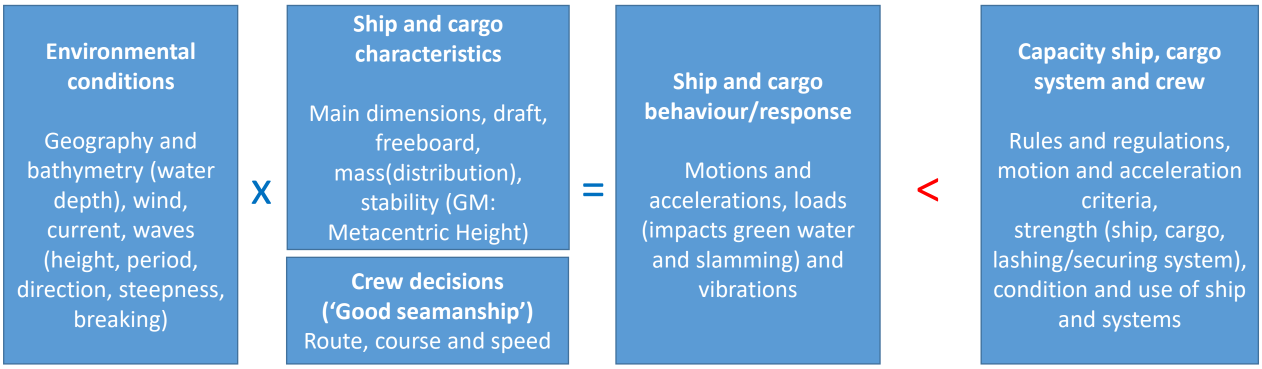
	Load value at buckling limit
Corner post analysis	416.3 ton

Limiting pressure and load values at yielding and buckling limits

6 DERIVATION OF LIMITING WAVE HEIGHTS

6.1 Comparison of the ship and cargo behaviour with its capacity

In this Chapter a comparison is made between the behaviour of the ship and cargo and its capacity to handle this behaviour and resulting loads. Based on this comparison, container ship-type specific limiting wave heights to prevent the loss of containers above the Wadden Islands can be estimated:



6.2 Methodology

The limiting wave heights to prevent the loss of containers above the Wadden Islands are derived for the three tested containerships (ULCS, Panamax and Feeder). They take the three most important phenomena[18] that may lead to container loss above the Wadden Islands into account:

1. Extreme (wave-frequency) ship motions and accelerations
2. Contact with the seabed
3. Impulsive green water loading against the containers

The first two phenomena are determined based on calculations as this allows the investigation of all relevant sea state conditions. When the response amplitude operator of the ship is multiplied with the wave spectrum, the ship response spectrum is obtained which allows us to derive the response maxima. The numerical model was validated and tuned when possible to the model test results. The third phenomenon, green water loading, could only be determined based on the model tests results because of its complex and non-linear behaviour.

In our present methodology, we compare the behaviour of the ship with the relevant capacity criteria for the statistical Most Probable Maximum (MPM) in 3 hours. The 3-hour MPM is easily obtained from the numerical assessment since the response statistics obey the Rayleigh distribution. If there are N oscillations in the 3-hour exposure time, the MPM agrees with the 1/N probability. For typical wave periods this probability is around 0.1% (1/1000).

It is important to realize that the *experienced* maximum (or measured maximum) in each sea state realization is different, even if the statistical parameters of the sea state are the same. Taken the

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[18] *As indicated in Chapter 4, the 4th mechanism that may contribute to container loss, slamming induced impulsive loading on the hull, could not be quantified with the present model tests and calculations. The estimate of the vibrations and accelerations resulting from wave slamming is an extremely complex task as it requires a correct modelling (numerically or in the basin) of the flexural response of the vessel, including both natural periods and damping. In the case of model tests this is usually done using scale models consisting of several segments (connected with each other by an aluminium beam with suitable properties). This was outside the scope of work of the present model tests. Although it is assumed that the three phenomena above are dominant in the loss of containers above the Wadden Islands, this issue should not be forgotten in future investigations.*

extreme values from a number of realization leads to a (Gumbel) distribution, of which the most occurring value is the MPM. There is thus a probability that the MPM is exceeded and this probability is 63.2% (also called the 37% percentile). The use of the MPM value as a short-term maximum is common throughout the naval engineering and applied in many class rules. Structural design regulation includes safety factors to account for the loading unknowns and statistical uncertainty of the extremes.

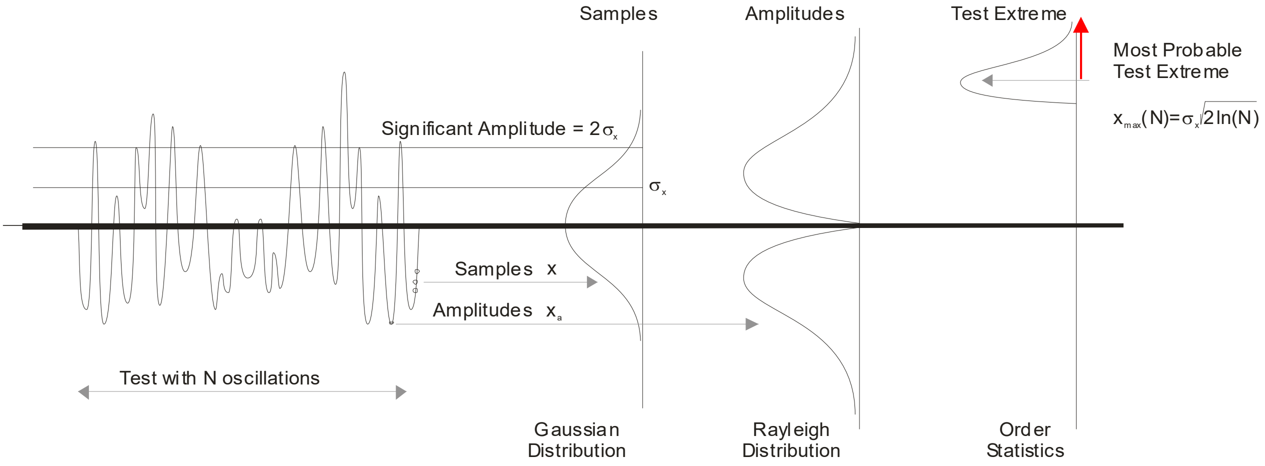
Alternatively, when the short-term probability distribution is known, for example from measurements, the MPM can be obtained as the value that fits the empirical distribution at the 1/N probability.

For linear quantities like the ship motion, the Most Probable Maximum (MPM, x_{MPM}) is related to the standard deviation (RMS or σ_x) of the predicted motion in the sea spectrum by the following relationship (valid for large N):

$$x_{MPM} = \sigma_x \sqrt{2lnN}$$

where N is the number of oscillations and σ_x equals the standard deviation of the signal x.

The Y-hour Most Probable Maximum (MPM) single amplitude (or most probable extreme) is a good measure for the short-term maxima in a Y hours storm, but still there is a chance that this value is exceeded. As mentioned, for linear systems the chance that this extreme is exceeded is theoretically 63.2% (red arrow in Figure below), for non-linear effects such as green water loading there are no theoretical models available[19]. This is one of the reasons why additional (and, depending on the expected behaviour, different) safety margins/factors are applied in ship design.



Typical distributions of signals like wave elevation or wave induced motions

It should also be noted that the present investigations focus on the short term statistics and risks: given a certain sea state for a certain duration of Y hours, what will be the risk of exceeding the capacity of this specific ship and its cargo? To determine the long-term overall risk of losing containers in this area on for example an annual basis, a long term statistical risk analysis needs to be carried out, considering the long term distribution of ship types, loading conditions, and storm conditions in the area. If such an analysis is made over the whole range it will be inherently an overall risk and not a specific risk level for a particular ship. The overall risk level, expressed in for example a limiting sea state, can then be conservative for a specific ship. Further discussion is needed before an approach is selected.

Given the above discussion, it is important to note that, although the presently derived limiting wave heights for the three containership types are very important indicators to reduce the risk of container

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[19] *For this reason MARIN performed additional tests in the summer of 2020 to get better insight in the distribution of the extremes. These results will be included in the update of this report.*

loss significantly, they cannot be considered as the final answer to prevent container loss completely. This is why we use the term ‘preliminary limiting wave heights’.

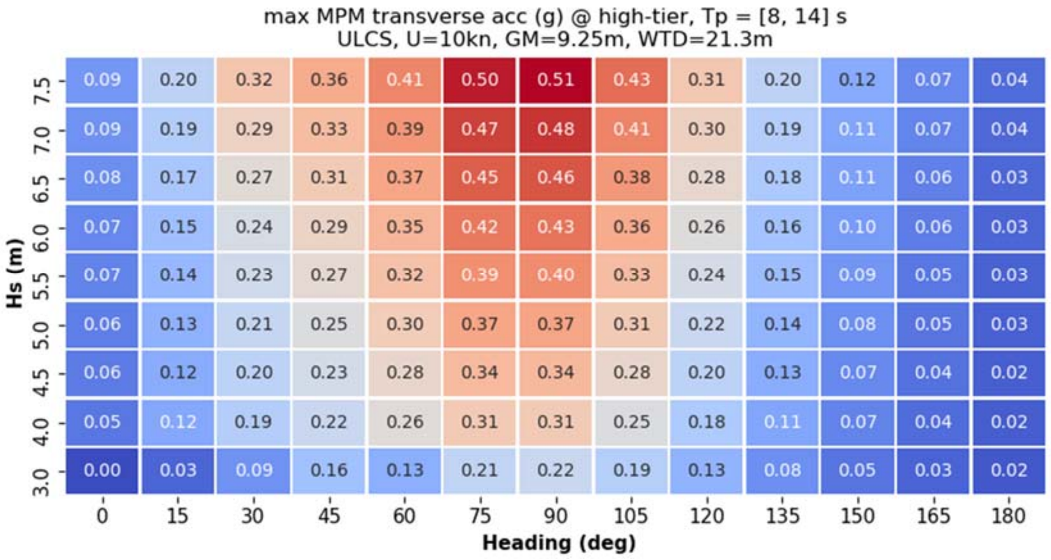
Another reason for using the word ‘preliminary’ is the variation in class criteria results for the limiting acceleration levels (see Chapter 5) and the differences in drafts and loading conditions that can occur for the ships sailing in this area.

6.3 Extreme (wave-frequency) ship motions and accelerations

To derive the preliminary limiting wave heights as a result of the transverse accelerations, the calculated accelerations were compared with the acceleration criteria of the different class societies. The lowest acceleration level provided by the class societies is used to derive the preliminary limiting wave heights. For each significant wave height in the Figures below, a realistic range of wave periods is used based on the wave scatter diagram of the area (see section 2.3). The largest acceleration value for this range of wave periods is used as reference value for this significant wave height. More details can be found in Report 32558-3-SEA.

6.3.1 ULCS

An example of the Most Probable Maximum (MPM) transverse accelerations as function of wave height and wave direction for the ULCS is shown below:

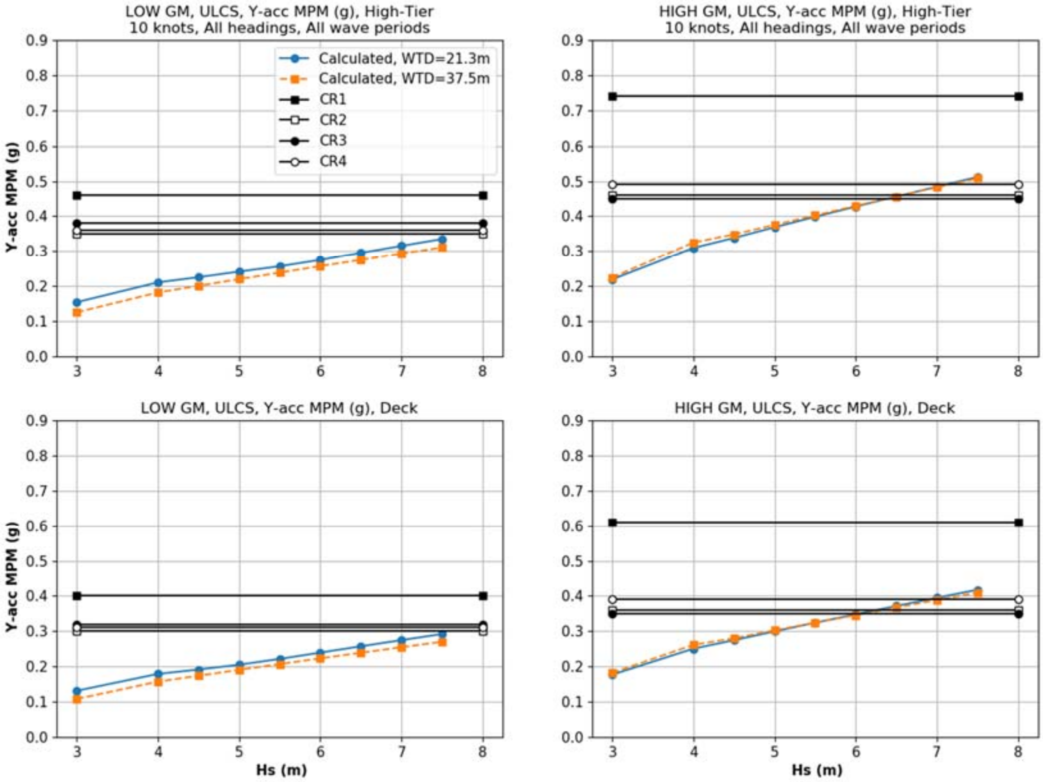


max MPM transverse acc (g) @ high-tier, Tp = [8, 14] s
ULCS, U=10kn, GM=9.25m, WTD=21.3m

Hs (m)	0	15	30	45	60	75	90	105	120	135	150	165	180
7.5	0.09	0.20	0.32	0.36	0.41	0.50	0.51	0.43	0.31	0.20	0.12	0.07	0.04
7.0	0.09	0.19	0.29	0.33	0.39	0.47	0.48	0.41	0.30	0.19	0.11	0.07	0.04
6.5	0.08	0.17	0.27	0.31	0.37	0.45	0.46	0.38	0.28	0.18	0.11	0.06	0.03
6.0	0.07	0.15	0.24	0.29	0.35	0.42	0.43	0.36	0.26	0.16	0.10	0.06	0.03
5.5	0.07	0.14	0.23	0.27	0.32	0.39	0.40	0.33	0.24	0.15	0.09	0.05	0.03
5.0	0.06	0.13	0.21	0.25	0.30	0.37	0.37	0.31	0.22	0.14	0.08	0.05	0.03
4.5	0.06	0.12	0.20	0.23	0.28	0.34	0.34	0.28	0.20	0.13	0.07	0.04	0.02
4.0	0.05	0.12	0.19	0.22	0.26	0.31	0.31	0.25	0.18	0.11	0.07	0.04	0.02
3.0	0.00	0.03	0.09	0.16	0.13	0.21	0.22	0.19	0.13	0.08	0.05	0.03	0.02

MPM transverse acceleration at high-tier location as function of wave heading and wave height (10 knots, high GM).

To derive the preliminary limiting wave heights, the calculated accelerations were compared with the acceleration criteria of the different class societies for the different water depths and stability (GM) values:



Comparison of calculated and class rule-based transverse accelerations (10 knots).

Combining the results for all ship speeds, gives the following overview table:

Southern route (21.3m), Speed = 0 to 10 knots & Northern route (37.5m), Speed = 0 to 10 knots									
GM condition	Container Location	CR1 AY (g)	Hs (m)	CR2 AY (g)	Hs (m)	CR3 AY (g)	Hs (m)	CR4 AY (g)	Hs (m)
Low GM (6.0 m)	High tier	0.46	> 7.5	0.35	> 7.5	0.38	> 7.5	0.36	> 7.5
	Deck	0.40	> 7.5	0.30	> 7.5	0.32	> 7.5	0.31	> 7.5
High GM (9.25 m)	High tier	0.74	> 7.5	0.46	≈ 6	0.45	≈ 6	0.49	≈ 7
	Deck	0.61	> 7.5	0.36	≈ 6	0.35	≈ 6	0.39	≈ 6.5

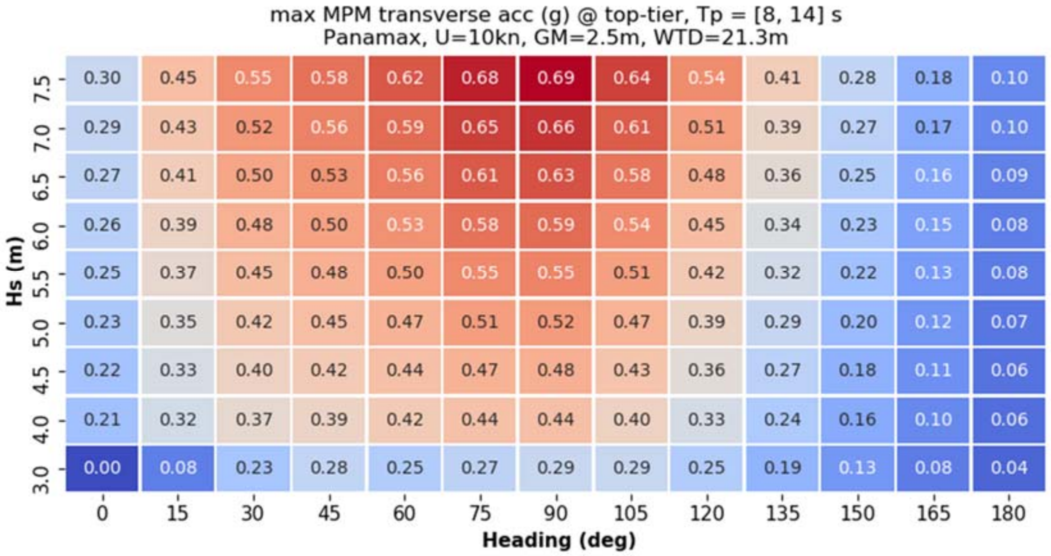
Limiting sea state height (Hs) given allowable transverse accelerations by class society (CR1 to CR4).

Based on the present findings (see for details Report 32558-3-SEA), the following is concluded:

- The largest transverse accelerations occur in beam seas condition.
- The transverse accelerations increase with increasing GM. The vertical accelerations are nearly independent from GM.
- Based on the lowest acceleration criteria of the class societies, the preliminary limiting wave heights for the ULCS are Hs=8.0m at low GM and Hs=6.0m at high GM (9.25m) for both routes.

6.3.2 Panamax

An example of the Most Probable Maximum (MPM) transverse accelerations as function of wave height and wave direction for the Panamax is shown below:

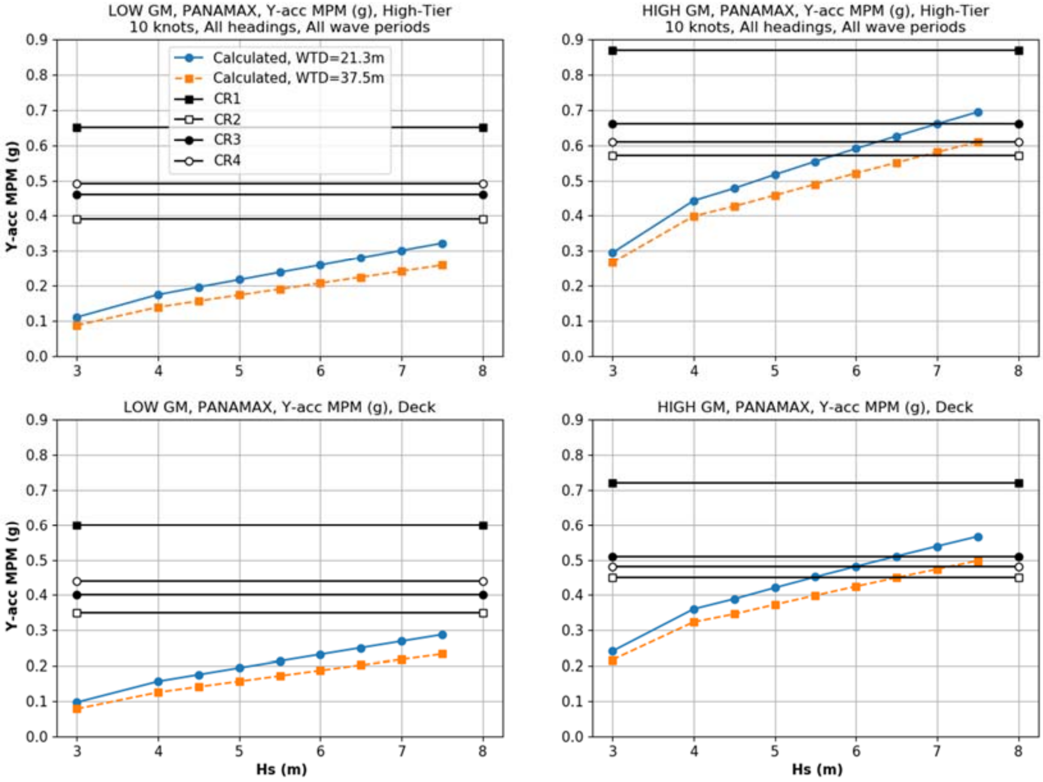


max MPM transverse acc (g) @ top-tier, Tp = [8, 14] s
Panamax, U=10kn, GM=2.5m, WTD=21.3m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
7.5	0.30	0.45	0.55	0.58	0.62	0.68	0.69	0.64	0.54	0.41	0.28	0.18	0.10
7.0	0.29	0.43	0.52	0.56	0.59	0.65	0.66	0.61	0.51	0.39	0.27	0.17	0.10
6.5	0.27	0.41	0.50	0.53	0.56	0.61	0.63	0.58	0.48	0.36	0.25	0.16	0.09
6.0	0.26	0.39	0.48	0.50	0.53	0.58	0.59	0.54	0.45	0.34	0.23	0.15	0.08
5.5	0.25	0.37	0.45	0.48	0.50	0.55	0.55	0.51	0.42	0.32	0.22	0.13	0.08
5.0	0.23	0.35	0.42	0.45	0.47	0.51	0.52	0.47	0.39	0.29	0.20	0.12	0.07
4.5	0.22	0.33	0.40	0.42	0.44	0.47	0.48	0.43	0.36	0.27	0.18	0.11	0.06
4.0	0.21	0.32	0.37	0.39	0.42	0.44	0.44	0.40	0.33	0.24	0.16	0.10	0.06
3.0	0.00	0.08	0.23	0.28	0.25	0.27	0.29	0.29	0.25	0.19	0.13	0.08	0.04

MPM transverse acceleration at high-tier location as function of wave heading and wave height (10 knots, high GM).

To derive the preliminary limiting wave heights, the calculated accelerations were compared with the acceleration criteria of the different class societies for the different water depths and stability (GM) values:



LOW GM, PANAMAX, Y-acc MPM (g), High-Tier
10 knots, All headings, All wave periods

HIGH GM, PANAMAX, Y-acc MPM (g), High-Tier
10 knots, All headings, All wave periods

LOW GM, PANAMAX, Y-acc MPM (g), Deck

HIGH GM, PANAMAX, Y-acc MPM (g), Deck

Comparison of calculated and class rule-based transverse accelerations (10 knots).

Combining the results for all ship speeds, gives the following overview table:

Southern route (21.3m), Speed = 0 to 10 knots									
GM condition	Container Location	CR1 AY (g)	Hs (m)	CR2 AY (g)	Hs (m)	CR3 AY (g)	Hs (m)	CR4 AY (g)	Hs (m)
Low GM (1.0 m)	Top tier	0.65	> 7.5	0.39	> 7.5	0.46	> 7.5	0.49	
	Deck	0.60	> 7.5	0.35	> 7.5	0.40	> 7.5	0.44	
High GM (2.5 m)	Top tier	0.87	> 7.5	0.57	5.7	0.66	7.0	0.61	
	Deck	0.72	> 7.5	0.45	5.5	0.51	6.5	0.48	

Northern route (37.5m), Speed = 0 to 10 knots									
GM condition	Container Location	CR1 AY (g)	Hs (m)	CR2 AY (g)	Hs (m)	CR3 AY (g)	Hs (m)	CR4 AY (g)	Hs (m)
Low GM (1.0 m)	Top tier	0.65	> 7.5	0.39	> 7.5	0.46	> 7.5	0.49	
	Deck	0.60	> 7.5	0.35	> 7.5	0.40	> 7.5	0.44	
High GM (2.5 m)	Top tier	0.87	> 7.5	0.57	6.9	0.66	> 7.5	0.61	
	Deck	0.72	> 7.5	0.45	6.7	0.51	≈7.5	0.48	

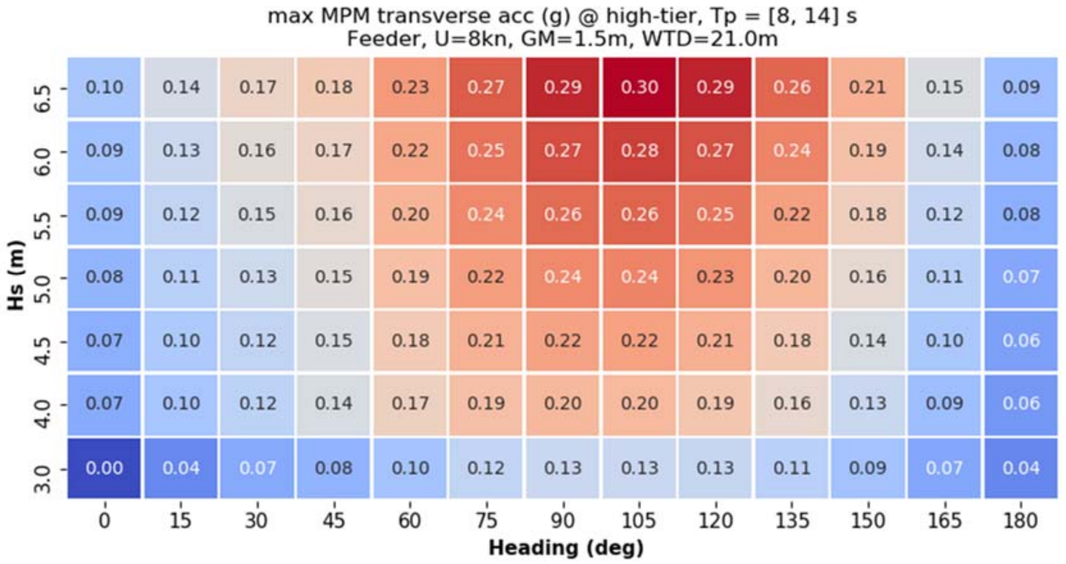
Limiting sea state height (Hs) given allowable transverse accelerations by class society (CR1 to CR4).

Based on the present findings (see for details Report 32558-3-SEA), the following is concluded:

- The largest transverse accelerations occur in beam seas condition.
- The transverse accelerations strongly increase with increasing GM. At GM=2.5m the accelerations are about 2.3 times larger than at GM=1.0m. The vertical accelerations are very similar for all GM conditions.
- The transverse accelerations *decrease* with about 10% on the northern route. The vertical accelerations *increase* by about 15%.
- Based on the lowest acceleration criteria of the class societies and highest GM value, the preliminary limiting wave heights for the Panamax are Hs=5.5m on the southern route and Hs=6.5m on the northern route.

6.3.3 Feeder

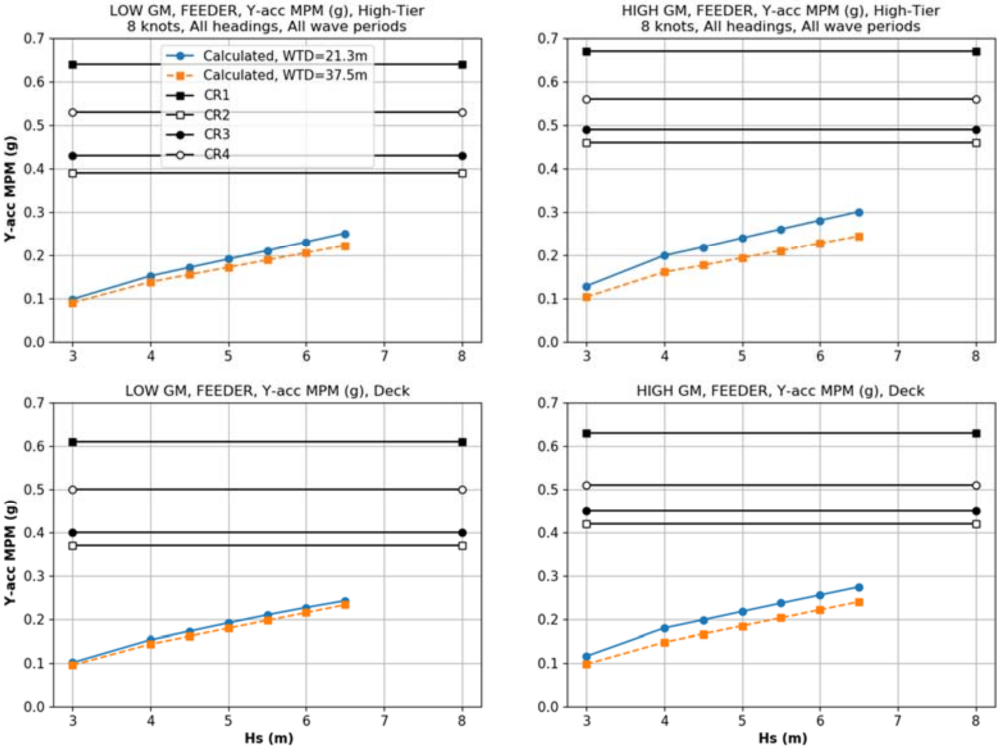
An example of the Most Probable Maximum (MPM) transverse accelerations as function of wave height and wave direction for the Feeder is shown below:



Hs (m)	0	15	30	45	60	75	90	105	120	135	150	165	180
6.5	0.10	0.14	0.17	0.18	0.23	0.27	0.29	0.30	0.29	0.26	0.21	0.15	0.09
6.0	0.09	0.13	0.16	0.17	0.22	0.25	0.27	0.28	0.27	0.24	0.19	0.14	0.08
5.5	0.09	0.12	0.15	0.16	0.20	0.24	0.26	0.26	0.25	0.22	0.18	0.12	0.08
5.0	0.08	0.11	0.13	0.15	0.19	0.22	0.24	0.24	0.23	0.20	0.16	0.11	0.07
4.5	0.07	0.10	0.12	0.15	0.18	0.21	0.22	0.22	0.21	0.18	0.14	0.10	0.06
4.0	0.07	0.10	0.12	0.14	0.17	0.19	0.20	0.20	0.19	0.16	0.13	0.09	0.06
3.0	0.00	0.04	0.07	0.08	0.10	0.12	0.13	0.13	0.13	0.11	0.09	0.07	0.04

MPM transverse acceleration at high-tier location as function of wave heading and wave height (8 knots, GM=1.5m).

To derive the preliminary limiting wave heights, the calculated accelerations were compared with the acceleration criteria of the different class societies for the different water depths and stability (GM) values:



Comparison of calculated and class rule-based transverse accelerations (8 knots).

Combining the results for all ship speeds, gives the following overview table:

Southern route (21.3m), Speed = 0 to 8 knots & Northern route (37.5m), Speed = 0 to 8 knots									
GM condition	Container Location	CR1 AY (g)	Hs (m)	CR2 AY (g)	Hs (m)	CR3 AY (g)	Hs (m)	CR4 AY (g)	Hs (m)
Low GM (0.8 m)	High tier	0.64	> 6.5	0.39	> 6.5	0.43	> 6.5	0.53	> 6.5
	Deck	0.61	> 6.5	0.37	> 6.5	0.40	> 6.5	0.50	> 6.5
High GM (1.3 m)	High tier	0.67	> 6.5	0.46	> 6.5	0.49	> 6.5	0.56	> 6.5
	Deck	0.63	> 6.5	0.42	> 6.5	0.45	> 6.5	0.51	> 6.5

Limiting sea state height (Hs) given allowable transverse accelerations by class society (CR1 to CR4).

Based on the present findings (see for details Report 32558-3-SEA), the following is concluded:

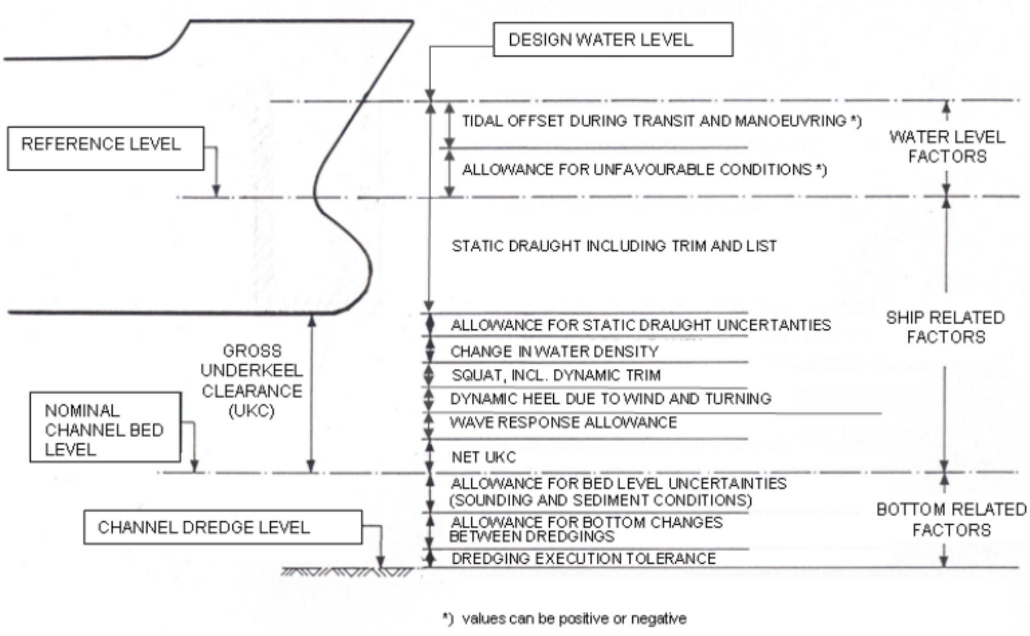
- The largest transverse accelerations occur in beam seas condition.
- The transverse accelerations increase with increasing GM.
- The accelerations will be similar on the northern and southern sailing routes.
- Based on the lowest acceleration criteria of the class societies, there is no preliminary limiting wave height for the Feeder in the investigated wave height range (up to Hs=7.5m).

6.4 Contact with the seabed

6.4.1 Dynamic Under Keel Clearance (dUKC) and wave response allowance

Preventing grounding or other types of bottom contact, the Under Keel Clearance (UKC) is an important consideration in the design of ports and waterways. In the PIANC ‘Harbour approach channels – Design

Guidelines’[20] a number of factors are discussed that influence the under keel clearance, see the Figure below. The wave response allowance is the factor presently under investigation.



Channel depth factors (not on scale), source: PIANC

In the present investigation, the wave response is determined based on the calculations presented in Report 32558-3-SEA. Once the rigid body motions are known, the vertical motions at the keel can be calculated. This is done for the points at the hull extremity at the keel at vessel side and at the bow. The calculations provide the MPM of the absolute vertical motions, which is denoted as the wave response allowance (or ‘motion allowance’). Knowing the water depth, the vessel draft and the wave response allowance, the remaining dynamic Under Keel Clearance is known.

To illustrate the wave response allowance and dynamic UKC, a motion time trace is created in the Figure below. The absolute motions on the windward side of the vessel are shown to be significantly larger than on the leeward side of the vessel, an observation that agrees with the findings in the tests.

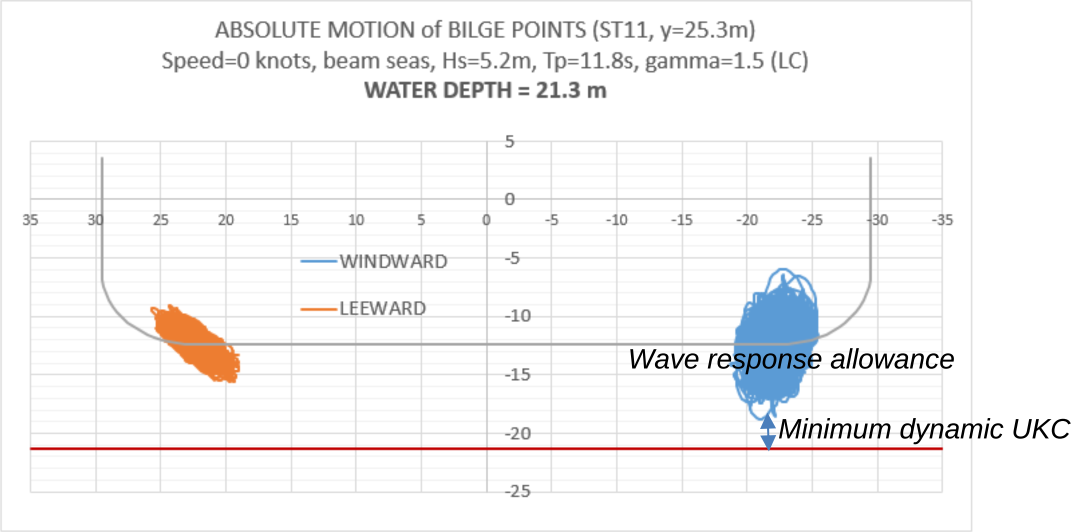


Illustration of wave response allowance and dynamic Under Keel Clearance (UKC) for the ULCS in shallow water of 21.3 m water depth. The Under Keel Clearance (UKC) in calm water is 8.9 m for this case.

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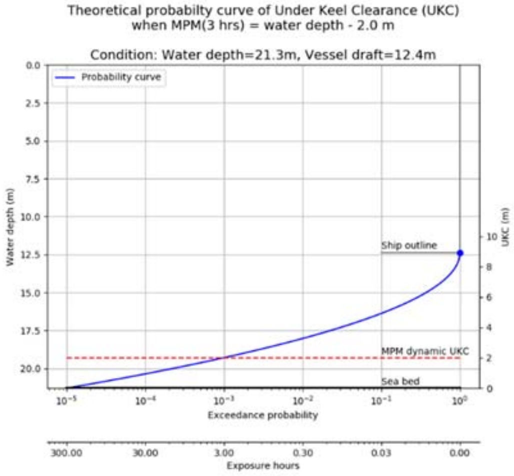
[20] *Report 121-2014*

To derive preliminary limiting wave heights to prevent bottom contact above the Wadden Islands, we have to realize that bottom contact is a critical event that requires hard criteria: the seabed should not be touched. However, ship motions in a seaway are a stochastic process that is determined by statistics and probabilities. Therefore MARIN proposes to use a minimum dynamic UKC of 2m as safety margin[21]: the Most Probable Maximum (MPM) vertical motion at any place at the keel (wave response allowance) should stay 2m from the seabed. We call this the required minimum dynamic UKC (dUKC).

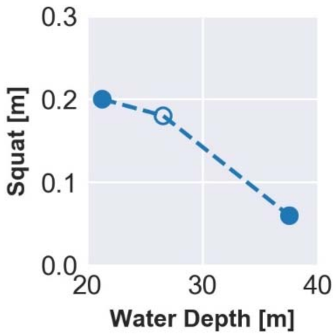
In Report 32558-3-SEA it is shown that, when we use the MPM in 3 hours as reference for the vertical motions of the keel (probability 10^{-3}), the probability that the keel touched the seabed is a factor 50 to 100 lower (10^{-5}). This is shown in the Figure below:



Probability of exceedance of the required minimum dynamic UKC of 2m (~10^{-3}), compared to the probability of touching the seabed (~10^{-5}).

The required minimum dynamic UKC of 2 metres as safety margin is also important to account for two other shallow water effects that were addressed in MARIN Report 31847-1-SHIPS ‘Behaviour of an Ultra Large Container Ship in shallow water’: squat (sinkage and trim) due to the interaction between the ship with forward speed and the seabed on one hand and set-down due to low frequency shallow water wave effects on the other hand.

The Figure below shows the squat of the ULCS at knots at the three water depths investigated:



Ship squat at 10 knots

The standard deviation of the set-down of the shallow water waves was in the order of 0.2 m for the most shallow water condition. Both effects need to be taken into account in the determination of the final limiting wave heights.

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[21] *This may need to be updated based on a long term risk analysis*

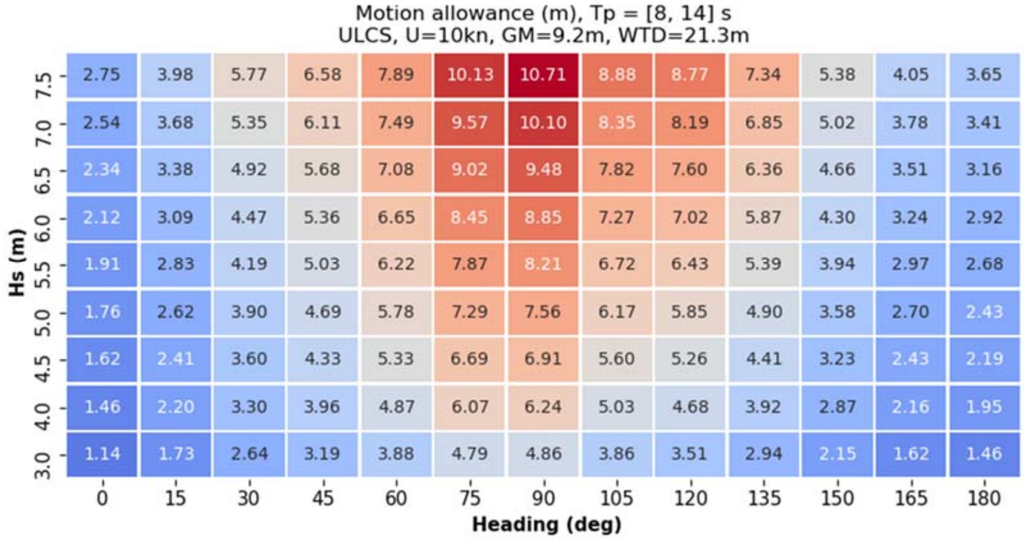
It should be noted that the derivation of limiting wave heights based on the required minimum dynamic UKC can only be done based on an actual water depth at the route and actual draft of the ship. Our present investigations focus on the minimum water depth during the MSC ZOE accident on January 1 and 2 of 2019 (21.3m) and the drafts of the 3 vessels under consideration. It should be noted, however, that at other locations along the route (for instance in the German part of the southern route) and in other tidal conditions even smaller water depths can occur. And although representative vessel types were selected (ULCS, Panamax and Feeder) for the present investigation, there is a variation in loading conditions and drafts within these vessel types (and for other ships sailing in this area).

To come to final limiting wave heights, it is important to perform an overall risk analysis that takes into account the long term distribution of weather conditions, water depth (bathymetry and tidal effects) and ship characteristics sailing in the area.

For each significant wave height in the Figures below, a realistic range of wave periods is used based on the wave scatter diagram of the area (see section 2.3). The largest wave response allowance (or 'motion allowance') for this range of wave periods is used as reference value for this significant wave height. More details can be found in Report 32558-3-SEA.

6.4.2 ULCS

The figure below shows an example of the wave response allowance (or motion allowance) of the ULCS: the MPM of the vertical motion anywhere at the keel for a ship speed of 10 knots and a high GM of 9.25m:

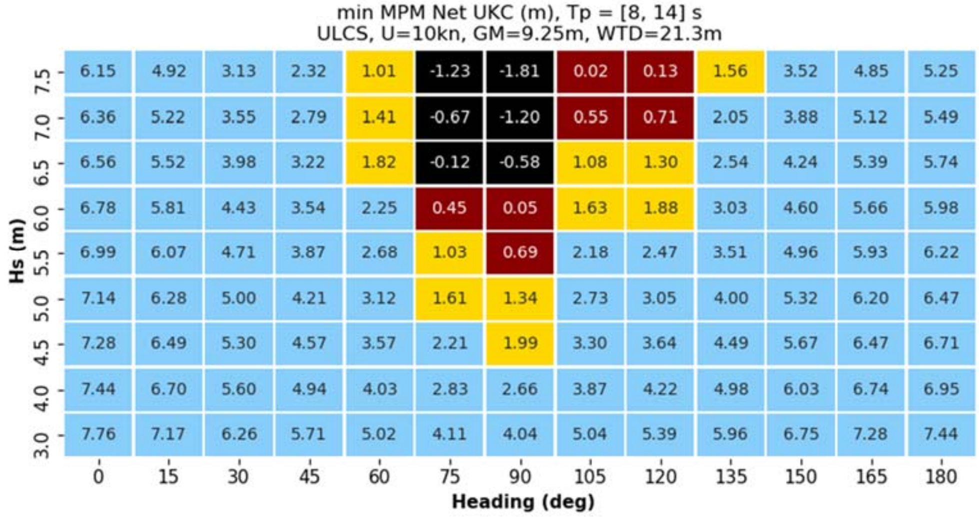


Motion allowance (m), Tp = [8, 14] s
ULCS, U=10kn, GM=9.2m, WTD=21.3m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
7.5	2.75	3.98	5.77	6.58	7.89	10.13	10.71	8.88	8.77	7.34	5.38	4.05	3.65
7.0	2.54	3.68	5.35	6.11	7.49	9.57	10.10	8.35	8.19	6.85	5.02	3.78	3.41
6.5	2.34	3.38	4.92	5.68	7.08	9.02	9.48	7.82	7.60	6.36	4.66	3.51	3.16
6.0	2.12	3.09	4.47	5.36	6.65	8.45	8.85	7.27	7.02	5.87	4.30	3.24	2.92
5.5	1.91	2.83	4.19	5.03	6.22	7.87	8.21	6.72	6.43	5.39	3.94	2.97	2.68
5.0	1.76	2.62	3.90	4.69	5.78	7.29	7.56	6.17	5.85	4.90	3.58	2.70	2.43
4.5	1.62	2.41	3.60	4.33	5.33	6.69	6.91	5.60	5.26	4.41	3.23	2.43	2.19
4.0	1.46	2.20	3.30	3.96	4.87	6.07	6.24	5.03	4.68	3.92	2.87	2.16	1.95
3.0	1.14	1.73	2.64	3.19	3.88	4.79	4.86	3.86	3.51	2.94	2.15	1.62	1.46

MPM of the wave response allowance (or motion allowance) of the ULCS: vertical motion at the keel

Based on these vertical motions, taking into account the vessel draft and water depth, the dynamic Under Keel Clearance (UKC) can be derived. The colors indicate the application of the criteria: blue (> 2.0 metres), yellow (between 1 and 2 metres), red (between 0 and 1 metre) and black (ship wants to penetrate the seabed):



min MPM Net UKC (m), Tp = [8, 14] s
ULCS, U=10kn, GM=9.25m, WTD=21.3m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
7.5	6.15	4.92	3.13	2.32	1.01	-1.23	-1.81	0.02	0.13	1.56	3.52	4.85	5.25
7.0	6.36	5.22	3.55	2.79	1.41	-0.67	-1.20	0.55	0.71	2.05	3.88	5.12	5.49
6.5	6.56	5.52	3.98	3.22	1.82	-0.12	-0.58	1.08	1.30	2.54	4.24	5.39	5.74
6.0	6.78	5.81	4.43	3.54	2.25	0.45	0.05	1.63	1.88	3.03	4.60	5.66	5.98
5.5	6.99	6.07	4.71	3.87	2.68	1.03	0.69	2.18	2.47	3.51	4.96	5.93	6.22
5.0	7.14	6.28	5.00	4.21	3.12	1.61	1.34	2.73	3.05	4.00	5.32	6.20	6.47
4.5	7.28	6.49	5.30	4.57	3.57	2.21	1.99	3.30	3.64	4.49	5.67	6.47	6.71
4.0	7.44	6.70	5.60	4.94	4.03	2.83	2.66	3.87	4.22	4.98	6.03	6.74	6.95
3.0	7.76	7.17	6.26	5.71	5.02	4.11	4.04	5.04	5.39	5.96	6.75	7.28	7.44

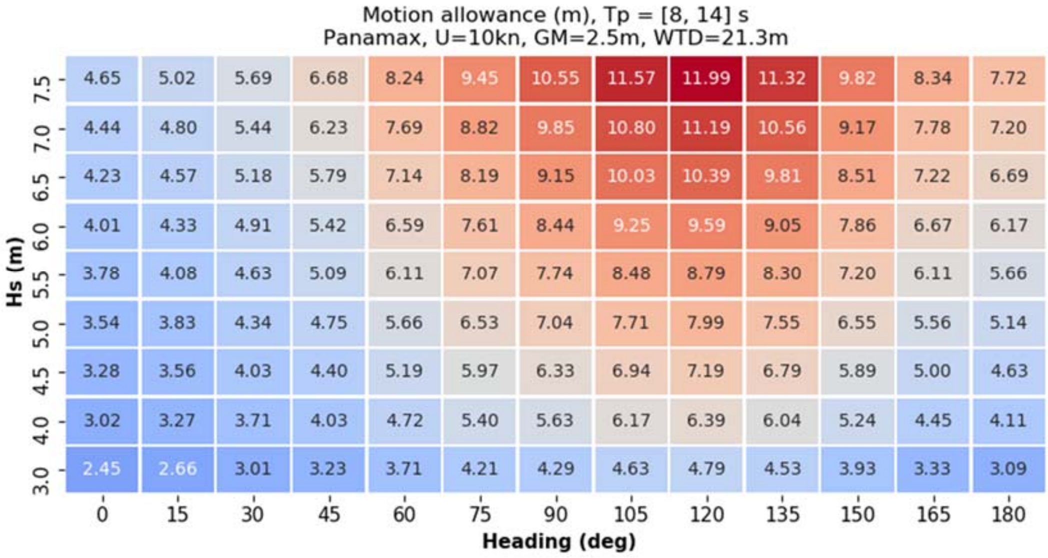
Minimum dynamic UKC in waves, GM=9.25m for speed of 10 knots.

Based on the present findings (see for details Report 32558-3-SEA), the following is concluded:

- The minimum dynamic UKC is affected by forward speed. The lowest dynamic UKC values are calculated in beam seas condition at zero forward speed.
- At low GM condition (GM=6m) the largest wave response allowance is found in bow quartering condition. When the GM is 9.25m or higher, the largest wave response allowance is found in beam seas condition due to the increase of roll motion.
- Requiring a minimum dynamic UKC of 2m, the limiting sea state for the ULCS is about Hs=4.5m for 0 to 10 knots forward speed range for beam sea conditions.
- An ULCS with a GM values exceeding 9.25m will experience critical UKC values is sea states well below Hs=4.5m for beam sea conditions.
- In head, stern and quartering seas condition there is no risk for bottom contact. The ULCS remains at least 5 to 6 m away from the sea bed in the highest sea states in any GM condition.

6.4.3 Panamax

The figure below shows an example of the wave response allowance (or motion allowance) of the Panamax: the MPM of the vertical motion anywhere at the keel for a ship speed of 10 knots and a high GM of 2.5m:

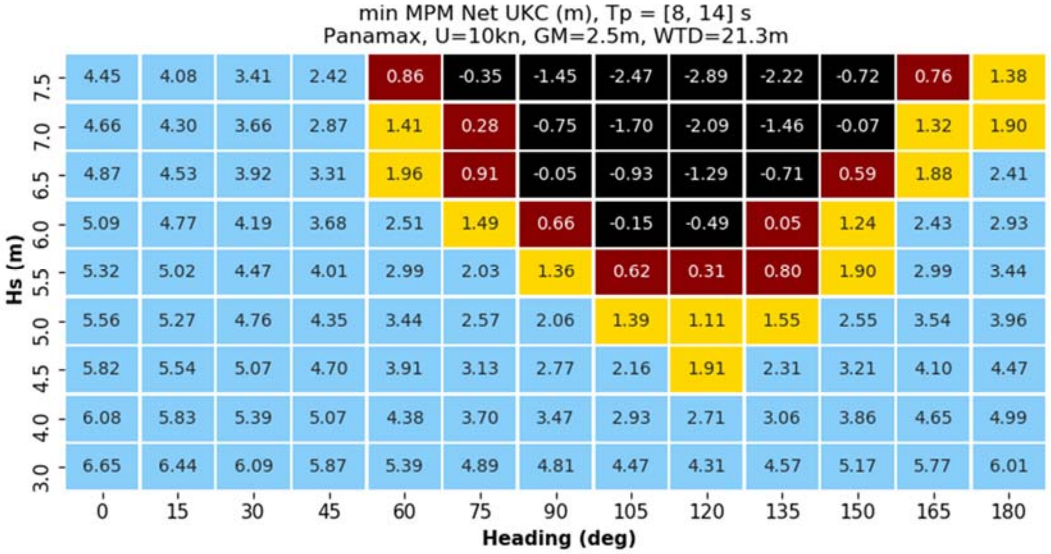


Motion allowance (m), Tp = [8, 14] s
Panamax, U=10kn, GM=2.5m, WTD=21.3m

Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
7.5	4.65	5.02	5.69	6.68	8.24	9.45	10.55	11.57	11.99	11.32	9.82	8.34	7.72
7.0	4.44	4.80	5.44	6.23	7.69	8.82	9.85	10.80	11.19	10.56	9.17	7.78	7.20
6.5	4.23	4.57	5.18	5.79	7.14	8.19	9.15	10.03	10.39	9.81	8.51	7.22	6.69
6.0	4.01	4.33	4.91	5.42	6.59	7.61	8.44	9.25	9.59	9.05	7.86	6.67	6.17
5.5	3.78	4.08	4.63	5.09	6.11	7.07	7.74	8.48	8.79	8.30	7.20	6.11	5.66
5.0	3.54	3.83	4.34	4.75	5.66	6.53	7.04	7.71	7.99	7.55	6.55	5.56	5.14
4.5	3.28	3.56	4.03	4.40	5.19	5.97	6.33	6.94	7.19	6.79	5.89	5.00	4.63
4.0	3.02	3.27	3.71	4.03	4.72	5.40	5.63	6.17	6.39	6.04	5.24	4.45	4.11
3.0	2.45	2.66	3.01	3.23	3.71	4.21	4.29	4.63	4.79	4.53	3.93	3.33	3.09

MPM of the wave response allowance (or motion allowance) of the Panamax: vertical motion at the keel

Based on these vertical motions, taking into account the vessel draft and water depth, the dynamic Under Keel Clearance (UKC) can be derived. The colors indicate the application of the criteria: blue (> 2.0 metres), yellow (between 1 and 2 metres), red (between 0 and 1 metre) and black (ship wants to penetrate the seabed):



Hs (m)	0	15	30	45	60	75	90	105	120	135	150	165	180
7.5	4.45	4.08	3.41	2.42	0.86	-0.35	-1.45	-2.47	-2.89	-2.22	-0.72	0.76	1.38
7.0	4.66	4.30	3.66	2.87	1.41	0.28	-0.75	-1.70	-2.09	-1.46	-0.07	1.32	1.90
6.5	4.87	4.53	3.92	3.31	1.96	0.91	-0.05	-0.93	-1.29	-0.71	0.59	1.88	2.41
6.0	5.09	4.77	4.19	3.68	2.51	1.49	0.66	-0.15	-0.49	0.05	1.24	2.43	2.93
5.5	5.32	5.02	4.47	4.01	2.99	2.03	1.36	0.62	0.31	0.80	1.90	2.99	3.44
5.0	5.56	5.27	4.76	4.35	3.44	2.57	2.06	1.39	1.11	1.55	2.55	3.54	3.96
4.5	5.82	5.54	5.07	4.70	3.91	3.13	2.77	2.16	1.91	2.31	3.21	4.10	4.47
4.0	6.08	5.83	5.39	5.07	4.38	3.70	3.47	2.93	2.71	3.06	3.86	4.65	4.99
3.0	6.65	6.44	6.09	5.87	5.39	4.89	4.81	4.47	4.31	4.57	5.17	5.77	6.01

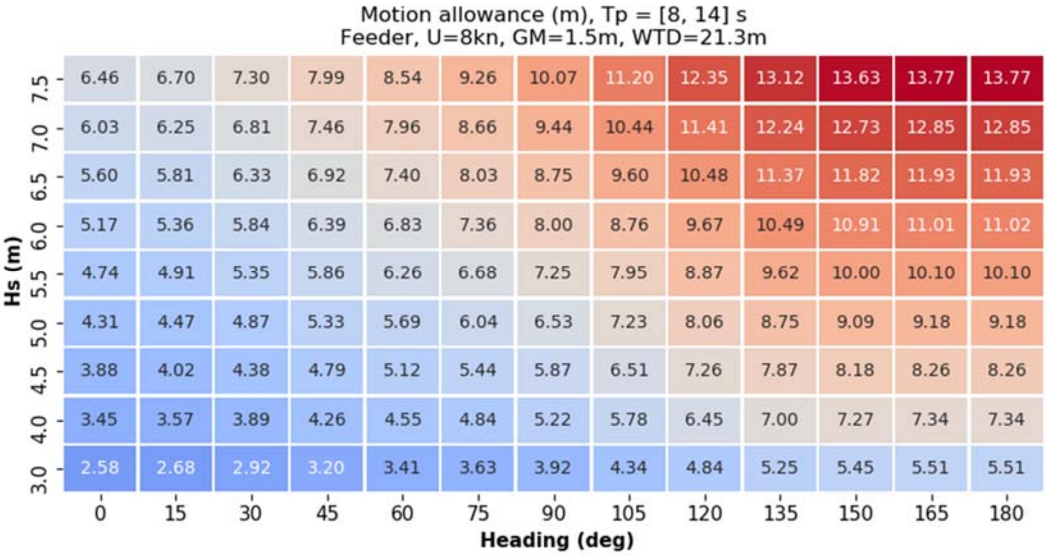
Minimum dynamic UKC in waves, GM=2.5m for speed of 10 knots.

Based on the present findings (see for details Report 32558-3-SEA), the following is concluded:

- The minimum dynamic UKC is not affected by forward speed.
- When the GM does not exceed 2.5m, the largest wave response allowance occurs in bow quartering condition at the bow of the vessel. The motion allowance is then about 1.60*Hs. In beam seas condition the wave response allowance is about 1.41*Hs.
- When the GM exceeds 2.5m the roll motions pick up and at GM=4m the wave response allowance in beam seas exceeds the allowance in bow quartering condition.
- Requiring a minimum dynamic UKC of 2m, the limiting sea state for the PANAMAX is about Hs=4.5m for bow quartering waves and 5m in beam seas when the GM does not exceed 2.5m. Otherwise the limiting sea state in beam seas drops to Hs=4m.
- When the GM does not exceed 2.5m, the dynamic UKC increases by about 0.5m or slightly more when the ship sails at 5 knots instead of 10 knots.

6.4.4 Feeder

The figure below shows an example of the wave response allowance (or motion allowance) of the Feeder: the MPM of the vertical motion anywhere at the keel for a ship speed of 8 knots and a high GM of 1.5m:

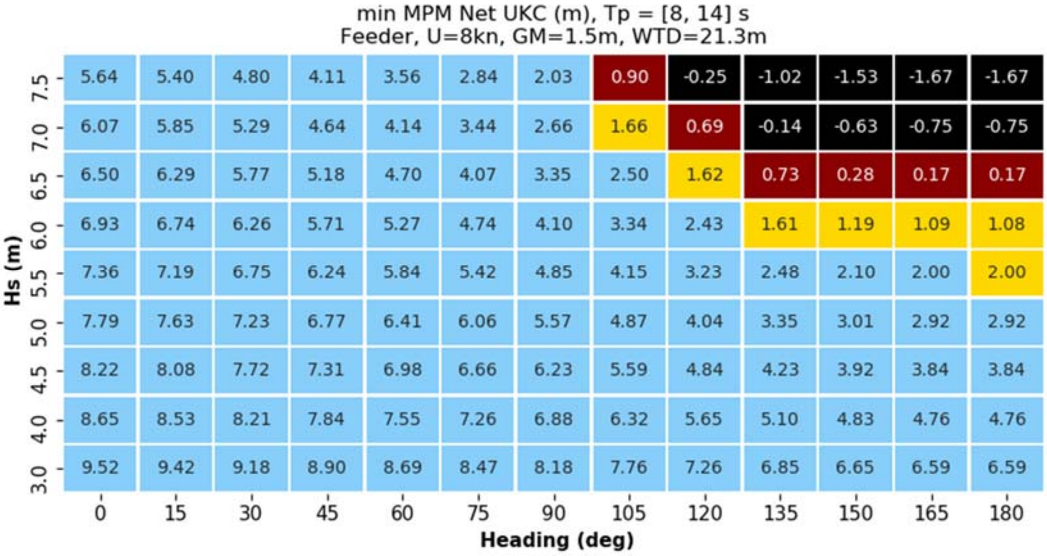


Motion allowance (m), Tp = [8, 14] s
Feeder, U=8kn, GM=1.5m, WTD=21.3m

Hs (m)	0	15	30	45	60	75	90	105	120	135	150	165	180
7.5	6.46	6.70	7.30	7.99	8.54	9.26	10.07	11.20	12.35	13.12	13.63	13.77	13.77
7.0	6.03	6.25	6.81	7.46	7.96	8.66	9.44	10.44	11.41	12.24	12.73	12.85	12.85
6.5	5.60	5.81	6.33	6.92	7.40	8.03	8.75	9.60	10.48	11.37	11.82	11.93	11.93
6.0	5.17	5.36	5.84	6.39	6.83	7.36	8.00	8.76	9.67	10.49	10.91	11.01	11.02
5.5	4.74	4.91	5.35	5.86	6.26	6.68	7.25	7.95	8.87	9.62	10.00	10.10	10.10
5.0	4.31	4.47	4.87	5.33	5.69	6.04	6.53	7.23	8.06	8.75	9.09	9.18	9.18
4.5	3.88	4.02	4.38	4.79	5.12	5.44	5.87	6.51	7.26	7.87	8.18	8.26	8.26
4.0	3.45	3.57	3.89	4.26	4.55	4.84	5.22	5.78	6.45	7.00	7.27	7.34	7.34
3.0	2.58	2.68	2.92	3.20	3.41	3.63	3.92	4.34	4.84	5.25	5.45	5.51	5.51

MPM of the wave response allowance (or motion allowance) of the Feeder: vertical motion at the keel

Based on these vertical motions, taking into account the vessel draft and water depth, the dynamic Under Keel Clearance (UKC) can be derived. The colors indicate the application of the criteria: blue (> 2.0 metres), yellow (between 1 and 2 metres), red (between 0 and 1 metre) and black (ship wants to penetrate the seabed):

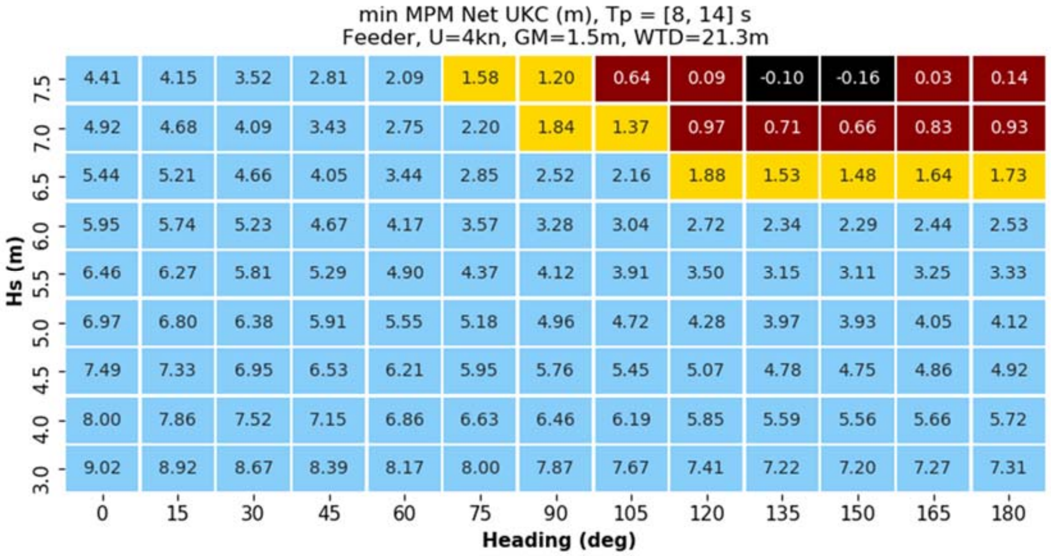


min MPM Net UKC (m), Tp = [8, 14] s
Feeder, U=8kn, GM=1.5m, WTD=21.3m

Hs (m)	0	15	30	45	60	75	90	105	120	135	150	165	180
7.5	5.64	5.40	4.80	4.11	3.56	2.84	2.03	0.90	-0.25	-1.02	-1.53	-1.67	-1.67
7.0	6.07	5.85	5.29	4.64	4.14	3.44	2.66	1.66	0.69	-0.14	-0.63	-0.75	-0.75
6.5	6.50	6.29	5.77	5.18	4.70	4.07	3.35	2.50	1.62	0.73	0.28	0.17	0.17
6.0	6.93	6.74	6.26	5.71	5.27	4.74	4.10	3.34	2.43	1.61	1.19	1.09	1.08
5.5	7.36	7.19	6.75	6.24	5.84	5.42	4.85	4.15	3.23	2.48	2.10	2.00	2.00
5.0	7.79	7.63	7.23	6.77	6.41	6.06	5.57	4.87	4.04	3.35	3.01	2.92	2.92
4.5	8.22	8.08	7.72	7.31	6.98	6.66	6.23	5.59	4.84	4.23	3.92	3.84	3.84
4.0	8.65	8.53	8.21	7.84	7.55	7.26	6.88	6.32	5.65	5.10	4.83	4.76	4.76
3.0	9.52	9.42	9.18	8.90	8.69	8.47	8.18	7.76	7.26	6.85	6.65	6.59	6.59

Minimum dynamic UKC in waves, GM=1.5m for speed of 8 knots.

The risks on bottom contact reduces with lower ship speed (4 knots):



Hs (m) \ Heading (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180
7.5	4.41	4.15	3.52	2.81	2.09	1.58	1.20	0.64	0.09	-0.10	-0.16	0.03	0.14
7.0	4.92	4.68	4.09	3.43	2.75	2.20	1.84	1.37	0.97	0.71	0.66	0.83	0.93
6.5	5.44	5.21	4.66	4.05	3.44	2.85	2.52	2.16	1.88	1.53	1.48	1.64	1.73
6.0	5.95	5.74	5.23	4.67	4.17	3.57	3.28	3.04	2.72	2.34	2.29	2.44	2.53
5.5	6.46	6.27	5.81	5.29	4.90	4.37	4.12	3.91	3.50	3.15	3.11	3.25	3.33
5.0	6.97	6.80	6.38	5.91	5.55	5.18	4.96	4.72	4.28	3.97	3.93	4.05	4.12
4.5	7.49	7.33	6.95	6.53	6.21	5.95	5.76	5.45	5.07	4.78	4.75	4.86	4.92
4.0	8.00	7.86	7.52	7.15	6.86	6.63	6.46	6.19	5.85	5.59	5.56	5.66	5.72
3.0	9.02	8.92	8.67	8.39	8.17	8.00	7.87	7.67	7.41	7.22	7.20	7.27	7.31

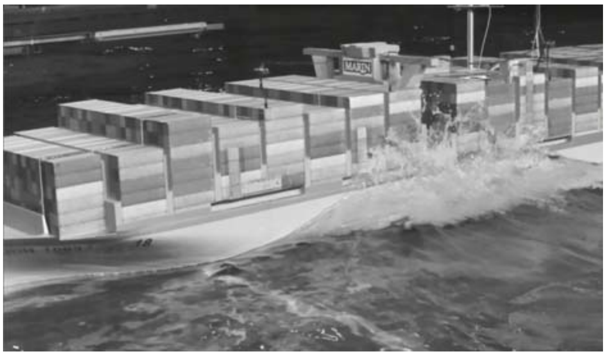
Minimum dynamic UKC in waves, GM=1.5m for speed of 4 knots.

Based on the present findings (see for details Report 32558-3-SEA), the following is concluded:

- There is no risk on bottom contact in beam seas condition in any sea state.
- The minimum under keel clearance for the Feeder will occur in (nearly) head seas condition at the bow of the ship.
- On the southern route, given a water depth of 21.3m, a vessel draft of 9.2m and a minimum required UKC of approximate 2m, the limiting wave height is Hs=5.5m for all GM conditions in case of (nearly) head seas. This occurs at the highest ship speed of 8 knots. At a lower ship speed, more realistic in these conditions, the limiting wave height increases to Hs=6.5m.
- As expected, there is no risk on bottom contact for a Feeder on the northern sailing route.

6.5 Impulsive green water loading against the containers

As indicated earlier, green water loading is a complex and non-linear phenomenon that can lead to damage of containers or can push over complete stacks of containers.



The resulting loads on the containers can be very large, see the tables below that indicate the total vertical force on the underside panel of a container and horizontal loads on the side panel of a container (of 30 m^2 on the bottom and 32 m^2 on the side) and the average pressure for the ULCS in shallow water of 21.3m.

	Vertical load	
Hs	Total load	Average pressure
[m]	[kN]	kPa
6.5	6234	209.7
7.5	22670	762.7

	Horizontal side load	
Hs	Total load	Average pressure
[m]	[kN]	kPa
6.5	2825	89.4
7.5	3790	120.0

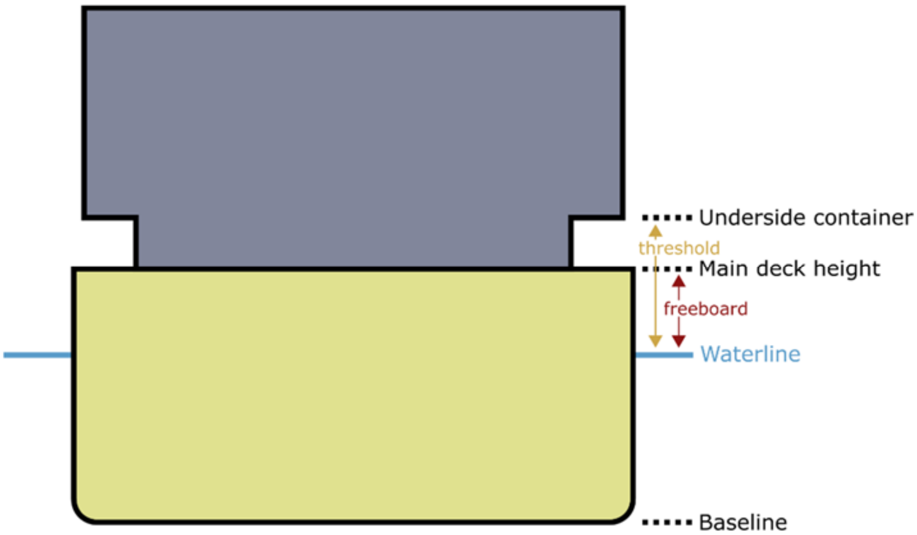
Maximum vertical load (top) and horizontal load (bottom) on the side container

If we compare these pressures with the allowable average pressures derived for a 40 ft container in Chapter 5, it is clear that the observed green water pressures are far above the allowable limits:

	Pressure at yielding limit	Pressure at the buckling limit
Side panel analysis	9.07 kPa	10.99 kPa
Front panel analysis	21.26 kPa	22.71 kPa

Limiting pressure and load values at yielding and buckling limits for a 40 ft container

Although the exact dynamic loading and response process of green water against (stacks of) containers needs further study, we concluded that for the derivation of the preliminary limiting wave heights the criterion should be that green water does not touch the containers. This can be ensured based on the criterion that the extreme relative wave motions along the side of the ship do not exceed the threshold of the lowest container, as shown in the Figure below:

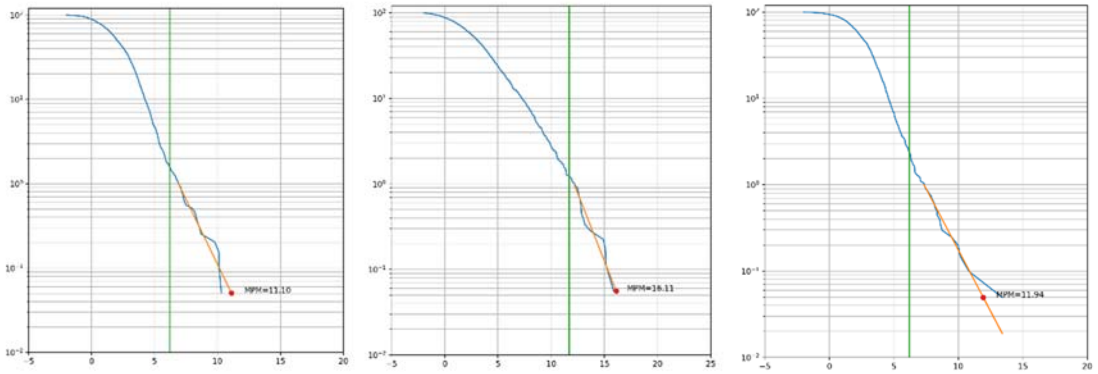


Definition of the freeboard (waterline to main deck level) and green water threshold for relative wave motions (waterline to underside container)

The values used are given in the Table below:

	ULCS	Panamax	Feeder
Freeboard	17.9 m	9.2 m	3.0 m
Threshold	20.4 m	11.7 m	5.5 m

Also in this case a Most Probable Maximum (MPM) values in 3 hour was used. The methodology to derive these MPM values for the relative wave motions is given in Report 32558-2-OB. As a result of the strongly non-linear behaviour of the relative wave motions and green water loading, the resulting MPM values need to be handled with care. The more non-linear the phenomenon is, the larger the uncertainty at low probability level. Further research is recommended to limit this uncertainty. Three examples of probability of exceedance plots of the relative wave motions and the determination of the 3 hours MPM values are given below:

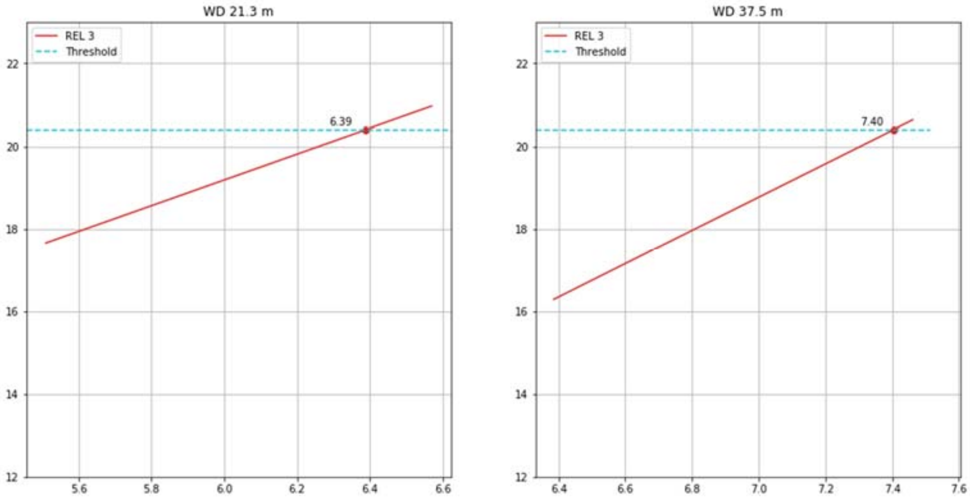


Examples of the determination of the 3 hours MPM value from the measured relative wave motions

The MPM estimates of the relative wave motions and associated significant wave heights for a given model set-up were subsequently fitted linearly, see the Figures below. The fit was the interpolated or extrapolated to derive the preliminary limiting wave heights. The preliminary limiting wave height is defined as the wave height, for which the MPM estimate is equal to the threshold to lowest container tier.

6.5.1 ULCS

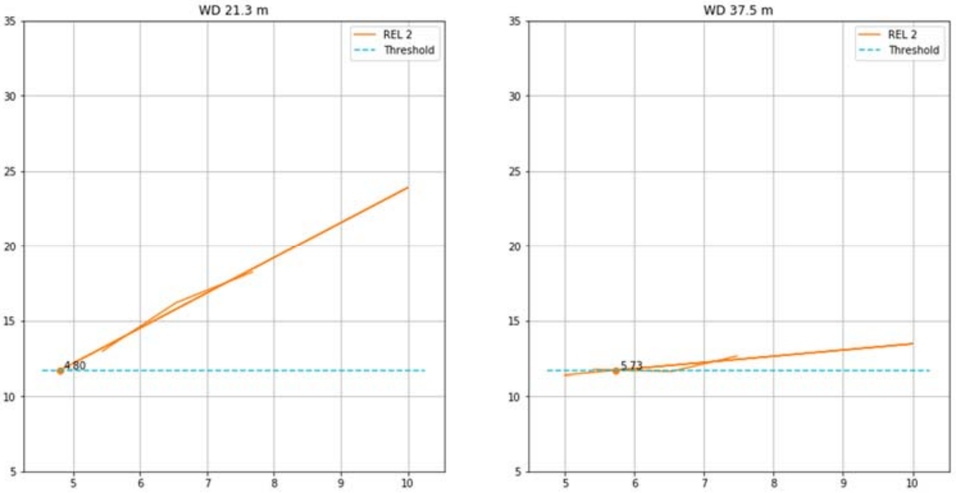
An estimation of the threshold wave height, above which the probability of experiencing green water is more than once in an exposure of three hours, yields a wave height of 6.4 m at a water depth of 21.3 m and 7.4 m at a water depth of 37.5 m.



Determination of the limiting wave height for green water of the ULCS based on the Most Probable Maximum (MPM) of the relative wave motions exceeding the threshold to the lowest container in a 3 hours storm.

6.5.2 Panamax

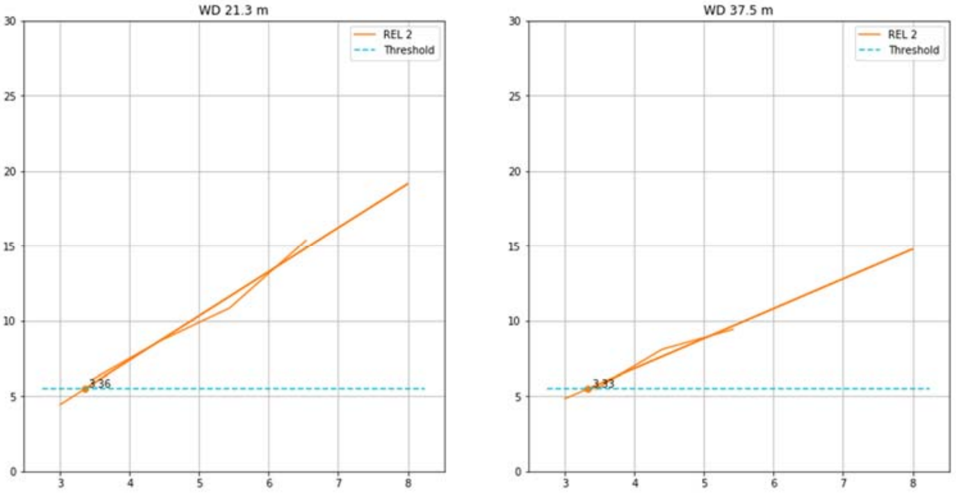
An estimation of the threshold wave height led to a value of 4.8 m in 21.3 m water depth and 5.7 m in 37.5 m water depth.



Determination of the limiting wave height for green water of the Panamax based on the Most Probable Maximum (MPM) of the relative wave motions exceeding the threshold to the lowest container in a 3 hours storm.

6.5.3 Feeder

An estimation of the threshold wave height led to a value of 3.4 m in 21.3 m water depth and 3.3 m in 37.5 m water depth. Contrary to the ULCS and Panamax ships, the threshold wave height is seen here to be little sensitive to water depth.



Determination of the limiting wave height for green water of the Feeder based on the Most Probable Maximum (MPM) of the relative wave motions exceeding the threshold to the lowest container in a 3 hours storm.

6.6 Summary of preliminary limiting wave heights

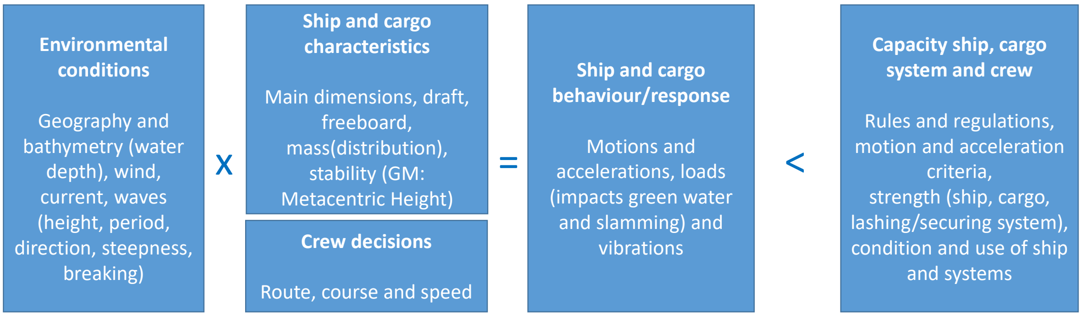
If we combine the results above for the three ship types and two routes, we come to the following overview of preliminary limiting wave heights (the bold criteria are the governing limiting phenomena per ship type and route)[22]. For the accelerations and bottom contact[23], all wave directions and occurring wave periods are considered. The limitations in wave height mainly occur with waves perpendicular to the route, or beam to the sailing direction (+/- 20 to 30 degrees) as the occurring phenomena are typically the strongest at these headings.

Route	**FEEDER** Assumptions: GM=0.8 to 1.5m 0 to 8 knots 9.20 m draft Freeboard 3.0 m	**PANAMAX** Assumptions: GM=1.0 to 2.5m 0 to 10 knots 12.20 m draft Freeboard 9.2 m	**ULCS** Assumptions: GM=6.0 to 9.25m 0 to 10 knots 12.40 m draft Freeboard 17.9 m
Northern route (37.5m water depth)	Hs > 7.5 m (accelerations) Hs > 7.5 m (bottom contact) **Hs ≈ 3.3 m (green water)**	Hs ≈ 6.5 m (accelerations) Hs > 7.5 m (bottom contact) **Hs ≈ 5.7 m (green water)**	**Hs ≈ 6 m (accelerations)** Hs > 7.5 m (bottom contact) Hs ≈ 7.4 m (green water)
Southern route (21.3m water depth)	Hs > 6.5 m (accelerations) Hs ≈ 5.5m (bottom contact)[24] **Hs ≈ 3.4 m (green water)**	Hs ≈ 5.5 m (accelerations) **Hs ≈ 4.5 m (bottom contact)** Hs ≈ 4.8 m (green water)	Hs ≈ 6 m (accelerations) **Hs ≈ 4.5 m (bottom contact)** Hs ≈ 5.9 m (green water)

In general the limiting wave heights in the shallow southern route are lower than in the northern deeper route: the risk of losing containers in the shallow southern route is higher than the deeper northern route.

However, also for the northern route limitations MARIN has derived preliminary limiting wave heights to prevent loss of containers. These limitations occur in beam seas relative to the route or ship heading.

To derive the final limiting wave heights to prevent container loss above the Wadden Islands, a long term (statistical) risk analysis is recommended. As indicated in the Figure below, this analysis should consider (the long term distribution of) the environmental conditions, the ship and cargo characteristics and the crew decisions (such as the course relative to the waves). It also requires transparency about the capacity of the ship and its cargo system (clear limiting criteria).



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[22] *For the limiting wave height for bottom contact the wave height is used at which the minimum dynamic UKC of 2 metres is reached, for the accelerations the lowest acceleration criteria of the 4 class societies is used and for green water the wave height at which the relative wave motions can reach the lowest container on the deck (threshold = freeboard+2.5m). In all cases the Most Probable Maximum (MPM) in a 3 hours storm is used.*

[23] *For the complex problem of green water only beam waves could be investigated at this stage.*

[24] *Possible bottom contact (minimum dynamic Under Keel Clearance < 2 m) is predicted for the Feeder for this wave height only in head waves and a speed of 8 knots. At a lower speed of 4 knots (more realistic in these conditions), the limiting wave height increases to 6.5 m.*

In more detail:

1. The present calculations and model tests were performed for a minimum water depth of 21.3 m, the minimum water depth on the southern sailing route during the MSC ZOE accident. It should be noted, however, that at other locations along the route (for instance in the German part of the southern route) and in other tidal conditions even smaller water depths can occur. Also the long term probability of the wave heights (and periods) needs to be taken into account, as well as the accuracy of the wave predictions. This requires a more detailed study of the bathymetry and longterm metocean conditions in the area (tides and waves).

2. The present investigations are focused on three typical containerships sailing in this area (ULCS, Panamax and Feeder) with their characteristics. However, within these ship classes and for other (intermediate or smaller) ships sailing in this area, still differences in draft, freeboard and loading condition can occur that might affect the seakeeping behaviour.

3. The present investigations focused on the three most important phenomena determined in the previous phase: extreme (wave-frequency) ship motions and accelerations, contact with the seabed and impulsive green water loading against the containers. The 4th mechanism, slamming induced impulsive loading on the hull, could not be quantified with the present model tests. Although it is assumed that the first three phenomena are dominant in the loss of containers above the Wadden Islands, this issue should not be forgotten in future investigations.

4. Accelerations from class rules were used as criteria for the transverse acceleration. The presented large variations between class rule values for extreme accelerations in lashing design calculations, illustrate the uncertainties in these criteria.

5. The behaviour of the ship is evaluated based on the statistical Most Probable Maximum (MPM) in 3 hours. Using a Most Probable Maximum (MPM) for a period of N hours is a generally applied methodology in Naval Architecture, but it is important to realize that an MPM value is not the highest value that can occur. This is one of the reasons why safety factors/margins are taken into account. This is especially relevant for complex (non-linear) phenomena such as green water and slamming. In the determination of the final limiting wave heights it is also important to take into account the storm duration (persistence) and time the ships are actually sailing in these conditions above the Wadden Islands.

6. The present investigations focus on the behaviour of the ships in waves. Tidal current and wind were not part of the study. Heeling of a ship in wind can reduce the dynamic Under Keel Clearance (dUKC).

7. Squat (sinkage and trim) due to the interaction between the ship with forward speed and the seabed and set-down due to low frequency shallow water wave effects should be taken into account explicitly in the determination of the minimum dUKC.

The determination of the final limiting wave heights requires the definition of an acceptable risk level for losing containers close to this Particularly Sensitive Sea Area (PSSA) by the government. This also requires a more transparent and consistent input on the acceptable acceleration levels from international organizations such as IMO and the class societies.

7 SUMMARY AND RECOMMENDATIONS

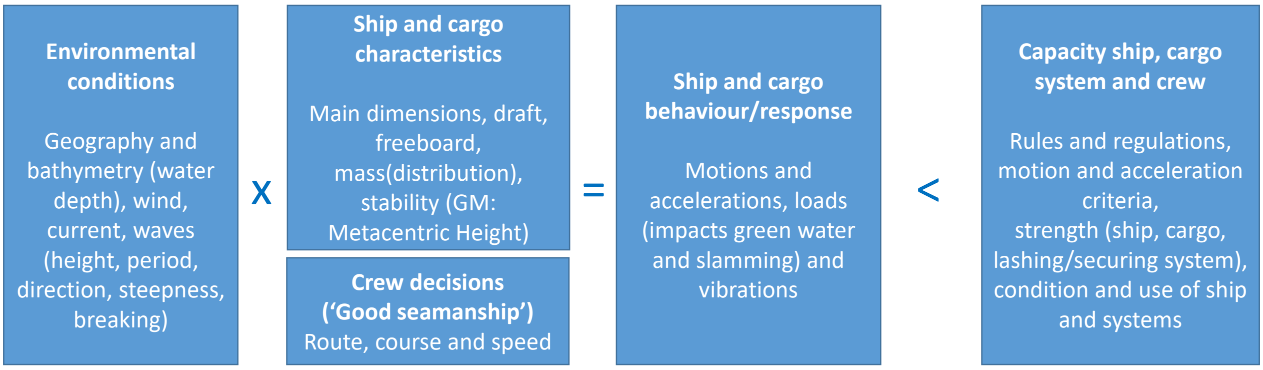
7.1 Summary

In the evening and night of January 1 to 2 of 2019, the Ultra Large Container Ship (ULCS) MSC ZOE lost 342 containers north of the Wadden Islands while sailing along the Terschelling-German Bight Traffic Separation Scheme (TSS) to Bremerhaven in north-westerly storm conditions. This resulted in large-scale pollution of the sea and Wadden Islands. As part of its investigations with the Dutch Safety Board (OVV), MARIN concluded that the most probable explanations for the loss of containers are:

1. Extreme (wave-frequency) ship motions and accelerations
2. Ship contact with the sea bottom
3. Lifting forces and impulsive loading on containers due to green water
4. Slamming-induced impulsive loading on the hull.

To prevent future loss of containers close to this Particularly Sensitive Sea Area (PSSA), the Ministry of Infrastructure and Water Management asked MARIN to investigate also other container ship types: beside Ultra Large Container Ships as the MSC ZOE (ULCS, typical length 379 m, beam 59 m), a shorter and narrower Panamax (typical length 279 m, beam 32 m) and a smaller container Feeder (typical length 163 m, beam 27 m). The importance of testing smaller ships was underscored when the feeder ‘Rauma’ lost 7 containers on February 11th 2020 in a significant wave height of approximately 4.5 to 5m.

Containership behaviour in storm conditions is a result of the interaction between the environmental conditions and the characteristics of the ship with its cargo. The ship response can be influenced by the decisions of the crew with respect to route, course and speed (‘Good seamanship’). A ship and its cargo are safe when their behaviour and loads are below the capacity (safe values) of the design. Damage can occur and containers can be lost when the loads on the ship and cargo exceeds the (structural) capacity of the cargo and/or its securing equipment:



In this step in the follow-up study for the Ministry of Infrastructure and Water Management, MARIN investigated based on model tests, calculations and literature research how three containership types behave in the complex conditions above the Wadden in the shallow southern route directly above the Wadden Islands and the deeper northern route and what this means for the loss of containers.

Based on the results of the present investigations (and the assumptions as summarized in the table and in sections 6.2 and 6.6) MARIN derived **preliminary limiting wave heights** for these ship types and routes. For the accelerations and bottom contact[25], all wave directions and occurring wave periods are considered. The limitations in wave height mainly occur with waves perpendicular to the route, or beam to the sailing direction (+/- 20 to 30 degrees) as the occurring phenomena are typically the strongest at these headings.

With wave heights above these preliminary limiting wave heights, the loading on the ships and their cargoes can exceed their capacity (safe values). The bold criteria are the governing limiting phenomena per ship type and route[26]:

Route	**FEEDER** Assumptions: GM=0.8 to 1.5m 0 to 8 knots 9.20 m draft Freeboard 3.0 m	**PANAMAX** Assumptions: GM=1.0 to 2.5m 0 to 10 knots 12.20 m draft Freeboard 9.2 m	**ULCS** Assumptions: GM=6.0 to 9.25m 0 to 10 knots 12.40 m draft Freeboard 17.9 m
Northern route (37.5m water depth)	Hs > 7.5 m (accelerations) Hs > 7.5 m (bottom contact) **Hs ≈ 3.3 m (green water)**	Hs ≈ 6.5 m (accelerations) Hs > 7.5 m (bottom contact) **Hs ≈ 5.7 m (green water)**	**Hs ≈ 6 m (accelerations)** Hs > 7.5 m (bottom contact) Hs ≈ 7.4 m (green water)
Southern route (21.3m water depth)	Hs > 6.5 m (accelerations) Hs ≈ 5.5m (bottom contact)[27] **Hs ≈ 3.4 m (green water)**	Hs ≈ 5.5 m (accelerations) **Hs ≈ 4.5 m (bottom contact)** Hs ≈ 4.8 m (green water)	Hs ≈ 6 m (accelerations) **Hs ≈ 4.5 m (bottom contact)** Hs ≈ 5.9 m (green water)

Preliminary limiting wave heights for the three ship types and southern and northern routes.

In general the limiting wave heights in the shallow southern route are lower than in the northern deeper route: the risk of losing containers in the shallow southern route is higher than the deeper northern route.

However, also for the northern route limitations MARIN has derived preliminary limiting wave heights to prevent loss of containers. These limitations occur in beam seas relative to the route or ship heading.

7.2 Recommendations

These **preliminary limiting wave heights** for these three containership types are important to reduce the risk of container loss significantly. We recommend to use these wave heights and other findings in this report for the decision making about the use of the routes above the Wadden Islands and the advice of the Coast Guard to ships sailing in the area.

Large roll motions and green water are, as mentioned, generally the strongest with waves perpendicular to the route, or beam to the sailing direction. When this type of behaviour occurs, sailing with low speed head into the waves is wise as part of good seamanship.

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[25] *For the complex problem of green water only beam waves could be investigated at this stage.*

[26] *For the limiting wave height for bottom contact the wave height is used at which the minimum dynamic UKC of 2 metres is reached, for the accelerations the lowest acceleration criteria of the 4 class societies is used and for green water the wave height at which the relative wave motions can reach the lowest container on the deck (threshold = freeboard+2.5m). In all cases the Most Probable Maximum (MPM) in a 3 hours storm is used.*

[27] *Possible bottom contact (minimum dynamic Under Keel Clearance < 2 m) is predicted for the Feeder for this wave height only in head waves and a speed of 8 knots. At a lower speed of 4 knots (more realistic in these conditions), the limiting wave height increases to 6.5 m.*

To determine the **final limiting wave heights** to prevent container loss above the Wadden Islands, a long term (statistical) risk analysis is recommended. As indicated in the Figure at the beginning of this Chapter, it is important to consider in this analysis (the long term distribution of) the environmental conditions, the ship and cargo characteristics and the crew decisions (such as the course relative to the waves). The aspects that are recommend for this risk analysis are given in this report (section 6.6). The determination of the final limiting wave heights requires the definition of an acceptable risk level for losing containers close to this Particularly Sensitive Sea Area (PSSA) by the government.

It is also recommended to further investigate the complex problem of water loading on the containers, especially for smaller ships such as Feeders with their low freeboard. Green water loading is the limiting factor for this type of ship on both routes. The (statistics of the) the complex non-linear relative wave motions and impacts loads and response of (stacks of) containers need further study to determine the risk level and limiting wave heights more accurately. Also the freeboard height plays an important role in this. We recommend to consider, beside beam waves, also head and bow quartering waves in this investigation. Changing heading with the bow into the waves at slow speed seems a logical decision with large roll motions and green water in beam waves. However, it is important to investigate whether in head or bow quartering waves green water can also hit the containers from the side or over the bow. As part of this investigation we also recommended to further consider parametric rolling in head waves[28]. Parametric rolling in head waves might occur for unfavorable combinations of wave length, wave period and natural roll period. It should be prevented that the decision to head into the waves, results in large motions due to parametric rolling. Although an extra set of tests on this topic did not show parametric rolling with the present small Feeder model, further tests are recommend to make sure this problem does not occur (or can be prevented by clear instructions to the crews).
Finally it is recommended to investigate crew response to this type of situations: how do they react (from the perspective of good seamanship) when large roll motions and green water on the deck occurs?

The results presented in this report and the preliminary limiting wave heights make concrete the subjects that are mentioned in the IMO Intact Stability code[29]. As shown in Chapter 5 and the supporting report[30], the determination of **final limiting wave heights** requires a more transparent and consistent input on the acceptable acceleration levels from international organizations such as IMO and the class societies[31].

- Container vessel dimensions have increased substantially over past few decades. Limited experience and statistics are available to account for this steep rise in ship dimensions, developments with weather-routed navigation, extreme GM ranges of recent ship designs, and weather dependent reductions on acceleration levels that have become commonly accepted over the past 10 years. Rule values used in lashing calculations may be different from motions that are acceptable in practice. It is important to increase knowledge about extent and probabilistic of loads acting on containers on board modern ultra large container ships.

- The large variations between class rule values for extreme accelerations and motions in lashing design calculation, as shown in Chapter 5, illustrate the differences and uncertainties in various extreme motion prediction load case models. So the fidelity of the probability of exceedance of the design points in the rules is not transparent and cannot be easily verified. It is also unclear how flag state authorities maintain control over the standards that are imposed on the industry in their name.

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[28] *Parametric rolling is also considered in the IMO 2nd generation intact stability criteria, but these do not consider explicitly the situation of high (breaking) waves in shallow water.*

[29] *See sections 3.7.5, 5.1.6 and 5.3.6 of Resolution MSC.267(85), adopted on 4 December 2008.*

[30] *MARIN Report 32558-5-PaS: 'Container securing, Overview current practice & regulatory framework'.*

[31] *Zoals SOLAS Chapter VI, de IMO 'Code of Safe Practice for Cargo Stowage and Securing' (CSS Code) en de 'class guidelines' voor 'container securing' van de verschillende classificatiemaatschappijen.*

- Good seamanship is essential to keep actual loads on cargo inside the limitations of the securing arrangements. However, there is at present no mandatory equipment on board to measure actual ship motions and accelerations. So ship crews do not always have means to relate actual vessel response to design points that are used in the lashing calculations. Also, the crew often doesn't know the rule design values that were used in lashing calculations. It is therefore recommended to support the crews of containership in a better way with the decision processes on board, so that they can recognize developing problems during operations and react.

We therefore recommend the government of The Netherlands to ask international attention for these important aspects based on the findings summarized in Chapter 5 and the supporting report.

Finally it is recommend to extend the investigations in the risk of losing containers along the Dutch cost to other areas of the North Sea, that also can show the combination of shallow water with high waves in some storm conditions.

Wageningen, September 2020
MARITIME RESEARCH INSTITUTE NETHERLANDS

Dr.ir. B. Buchner
President

SHORT LIST OF ABBREVIATIONS, ACRONYMS, SYMBOLS AND UNITS

Abbreviations and acronyms

CSM	Cargo Securing Manual
CSS	Cargo Stowage and Securing
FS	Free-Surface
LC	Long-Crested (waves)
MARIN	Maritime Research Institute of the Netherlands
MI&W	Ministry of Infrastructure and Water Management
MPM	Most Probable Maximum
MSC	Mediterranean Shipping Company
NACA	National Advisory Committee for Aeronautics
SC	Short-Crested (waves)
TSS	Traffic Separation Scheme
UKC	Underwater Keel Clearance
ULCS	Ultra Large Container Ship (with capacity of 10,000 TEU or higher)

Symbols

B	Ship breadth, ship damping coefficient
C	Ship stiffness coefficient
COG, CoG	Centre of Gravity
CB	Block Coefficient
D	Ship Depth
EGA	Effective Gravity Angle
F	Excitation force or moment
g	Gravity (9.81 m/s^2)
GM	Metacentric height
GZ	Buoyancy-induced restoring moment lever arm, measure for ship stability
Hs	Significant wave height
kxx	Ship radius of inertia with respect to the roll motion
kyy	Ship radius of inertia with respect to the pitch motion
kzz	Ship radius of inertia with respect to the yaw motion
LPP	Ship length between perpendiculars
M	Ship mass or inertia
MPM	Most Probable Maximum (see section 6.2)
NOCC	Number of occurrences
std	Standard deviation
T	Ship draught
T1	Mean period of irregular process (e.g. wave, motion)
TA	Ship draught at aft perpendicular
Texp	Exposure time
TF	Ship draught at fore perpendicular
Tp	Wave peak period
Vs	Ship speed
x	Motion in mode x (surge, sway, heave, roll, pitch yaw)
$\dot{x}$	Velocity in mode x (surge, sway, heave, roll, pitch yaw)
$\ddot{x}$	Acceleration in mode x (surge, sway, heave, roll, pitch yaw)
μ	Mean wave heading
σ	Standard deviation

Units

m	metre
kn	knot
rad	radian
s	second
deg	degree
min	minute
N, kN	Newton, kilo Newton

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